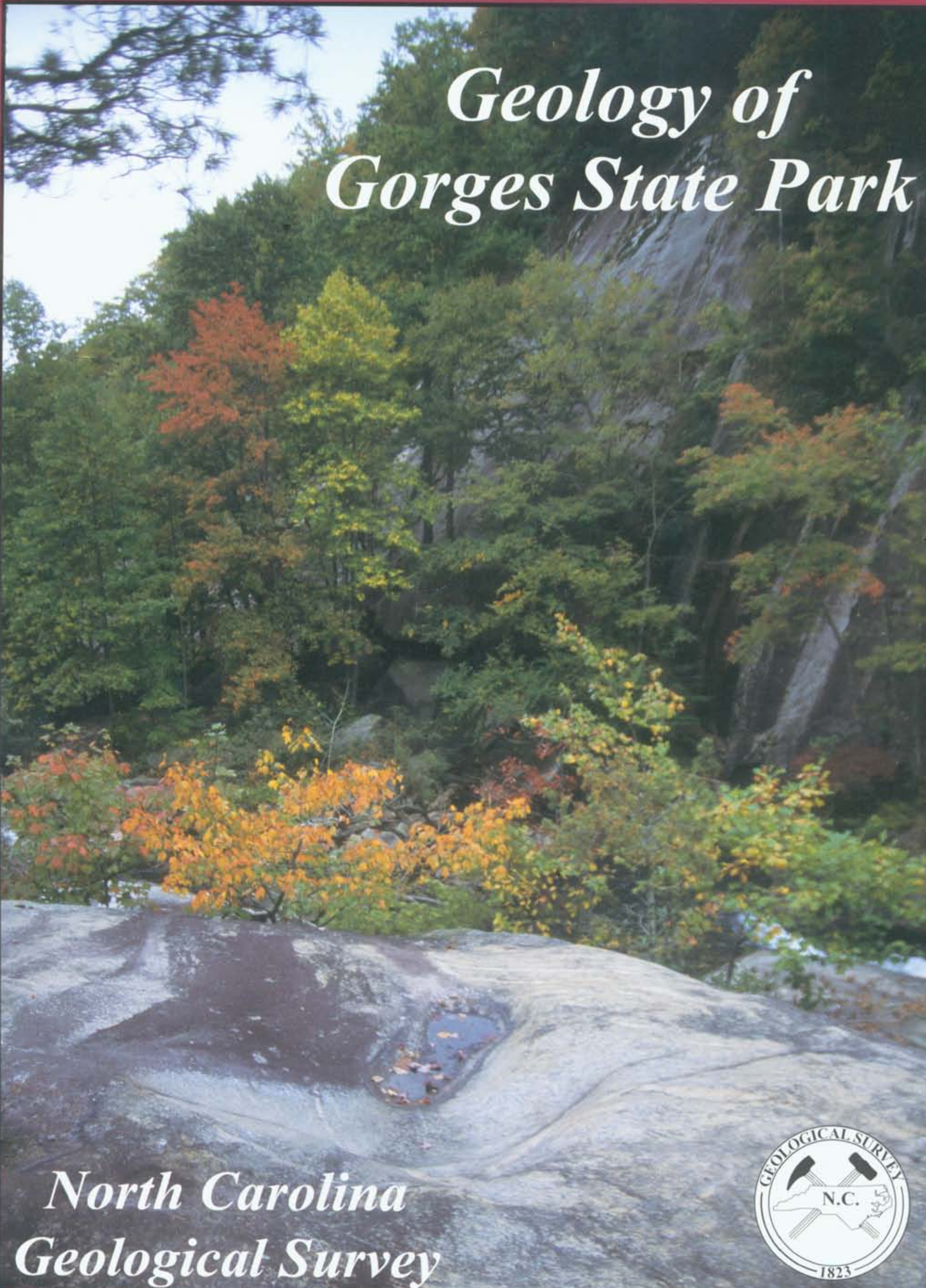
# Geology of Gorges State Park



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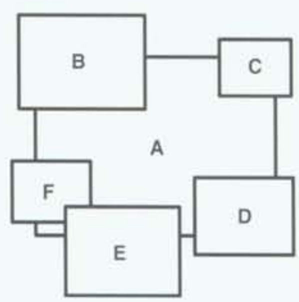


**Front Cover:** *Fall colors against cliffs of Toxaway Gneiss at The Narrows along the Toxaway River. Inside Front Cover: Photomosaic of some of the many geologic scenes in Gorges State Park.* ***A:*** *Flood deposited boulder in Toxaway Creek on a cool fall day.* ***B:*** *Waterfall along Auger Fork Creek at its confluence with Maple Springs Branch.* ***C:*** *Outcrop-scale brittle faults in migmatitic metagraywacke of the Tallulah Falls Formation on the trail to Wintergreen Falls.* ***D:*** *Flood-scoured channel of the Toxaway River below US Highway 64 and the Lake Toxaway Dam.* ***E:*** *Metagraywacke of the Tallulah Falls Formation along Auger Hole Road.* ***F:*** *The lime kilns along Bearwallow Creek.*

# *Geology of Gorges State Park Transylvania County North Carolina*

Information Circular 31

by

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# GEOLOGY OF GORGES STATE PARK

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# GEOLOGY OF GORGES STATE PARK

**North Carolina Geological Survey**
**Division of Land Resources**
**North Carolina Department of Environment and Natural Resources**

## INTRODUCTION

The rugged mountains, deep river gorges, and cascading waterfalls of Gorges State Park record a long and sometimes turbulent geologic history that began over a billion years ago. Geologic forces were shaping the landscape long before the mountains we see now formed, and these forces continue today. The tiles that make up this geologic mosaic are hidden beneath the wooded slopes, and within the cliffs, waterfalls, and floodplains, and when pieced together by detailed geologic study, the story of a dynamic Earth emerges. Sequences of rock and the fabrics and features in them tell of continents torn apart and colliding.

The Park's rugged landscape, with active landslides and flood deposits, reminds us that the erosive power of streams and rivers never rests, and that the final chapter of the geologic record has yet to be written. Future generations of geologists will learn more, understand more, and will undoubtedly add to the never-ending story of our ever-changing Earth.

This Information Circular presents the geologic story of Gorges State Park — its physiography and geomorphology, rocks and structures, mineral resources, ancient tectonic history, and catastrophic events in its recent history that have resulted in slope movements and surficial deposits.

Two companion geologic maps show the generalized geology of the bedrock (pl. 1), and slope movements and related surficial deposits (pl. 2). These maps were derived from more detailed geologic maps prepared as part of the geologic inventory of Gorges State Park (Merschat and others, 2003; and Wooten and others, 2003). The bedrock geologic map portrays the distribution of the principal rock types, geologic structures, and mineral resources that underlie the Park. The slope movements and related surficial deposits map depicts landslides and landslide-prone areas, as well as transported material such as flood and landslide deposits. Appendices contain additional information for educational study and interpretive programs. For the geologic layperson, a glossary of common geologic terms is included following the appendices, as well as a geologic time scale on the inside back cover.

Please note that while rock and mineral collecting are STRICTLY PROHIBITED, visitors are encouraged to explore and enjoy the rich geologic bounty that Gorges State Park has to offer. The staff members of the North Carolina Geological Survey and the Division of Parks and Recreation hope you have a pleasant experience.

## PHYSIOGRAPHY AND GEOMORPHOLOGY

Gorges State Park (fig. 1) lies within the Blue Ridge physiographic province of the Southern Appalachian Mountains. The Blue Ridge is an active landscape that has undergone substantial change since the last significant mountain-building episode over 200 million years ago. A balance of earth forces — uplift, erosion, and rock resistance — best explains the development of this landscape through geologic time.

The steep-sloped ridges and deeply incised stream valleys of Gorges State Park are part of the Blue Ridge Escarpment, a pronounced regional landform in the Southern Appalachians that marks the physiographic change between the mountainous Blue Ridge province and the lower, rolling topography of the Piedmont province (fig 2).

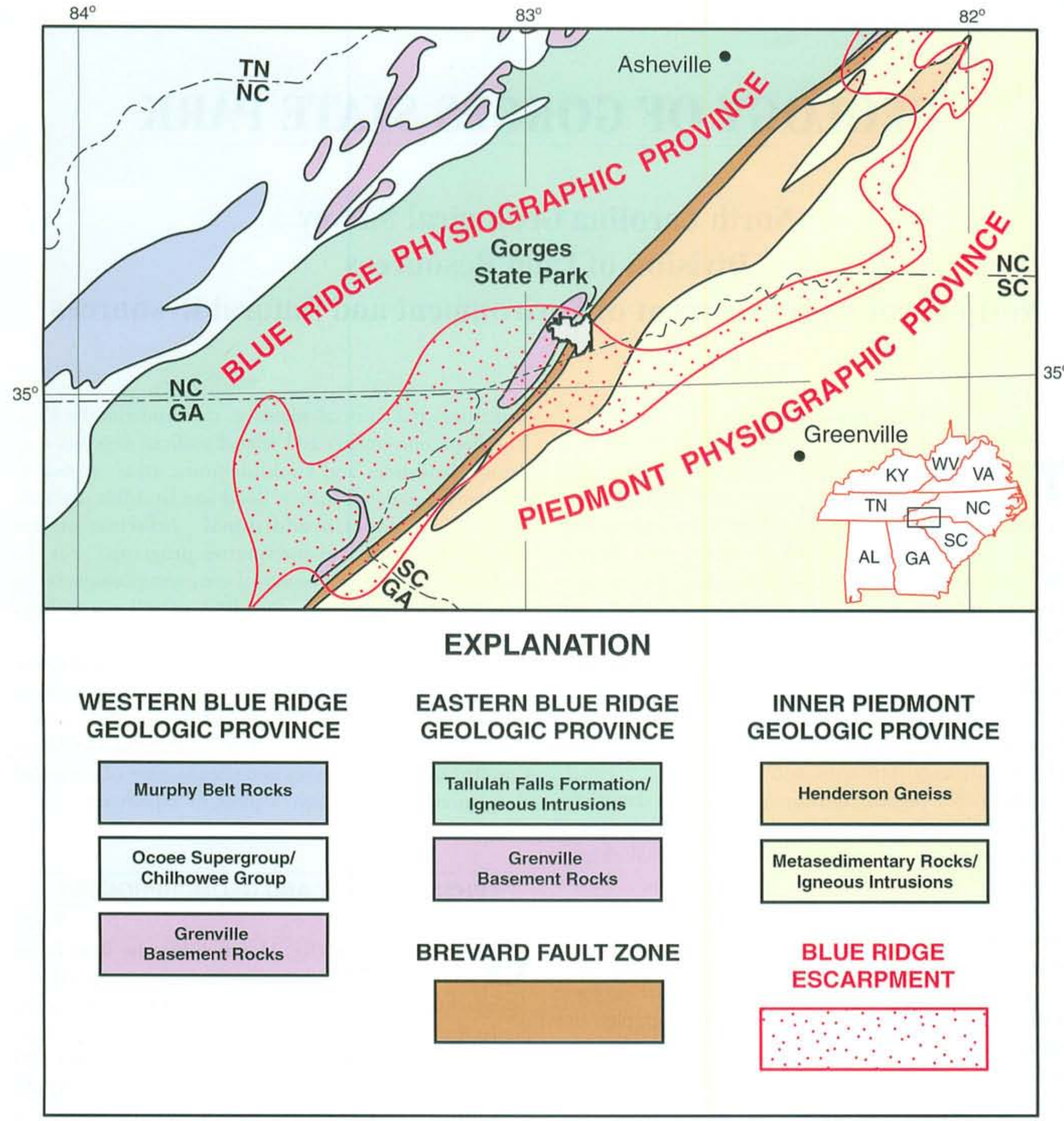



**Figure 1.** Location of Gorges State Park with respect to the major geologic and physiographic provinces in the Southern Appalachian Mountains. The Park lies within the Blue Ridge Escarpment of the Blue Ridge physiographic province, but straddles the Blue Ridge geologic province, the Brevard fault zone, and the Inner Piedmont geologic province. Black box within southeastern United States inset map shows area of larger scale map. Modified from Williams (1978), Hack (1982), and Horton and Zullo (1991).

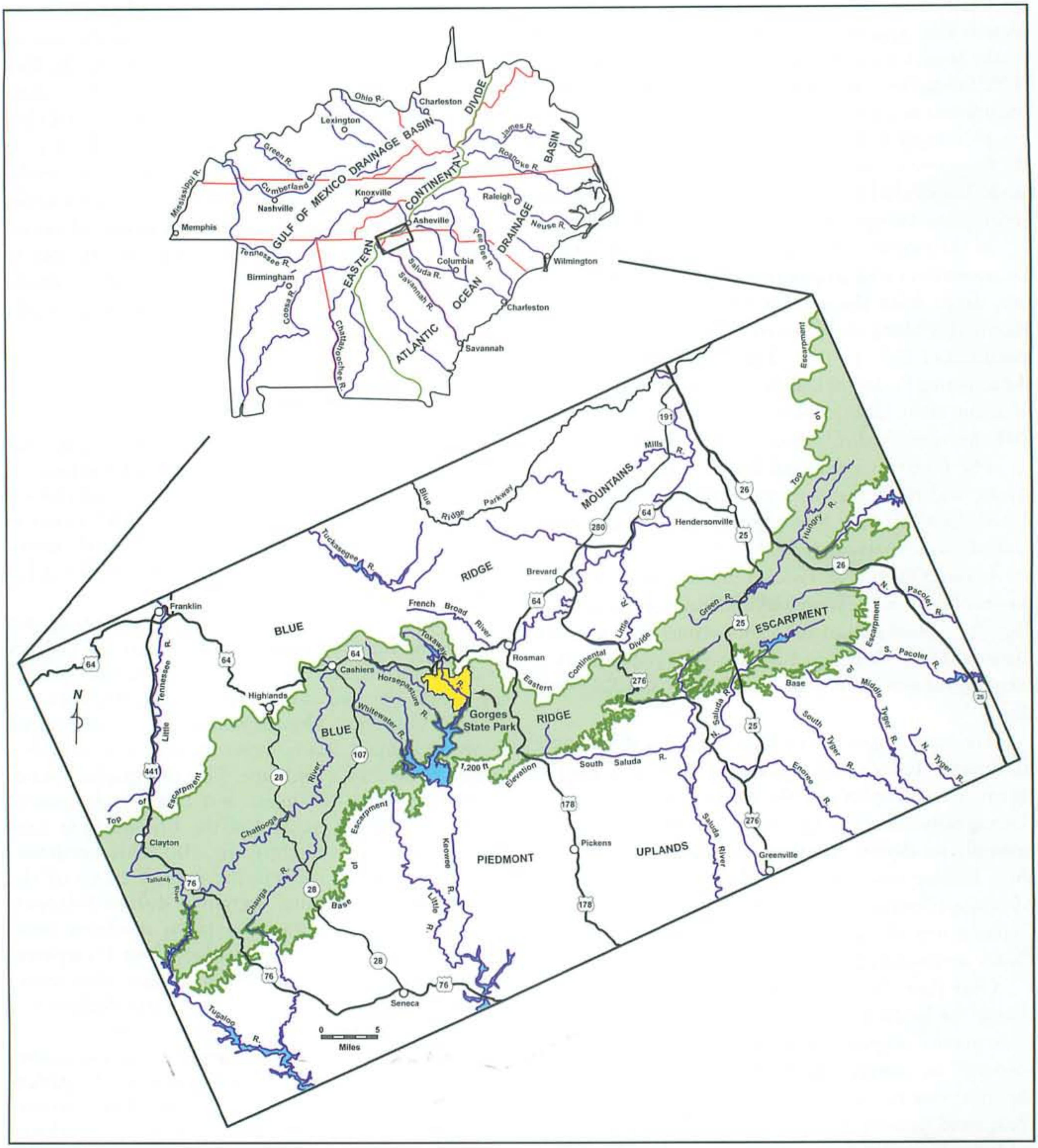



**Figure 2.** Location of the Blue Ridge Mountains, Blue Ridge escarpment, and Piedmont Uplands in the region around Gorges State Park. In the vicinity of the Park, the top of the Blue Ridge Escarpment coincides with the Eastern Continental Divide. The Eastern Continental Divide in the southeastern United States, shown on the smaller-scale inset map, separates drainages that flow into the Gulf of Mexico from those that flow into the Atlantic Ocean. Inset map modified from Hack (1982).

The Blue Ridge Escarpment (Escarpment) as delineated in figure 2 coincides roughly with the position of the Escarpment shown by Clark (1993), and includes plateau-like, upland weathering surfaces recognized in nearby South Carolina by Acker and Hatcher (1970). Hack (1982) ended his southwestern extension of the Blue Ridge Escarpment near Rosman, North Carolina, because of the complex, rugged topography there. The greater width of the Escarpment southwest of Rosman shown in figure 2 results from including much of the rugged topography that encompasses Gorges State Park as part of the Escarpment.

In the vicinity of Gorges State Park, the Blue Ridge Escarpment is a wide strip of steep, highly dissected terrain that drops from the eastern edge of the Blue Ridge Mountains along the Eastern Continental Divide at elevations of 2800-4770 ft (about 850-1450 m) down to the adjoining Piedmont Uplands beginning at an elevation of about 1000-1200 ft (305-365 m) (fig. 2). Near the Park this vertical relief is about 1300 ft (400 m).

The Eastern Continental Divide separates streams, creeks, and rivers that flow westward (e.g., the French Broad River) into the Mississippi River System and the Gulf of Mexico beyond, from those flowing eastward into the Atlantic Ocean. The Park lies entirely within the headwaters of the Keowee River and the Savannah River Basin (fig. 3). Nearly all of the Park's waters flow into the Toxaway River, then into Lake Jocassee, and ultimately into the Atlantic Ocean via the Keowee and Savannah Rivers.

The early origins of the Blue Ridge Escarpment are uncertain. Today's landscape appears to be a product of recent tectonic uplift and the erosive power of streams flowing eastward to the Atlantic Ocean along courses that generally are shorter, straighter, and more energetic than those flowing westward across the Blue Ridge into the Mississippi drainage and the Gulf of Mexico (Hack, 1982). Consequently, the Escarpment and Eastern Continental Divide are migrating westward through headward erosion.

Over time this headward erosion will continue to change the landscape. As the streams flowing down the Escarpment migrate westward they will eventually intercept, or capture, streams that once flowed toward the southwest or northeast. Acker and Hatcher (1970) recognized present-day stream patterns that preserved evidence of past stream capture along the Blue Ridge Escarpment in nearby South Carolina. The terrain near the Park will likely change in the distant future as tributaries of Auger Fork Creek and Frozen Creek migrate northwestward across the Eastern Continental Divide and capture the headwaters of the northeast-flowing South Fork of Flat Creek (fig. 3).

The Escarpment is almost entirely in slope; such a landscape contains numerous rock exposures, varying from small outcrops to large overhangs, cliffs, and pavements, as well as continuous bedrock exposures in the stream channels. Bedrock exposures are so plentiful in the Park that it is nearly impossible to examine them all. Impressive exposures can be seen in the bedrock channels and cliff-lined gorges of the Toxaway River and Bearwallow Creek. Numerous waterfalls and cascades along some of the smaller streams, and a few rock pavements on the rounded knobs of Grassy Ridge and western slopes of Grindstone Mountain provide other exemplary exposures. In contrast, areas of deep weathering and significant saprolite development occur on the interfluvial ridges, spurs, and small divides between the major creeks and rivers.

#### Geologic Controls on Landforms

The underlying bedrock forms the template for nearly all of the Park's landforms. Varying resistance of the different rock types to weathering and erosion delineates patterns within the landscape. Differences in the orientation of rock layers and foliations, and the joints, faults and other fractures cutting across them further modify the bedrock template.

Although rounded and subdued by weathering and erosion over hundreds of thousands of years, the bedrock structure formed during the Paleozoic reveals itself in the northeast- and southwest-trending streams and dissected ridgelines. The color-infrared aerial photograph shown in figure 4 clearly shows the northeast-southwest "grain" of the Park's landscape. This topographic "grain" is inherited from a similar, but larger-scale pattern highlighted by the transect of the Brevard fault zone across Transylvania County (fig. 3). This northeast-southwest pattern reflects the overall trend of the Appalachian Mountains ingrained during Paleozoic orogenic events. Following a similar northeast trend across the region (fig. 2), the Blue Ridge Escarpment may be one of several *en-echelon* fall lines that record Cenozoic uplift across the Blue Ridge and Piedmont of North Carolina and Virginia (Weems, 1998).

The strike of bedrock units, as well as foliations, joints, faults, and other fractures strongly influence the pattern of streams and rivers in and around the Park. Streams that generally follow the dominant northeast-southwest "grain" in the bedrock include Holly Pen Creek, Auger Fork Creek, Maple Spring Branch and Toxaway Creek. The Horsepasture River and the upper reach of the Toxaway River flow southeast, nearly perpendicular to the older northeast-southwest grain. When viewed together on a map, these two orientations combine to form a crudely rectangular drainage pattern. This close

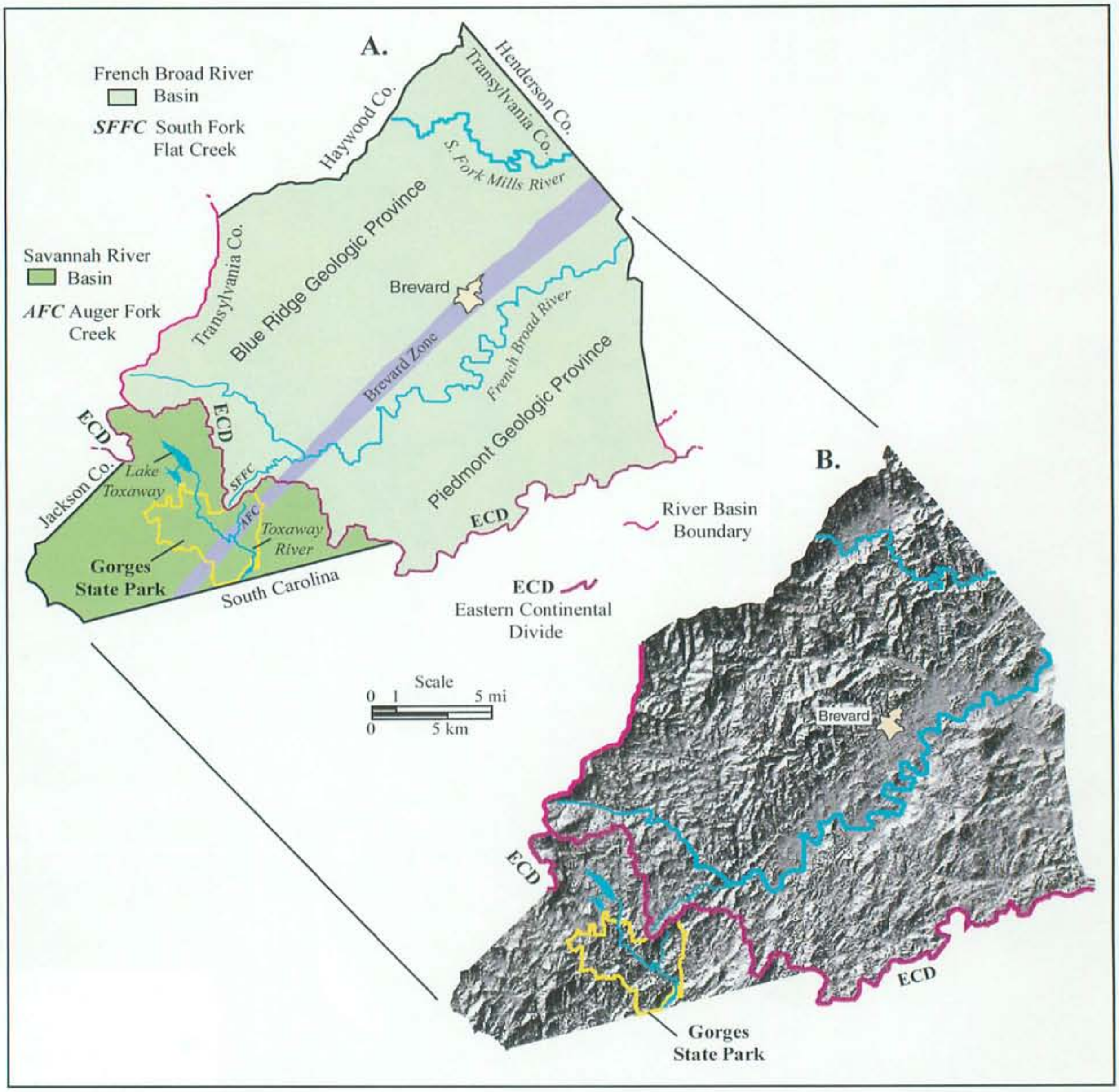



**Figure 3.** Geomorphic features of Transylvania County. **A.** Map showing the location of the Eastern Continental Divide (ECD) that separates waters of the Savannah River basin, that flow into the Atlantic Ocean, from the waters of the French Broad River Basin that flow into the Gulf of Mexico. In both river basins, the Brevard fault zone separates the Blue Ridge geologic province from the Piedmont geologic province. The Eastern Continental Divide coincides with the top of the Blue Ridge Escarpment in Transylvania County. Streams along the Blue Ridge Escarpment are actively eroding headward. For example, the headwaters of Auger Fork Creek (AFC), now in Gorges State Park, will eventually migrate northwestward and could intercept, or capture, the headwaters of the South Fork of Flat Creek (SFFC) a tributary of the French Broad River. **B.** Digital shaded relief map illustrating the topographic expression of major geomorphic features in Transylvania County. The Brevard fault zone roughly coincides with the northeast-trending, topographic low that passes through Brevard and Gorges State Park.

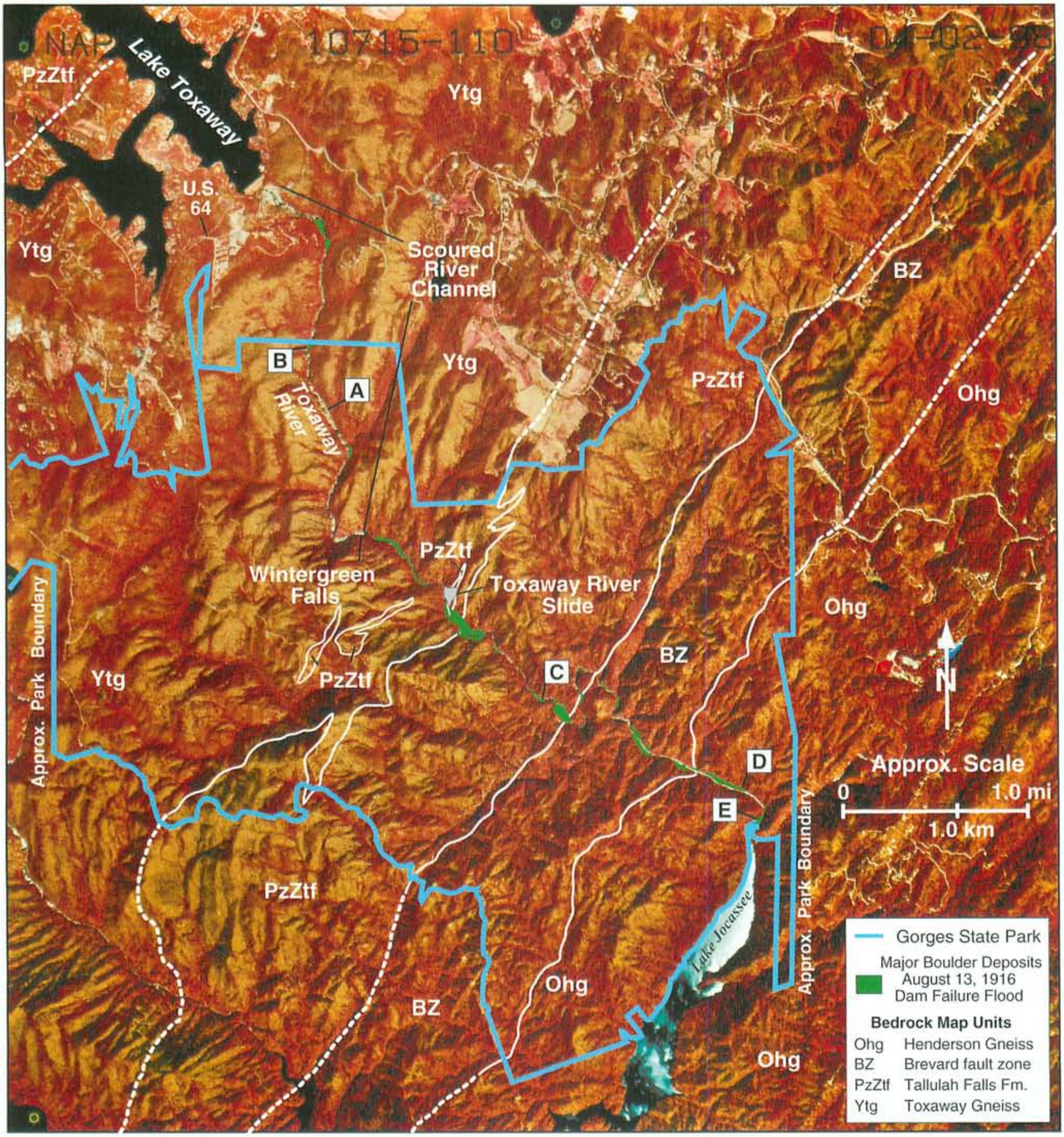



**Figure 4.** April 2, 1998 color-infrared aerial photograph of the Gorges State Park area showing main bedrock map units, and locations of the major boulder deposits and scoured river channel that resulted from the August 13, 1916 dam failure. Also shown are the Toxaway River slide, locations of photographs shown in figure 14 (location A) and figure 22 (locations B, C, D, and E). Bedrock contacts depicted with a solid line are based on detailed mapping in the Park; dashed contacts are based on other mapping, limited reconnaissance, and along-strike extensions of mapped contacts. Cobble- to sand-sized flood deposits from the 1916 dam failure also underlie Lake Jocassee.

relationship between bedrock and topography in the Park is not unusual. A number of studies in the nearby Blue Ridge and Piedmont have also demonstrated the importance of bedrock-related controls on the landscape (see Acker and Hatcher, 1970; Clark, 1993; Hatcher, 1993; and Garihan and others, 1988).

The ancestral Toxaway River and other streams, seeking paths of least resistance down the Blue Ridge Escarpment, probably exploited northwest-southeast fracture zones. Many individual joints measured in the Park strike northwest, reinforcing the idea that what we see in outcrop is a smaller-scale reflection of regional geologic patterns. These joints and other fractures record younger stresses on the rocks as they cooled and became brittle during late Paleozoic mountain-building. Some joints and other fractures probably formed later, perhaps during the Mesozoic as the crust extended with the opening of the Atlantic Ocean, or even later in response to uplift of the mountains during the Cenozoic.

A detailed look at stream pathways shows that many have angular bends in their channels. Bends in the Toxaway and Horsepasture Rivers mark changes in the orientation of linear stream segments where their channels follow a northeast-southwest foliation or fracture zone for some distance before flowing again toward the southeast. Bearwallow Creek is an excellent example of a stream whose flow direction changes abruptly in response to different structural components within the bedrock template. A similar angular pattern continues downstream along the Keowee River (Acker and Hatcher, 1970) that begins at the confluence of the Toxaway and Whitewater Rivers.

Sudden changes in the flow direction of a larger stream can occur where it is joined by one of its tributaries. Good examples of this type of change can be found where Holly Pen Creek joins Bearwallow Creek, and where Indian Creek and Toxaway Creek flow into the Toxaway River. At the latter two locations, the southeast flow of the Toxaway River above the confluence changes toward the southwest to be more in line with the flow direction of the tributary. This type of stream pattern indicates that at these confluences northwest-southeast oriented bedrock structures intersect those with a northeast-southwest trend.

Close examination of a color-infrared aerial photograph of the Park (fig. 4) reveals a chevron pattern highlighted by shadows and color differences in vegetation visible south and east of Wintergreen Falls. The more gently sloped, southeast-facing hillsides (dip slopes), follow the foliation dip in the rock layers, while the steeper northwest- to northeast-facing slopes (scarp and oblique slopes) follow the upturned edges of the layers. Upturned edges of the stacked layers of rock tilted to the southeast intersect to form the tips of the chevrons rounded by erosion. Joints likely control the orientations of the scarp and oblique slopes, and in many cases, small streams and draws follow the lower edges of the scarp slopes. Most of the past slope movements observed in the Park occur along scarp slopes because they tend to be steeper than slopes that follow the foliation dip. Figure 5 shows both the distribution of slope aspects and topographic trends in and around the Park.

### Present-Day Landscape

Weathering, erosion, and slope movements (i.e., landslides) continually modify the bedrock-controlled landscape. Deep weathering produces saprolite, (i.e., completely decomposed rock with recognizable relict mineralology, texture, and fabric) that occurs locally on some ridge tops and stream divides. Downcutting streams, erosion, and slope movements remove material from steep side slopes and deposit it as colluvium along foot slopes, and as alluvium along low-gradient reaches of streams and rivers. These transported, or surficial, deposits usually occur on the more gently sloped ground below steep slopes (e.g., foot slopes east of Lake Jocassee) and are collectively called regolith. Regolith is the general term applied to the unconsolidated soil, sediment, and fragmental rock (both residual and transported) that overlie bedrock.

Deep saprolite, up to 12 ft (4 m) or more thick on interfluvial ridges in the Park, indicates that many features in the present-day landscape are ancient. Pavich (1986) calculated that weathering in granitic rocks in the humid southeast produces about 3 ft (1 m) of saprolite in 250,000 years. This estimate suggests that it may have taken up to 1 million years to produce the deep weathering locally preserved in the Park. In many other places, however, the regolith is much thinner, indicating that erosion has kept pace with weathering. Further evidence for the Park's ancient landscape are the abundant eastern hemlocks (*Tsuga canadensis*), also informally known as Canadian hemlocks. These trees may be remnants of the boreal forest that once covered the lower elevations of the Blue Ridge Mountains during Pleistocene glaciation (see Delcourt and Delcourt, 1985).

The ages of the debris fans and other surficial deposits are difficult to estimate. Indirect estimates made from the degree of weathering of the rock cobbles and the color of the soil matrix in near-surface exposures of debris and colluvium (Mills and Allison, 1995; Mills, 1998) indicate that some of these deposits may have formed during the late Pleistocene and range in age from 10,000 to 75,000 years old. Some deposits buried deep within the debris fans may be considerably older, perhaps as much as

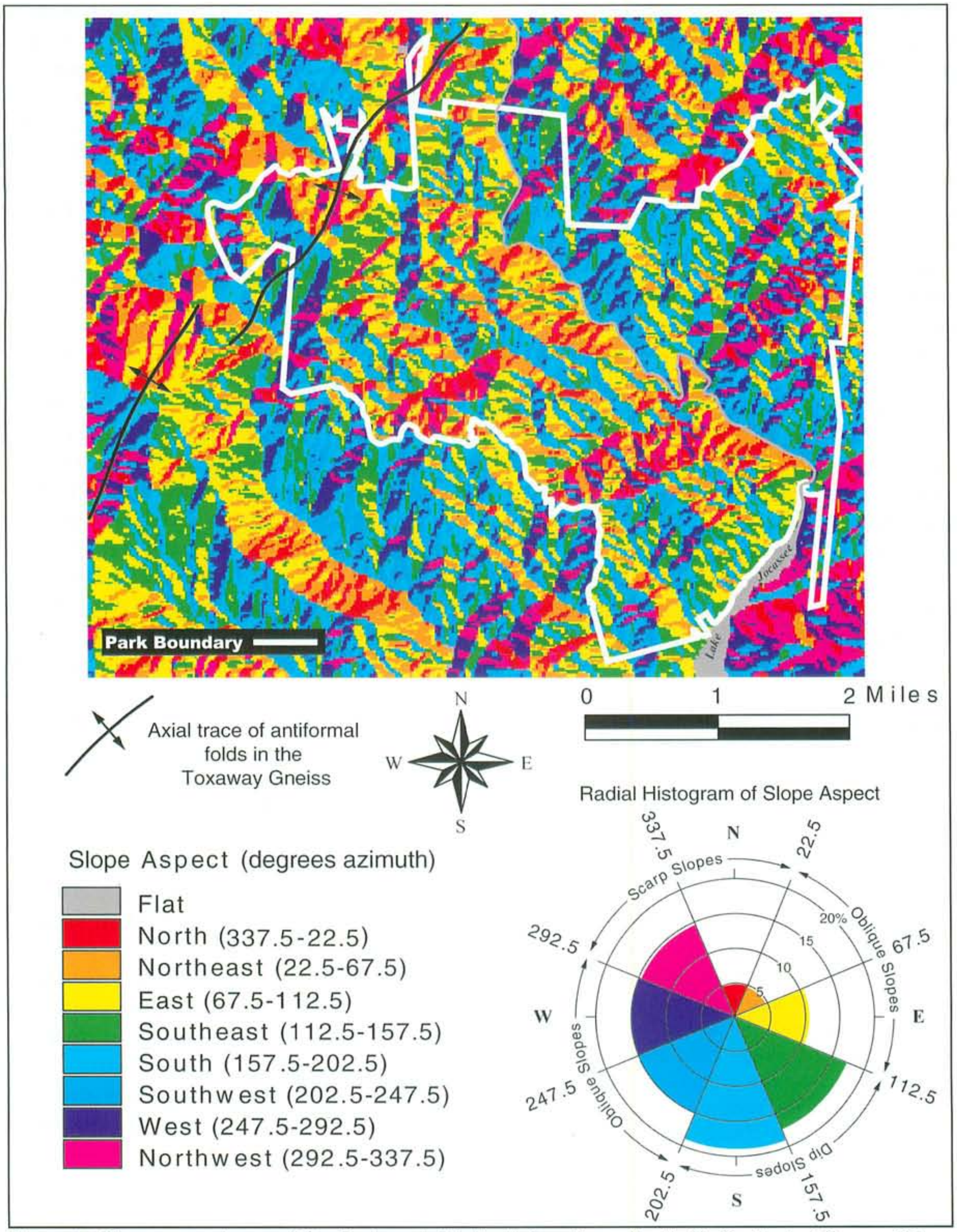



**Figure 5.** Slope aspect map of the Park and vicinity derived from the U. S. Geological Survey 30-meter digital elevation model (DEM). The radial histogram shows the relative percentages of the slopes in the entire area that correspond to the specified ranges in azimuth. Also shown are the slope aspects that correspond generally with the dip, oblique, and scarp slopes (defined by the dip direction of the dominant foliation) in the area southeast of the axial trace of antiformal folds in the Toxaway Gneiss. In the vicinity of the Park, these folds mark the location where the foliation dip direction changes directions at the ground surface. Southeast of the axial traces, the dominant dip direction of the foliation is toward the southeast. Northwest of the axial traces, the dominant dip direction is toward the northwest.

130,000 years. Given the flood history of this actively eroding landscape, portions of the fans and other debris deposits have also accumulated within the last century.

Extensive, thick debris fan and colluvial aprons mantling foot slopes are conspicuously absent in the Park, in contrast with thick accumulations reported higher in the Blue Ridge Mountains by Mills (1983), Gryta and Bartholomew (1983), Soller and Mills (1991), and Mills (1998). Hatcher (1973) also noted a lack of extensive colluvial deposits on slopes in nearby South Carolina in an area along the Blue Ridge Escarpment with similar bedrock geology as the Park. One possible explanation is that erosion in the Park has kept pace with deposition on the steep slopes, and the thick deposits did not accumulate. Floodwaters along the rivers and streams have also removed some of the debris deposits. At some locations in the Toxaway River gorge one can see debris deposits that were probably eroded and truncated by the catastrophic 1916 dam failure torrent. However, part of the answer may also lie in the Park's low elevation within the Blue Ridge Mountains. Paleovegetation maps by Delcourt and Delcourt (1985) show boreal forests covering lower elevations of the Blue Ridge during Pleistocene glaciation. Sparse, tundra vegetation covered higher elevations [e.g., above 4920 ft (1500 m) near the North Carolina-Georgia border]. It may be that less erosion and accumulation of debris occurred on forested slopes than on the less protected, tundra-covered slopes at higher elevations.

## BEDROCK GEOLOGY

Gorges State Park is unique within the North Carolina Park System in that it includes rocks of both the eastern Blue Ridge and Inner Piedmont provinces, and the Brevard fault zone, which separates the two (fig. 1). Northwest of Auger Hole Road (the main north-south thoroughfare through the Park), rocks of the eastern Blue Ridge province underlie the steep slopes of Fifteen Mile Ridge, Chestnut Mountain, Grassy Ridge, and the upper Toxaway River Gorge.

Eastern Blue Ridge rocks are subdivided into two distinct packages: (1) 1.15 billion-year-old granitic gneisses of the Toxaway Gneiss; and, (2) 500-to 600-million-year- old metamorphosed sedimentary and volcanic rocks of the Tallulah Falls Formation. From about Auger Hole Road to the southeast, rocks of the Brevard fault zone and Inner Piedmont province crop out along Grindstone Mountain, Maple Spring Branch, and the lower Toxaway River Gorge.

Most of the rocks in the Brevard fault zone (the Chauga River Formation of Hatcher, 1969) are metasedimentary and are slightly younger than the Tallulah Falls Formation. Around Lake Jocassee, 490 million-year-old granitic gneisses of the Henderson Gneiss compose this part of the Inner Piedmont province.

### Toxaway Gneiss

Rocks of the Toxaway Gneiss are the oldest in the Park, and are referred to as "basement" because they formed during the earliest episode of mountain-building in the southern Appalachians and are older than all of the rocks above them. The unit is named for exposures in the Toxaway River just below the Lake Toxaway Dam on U.S. Highway 64 just north of the Park (Hatcher, 1977). Rocks of the Toxaway Gneiss outcrop in the upper gorges of the Toxaway River and Bearwallow Creek, and on the high, rounded knobs of Grassy Ridge.

Within the park, the Toxaway Gneiss consists of two rock units: (1) layered biotite granitic gneiss; and (2) megacrystic biotite granitic gneiss (pl. 1). Layered biotite granitic gneiss consists of both weakly layered and well-layered rock types. Well-layered biotite granitic gneiss exhibits distinct, alternating dark-colored biotite-rich and lighter colored quartz- and feldspar-rich bands (fig. 6A). Megacrystic biotite granitic gneiss is characterized by abundant, large eye-shaped grains (augen) of feldspar (fig. 6B).

Rocks of the Toxaway Gneiss are at least 1.15 billion years old (Carrigan and others, 2003), and are most likely of felsic (feldspar-rich) igneous intrusive origin. All rocks of the Toxaway Gneiss were metamorphosed during the Middle Proterozoic Grenville orogeny about one billion years ago (Carrigan and others, 2003). These rocks were again strongly overprinted during Paleozoic metamorphism and mylonitization, which altered and realigned their constituent minerals.

Significant exposures of the Toxaway Gneiss occur in the gorges of the Toxaway River and Bearwallow Creek. A nearly continuous bedrock channel of Toxaway Gneiss exists along the Toxaway River from US 64, outside the Park's northern boundary, to Big Spice Cove within the Park, and another occurs along Bearwallow Creek.

Four small areas of biotite schist and amphibolite crop out within the Toxaway Gneiss. The origin of these rocks is uncertain, but may represent either (1) younger mafic intrusions that cross cut the older Toxaway Gneiss, or (2) xenoliths — pre-existing rocks that were incorporated, but not assimilated, during intrusion of the Toxaway Gneiss.

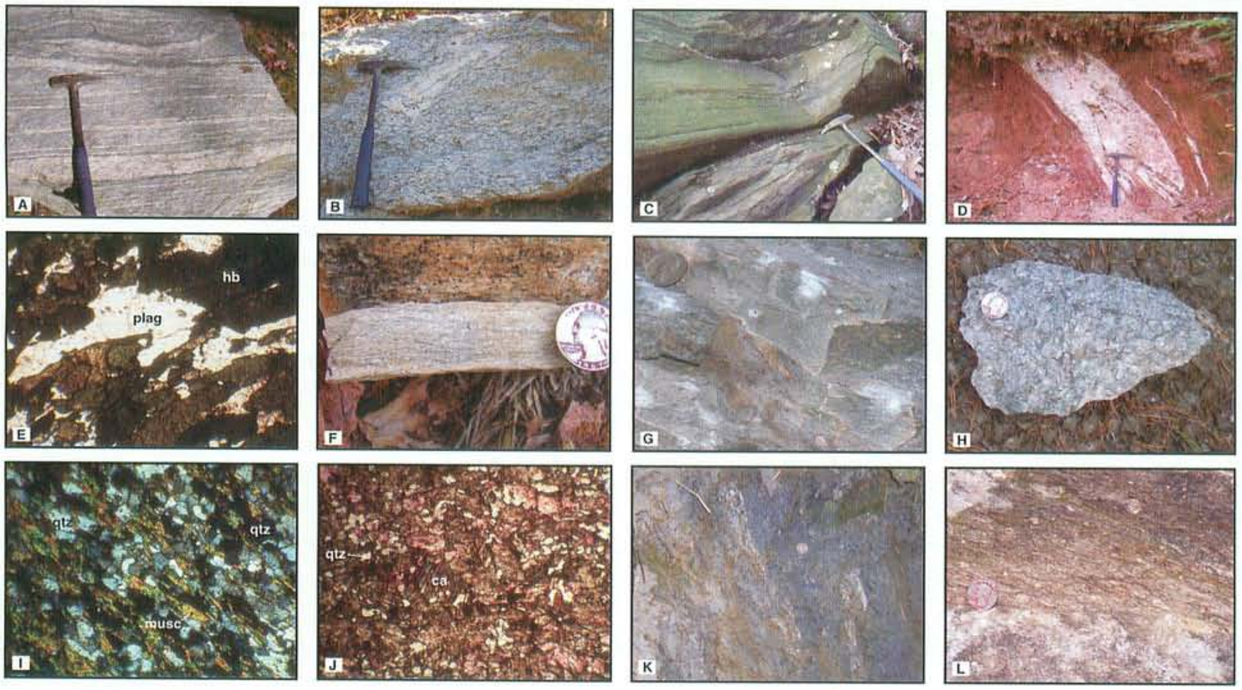



**Figure 6.** Some of the characteristic rock types of Gorges State Park. *Distances given are linear, not roadway or trail distances.* **A.** Compositionally banded Toxaway Gneiss; the rock hammer is for scale and is about 16 in (40 cm) long. The photograph is of a large landscape boulder at the north end of the Grassy Ridge access area parking lot on Bohaynee Road (NC State Route 281). The boulder is from the nearby Whitewater Quarry. **B.** Megacrystic Toxaway Gneiss; rock hammer for scale. Photograph taken at a roadside outcrop along U.S. Highway 64 at Toxaway Dam. **C.** Metagraywacke of the Tallulah Falls Formation; rock hammer for scale. Photograph taken at a roadside outcrop along Auger Hole Road (field guide STOP 6B). **D.** Saprolitic exposure of pegmatite within mica schist of the Tallulah Falls Formation; rock hammer for scale. Photograph taken at a roadside exposure along Auger Hole Road, approximately 0.9 miles (1.5 km) north of the ford over the Toxaway River. **E.** Photomicrograph of amphibolite within the Tallulah Falls Formation. Note the mineral grains of hornblende (hb) and plagioclase feldspar (plag). Field of view is approximately 1.6 mm x 1.2 mm. The sample is from the western end of Chestnut Mountain (field guide STOP 5B). **F.** Mylonitic Henderson Gneiss within the Brevard fault zone; the quarter is for scale. Note the small feldspar augen in this sample, and compare it with the photograph of Henderson Gneiss in L. Photograph taken on the southwestern end of Grindstone Mountain, approximately 0.6 miles (1.0 km) southeast of Auger Hole Road at its crossing over Wild Hog Branch. **G.** Metagraywacke of the Brevard fault zone; quarter for scale. Note the greenish gray color of the rock. Photograph taken along the Toxaway River, approximately 0.2 mi (0.3 km) southeast of Auger Hole Road at its ford over the Toxaway River. **H.** Fish-scale phyllonite of the Brevard fault zone; quarter for scale. Photograph taken at the southwestern end of Grindstone Mountain, approximately 0.7 mi (1.1 km) south of Auger Hole Road at its crossing over Wild Hog Branch. **I.** Photomicrograph of metasiltstone within the Brevard fault zone. Note the mineral grains of muscovite (musc) and quartz (qtz). Field of view is approximately 1.6 mm x 1.2 mm. The sample is from an exposure on the southwestern end of Grindstone Mountain, approximately 0.7 miles (1.1 km) southeast of Auger Hole Road at its crossing over Wild Hog Branch. **J.** Photomicrograph of marble within the Brevard fault zone. Note the mineral grains calcite (ca) and quartz (qtz). Field of view is approximately 1.6 mm x 1.2 mm. The sample is from an abandoned quarry adjacent to the lime kilns along Bearwallow Creek (field guide STOP 8B). **K.** Graphitic schist within the Brevard fault zone; quarter for scale. Photograph taken at a small roadside outcrop along Auger Hole Road, approximately 0.2 miles (0.3 km) southwest of the Frozen Creek access area parking lot on Frozen Creek Road (NC State Route 1139). **L.** Porphyroclastic Henderson Gniess; quarter for scale. Note the large feldspar augen. Photograph taken at the confluence of the Toxaway River and Lake Jocassee.

#### Tallulah Falls Formation

Overlying the Toxaway Gneiss is a thick heterogeneous sequence of metasedimentary and mafic metavolcanic rocks of the Late Proterozoic to early Paleozoic (500 to 600 million years old) Tallulah Falls Formation (pl. 1). Rocks of the Tallulah Falls Formation serve as "cover" to the underlying basement rocks of the Toxaway Gneiss. The Tallulah Falls Formation was named for exposures of similar rock types around Tallulah Falls in northeast Georgia by Hatcher (1971).

In the Park, metasedimentary rocks of the Tallulah Falls Formation crop out between the Toxaway Gneiss and Brevard fault zone and consist mostly of metagraywacke and mica schist (figs. 6C-D). Metagraywacke, a variety of metamorphosed, muddy sandstone, is the dominant rock type. Mica schist, the metamorphosed product of finer-grained siltstone and shale, is also abundant, particularly near the fault contact with the underlying Toxaway Gneiss. Metagraywacke is fine- to medium-grained, granoblastic, and composed of quartz, feldspar, biotite, muscovite, garnet, epidote, and traces of apatite. Mica schist is medium- to coarse-grained, lepidoblastic, and composed of quartz, feldspar, biotite, muscovite, and garnet. Both rock types are interlayered, and laterally and vertically gradational with one another. The two units shown on the bedrock geologic map (pl. 1) are divided on the relative abundance of one rock type over another, and reflect variation within the original marine sedimentary package during deposition on the continental margin 500 to 600 million years ago.

Concordant amphibolite (fig. 6E) and altered ultramafic rock constitute a minor, but tectonically significant component of the Tallulah Falls Formation. Relict olivine grains in an altered ultramafic rock body clearly indicate an igneous origin. These rocks are most likely the metamorphosed equivalents of originally mafic and ultramafic plutonic and volcanic rocks, which intruded the sedimentary sequence as dikes and sills, or formed as lava flows, or possibly pyroclastic deposits.

In his authoritative work in northeastern Georgia and southwestern South Carolina, Hatcher (1971, 1973) defined four constituent members of the Tallulah Falls Formation: a basal graywacke-schist-amphibolite member, an aluminous schist member, and an upper graywacke-schist member that grades into a quartzite-schist member only around the Tallulah Falls dome. Since that time, all rock types (except the quartzite-schist member) have been traced north of the Tallulah Falls dome into the eastern Blue Ridge and Inner Piedmont of North Carolina (Hatcher, 1987; Hatcher and Bream, 2002).

Following the work of Horton (1982) on the nearby Rosman quadrangle to the north, elements of Hatcher's (1971) Tallulah Falls stratigraphy were recognized in Gorges State Park: schist, metagraywacke, and amphibolite adjacent to the contact with the Toxaway Gneiss correlate with the basal graywacke-schist-amphibolite member. Garnet mica schist, which locally contains small amounts of kyanite, and possibly minor amounts of sillimanite, occurs within the schist and metagraywacke unit. The garnet mica schist is interlayered with metagraywacke and porphyroclastic schist. Along strike northeast of Bearwallow Creek, the garnet mica schist is associated with amphibolite, in some cases both above and below the schist.

Although kyanite, or other aluminosilicate minerals are not prevalent in the garnet mica schist, it may be correlative with the middle aluminous schist member described by Hatcher (1971, 1973). Kyanite was observed in several stream sediment heavy mineral samples, and garnet was observed in most heavy mineral samples, suggesting that there may be other garnet mica schist units not yet mapped in the Park.

Rocks of the Tallulah Falls Formation were metamorphosed during the Paleozoic 350 to 450 million years ago (Miller and others, 2000; Moecher and Miller, 2000; Carrigan and others, 2003). During metamorphism, quartz and feldspar (and some mica) in metagraywacke and mica schist melted and recrystallized into pods, stringers, and layers of migmatite and pegmatite that commonly parallel the dominant layering in the host rock (fig. 6D). Migmatite pods and stringers are fine- to medium-grained, and up to several inches (centimeters) thick. Pegmatite pods and layers are medium- to very coarse-grained, and up to 3 ft (1 m) thick.

Fresh exposures of the Tallulah Falls Formation crop out in the stream channel and cliff-lined gorges of the Toxaway River and Bearwallow Creek. They are very well exposed in outcrops and saprolite exposures along the trail to Wintergreen Falls, Augerhole Road, and on the access road along the ridgeline south of the Toxaway River.

#### Rocks of the Brevard fault zone

Rocks of the Brevard fault zone lie in a linear belt between the Tallulah Falls Formation and the Henderson Gneiss (pl. 1). These rocks were first recognized in western North Carolina by Keith (1907), but Hatcher (1969), working in South Carolina, established a stratigraphic sequence (the Chauga River Formation) which consists of phyllonite, graphitic phyllonite, carbonate, and some quartzite.

In the Park, Brevard fault zone rocks include metagraywacke, phyllite, phyllonite, marble, metasiltstone, and graphitic breccia. These rocks have been demonstrated to overlie the Tallulah Falls Formation in South Carolina and are probably early Paleozoic in age (Hatcher, 1969; 1971).

Additionally, a tectonically emplaced thrust slice (a tabular panel of rock bounded by faults) of feldspar-rich mylonitic granitic rock of the Henderson Gneiss (fig. 6F) separates the metasedimentary sequence. Regional metamorphism and multiple periods of faulting during the Paleozoic within the fault zone obscure stratigraphic relations between some units.

Metagraywacke is fine-grained, granoblastic, and composed of quartz, muscovite, feldspar, biotite, chlorite, and traces of epidote and iron sulfides. Metagraywacke in the Brevard fault zone is distinguished from feldspar-rich metagraywacke in the Tallulah Falls Formation by its quartz- and chlorite-rich, vitreous appearance and greenish cast (fig. 6G). Interlayers of phyllite and phyllonite are common. Phyllite is a mica-rich, schistose rock similar to mica schist, but is of lower metamorphic grade and finer-grained. Phyllonite is also a mica-rich rock, but is of tectonic origin (fig. 6H). Metasiltstone occurs as interlayers within the phyllite and phyllonite unit of the Brevard fault zone. Metasiltstone is intermediate in grain-size between metagraywacke and phyllite, but is typically more quartz-rich and not as micaceous as phyllite (fig. 6I). Marble is a fine-grained, metamorphosed limestone composed of calcite, quartz, muscovite, feldspar, chlorite, iron sulfides, and traces of apatite and zircon (fig. 6J). It occurs in several lenses, but these lenses may be the exposed parts of a more continuous carbonate unit. Graphitic schist and breccia occur locally along the northwestern edge of the Brevard fault zone (fig. 6K). The breccia consists of a cohesive, chaotic mass of brecciated metagraywacke within finer-grained graphite-rich schist.

Excellent exposures of metagraywacke and graphic breccia can be seen in the waterfalls, cliffs, and overhangs at the confluence of Auger Fork Creek and Maple Spring Branch. Marble is best exposed in an abandoned quarry at the lime kilns near the mouth of Bearwallow Creek. Good exposures of phyllite, phyllonite, and metasiltstone occur in the Toxaway River gorge and along an access road at the southern boundary of the Park. Rocks of the Henderson Gneiss within the fault zone crop out along the access road to Lake Jocassee.

### Henderson Gneiss

Rocks of the Henderson Gneiss crop out south of the Brevard fault zone around Lake Jocassee (pl. 1). These rocks are the youngest in Gorges State Park — only about 490 million years old (Carrigan and others, 2003). The Henderson Gneiss was named for typical exposures in Henderson County, North Carolina, by Keith (1905, 1907).

The Henderson Gneiss in the Park is a variably mylonitized biotite granitic augen gneiss, distinguished by medium- to coarse-grained, rounded to elongated porphyroclasts (augen) of feldspar, up to 0.6 in (1.5 cm) in diameter, in a finer-grained matrix of quartz, feldspar, biotite, muscovite, and epidote (fig. 6L).

Lemmon (1973) and Lemmon and Dunn (1975) interpreted the Henderson Gneiss to be of igneous origin. Paleozoic high-grade metamorphism and intense mylonitization along the Brevard fault zone during multiple periods of faulting produced the characteristic rock observed in the Park today.

The best exposures of the Henderson Gneiss occur in the lower Toxaway River gorge and along the western shore of Lake Jocassee. The access road to the lake also offers saprolitic exposures of the rock.

### Metamorphism

At least two significant episodes of regional metamorphism affected the rocks of Gorges State Park. The first was a very high-grade event during the Middle Proterozoic Grenville orogeny (about one billion years ago). The second was a high-grade event during the early to middle Paleozoic. The Toxaway Gneiss was metamorphosed during the Grenville orogeny (Carrigan and others, 2003), before all of the other rocks in the Park even existed.

Early to middle Paleozoic metamorphism affected all of the rocks in the Park. In the Blue Ridge rocks, Paleozoic metamorphism reached middle- to upper-amphibolite facies. At the peak of metamorphism, temperatures and pressures reached 1025° to 1200° F (555° to 650° C) and 14,500 to 58,000 psi (1 to 4 kilobars or 1020 to 4080 kg/cm$^2$) of pressure — equating to burial depth of 3 to 9 miles (5 to 15 km). In the Tallulah Falls Formation, Paleozoic prograde metamorphism altered previously unmetamorphosed sandstones, shales, and basalt to metagraywacke, mica schist, and amphibolite, respectively, and developed their characteristic texture, fabric, and foliation. Kyanite, a mineral indicative of middle- to upper-amphibolite facies metamorphism, is preserved in some rocks of the Tallulah Falls Formation.

For the previously metamorphosed rocks of the Toxaway Gneiss, Paleozoic metamorphism was retrograde. Retrograde metamorphism causes changes in a rock in response to temperatures and pressures that are lower than those in previous metamorphic events. Earlier formed Grenville textures, fabrics, and metamorphic mineral assemblages were "reset" and nearly completely overprinted by new foliation. Amphibolite found within the Toxaway Gneiss was partially retrograded to biotite schist during Paleozoic metamorphism.

During Paleozoic metamorphism, rocks of the Brevard fault zone were initially metamorphosed to lower amphibolite facies, and the Henderson Gneiss to upper amphibolite facies (Hatcher, 2001). Fluid flow during late Paleozoic faulting along the Brevard fault zone pervasively retrograded and overprinted rocks (within the fault zone and the adjacent Henderson Gneiss) to greenschist facies.

## Structures

Nearly every outcrop in Gorges State Park preserves structural features that attest to multiple episodes of metamorphism and deformation throughout geologic time. A foliation, the planar arrangement of constituent mineral grains in metamorphic rocks, is the most common feature.

Much of the layered biotite granitic gneiss in the Toxaway Gneiss and metagraywacke in the Tallulah Falls Formation exhibits a primary foliation. This compositional banding consists of light- and dark-colored minerals segregated into distinct layers (fig. 6A). In the Toxaway Gneiss, the banding is the result of several high-grade metamorphic events that have affected the rock since its formation in the Middle Proterozoic. In metagraywacke of the Tallulah Falls Formation, however, the bands may reflect original depositional layering that was recrystallized during early to middle Paleozoic metamorphism.

Many of the rocks in the Park, particularly those in the Brevard fault zone and Henderson Gneiss, display a mylonitic foliation. Extreme granulation and ductile shearing during faulting produce mylonitic foliations. In quartz- and feldspar-rich rocks, a mylonitic foliation is characterized by a distinct streaky or finely laminated appearance, and porphyroclastic mineral grains appear to be rotated within the layers.

Coarser-grained mylonitic rocks in the Toxaway Gneiss and Henderson Gneiss exhibit a flaser or wavy structure defined by abundant mica minerals enclosing "eye-shaped" porphyroclastic augen of feldspar (figs. 6B and L). Highly sheared mica-rich rocks, named phyllonites, are characterized by lenticular muscovite-aggregate porphyroblasts. These porphyroblasts are flattened in the mylonitic foliation planes and give rise to a distinctive "fish scale" or "button" appearance (fig. 6H) similar to that described by Horton (1982) in mica-rich rocks of the Brevard fault zone.

### Folding

Changes in the orientation of foliation define outcrop- and map-scale folds throughout the Park. Rocks bend, or fold, in response to compression within the Earth's crust. In many outcrops, foliation is folded into "U"-shaped synforms and "A"-shaped antiforms (fig. 7A). Tight folds locally deform the mylonitic foliation along the fault contact between the Toxaway Gneiss and Tallulah Falls Formation (figs. 7B and C). Most of these outcrop-scale folds appear to have formed simultaneously with development of foliation during regional metamorphism.

At map-scale, several prominent antiforms, the axial traces of which trend across the Park nearly perpendicular to Grassy Ridge, fold the foliation within the Toxaway Gneiss into a regional antiformal structure (Livingston, 1966; Horton, 1982). Northwest- and southeast-dipping foliations on either side of the axial traces define the fold limbs (pl. 1). To the west and at depth, the regional antiformal structure becomes overturned to the northwest (Hatcher, 2002a). These map-scale folds may have formed shortly after the Paleozoic peak metamorphic event in the region.

### Faulting

Rocks also respond to stress within the Earth's crust by faulting. A fault is the displacement of a rock mass along a fracture or zone of shear (fig. 8). Faulting is a dominant structural mechanism that deformed many of the rocks in Gorges State Park. Faulting under high temperatures and pressures deep within the Earth's crust produced the mylonitic foliation observed in the Brevard fault zone and in many other rocks throughout the Park.

A pre- to synmetamorphic fault separates rocks of the Toxaway Gneiss and Tallulah Falls Formation (pl. 1). The mylonitic foliation in rocks along the contact between the two units is tightly folded, suggesting that the fault formed slightly before, or simultaneously with, peak regional metamorphism, probably in the early to middle Paleozoic. The fault surface is also broadly folded at map-scale, possibly indicating additional folding after peak metamorphism. Several klippes, erosional remnants of the thrust sheet carrying rocks of the Tallulah Falls Formation in its hanging wall, are isolated north of the main trace of the fault in the vicinity of Indian Camp Branch and just north of the Toxaway River (pl. 1).

The largest and most significant fault in Gorges State Park is the Brevard fault zone (pl. 1). The Brevard fault

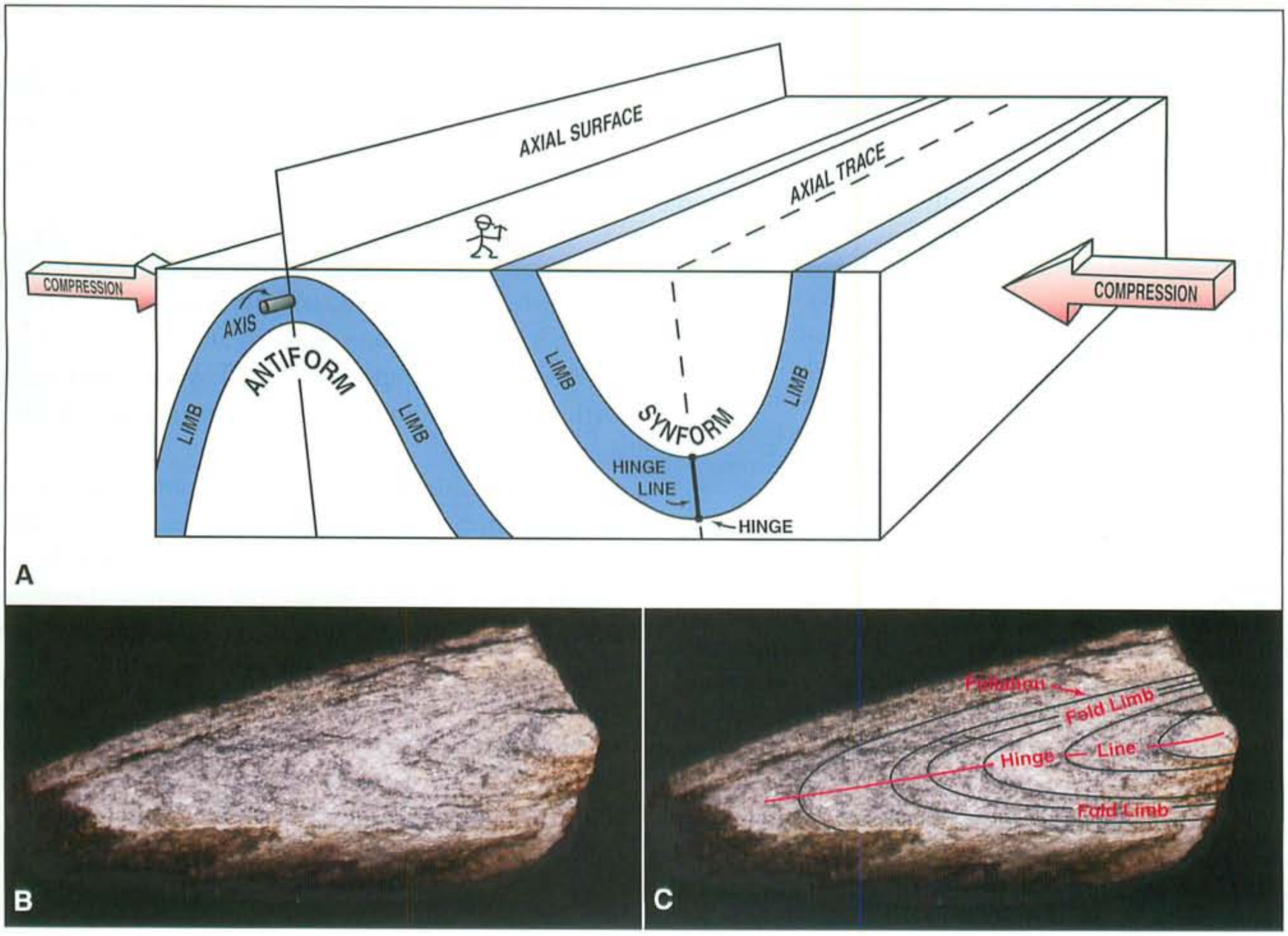



**Figure 7. A.** Graphic of fold elements (definitions for each fold element are provided in the glossary). **B** and **C**. Tightly folded mylonitic foliation in the Toxaway Gneiss at the fault contact with the Tallulah Falls Formation. This style of folding indicates that the faulting between the Toxaway Gneiss and the Tallulah Falls Formation probably occurred just before, or during, peak metamorphism in the Paleozoic. **B.** Photograph of the folded rock sample, which is about 3 in (7.6 cm) long. **C.** Photograph of the same fold showing various fold elements.

zone is a regional structure that extends more than 450 miles (725 km) from Virginia to Alabama. In the Park, rocks of the fault zone crop out from Frozen Creek Road in the northeast to Turkeypen Gap and upper Bear Creek in the southwest.

Although no longer active, the Brevard fault zone has a long history of repeated displacement (Hatcher, 2001). The earliest deformation occurred in the early to middle Paleozoic, and consisted of both dip-slip (thrust faulting) and dextral (right-lateral) strike-slip movement (Bobyarchick and others, 1988). At the time, rocks within the fault zone were under intense heat and pressure deep within the Earth's crust, and deformed ductilely in response to the faulting. This initial faulting weakened the rocks within the zone, so in the late Paleozoic, the fault zone was reactivated, initially as a dextral strike-slip fault (Edelman and others, 1987), and finally as a dip-slip thrust fault confined to a narrow strip along the western edge of the fault zone known as the Rosman Fault (Horton, 1982). Dip-slip thrust faulting occurred under less intense heat and pressure, so the rocks fractured and faulted brittlely (Horton and Butler, 1986).

In many of the larger outcrops throughout the Park, one can observe other small faults and shear zones displacing foliation, pegmatite veins, and migmatitic stringers and pods by only a few feet (1 m) or less (figs. 8D and E). Some of these outcrop-scale faults may have formed during regional metamorphism, folding, and faulting in the Paleozoic, but others may have formed later, during the Mesozoic or Cenozoic (for example, see Prowell, 1983).

Another common structural feature observed in most outcrops is joints. Unlike faults, joints are fractures or cracks in a rock mass along which there has been no appreciable displacement. Joints form by regional crustal extension, contraction, or as weathering and erosion remove layers of rock at the Earth's surface, relieving pressure on underlying rock layers and allowing them to expand upward and outward, creating cracks and fractures (fig. 9).

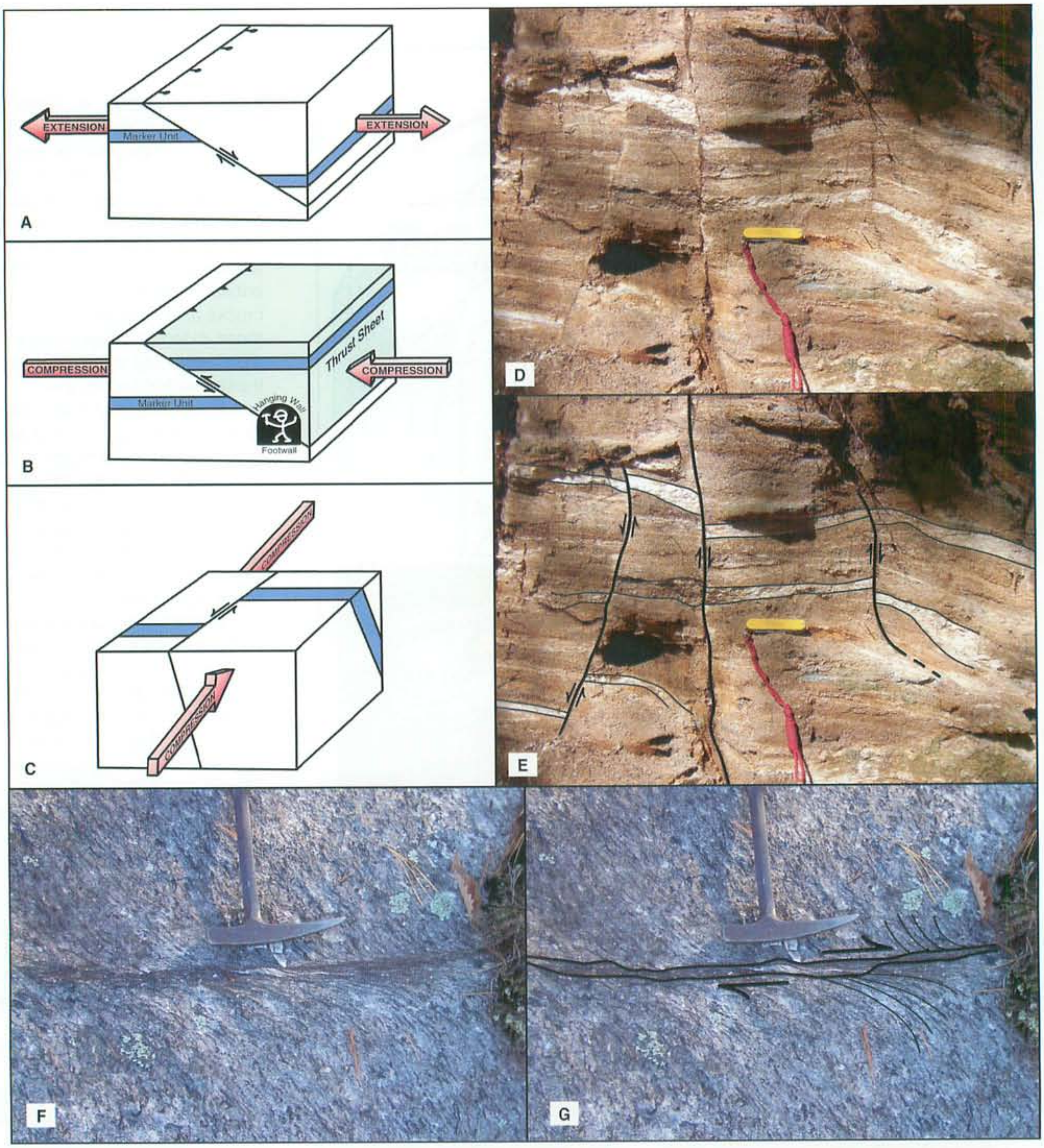



**Figure 8.** Classification and terminology of faults. **A.** Normal fault. **B.** Thrust fault. **C.** Strike-slip fault. Graphic definitions of a hanging wall (the overlying side of a fault), footwall (the underlying side of a fault), and thrust sheet (the body of rock above a large-scale thrust fault) is shown in green in **B.** **D.** Photograph of several small outcrop-scale brittle faults that displace dark metagraywacke, medium-colored mica schist, and light-colored migmatitic layers of the Tallulah Falls Formation; pocket knife is about 2.0 in (10c.0 cm) long. Photograph taken at a saprolitic outcrop along the trail to Wintergreen Falls, about 0.6 miles (1.0 km) northwest of Auger Hole Road. **E.** The same photograph as in **D,** but showing the traces of the faults. Notice that the light-colored migmatitic layers (marker units) do not "line up" across the fault surfaces, indicating displacement. **F.** Photograph of a small ductile shear zone in the Toxaway Gneiss; rock hammer head is about 9.0 in (23.0 cm) long. Photograph taken at a pavement outcrop on Grassy Ridge, about 0.4 miles (0.6 km) southeast of the Grassy Ridge access area parking lot. **G.** The same photograph as in **F,** but showing the trace of the shear zone. Notice how the foliation in the Toxaway Gneiss (the marker unit) is dragged into the shear zone, indicating displacement.

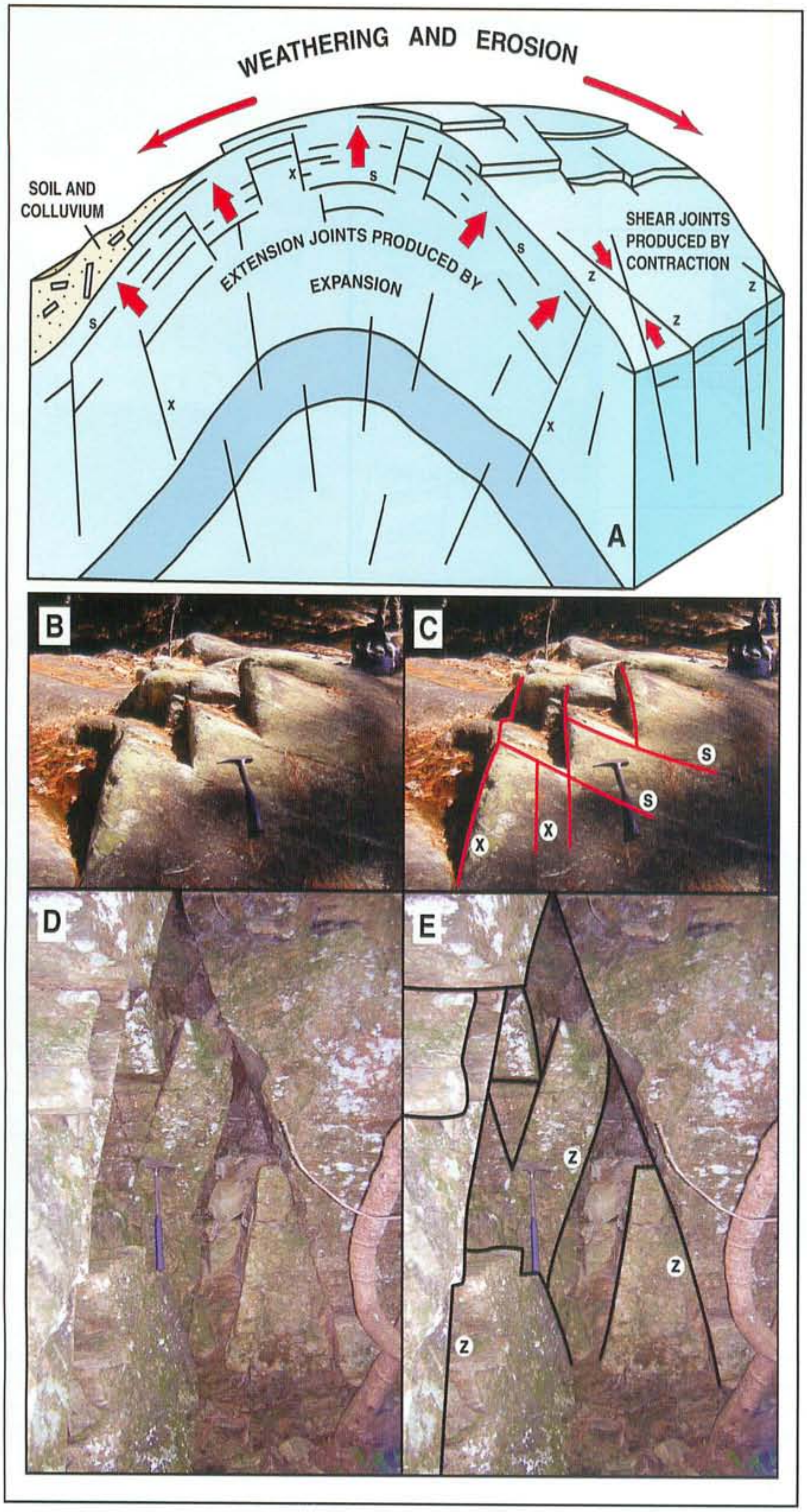



**Figure 9. Joints. A.** Schematic diagram showing the formation of extensional and contractional joints. As weathering and erosion remove rock at the Earth's surface, pressure is relieved on underlying rock, allowing it to expand upward and outward, creating extensional cracks and fractures. Some of these extensional joints (x) can dip steeply into the rock, such as those that form along the upwarped hinges of folds. Sheet joints (s), however, have shallow dips and mimic the shape of the overlying topography. Weathering and erosion sometimes spall and strip (exfoliate) sheets of rock away like peels of an onion, producing rounded or dome-shaped pavement outcrop. Compression, or contraction, of the rock mass during folding produces shear joints (z) on the limbs of folds. **B.** Photograph of extensional joints in an exposure of Toxaway Gneiss along the Toxaway River, approximately 0.8 miles (1.3 km) northwest of Auger Hole Road at its ford over the Toxaway River; the rock hammer is for scale. **C.** Extensional joint surfaces (x) are highlighted in the same photograph as in **B.** The shallow dipping surfaces (s) are joint planes developed along pre-existing foliation surfaces in the gneiss. **D.** Photograph of contractional, or shear joints in an outcrop of metasiltstone approximately 0.3 miles (0.5 km) southeast of Auger Hole Road at its ford over the Toxaway River. Intersecting shear joints like these are called conjugate sets. The rock hammer for scale is about 16 in (40 cm) long. **E.** Shear joint surfaces (z) are highlighted in the same photograph as in **D.**

Joints allow rainwater to penetrate rocks below the surface and supply bedrock aquifers with ground water. Penetrating water along joints also helps to decompose rocks beneath the surface and makes them more susceptible to weathering and erosion. Since it is easier for surface streams, creeks, and rivers to erode down through jointed, fractured, and weathered bedrock than to erode and meander across the landscape through less fractured and weathered bedrock, joints directly control the location of many of the streams, creeks, and long stretches of the Toxaway River within the Park.

### Tectonic History

The following summary of the tectonic history of the rocks and structures of Gorges State Park is a compilation of more than a century of work by many Appalachian geoscientists. Primary sources of information for this summary are Hatcher and others (1989) and Horton and Zullo (1991). Readers are encouraged to refer to these volumes and their accompanying references for data, discussions, and syntheses.

The geologic history of the rocks in Gorges State Park began more than a billion years ago with the Grenville orogeny, the first of several major mountain-building events to affect this part of the Southern Appalachians (fig. 10). During the Grenville orogeny, global geologic forces assembled a large continental landmass called Rodinia, of which the ancestral North American continent was a part (Hoffman, 1991; Moores, 1991; Rogers, 1996; Weil and others, 1998; Karlstrom and others, 1999) (fig. 11). Early in the Grenville event (1.15 billion years ago), igneous intrusions crystallized from magma within the crust of Rodinia. In the later stages of the Grenville event, about one billion years ago, these intrusions were highly metamorphosed and altered (Carrigan and others, 2003), and some became the rocks now recognized in Gorges State Park as the Toxaway Gneiss.

After the Grenville orogeny, all was quiet for the next several hundred million years, until the Late Proterozoic, about 700 million years ago, when global geologic forces began to rift (break) the continent of Rodinia apart (Aleinikoff and others, 1995). Around 565 million years ago, rifting along the eastern margin of the ancestral North American continent, called Laurentia, signaled the final breakup of Rodinia, and created a new ocean basin between the fragmented continental pieces. This ancient ocean basin between the rifted pieces of Rodinia is called the Iapetus Ocean.

Weathering and erosion of the Laurentian continent produced sediments that filled rift basins along its margin, and on the continental slope and rise (Hatcher, 1978). Sediments on the outer continental rise were interlayered with mafic dikes, sills, and lava flows. These sediments eventually hardened into rock and were later metamorphosed to produce the rock unit now recognized in the Park as the Tallulah Falls Formation.

For the next 200 million years or so, sediments and volcanic rock continued to fill the ocean basin. It was also during this time that rocks of sedimentary origin, now within the Brevard fault zone, were deposited (Hatcher, 1969; 1972). Marble in this sedimentary sequence indicates deposition in a marine environment. Little more is known about their origin, but rocks that later became the Brevard fault zone were most likely deposited slightly after the Tallulah Falls Formation somewhere in the Iapetus Ocean (Hatcher, 2002b).

By the early Ordovician, around 500 million years ago, the ancient Iapetus ocean basin that was born during continental rifting in the Late Proterozoic began to close. By 460 million years ago, the ocean had closed so much that Laurentia began to collide with a chain of volcanic islands, signaling the start of Paleozoic mountain-building that would last for the next 175 million years and culminate with the complete closure and destruction of the ocean basin.

About the time that the Iapetus ocean started to close, the last major rock unit of Gorges State Park formed. The Henderson Gneiss formed about 490 million years ago (Carrigan and others, 2003). The rocks probably crystallized initially from granitic magma that intruded sediments far offshore from the continental margin (Hatcher, 2002). During Paleozoic mountain-building, the Henderson Gneiss was metamorphosed and deformed into the mylonitic rock now observed in the park.

At the onset of Paleozoic mountain-building, sometime around 460 million years ago, major thrust faults in the Earth's crust, deformed rocks throughout the southern Appalachian Mountains. In the vicinity of Gorges State Park, sedimentary and igneous rocks of the Tallulah Falls Formation were thrust over rocks of the Toxaway Gneiss. A little later, between 450 and 350 million years ago, these rocks — muddy sandstone, shale, and basalt — underwent metamorphism and recrystallized to form the metagraywacke, mica schist, and amphibolite seen in the Park today. Foliation, folds, pegmatite, and migmatite within the Tallulah Falls Formation most likely developed during this metamorphism. Granitic rocks of the Toxaway Gneiss were again metamorphosed for a second time in their history, overprinting earlier textures and fabrics.

Shearing that produced the Brevard fault zone and deformed the adjacent Henderson Gneiss began between 450 and 350 million years ago. During this early stage

1. Rejuvenation of mountains by tectonic and isostatic uplift; continual weathering and erosion, and development of modern-day landscape in the last ~65 million years.

2. North America separates from Africa; formation of Atlantic Ocean around ~220 million years ago.

3. Culmination of Paleozoic mountain building ~260 to 320 million years ago; reactivation of Brevard fault zone, and formation of Rosman fault.

4. Metamorphism of Tallulah Falls Formation, Brevard fault zone rocks, and Henderson Gneiss ~350 to 450 million years ago; formation and faulting along Brevard fault zone.

5. Onset of Paleozoic orogeny and formation of Pangea; Tallulah Falls Formation faulted over Toxaway Gneiss ~460 million years ago.

6. Crystallization of Henderson protolith ~490 million years ago.

7. Deposition of Brevard fault zone protoliths slightly after deposition of the Tallulah Falls Formation.

8. Deposition of Tallulah Falls Formation protoliths ~500 to 600 million years ago

9. Continental rifting; formation of Laurentia (ancestral North America) ~565 to 700 million years ago.

10. Grenville orogeny and formation of Rodinia; metamorphism of Toxaway Gneiss ~1.0 billion years ago.

11. Crystallization of Toxaway Gneiss protolith ~1.15 billion years ago.

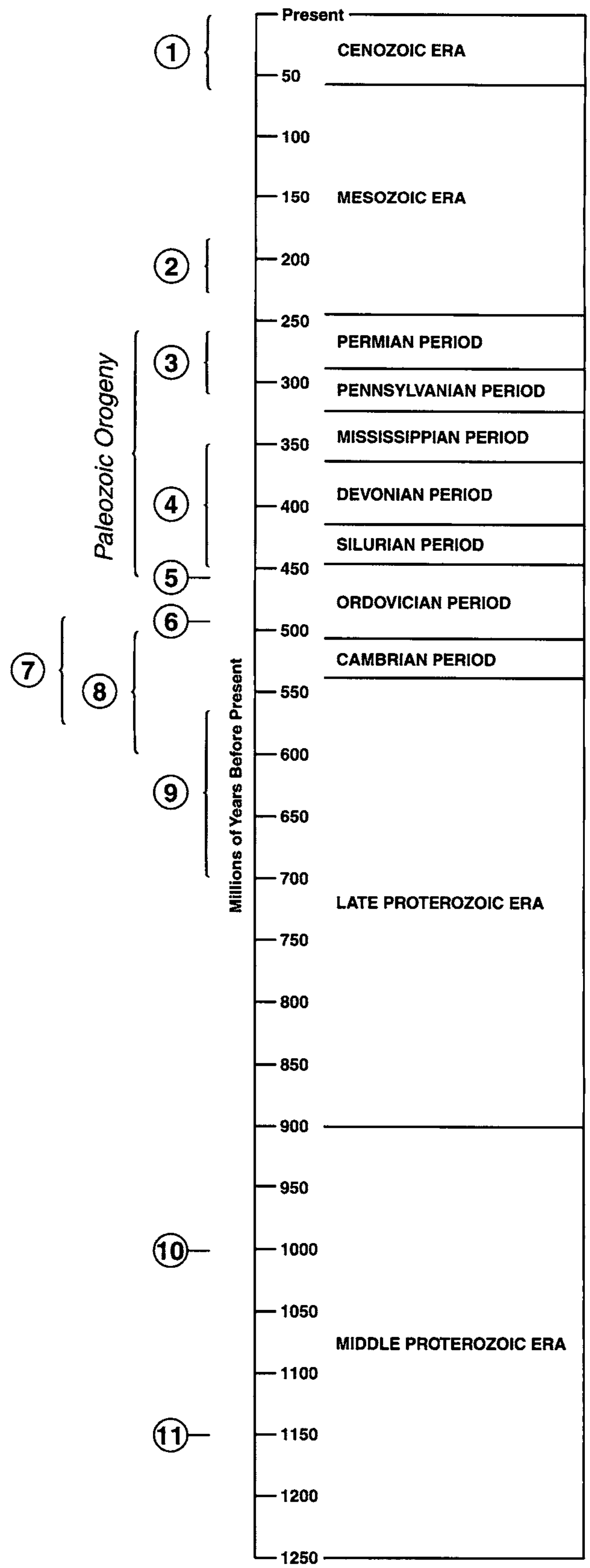



**Figure 10.** A geologic time line for Gorges State Park, showing the timing of major events in the geologic evolution of the Park. Refer to text for discussion and citations.

of faulting, rocks of the Brevard fault zone and Henderson Gneiss were also metamorphosed (Hatcher, 2001).

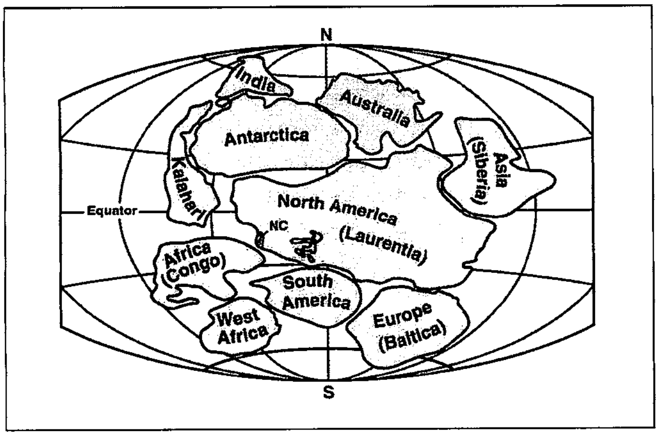



**Figure 11.** Paleogeography of the supercontinent Rodinia at the close of the Grenville orogeny about one billion years ago. The continent of Laurentia (ancestral North America) is a central landmass within the supercontinent. Note the location of what will become the state of North Carolina one billion years later. The Great Lakes are shown for reference. Diagram modified from Carrigan and others (2003), Scotese (2001), and Hoffman (1991).

Paleozoic mountain-building in the southern Appalachians culminated around 320 million years ago when the Laurentian and African continents collided to form the supercontinent of Pangea (Hatcher, 2002c) (fig. 12). The collision ushered in the grandest of all mountain-building events in the southern Appalachians. Rocks of the Blue Ridge and Inner Piedmont were shoved some 300 miles (483 km) westward along major faults in the Earth's crust to their present-day positions. Rock masses were piled one on top of the other and arched upward as the thrust sheets were stacked (Hatcher, 2002c).

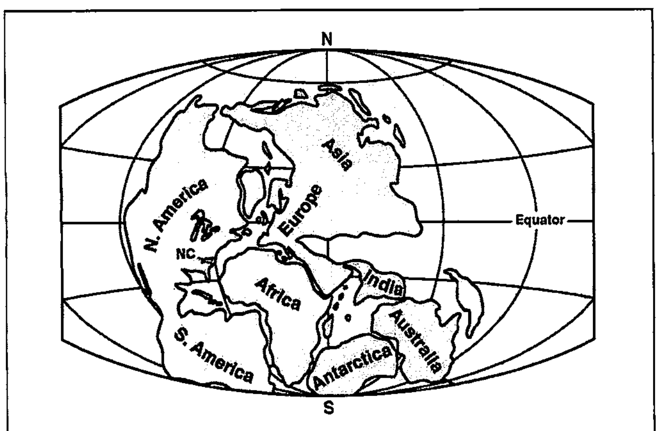



**Figure 12.** Paleogeography of the supercontinent Pangea at the close of Paleozoic mountain-building about 260 million years ago. Note the location of what will become the state of North Carolina. The Great Lakes are shown for reference. Diagram modified from Scotese (2001).

In the vicinity of Gorges State Park, a reactivated Brevard fault zone took part in this massive crustal movement. Strike-slip faulting overprinted the earlier mylonitic foliation and imparted new textures and fabrics as the rocks of the fault zone and Henderson Gneiss were retrogressively metamorphosed to greenschist facies. Finally, the development of the Rosman thrust fault at the western edge of the Brevard fault zone marked the last gasp of crustal faulting at the close of Paleozoic mountain-building (Horton and Butler, 1986; Bobyarchick and others, 1988).

Following this final episode of mountain-building, a range of high mountains dominated the landscape of western North Carolina some 260 million years ago. By 220 million years ago, during the Mesozoic, the African and North American continents began to split apart to create the modern Atlantic Ocean. Large rift basins, not unlike those that formed in this region during continental rifting some 500 million years before, broke the landscape from New England to Mississippi. In the mountains, crustal extension created joints that accelerated weathering and erosion. Sediments eroded from the mountains and filled the rift basins, then spilled out onto the lowlands to form some of the basal sedimentary rocks of the present-day Coastal Plain. By the start of the Cenozoic Era about 65 million years ago, the high mountains formed during the Alleghanian orogeny some 200 million years earlier were nearly completely eroded.

Sometime during the Cretaceous Period (late Mesozoic Era — see geologic time scale on inside of back cover), the crustal extension that characterized the earlier Mesozoic Era became compressional (Prowell, 2000), and created the forces that again caused uplift of the mountains. But it was not until the Miocene Epoch (between 10 and 5 million years ago) during the Middle Cenozoic Era that there was enough relief on the rejuvenated southern Appalachian Mountains to shed large volumes of sediment (Weems, 1998). Similar deposits reported by Weems (1998) indicate another pulse of uplift began in the Pliocene Epoch (about 5 to 1.8 million years ago during the late Cenozoic Era. Prowell (2000) reported that Cenozoic uplift has raised Cretaceous marine deposits 1000 ft (300m) above the present sea level in south-central Tennessee. These lines of evidence suggest that although the rocks in the mountains date back to the Proterozoic and Paleozoic, the mountainous landscape we see today is Cenozoic in age.

Pulses of tectonic uplift and ongoing isostatic uplift over the last 65 million years of Earth's history have raised new mountain peaks in the Southern Appalachians (which continue to rise ever so slowly even to this day), while weathering and erosion have continually worked toward their denudation. Just over the last 1.5 to 1.65 million years, landslides and other slope movements have occurred throughout the mountains to reduce their height as rivers and their tributaries have transported large volumes of eroded material to the coast. This cyclical balance of uplift, weathering, and erosion never ends, and is responsible for the continual evolution of the present-day and future landscape.

## SLOPE MOVEMENTS AND RELATED SURFICIAL DEPOSITS

Quaternary age slope movements and surficial deposits occur throughout Gorges State Park (see pl. 2) and reflect geologic processes that are still active today. Plate 2 shows three main categories of Quaternary map units: 1) slope movements (i.e., landslides); (2) hillslope deposits; and, (3) alluvium. Slope movements, along with erosion and sediment transport by rivers and streams, are the predominant processes that form the hillslope deposits and alluvium. These unconsolidated deposits, derived largely from the weathering, erosion, and transport of the underlying bedrock, are the youngest geologic deposits in the Park. Because surficial deposits have been transported by gravity and water, they are distinguished from residual deposits derived from in-place, weathered rock. Even though some of the surficial deposits are perhaps hundreds of thousands of years old, they formed when the overall landscape looked much as it does today. Some of the surficial deposits, however, were deposited as recently as the 20th century.

Instead of "landslide," the general term"slope movement" is used here because it also includes material (i.e., debris and rock) that is transported by sliding, flowing and falling. The way slope movements are named, or classified, is described in Appendix A. Plate 2 delineates those areas where a slope movement process (e.g., rockfall) has occurred, or is occurring. Table 1 summarizes the main types and characteristics of slope movements found in the Park.

Alluvium is sediment deposited by streams, rivers, and floodwaters, and is generally confined to their channels and floodplains. Hillslope deposits, however, form by the gravitational downslope movement of regolith and rock. Hillslope deposits can also form by rapid slope movements such as debris slides, debris flows, and rock fall; or by slower processes such as the gradual movement of regolith by creep.

Colluvium is the general term applied here to the latter, typically formed by erosion and creep. Hillslope deposits can also contain alluvial constituents (see fig. 13A). In many cases, fan- or lobe-shaped alluvial deposits at stream outlets consist mainly of reworked hillslope deposits derived upslope from the fan. Continued stream action usually winnows away the finer-grained material leaving behind the gravel, cobbles, and boulders.

Many of the individual hillslope deposits shown on Plate 2 undoubtedly originated from one or more slope movements that occurred hundreds, if not thousands, of years ago. In many cases dense vegetation obscures features such as breaks in the ground (scarps), source areas (scars), and scoured channels (tracks) that indicate relatively recent slope movement activity. With time, erosion and weathering further subdue these features, and in some cases remove them altogether. If features such as scars, scarps, or debris flow tracks could be recognized, then a map unit was classified as a slope movement rather than a hillslope deposit.

Generalized descriptions of the slope movements and surficial units shown on Plate 2 follow. Further descriptions of the map units are included on the plate as well.

### Alluvium

Alluvium is the term for the unconsolidated accumulations of silt, sand, cobbles, and boulders deposited by streams and rivers. Aside from the 1916 flood deposits along the Toxaway River (described later), and the ubiquitous deposits of rounded gravel and cobbles in narrow stream channels, extensive accumulations of alluvium are relatively rare in the Park. Most drainages have steep gradients with narrow channels controlled by bedrock outcrop. For this reason, wide, gently sloping floodplains where alluvial deposits can accumulate are generally absent, except along the shores of Lake Jocassee. The gentle slopes around, and beneath, the lake are covered with 1916 and younger flood deposits. Alluvial deposits have also accumulated along the lower-gradient reaches of the major streams such as Holly Pen Creek, Auger Fork Creek, and the upper reach of Bearwallow Creek.

Fan-shaped deposits of alluvium (alluvial fans) can be found along tributary outlets where they flow into the Toxaway River. These alluvial fans may also contain reworked and winnowed debris deposits that have traveled down drainage courses. A good example of a cobble-boulder alluvial fan deposit can be found where Toxaway Creek flows into the Toxaway River. Alluvial deposits generally do not present a significant slope movement hazard because they occur on gentle slopes. Localized, minor movements can occur where streams have incised into the alluvium leaving steep banks.


**Figure 13.** Quaternary debris and alluvial deposits. **A.** Interlayered components of a composite debris fan exposed in a bank along the east shoreline of Lake Jocassee (Field Trip Stop 13S). Debris fans accumulate over thousands of years and are typically made up of a mixture of deposits originating as debris flows, rockfall, colluvium, and alluvium. Layer 1, a non-statified sandy silt, is the finest-grained layer in the sequence, and is possibly a buried ancient soil horizon. Subangular to subrounded gravel in a light brown, silty sand matrix marks the erosional base of layer 2. A 12 in (30 cm) long, partly decomposed clast of the Henderson Gneiss is outlined in layer 2. The highly variable grain size and lack of internal stratification in this layer, along with its erosional base indicates it may be an ancient debris flow deposit. Interstratified sand and rounded gravel horizons in layer 3 indicate stream laid deposits. Coarse-grained, angular rock fragments mark the irregular, erosional base of layer 4, another possible debris flow deposit. **B.** Boulder of the Henderson Gneiss stands in relief on the ground surface of a debris fan deposit upslope from the exposure shown in 13A. The long dimension of the boulder is about 8 ft (2.5 m). This and other boulders indicate that the debris fan deposits include rockfall that originated from cliffs upslope. **C.** Subangular to subrounded gravel and cobbles suspended in a red-brown, clay-silt-sand matrix delineate the erosional base of a possible ancient debris flow deposit (Qdfl). Stratified sand and gravel stream deposits at the base of layer Qa fine upward to silty sand. This exposure along Auger Fork road near Chestnut Creek also illustrates the composite nature of Quaternary debris deposits. The shovel handle is about 16 in (40 cm) long. **D.** An ancient debris deposit exposed along Auger Fork road is made up of partly- to completely decomposed, angular rock fragments of the Tallulah Falls Formation supported in a red-brown, clay-silt-sand matrix. This debris deposit may have formed from a debris flow, or by rainwash and the slow, continuous downslope creep of sediment characteristic of colluvium.

## Hillslope Deposits

### Debris and Debris Fan Deposits

Debris and debris fan deposits are texturally similar in that they contain poorly sorted, silt- to boulder-sized material. Debris typically forms elongate deposits along perennial stream valleys, while debris fans form apron-like deposits along foot slopes. The elongate tongues of debris tend to occur on dip slopes (e.g., southeast-facing slopes), in contrast with debris fans that tend to form below northwest-facing scarp slopes or southwest-facing oblique slopes.

Although of limited extent elsewhere in the Park, excellent examples of debris fan deposits are exposed along foot slopes above the east shore of Lake Jocassee. Here, tributary streams have cut through coalescing fan deposits with source areas above the lake in the steep, northwest-facing scarp slopes of the Henderson Gneiss. Boulders, some larger than 8 ft (2.5 m), rest on the interfluves and side slopes above streams (figs. 13A and B). Low lake levels expose good examples of composite debris fan deposits with alluvium (rounded rock fragments) and debris (angular rock fragments) along wave cut banks.

Both debris and debris fans deposits are accumulations of transported material that originated mainly from debris slides, debris flows, and rockfall from steep source areas upslope. Colluvium can also make up part of debris deposits. Past and present-day streams have incised, eroded, and winnowed most of the debris and debris fan deposits; therefore, they are usually reworked and include an alluvial component.

In general, these deposits do not present a significant slope movement hazard in their undisturbed state. Because debris deposits tend to be deep, loose accumulations of soil and rock mixtures, they can become unstable in steep-sided excavations such as road cuts. Debris deposits record past slope movement activity, and indicate potentially unstable or marginally stable hillsides in the upslope source areas.

### Undifferentiated Colluvium

Accumulations of gravel, cobbles, and boulders suspended in a clay, silt, and sand matrix sporadically mantle hillslopes and hillslope hollows throughout the Park. These gravitational deposits, usually in the state of transport, are mapped as undifferentiated colluvium. Like debris deposits, rock fragments within the colluvium are usually angular to subangular; however, the deposits here lack the fan, or tongue-shaped morphology typical of debris.

As mapped here, colluvium represents deposits formed mainly by slow gravitational creep rather than from more rapid forms of slope movement such as debris flows. A number of areas in the Park are covered by thin colluvium, and only thicker accumulations are mapped and shown on Plate 2. The deep red-orange colored clayey matrix, and the completely decomposed rock fragments that make up some of the colluvial deposits (fig. 13D) indicate they are probably tens, if not hundreds, of thousands of years old.

## Slope Movements

### Debris Slides and Debris Flows

Numerous debris slides occur throughout the Park. Debris slides typically occur on steep slopes (greater than 35°) along drainages and in drainage headwalls on scarp slopes. Most occur on slopes above the Toxaway River and its major tributaries, but debris slides also occur on steep dip slopes overlying rocks of the Brevard fault zone along the northwest side of Auger Fork. Most are small, less than 65 ft (20 m) wide by 80 ft (25 m) long, and less than 6-9 ft (2-3 m) deep. One exception is a 100-ft wide by 70-ft (21 m) long debris slide on the east side of the Toxaway River about 200 ft (60 m) downstream from the confluence with Panther Branch.

Debris slides can be recognized as shallow elliptical features with an arc-shaped main scarp and an accumulation of displaced regolith downslope. Almost invariably, debris slides are found in marginally stable areas that show evidence of soil creep such as curved tree trunks and regolith accumulations behind tree trunks (i.e., soil buttressing). Oversteepening of slopes by the Toxaway River during the August 1916 Toxaway dam failure torrent was probably a contributing factor in initiating debris slides along the lower slopes of the Toxaway River gorge upstream from Step Around Falls to about 400 ft (120 m) below the Park boundary.

Debris slides are distinguished from debris flows by the water content of the displaced regolith. Debris slides usually do not contain sufficient water for them to mobilize (i.e., liquefy) and rapidly travel great distances downslope. Debris flows, however, do liquefy and move rapidly downslope.

Although debris and debris fan deposits give evidence of past debris flow activity, mapping identified only a few clearly recognizable debris flow scars and associated tracks. Two of these debris flows appear to be related to past road construction prior to the designation of the area as a park.

A sharp contact between firm bedrock and loose colluvium characterizes the steep slopes prone to debris slides and flows. Especially susceptible areas are those where colluvium has collected in small hollows and wedges formed by a buried, irregular bedrock surface. The higher permeability of the colluvium contrasts with the relatively impermeable bedrock, allowing infiltrating water to accumulate along the contact and increase the destabilizing pore-water pressures.

Small debris slides present a relatively limited hazard unless the water content becomes sufficient for them to mobilize into debris flows. Usually confined to existing drainages, the soil, rock, and water mixture characteristic of a debris flow can move downslope at speeds greater than 30 mi/hr (48 km/hr) with a force sufficient to bury, damage, or destroy buildings and bridges.

### Rockfalls

Rockfalls are active throughout the Park and occur mainly in two geomorphic settings: on slopes oblique to the dip of the bedrock foliation along the steep walls of the Toxaway River; and on northwest-facing scarp slopes. Rockfalls occur in all major rock units where discontinuities (planes of weakness) in the rock are oriented and intersect in such a way that the blocks of rock between the planes fall from a rock face. Wedging along these planes by repeated freeze-thaw cycles and tree roots incrementally push the blocks of rock outward toward a free face until the frictional resistance along the sides of the blocks is overcome, and they topple or fall.

Rock cliffs along the Toxaway River are prone to rock fall (fig. 14) because steeply dipping, northwest-striking joint sets subparallel the gorge walls. In contrast, northeast-striking fractures create planes of weakness in cliff lines along northwest-facing scarp slopes like those east of Lake Jocassee, making them susceptible to rockfall. Rock overhangs form on oblique and scarp slopes where joint and foliation planes intersect to leave unsupported rock ledges susceptible to rock fall. An excellent example of rockfall from an overhang is just below the confluence of Maple Spring Branch and Auger Fork Creek. Here the stream undercuts graphitic breccia and brecciated phyllonite along the Rosman fault, leaving an unstable overhang.

Although rockfall can occur in response to heavy precipitation, it can also occur during periods with little or no rainfall. Repeated freeze-thaw cycles can often trigger rockfall as ice wedging along discontinuities in the rock pushes apart blocks. Earthquakes can also trigger rockfall.

Rockfall from the numerous cliffs and overhangs presents a significant, but avoidable, hazard. Most of the areas prone to rockfall (except a few roadcuts) are in remote areas that are difficult to access. Rockfalls occur suddenly, often without warning, and do not necessarily coincide with heavy rainfall; therefore, the exact timing of rockfall events is nearly impossible to predict. For this reason it is best to avoid approaching cliffs and overhangs.

### Rockslides

Aside from the Toxaway River slide described below, only four rockslides were observed in the Park. The four rockslides are on slopes that conform to the southeast-dipping rock foliation along incised reaches of the Toxaway River and Auger Fork Creek. All four are past-active, and less than 60 ft (18 m) wide by 60 ft (18 m) long. In all cases, the blocks of detached rock slipped along weak zones parallel to the foliation planes.

#### Toxaway River Slide

The most prominent, active slope movement identified in the Park is the Toxaway River slide (see inset map, pl. 2). It is located on the east side of the Toxaway River about 1970 ft (600 m) downstream from the confluence with Panther Branch. Encompassing about 4 acres (approx. 16,200 m$^2$), nearly the size of four football fields, the slide is an excellent example of an active geologic process. The toe of the slide encroaches upon the Toxaway River, and the uppermost limit of the arcuate main scarp extends about 600 ft (180 m) upslope. The old roadbed that serves as the trail to Wintergreen Falls crosses the active toe area of the slide. Although Thomas (1998) shows the location of the slide, detailed geologic and topographic mapping, and tree-ring studies were conducted to help assess the type and extent of the slide, as well as its movement rate, history, and any potential hazards.

### Characteristics

The land surface of the Toxaway River slide includes many classic features of an active slope movement. Material removed from the upper part of the slide travels downslope, and leaves behind a concave, or bowl-shaped hollow on the hillside. Accumulations of material form bulges, or convex topogragphy along the lower slopes. Hummocky, uneven ground with mounds and depressions reflects how different areas within the slide are actively compressed, while others are pulled apart. Arc-shaped scarps impart a stair-stepped appearance to the hillside and mark where the ground surface has dropped down abruptly. Tilted and curved trees give further evidence that the ground is moving (figs. 15A and B).

Technically, the slide is classified as an active, composite, weathered-rock slide (Appendix A). The total translational movement is estimated to be on the order of about 60 ft (18 m) as determined graphically along cross-section A-A' (pl. 2). The term composite indicates there are components of translational and rotational movement. Translational movement along a planar failure surface at depth appears to predominate over rotational movement. Back-tilted trees indicate a rotational

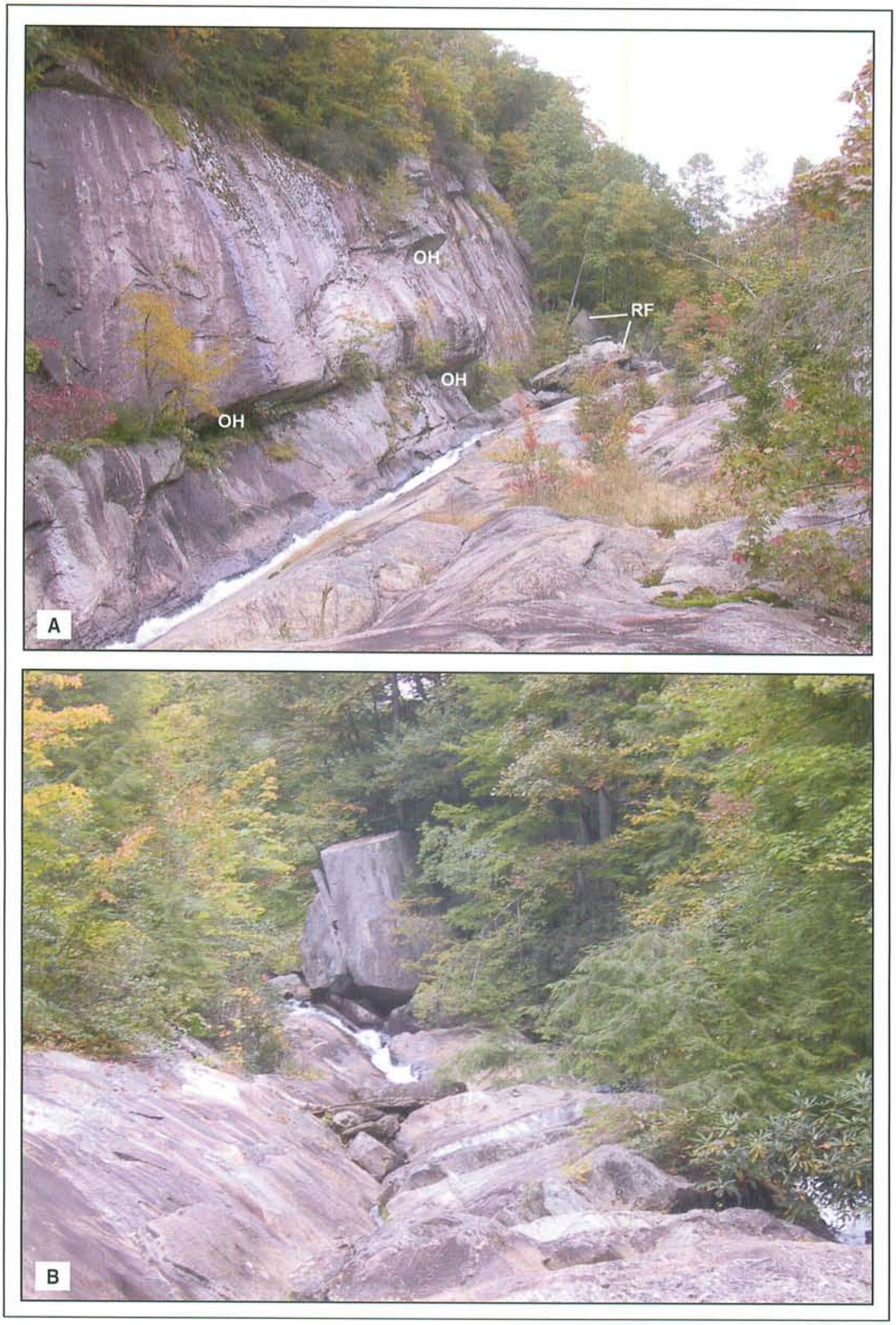



**Figure 14.** Rockfalls. **A.** A rockfall deposit (RF) below a cliff face of the Toxaway Gneiss along the upper Toxaway River gorge upstream of The Narrows (location A, fig. 4). Joint planes that dip into the cliff face intersect exfoliation joints that parallel the cliff face to create rock overhangs (OH) susceptible to rockfall. **B.** A rockfall boulder of the Toxaway Gneiss over six feet high along the upper Toxaway River upstream of The Narrows (near location A, fig. 4). The source area for the rockfall is upslope of the trees to the right.


**Figure 15.** Curved trees growing on the Toxaway River slide. Slide movement causes the entire tree to lean. As the rate of slide movement decreases the upper part of the tree resumes vertical growth resulting in a curved trunk. **A.** A large curved conifer, about 18 in (46 cm) in diameter, growing in the main body of the slide. Arrow points to person at base of tree for scale. **B.** A smaller conifer, about 8 in (20 cm) in diameter, growing just upslope of where the trail crosses the toe of the slide. This and other curved trees in the vicinity indicate movement within this portion of the slide sometime during the last 10-15 years. Photographs courtesy of Malcolm Schaeffer.

component within some slide blocks; however, the absence of surface slope reversals (i.e., slopes that tilt back toward the hillside) on the slide blocks indicates that the rotational component of movement is less than the translational component.

Exposures in the scarps indicate that the bulk of material moving downslope is weathered bedrock of the Tallulah Falls Formation and the Toxaway Gneiss (figs. 16A and B). The term "weathered" modifies the term "rock" because the displaced blocks of rock within the slide are partly to completely decomposed, but retain the relict mineralogy, textures, and fabric of the original bedrock. The terms "partly decomposed" and "completely decomposed" are used to describe progressive degrees of rock weathering in the Unified Rock Classification System (Williamson, 1984).

The granitic Toxaway Gneiss decomposes to silty sand, while the metasedimentary rocks of the Tallulah Falls Formation weather to micaceous silty sand with a higher percentage of silt than the weathered Toxaway Gneiss. Scarps in the slide truncate and expose a distinctive layer of red-orange colluvium that overlies the residual regolith. At depth, the failure surface is interpreted to be at the contact between weathered and unweathered bedrock; however, subsurface information below the depth of hand augering is not available.

Detailed mapping in the slide revealed mylonitic rocks at the contact between the two rock units, and that the rocks of the younger Tallulah Falls Formation are enveloped by the older Toxaway Gneiss. These relationships lead to the interpretation that here, the schists and metagraywackes of the Tallulah Falls Formation form a "klippe," (i.e., an isolated remnant of a thrust sheet), in fault contact with the granitic Toxaway Gneiss. In this respect, the slide is unique because it preserves evidence of ancient faults and modern-day slope movement.

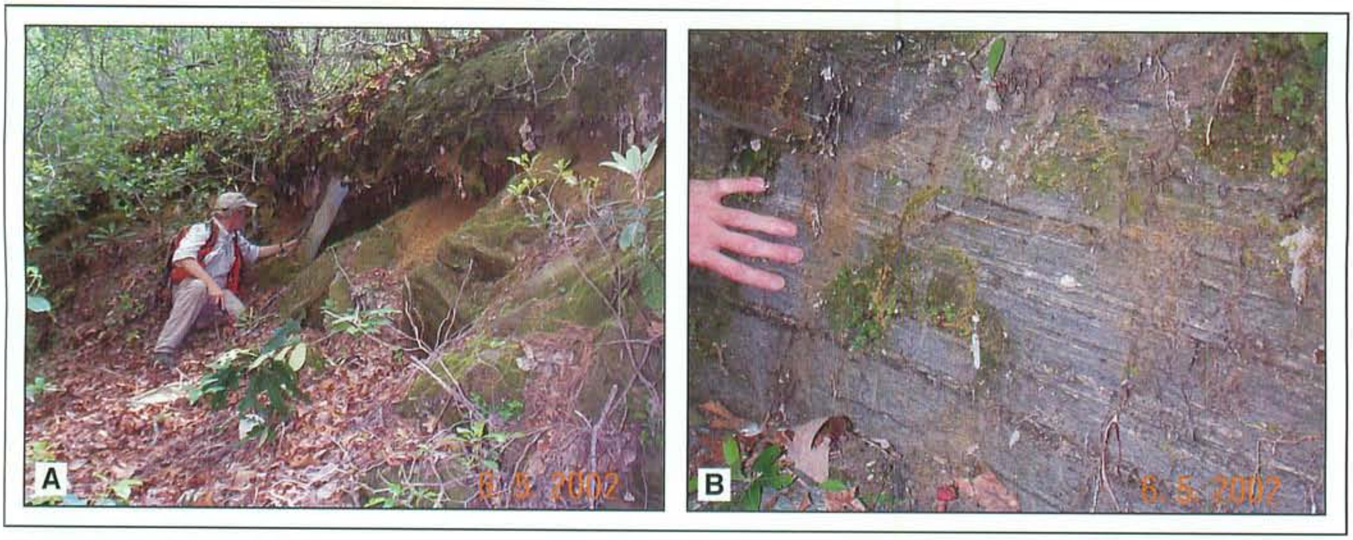



**Figure 16.** Bedrock exposed in the main scarp of the Toxaway River slide. **A.** Partly decomposed Toxaway Gneiss exposed in the main scarp of the Toxaway River slide. The down-dropped part of the slide is in the left foreground. **B.** Completely decomposed, mylonitic Toxaway Gneiss exposed in the main scarp of the Toxaway River slide. White, elongate porphyroclasts of potassium feldspar are flattened in the plane of the mylonitic foliation, delineated here by alternating light and dark banding. Photographs courtesy of Malcolm Schaeffer.

### Movement History and Rates

For the most part, movement rates of the slide have not exceeded the ability of trees to stay rooted and resume vertical growth after tilting. In parts of the slide, large trees do not appear to be significantly curved or tilted. Assuming the slide initiated in 1916 and has moved about 60 ft (20 m) downslope by the year 2000, the average rate of movement is about 8-9 in/yr (2-3 cm/yr). Taken together, these indirect lines of evidence suggest the overall average rate of slide movement is relatively slow, perhaps on the order of only a few inches per year depending on rainfall amounts. Numerous haphazardly fallen trees, and unvegetated lobes of slide debris that would indicate relatively recent rapid movement were not observed.

Different parts of the slide probably move at different rates and times as parts of the slope adjust to reach equilibrium in response to precipitation. Deformed saplings and unvegetated scarps indicate that the toe of the slide at cross-section A-A' has been active within the last 15 years; it is probably one of the more active areas within the slide. This area may correspond with an active slide in the vicinity of Panther Branch reported by Hatcher (1973). In that report, movement was attributed to heavy rainfall during the winter and spring of 1972-1973.

Tree-ring analyses of larger trees on, and adjacent to the slide, indicate a period of movement associated with prolonged, above average rainfall for the period from about 1965 to 1974. Heavy rains from Hurricane Agnes in June 1972 fall within this timeframe and probably contributed to movement of the slide. A decrease in growth rate for the tree on the slide during this time interval coincides with an increased growth rate for the control tree adjacent to the slide. Disturbance of the root system by slide movement is a factor that can cause a sudden decrease in tree growth rate (Terasmae, 1975). Above average rainfall can trigger slide movement, while at the same time result in increased growth rates for trees not on the slide. De Boer and Archibold (2001) observed a similar pattern of increased precipitation and slide movement that corresponded with decreased tree growth rates for trees on slides, and increased growth rates for other trees not on the slides. Figures 17A and B show plots of growth rates, and increment cores for an eastern hemlock (*Tsuga canadensis*) on the Toxaway River slide, and a nearby control tree adjacent to the slide (the eastern hemlock is also informally known as the Canadian hemlock).

When movement began on the slide is not known. Because the scarps cut across the colluvium, which does not mantle the scarp slopes, earliest movement clearly post-dates the development of the colluvial soil profile. Aerial photographs from April 28, 1953, show gaps in the tree canopy and evidence for sedimentation into the Toxaway River at the current location of the slide, suggesting that movement had already occurred. A plausible time for initial movement would be shortly after the August 13, 1916 dam failure. A bend in the river channel would have directed the flood torrent toward what is now the toe of the slide. Floodwaters may have eroded the slope along the river before water from the preceding heavy rains had drained from the slope. The combination of the oversteepened slopes and increased pore-water pressures could have triggered initial movement of the slide.

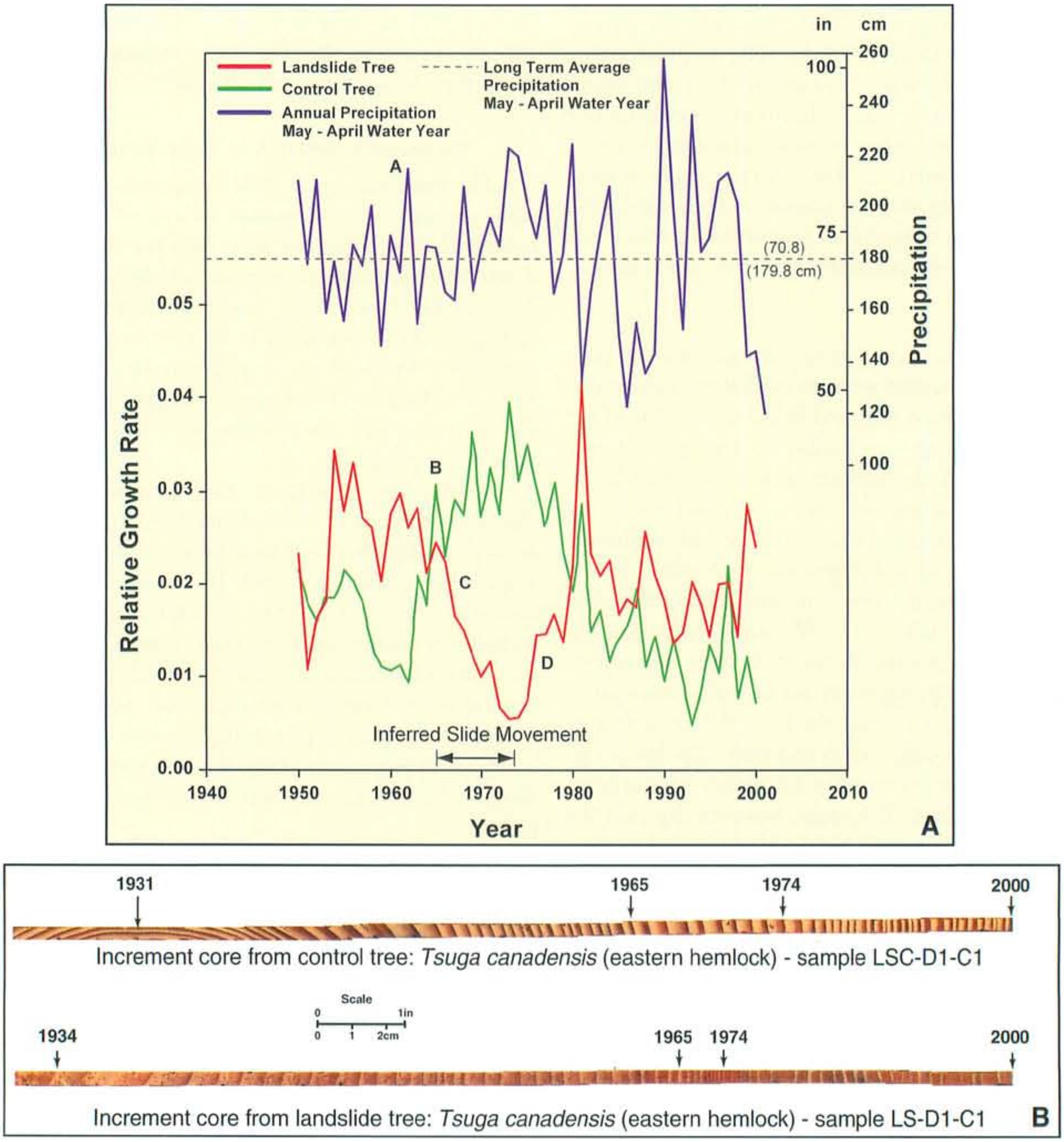



**Figure 17. A.** Plot relating the relative growth rates for a tree on the Toxaway River slide, and a control tree adjacent the slide, and precipitation for the May-April Water Year at the main climate station at the U.S. Forest Service Coweeta Hydrologic Laboratory, Otto, N.C. Increase in precipitation **(A)** resulted in an increase in tree growth rate on the control site **(B)**, but a steady decline in growth rate on the landslide **(C)**. This pattern suggests that infiltrating rain increased pore-water pressure and triggered movement on the slide in the mid- to late 1960s through the early 1970s sufficient to disrupt root activity causing a subsequent decrease in annual growth for trees on that site. Heavy rains from Hurricane Agnes in June 1972 also may have contibuted to movement on the slide. The abrupt increase in growth rate for the slide tree after 1974 **(D)** could be the result of the tree growing reaction wood to regain vertical growth. Jacoby (2000) noted a similar pattern in increment cores taked from tilted conifer. Curved saplings and unvegetated scarps indicate movement over the last 10-15 years within the toe area of the slide, possibly related to the precipitation peak in 1989. **B.** Increment cores from the landslide and control trees (Tsuga canadensis) or eastern hemlock, sampled on September 26, 2001. The 1.8 in (45 mm) growth during 1965-74 on the control tree represents 28% of the total growth from 1934-74, while 0.5 in (13mm) of growth for the same period on the slide tree represents only 7% of the growth from 1934-74. An increment core (not shown) for an Acer rubrum (red maple) on the slide also shows a similar decline in growth rate for the period 1965-74.

Scarps that are now forming above the main scarp (i.e., the bounding scarp with the greatest vertical displacement) indicate that the slide is propagating upslope toward the west. Eventually these new scarps will become the main scarp. Infiltrating rainfall along the scarps increases the pore water pressures at depth causing further movement. This, in turn, leads to more displacement along existing scarps, and the formation of new scarps. Continued repetition of this cycle illustrates the self-perpetuating nature of the slide.

#### Geologic Causes

Although oversteepened slopes and elevated pore water pressure associated with the rainfall and subsequent dam failure may have triggered initial movement of the slide, the underlying causes relate to geology. Because information from the subsurface is very limited, our concepts of specific geologic causes are based mainly on features exposed at the surface. Two sets of southwest-dipping joints, and outcrop-scale, high-angle brittle faults occur in rocks exposed in and around the slide (see pl. 2). The planes of the joints and faults dip downslope in the general direction of slide movement. The moderately dipping joints are favorably oriented to be planes of weakness along the basal failure surface of the slide. The high-angle joints and faults dip downslope and are favorably oriented to be planes of weakness parallel to the scarps. Foliations, however, dip into the hillside and do not appear to be a direct causal factor.

A wet-weather spring near the upper contact between the rocks units, and water encountered in a nearby shallow hand-auger hole, indicates that ground water occurs along this contact. Ground water entering the slide mass along this contact (and elsewhere) contributes to both increased weathering and pore-water pressures. The thickness of the completely weathered bedrock in the slide is unusual for the steep valley walls where erosion has usually removed such material. The micaceous, silt-rich soil derived from the weathered metasedimentary rocks of the Tallulah Falls Formation in the central part of the slide is a low shear strength material, and is a likely factor that contributes to the unstable slope.

#### Hazards

Because movement rates appear to be relatively slow, on the order of just a few inches per year, the slide presents a minimal hazard to hikers. One area does present a potential hazard near the trail at the south end of the slide. Rockfall from a near vertical section of the lateral scarp has accumulated upslope from the trail. Dilated and favorably oriented fractures exposed in the scarp indicate the potential for future rockfall of boulders up to 3 ft (1 m) long or larger. No immediate hazard appears to threaten the trail; however, hikers should not climb the rocks or approach the rock scarp.

### Geomorphic Settings of Slope Movements

The vast majority of slope movement features occur along incised river and stream valleys, or on scarp and oblique slopes. These are areas with the steepest slopes. Active down-cutting produced steep valley walls along the Toxaway River, and along Auger Fork Creek and Maple Spring Branch, particularly downstream from their confluence. Erosion and oversteepening of the lower slopes along the Toxaway River by the August 13, 1916 dam failure torrent also contributed to the instability of certain areas of the gorge.

Scarp slopes (slope aspect nearly perpendicular to dip direction of the rock) and oblique slopes (slope aspect at an angle to dip direction) tend to be steeper than the dip slopes that conform to rock layers tilted toward the southeast (figs. 5 and 18). Examples of scarp slopes include the northwest-facing slopes above Lake Jocassee, Grindstone and Chestnut Mountains, and above the lower reach of Auger Creek, all of which show evidence of slope movement. Examples of oblique slopes are the steep northeast-facing slopes along the southwest side of the Toxaway River, and southwest-facing slopes along Grassy Ridge.

Concave topography typifies the steep, unstable areas within scarp slopes. Here, the bowl-shaped topography leads to convergent shallow groundwater flow lines, causing the buildup of pore-water pressure during periods of heavy rainfall. Coincidentally, most of the scarp and oblique slopes have a northerly aspect to their exposure; therefore, the higher soil moisture content generally associated with north-facing slopes may also be a destabilizing factor.

The southeast-facing lower slopes above Auger Fork and Maple Spring Branch are examples of unstable dip slopes. Midslope accumulations of colluvium and debris along the lower gradient reaches of streams above Auger Fork Road provide evidence of past slope movement activity. Past debris flow or debris slide activity that contributed to these accumulations probably originated from steep dip slopes in drainage headwalls upslope.

### Rainfall Thresholds

The amount and duration of rainfall needed to trigger debris flows and other precipitation-driven slope movements varies. Localized cloud bursts as well as long-duration rainfall from tropical storms and hurricanes over

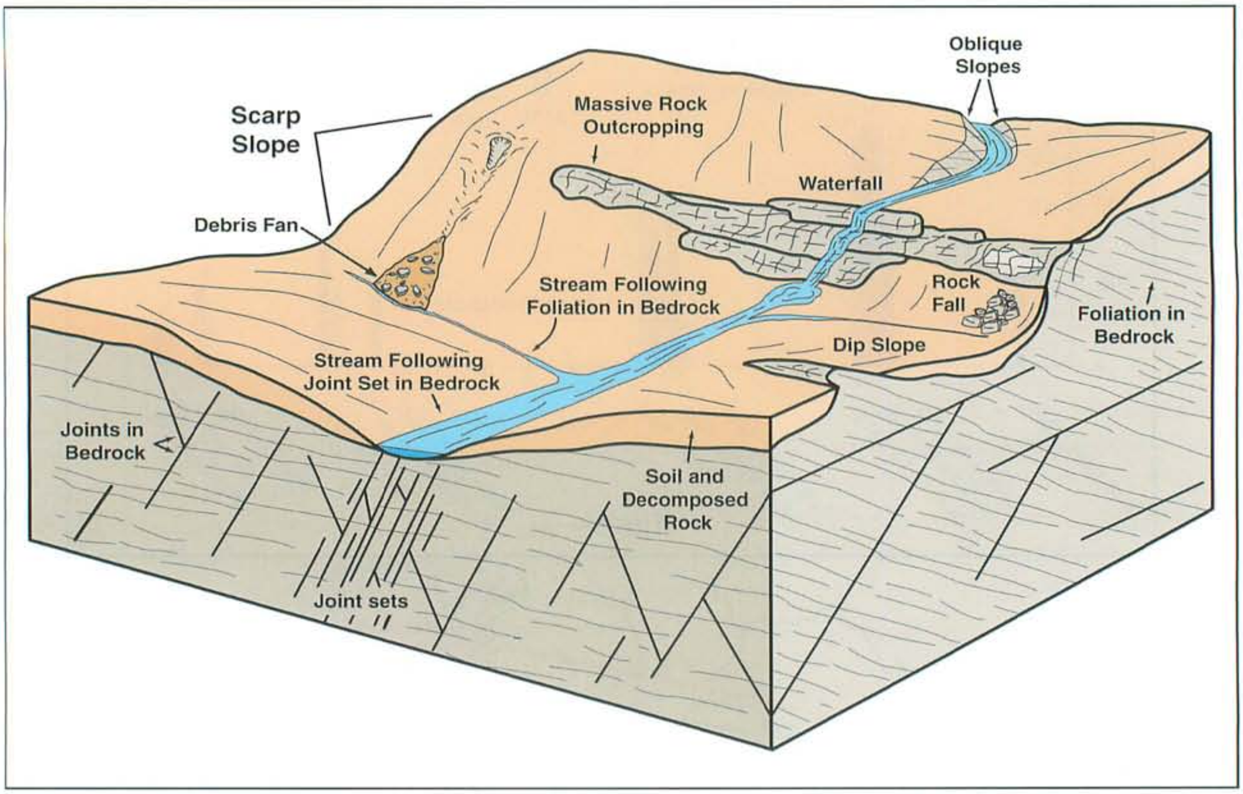



**Figure 18.** Diagram showing landscape features related to the underlying bedrock. Rockfall and debris fans are more common on scarp and oblique slopes that are generally steeper than the dip slopes that conform to the bedrock foliation. Streams follow weaker zones in the underlying bedrock that parallel joint sets and foliation planes to establish their channels.

large areas can initiate debris flows (Clark, 1987). Periods of intense rainfall preceded by high antecedent moisture conditions are particularly prone to produce debris flows (Neary and Swift, 1987).

Figure 19A shows rainfall amounts associated with major debris flow events in North Carolina. Figure 19B shows the paths of selected hurricanes that caused widespread flooding and debris flows in the Blue Ridge Mountains, including Transylvania County. In a study of debris avalanches [flows] in the eastern United States, Eschner and Patric (1982) estimated that a minimum of about 5 in (125 mm) of rainfall over a 24-hour period was needed to initiate widespread debris flows. On slopes modified by road construction, however, 24-hour rainfall amounts of just 2.4 in (approx. 60 mm) can trigger debris flows (Wooten, 1998).

## MAJOR HISTORICAL FLOOD AND DEBRIS FLOW EVENTS

In addition to causing extensive flooding, storms and hurricanes that track over the Blue Ridge Mountains often trigger slope movements such as debris flows and debris slides. Records show major storms and hurricanes have affected the region as early as April 1791 (Tennessee Valley Authority, 1964). Major flood events known to have affected the upper French Broad region include those in June 1876, May 1901, August 1910, July and August 1916, August 1940, June-August 1949, and August 26, 1961 (TVA, 1964; Scott, 1972).

Intense rainfall from some of these storms and hurricanes has produced major debris flow events in western North Carolina, including Transylvania County (fig. 20). Infiltrating rain builds up water pressure within the regolith and overcomes its shear strength, causing the ground surface to rupture and the material to move downslope as debris slides. If sufficient water is present, the soil and rock mixture can mobilize (liquefy) and flow rapidly down steep slopes, usually along drainage courses, as debris flows. Where preserved, debris slide and debris flow deposits record past storms and hurricanes long after the floodwaters have receded.

### July 15-16, 1916

After the remains of an early July hurricane or tropical storm passed over western North Carolina, produc-

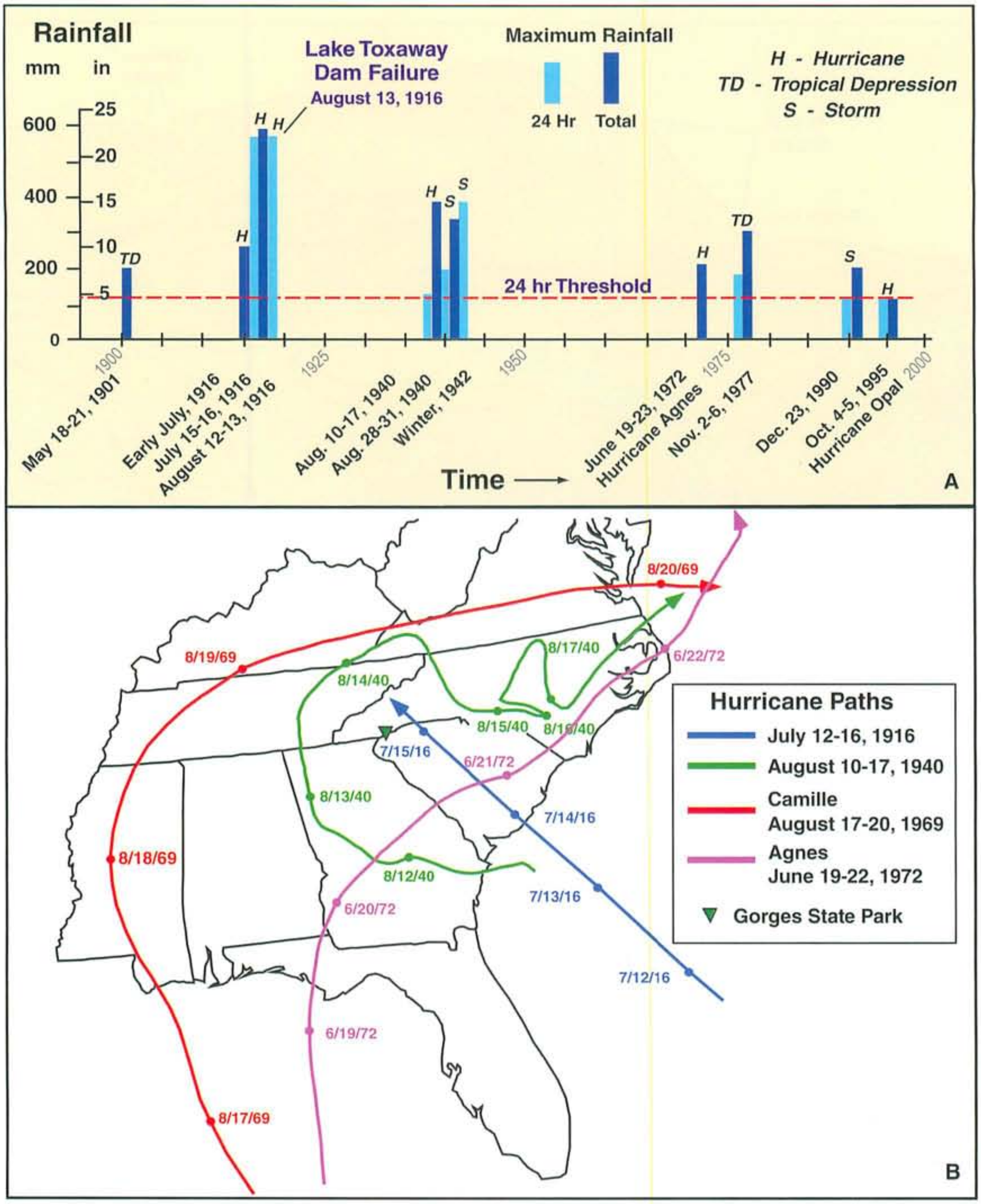



**Figure 19. A.** Chart showing rainfall amounts that triggered debris flow events in western North Carolina. The Lake Toxaway dam failed after two and possibly three hurricanes tracked over the Southern Appalachians within six weeks. The 24-hour threshold line shows the minimum 24-hour rainfall needed to trigger widespread debris flows in the Southern Appalachians as estimated by Eschner and Patric (1982). **B.** Paths of 20th century hurricanes that caused widespread flooding and major debris flow events in the Southern Appalachians. Major debris flow events occurred in western North Carolina in 1916 and 1940. The July 12-16, 1916 hurricane followed the weak remnants of an early July hurricane that had dropped up to ten inches of rain on western North Carolina. A third tropical storm moved ashore from the Gulf of Mexico (exact path unknown) and tracked over western North Carolina on August 13, 1916, causing the dam at Lake Toxaway to fail. Heavy rains, along with the slow rate of movement of the mid-August 1940 hurricane, set off hundreds of debris flows. In 1972, Hurricane Agnes initiated debris flows and debris slides in western North Carolina, although the path was to the east. In 1969, Hurricane Camille triggered hundreds of debris flows in the Blue Ridge Mountains of Virginia, causing extensive damage and loss of life. Map adapted from Scott (1972) and Bailey and others (1975).

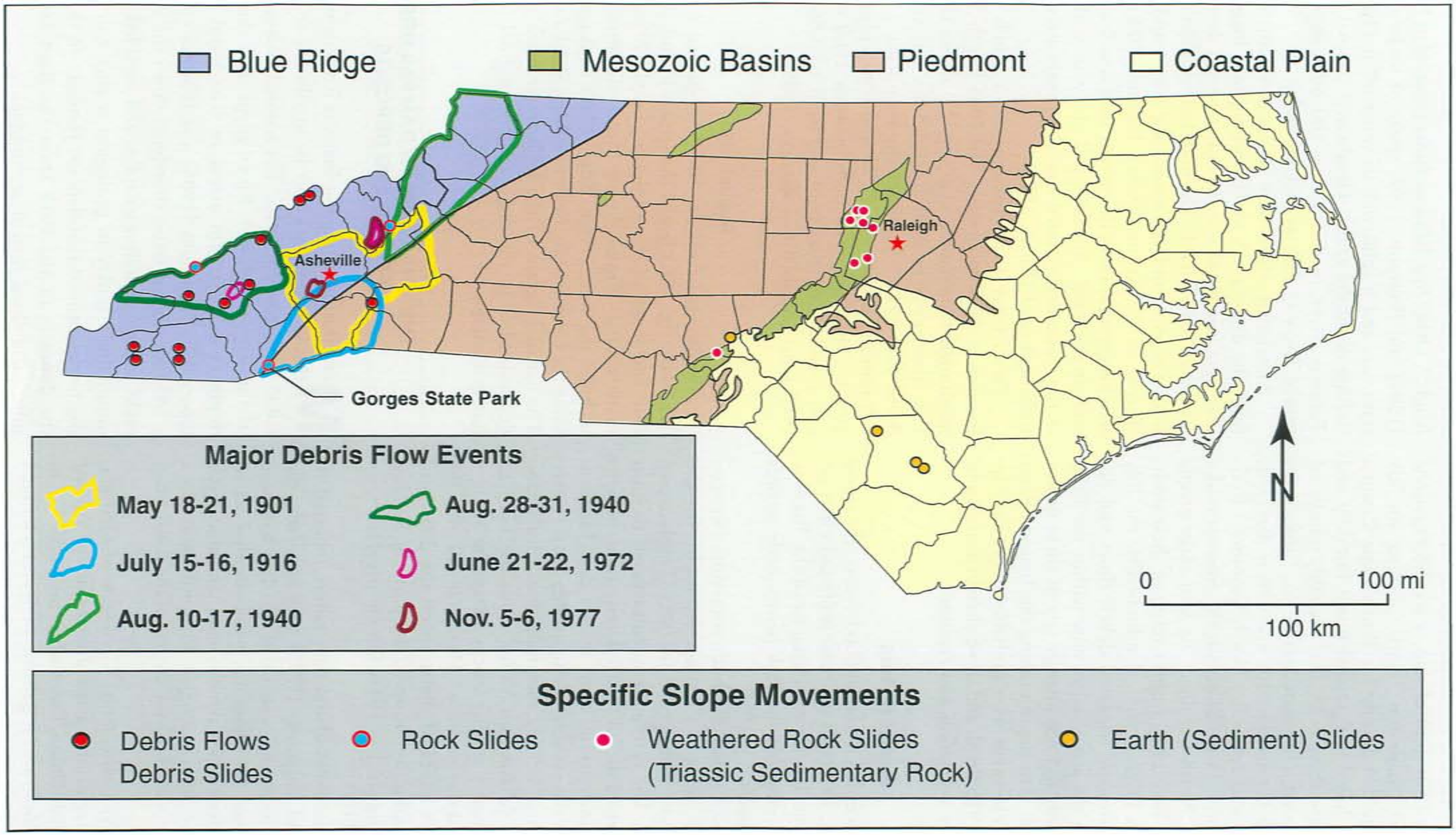



**Figure 20.** General locations of major debris flow events and selected specific slope movements in North Carolina. The map shows the approximate areas in North Carolina affected by major debris flow events as reported in the literature (Scott, 1972; Pomeroy,1991; Neary and Swift, 1987; and, Clark, 1987) Major debris flow events are those with numerous debris flows.

ing nearly 10 in (250 mm) of rain, a second hurricane came ashore over Charleston, South Carolina, on July 14, 1916, and headed directly for Transylvania County. Heavy rains on July 15-16 caused much flooding and damage from slope movements that probably numbered in the hundreds over a five-state area (TVA, 1964; Scott, 1972). Among the hardest hit areas were Brevard, Hendersonville, and Asheville, North Carolina. Residents reported over 45 landslides on the mountainsides around Brevard, North Carolina. At least three people were killed near Brevard as a direct result of these probable debris flows (TVA, 1964). Undoubtedly, the July 15-16, 1916 hurricane triggered debris flows and debris slides along the steep slopes now within the Park, although this study did not identify any of these deposits with certainty. Any deposits along the Toxaway River from the July 1916 event were probably swept away by the August 13, 1916 flood, and those elsewhere are probably obscured by vegetation and erosion.

#### August 13, 1916

Of all the recorded historical flood events, the storm of August 12-13, 1916 had the most profound effect on the Toxaway River. The present character of the Toxaway River channel throughout the Park permanently records the events of August 13, 1916.

Lake Toxaway, originally built sometime between 1890 and 1905, served as a main attraction for the Toxaway Inn resort that opened in 1903 (Lovelace and Jackson, 1990). The earthen dam constructed to form the lake had survived the July 1916 floods. Rain, perhaps as much as 23 inches (580 mm) in one day (Johnson, 1997), began on the evening of August 12, 1916 (Parris, 1972). Carpenter (1975) surmised that a hurricane moving up the Mississippi Valley from the Gulf of Mexico had joined a smaller storm advancing along a cold front toward the southeast. Heavy rainfall from the combined storms increased the stress on the dam until it failed catastrophically around 7:10 p.m. on Sunday, August 13. (August 14, 1916 Greenville News, *in* Plemmons, 1984).

First-hand accounts of the dam failure reported in Parris (1972) and Carpenter (1975) vary as to why the dam failed. Some reports stated that the dam had been leaking at the base for sometime, while another stated that water had overtopped the clay dam, and that water continued to rise Sunday, August 13, until there was a four-foot tide (presumably over the top of the dam) when the dam failed.

Dr. S. W. McCallie, State Geologist of Georgia, conveyed the magnitude of the disaster in the August 18, 1916 Savannah Union Times when he stated "...an estimated 5,376,548,571 gallons of water changed hands." Other first-hand accounts reported in Plemmons (1984) and (Johnson, 1997) spoke of rocks as large as train cars and a solid wall of water 30 ft (10 m) high rushing down the valley. Floodwaters scoured the upper Toxaway River, removing trees and other vegetation to expose Toxaway Falls as they are today.

Fortunately, there were no known human fatalities from the disaster. A mule working in a logging camp near the Cane Break was the only reported death directly attributed to the flood. The mule bolted when unhitched from a wagon, and ran toward the water, and drowned (Parris, 1972; Barton, 1988). Barton (1988) reported that his grandmother's house near the Cane Brake washed away in the flood. Jule Chappell who witnessed the flood at the Cane Brake stated that the floodwaters left only rocks and sand (Parris, 1972).

Present-day Lake Toxaway is in much the same location as the original lake. The 1905 Pisgah 30-minute quadrangle topographic map (fig. 21) shows the level of Lake Toxaway to be 2998 ft (913.8 m), very close to the 3,000-foot (914.4 m) level shown on the 1946 Reid 7.5-minute quadrangle (1:24,000 scale, photorevised 1990). The dam was rebuilt between 1960 and 1961, and retains a normal pool elevation of 3,008.21 feet (917.1 m) (Applied Geosciences, 1999).

#### August 1940

The floods of August 10-17, 1940 and August 28-31, 1940 (fig. 20) affected the region in and around the Park and much of the southeast as well. A topographic map labeled "Duke Power Montvale Survey 1941" includes the note "High Water Mark of August 1940" along the Horsepasture River near Milk Sick Cove Branch. The actual location of the high water mark cannot be determined from the map, and the original map is no longer available.

## THE 1916 TOXAWAY DAM FAILURE EFFECTS AND DEPOSITS

Many features along the Toxaway River's entire course through the park can be attributed to the dam failure of August 13, 1916. The scoured bedrock channel of the upper Toxaway River gorge and the boulder deposits downstream attest to first-hand accounts reported in Plemmons (1984) and Johnson (1997) that a "30-foot wall of water thundered down the valley, and rocks as large as train cars rolled and tumbled down the mountain." Rarely in geological science can the exact day be determined that deposits formed. In this respect, the deposits in the Park from the dam failure and subsequent flood torrent are unique.

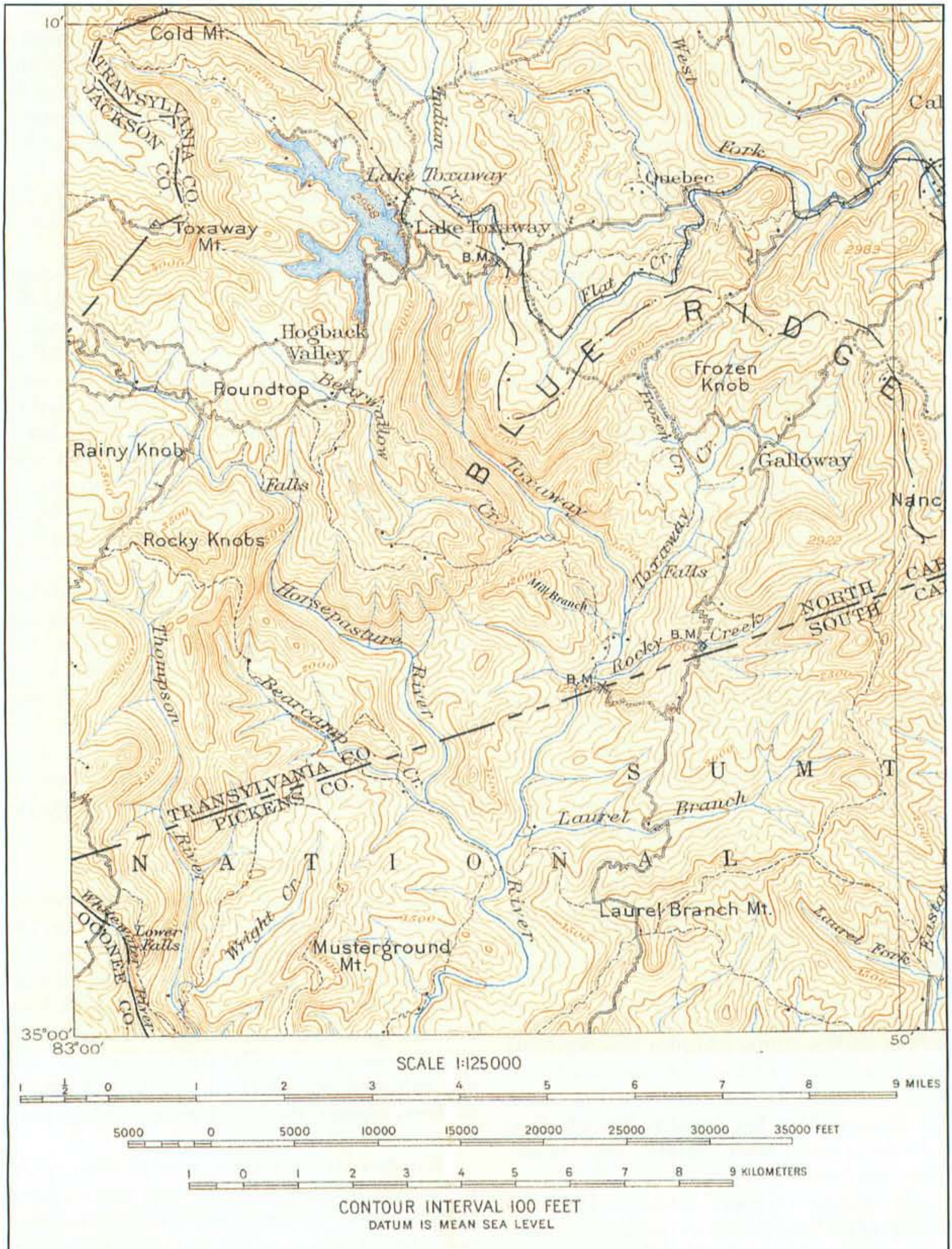



**Figure 21**. Excerpt from the 1905 U. S. Geological Survey topographic map of the Pisgah 30-minute quadrangle (Wilson and others, 1905) that shows Lake Toxaway prior to the failure of the dam on August 13, 1916. This map was surveyed in 1886-88 and 1895-96, and revised in 1904-05. The original lake is essentially in the same location as the present-day lake. The differences in the course of the Toxaway River at the confluence with Bearwallow Creek between this map and current maps is most likely the result of inaccuracies in the older map. North is toward the top.

The flood torrent scoured regolith and vegetation from a 2.1-mile (3.5 km) reach of the river gorge, exposing bedrock nearly continuously from Lake Toxaway downstream to Wintergreen Falls (fig. 4). Truncating colluvium and tributary alluvial fans along hillslopes adjacent to the river channel, the torrent undoubtedly triggered rockfall, rockslides, and debris slides that are still periodically active (fig. 14). Boulder levees left by the torrent divert smaller streams along their inboard flanks where they block tributary outlets along valley foot slopes. In some cases, the boulders constrict the river channel, impounding stratified sand- and gravel-size alluvium behind them. An example of these post-1916 deposits is located along the Toxaway River just upstream from its confluence with Indian Creek. Some of the alluvium deposited by Bearwallow Creek just upstream of where it joins the Toxaway River may have been impounded by the 1916 boulder terrrace immediately upstream of the confluence.

The torrent from the dam failure was a rapid-moving mixture of clay- to boulder-size sediment and water, and therefore, could technically be classified as a debris flow. Because floodwater was the primary transporting agent, the deposits are included here as alluvium. Discontinuous boulder levees and sheet deposits from the torrent occur along the river from the Park boundary downstream to Lake Jocassee. Boulders in these deposits commonly range in size from 6-30 ft (2-6 m) long, the largest being about 40 ft (12 m). Most of the extensive flood deposits occur below Wintergreen Falls; although, isolated remnants are preserved along the Toxaway River downstream from the Park boundary to just below Indian Creek. Individual boulders up to 40 ft (12 m) in length, chaotic boulder piles, and locally imbricated boulders attest to the floodwater origin of the deposits (fig. 22). Crests of the boulder levees stand 6-40 ft (2-12 m) above the present river level, recording minimum floodwater elevations.

The finer-grained, cobble-, gravel-, and sand-size sediment from the flood forms a blanket-like, floodplain deposit from upper Lake Jocassee into South Carolina over 11 miles (18 km) downstream from the original dam. The Toxaway River has downcut through these, and other side stream deposits, making them readily visible when lake levels are low.

A rough estimate of about 30 mi/hr (48 km/hr) for the velocity of the flood torrent was made at a location along a bend in the Toxaway River just below the confluence with Indian Creek. This approach used a formula for estimating the velocity of debris flows presented in Chen (1987) based on the radius of channel bend, channel gradient, and superelevation angle of the debris flow around the bend.

The superelevation angle was approximated by sighting a line with a clinometer from the top of a 30-foot- (10 m) high boulder levee (i.e., minimum water height on the outside of the bend) across the channel to an apparent scour line on a rock face. Values for the channel gradient and radius of channel curvature were determined from the Reid, 7.5-minute quadrangle, topographic map (U.S. Geological Survey, 1:24,000 scale). At this location a wall of water at least 30 ft (9 m) high thundered through the gorge at about 30 mi/hr (48 km/hr) or faster.

A comparison of the 1905, 30-minute topographic map (U. S. Geological Survey, 1:250:000 scale) (fig. 21) with the Reid 7.5-minute quadrangle, topographic map (1946, photorevised 1990) reveals many differences between the drainage patterns shown on the two maps. Most of the differences appear to be related to the more accurate topography and larger scale of the later map. For example, the confluence of Auger Fork Creek with the Toxaway River is not accurately located on the 1905 map. Similarly, the 1905 map inaccurately depicts the course of the Toxaway River at its confluence with Bearwallow Creek.

Some of the localized differences between the maps along the Toxaway River and its tributaries may, however, be the result of the flood torrent. For example, the 1905 map shows the confluence of Mills Branch and the Toxaway River further north than the 1946 map (see pl. 2). On the 1946 map, Mills Branch turns abruptly southwest where it comes in contact with the flood deposits, then follows the edge of the deposits about 1600 ft (490 m) before it reaches the Toxaway River.

#### Age of the Flood Torrent Deposits

Tree-ring analyses of increment borings from eastern hemlock (*Tsuga canadensis*), white pine (*Pinus strobus*), and pitch pine (*Pinus rigida*) support a 1916 origin for the flood deposits. Of five large trees sampled that were clearly growing on top of the flood deposit boulders, the tree rings indicated that the oldest tree sampled began growth in about 1917. Had tree ring counts been found that indicated trees older than 1916 were growing on the flood deposits, then the deposits may have pre-dated 1916.

Floodwaters after 1916, such as those of August 1940, have undoubtedly reworked and modified the 1916 deposits. In some cases the boulder levees have two subparallel crests, with the lower crest nearer the river. Some boulder levees have a flat, terraced surface below the crest, on the side nearest the river. These features indicate that post-1916 floods may have modified the original boulder levees. It is possible, however, that some of these features could have resulted from pulses of flow from the dam failure torrent that

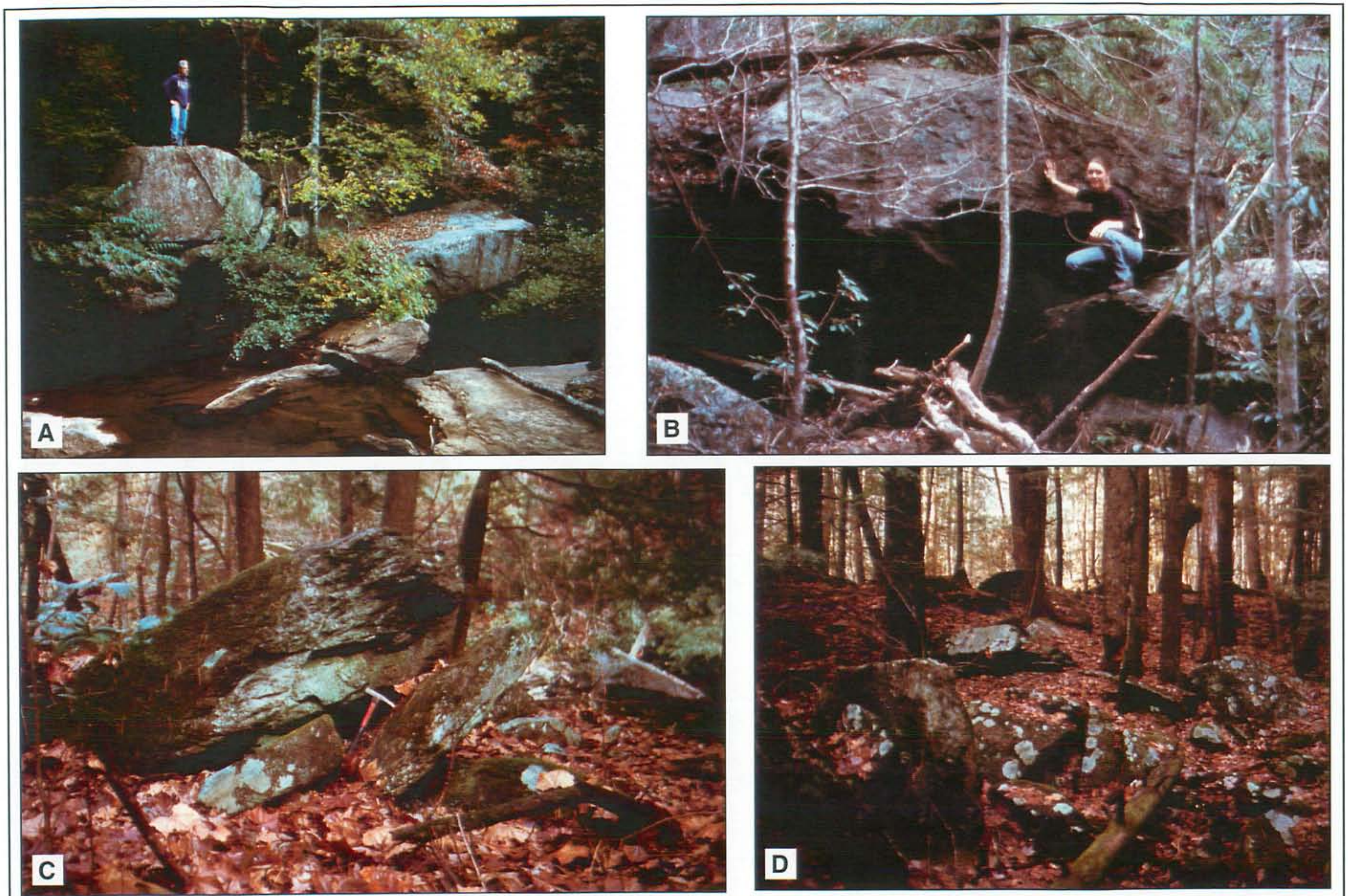



**Figure 22**. Boulder deposits along the Toxaway River from the August 13, 1916 dam failure and resulting flood torrent. See figure 4 for locations of photographs. **A**. Flood deposit boulders along the Toxaway River near the Gorges State Park boundary about 1.1 mi (1.8 km) below the original dam. Downstream is to the right. Location B of figure 4. **B.** Boulder of Toxaway Gneiss deposited by the flood outside the present Toxaway River channel nearly 4 mi (6.4 km) below the original dam. Location C of figure 4. **C.** Imbricated boulders in the 1916 flood deposit about 5.75 mi (9.3 km) downstream from the original dam. Rock hammer for scale; downstream is to the right. Location D of figure 4. **D.** Boulder levee nearly 6 mi (9.7 km) downstream from the original dam. The levee crest is about 12 ft (4 m) above the present river elevation. Post-1916 tree growth is established on the deposit. Location E of figure 4.

originated from the formation and bursting of debris dams along the river channel as the floodwaters progressed downstream.

Long after the memories of those who witnessed the floods dim, and pictures and accounts written on paper fade, the boulders left by the floodwaters will remain. August 13, 1916 is, at least from a human frame of reference, a permanent part of the geologic record.

## MINERAL RESOURCES

Local residents in and around Gorges State Park have used the Earth's resources for generations. Although no mining activity occurs in the Park today, several economic mineral deposits remain, but they are of little or no commercial value. They are far more valuable for their historical significance. Active mining for crushed stone and fill material does occur outside of the Park in the surrounding area.

### Mineral Resources of Historical Significance

Several small lenses of marble crop out in the Park within the Brevard fault zone. Marble was quarried from one deposit in the late 1800s and early 1900s (Watson and Laney, 1906). The quarry is located about 0.25 miles (0.4 km) southwest of the confluence of Bearwallow Creek and the Toxaway River. Kilns constructed adjacent to the quarry burned the marble into quicklime for use as building lime and fertilizer (Conrad, 1960).

Mica was recovered intermittently from a shallow prospect pit at the head of Chestnut Branch, approximately one mile (1.7 km) north of its confluence with the Toxaway River in the late 1800s and early 1900s (Robert Hoxit, oral communication, 2002). At that time, one of the many uses for large sheets of muscovite mica was to make window panes for wood and coal burning stoves. Barton (1988) reported another mica prospect near the head of Wild Hog Fork, about 0.5 miles (0.6 km) north of Turkeypen Gap. Coarse muscovite mica occurs in pegmatite float and in outcrop at both of these sites, but all evidence of prospecting has long since been covered by colluvium and vegetation.

An abandoned talc mine is located on private land just outside of the Park boundary, approximately 0.75 miles (1.4 km) northeast of the confluence of Panther Branch and the Toxaway River. Talc sawed from the mine was used locally for building stone in the 1930s (Robert Hoxit, oral communication, 2002). Smaller deposits of talc occur within the Park, but none show evidence of ever being mined.

Graphite occurs locally in graphitic schist and breccia along the Rosman Fault in the Brevard fault zone. Graphite is used as a lubricant and, when mixed with clay, as the "lead" in pencils. All of the deposits in the Park, however, are too small to have ever been mined commercially.

### Active Quarries

Several active quarries and borrow pits occur outside of the Park in the surrounding area, and some provide Gorges State Park with valuable construction material. LBM Industries of Sapphire, North Carolina, operates the Whitewater Quarry, located northwest of Bohaynee Road, approximately 1.5 miles (2.3 km) south of its intersection with U.S. Highway 64. Biotite granitic gneiss of the Toxaway Gneiss is mined from the quarry and crushed for construction aggregate and other uses. The quarry supplies the Park with stone for parking areas, roads, trails, and other projects.

A small borrow pit is located adjacent to the Park boundary, approximately 0.4 miles (0.6 km) northeast of upper Bearwallow Falls. Saprolitic biotite granitic gneiss of the Toxaway Gneiss has been excavated from the pit, presumably for local use as fill material. Saprolitic mica schist and metagraywacke of the Tallulah Falls Formation have been excavated from a smaller borrow pit, located about one mile (3.1 km) northeast of the confluence of Panther Branch and the Toxaway River on privately owned land. A third borrow pit is located within the Park, approximately 0.2 miles (0.3 km) northwest of the intersection of Frozen Creek Road and Auger Fork Road. Colluvial soil was excavated from the pit during construction of a parking area on Frozen Creek Road.

## FIELD GUIDE AND DESCRIPTION OF GEOLOGIC POINTS AND FEATURES OF INTEREST

The following is a listing and description of just some of the many geologic points and features of interest to see in Gorges State Park. Locations are shown on plates 1 and 2, and are designated with B for bedrock (pl. 1) or S for surficial (pl. 2). Park staff can assist with more detailed directions to each locality.

### STOP 1B — Toxaway Gneiss on Grassy Ridge

Rocks of the Toxaway Gneiss are the oldest in Gorges State Park — they are more than a billion years old. Here at this acre-size rock pavement outcrop, one can see a variety of textures, fabrics, and structures within the gneiss. Most of the rock in the exposure exhibits a flaser, or wavy fabric defined by abundant dark-colored grains of biotite that wrap around and envelop large megacrysts of potassium feldspar. Other mineral constituents in the matrix, or finer-grained portion of the rock, include quartz, muscovite, epidote, and traces of apatite and zircon. Distinct foliation (compositional banding) is another common fabric observed here and elsewhere within the Toxaway Gneiss. Compositional bands, ranging from less than an inch to a few inches (millimeters to centimeters) thick, consist of light-colored layers of mostly feldspar and quartz that alternate with darker-colored, biotite-rich layers and give the rock its "gneissic" appearance.

Although the Toxaway Gneiss was metamorphosed to very high grade during the Grenville orogeny about a billion years ago, most of these characteristic textures and fabrics we see today were probably imparted on the rock when it was metamorphosed a second time during Paleozoic mountain-building 350 to 450 million years ago. Constituent mineral grains were altered and aligned parallel to foliation in younger Tallulah Falls Formation rocks to the east.

In this and many other large outcrops throughout the Park, one can observe small faults and shear zones displacing foliation, pegmatite veins, and migmatitic stringers and pods by only a few feet (1 m) or less. Some of these outcrop-scale faults and shear zones may have formed during regional metamorphism, folding, and faulting in the Paleozoic, but others may have formed later, during Mesozoic or Cenozoic regional uplift.

Joints are another common structural feature observed here. Unlike faults, joints are fractures or cracks in a rock along which there has been no appreciable displacement. Joints form by regional crustal extension or contraction, or as weathering and erosion remove layers of rock at the Earth's surface, relieving pressure on underlying rock layers and allowing them to expand upward and outward, creating cracks and fractures. While many joints dip steeply into the rock, a few have shallow dips and mimic the shape of the overlying topography. These shallow-dipping, concentric cracks are called sheet joints, and as weathering and erosion spall and strip sheets of rock away like peels of an onion, rounded or dome-shaped, flat-lying pavement outcrops such as this are formed. This process is known as exfoliation. Looking Glass Rock in Henderson County and Stone Mountain at Stone Mountain State Park in Wilkes County are excellent examples of exfoliated rock domes.

In Gorges State Park, pavement outcrops are relatively few. Several smaller exfoliation pavements occur on other gently rounded knobs and spurs of Grassy Ridge, and a few more exist on the lower-lying knobs just north of Lake Jocassee. There, the Henderson Gneiss, a granitic rock type similar to the Toxaway Gneiss but much younger in age, underlies the hills. Exfoliated pavement outcrops are very rare on the steeper slopes of the Blue Ridge Escarpment between Grassy Ridge and Grindstone Mountain. On the steep-sloped terrain of the Blue Ridge Escarpment, weathering and erosion accentuate steeply inclined joints to produce high cliffs and bluffs overlooking the Toxaway River, Bearwallow Creek, and other streams and creeks. A few pavement outcrops do occur in the channel of the Toxaway River (i.e., the Narrows) (fig. 23), but these pavements were scoured out by floodwaters when the earthen dam constructed to form Lake Toxaway failed on August 13, 1916.

### STOP 2B – The Blue Ridge Escarpment from Grassy Ridge

Gorges State Park straddles the steep and rugged slopes of the Blue Ridge Escarpment, a prominent, regionally extensive erosional feature that marks the physiographic break between the high, mountainous terrain of the Blue Ridge Physiographic Province and the low, rolling hills of the Piedmont Physiographic Province (figs. 1 and 2). Spectacular views across the Blue Ridge Escarpment to the South Carolina Piedmont beyond are afforded the visitor here, and elsewhere along the southeastern end of Grassy Ridge.

In Transylvania County, the Eastern Continental Divide coincides with the top of the Blue Ridge Escarpment. The Divide separates streams, creeks, and rivers that flow westward into the Mississippi River System (and ultimately the Gulf of Mexico), from those that flow eastward into the Atlantic Ocean. The Blue Ridge Escarpment is the product, at least in part, of the vigorous headward erosion of Atlantic-flowing streams into the mountains of the Blue Ridge. Its early origins are still subject to debate, but many geologists now believe that "recent" (geologically speaking, in the last 65 million years) uplift of the Blue Ridge Mountains created an initial scarp which has since been dissected and eroded back to its present position.

Remnants of high mountains that once occupied the Piedmont to the south (like Six-Mile Mountain in South Carolina) are more resistant to erosion than the rocks underlying the land around them. These isolated mountains or hills are called monadnocks. They mark the former position of the Blue Ridge Mountains and the Escarpment at previous stages in the evolution of the landscape. As erosion continues, mountains and ridges along the present Escarpment that are more resistant to weathering and erosion will form new monadnocks as the Escarpment continues to migrate toward the northwest.

Geologically, rocks of the billion-year-old Toxaway Gneiss in the Blue Ridge Geologic Province underlie this overlook on Grassy Ridge. From this vantage point, one

**Figure 23.** Flood-scoured bedrock surface of the Toxaway Gneiss. The August 13, 1916 flood scoured most, if not all, of the upper slope here. Location is about 1000 ft (300 m) downstream from the upper Park boundary (between locations A and B on figure 4). Downstream is from the foreground toward the right middle ground.

looks out across 500- to 600-million-year-old metamorphosed sedimentary and volcanic rocks of the Tallulah Falls Formation, toward the ancient Brevard fault zone in the valley behind Chestnut Mountain in the foreground. Rocks of the 490-million-year-old Henderson Gneiss crop out on the long ridges just beyond the Brevard fault zone in the Inner Piedmont province of South Carolina.

#### STOP 3B – Upper Bearwallow Falls

Upper Bearwallow Falls is just one of the many cascades and waterfalls found throughout Gorges State Park. In the Park, the size, shape, and location of nearly every creek, river, and waterfall is controlled in some way by features in the bedrock beneath it (fig. 18).

Most cracks and fractures in bedrock are known as "joints," and are created as weathering and erosion remove layers of rock at the Earth's surface, thus relieving pressure on underlying rock layers and allowing them to expand and crack. Some joints are also formed by earlier internal stresses deeper within the Earth's crust. Joints often develop in inherent planes of weakness in the bedrock. Exposure to weathering and erosion sometimes causes cracks to form at contacts between different rock types, or along the foliation in metamorphic rocks.

Joints allow rainwater to penetrate beneath the surface of the Earth and chemically decompose the bedrock along the cracks. The weathered and decomposed rock is more easily eroded than the surrounding unweathered bedrock. Creeks and rivers exploit these jointed and weathered zones in the bedrock and cut down through the rock layers to form deep bedrock channels rather than meander and migrate sideways across the landscape. For example, Bearwallow Creek and the Toxaway River generally flow from northwest to southeast, parallel to the trend of a dominant set of joints in the Toxaway Gneiss. Auger Fork and Holly Pen Creeks, on the other hand, flow southwest and northeast, respectively, taking advantage of cracks and fractures that developed along contacts between different rock types and foliation planes near the Rosman Fault and within the Brevard fault zone.

Here at Upper Bearwallow Falls, joints in the Toxaway Gneiss play a vital role in the size and shape of the cascade. Downstream from the falls, Bearwallow Creek follows a set of steeply dipping joints that parallel the creek channel. At the falls, two sets of joints in the

Toxaway Gneiss cut across Bearwallow Creek at nearly right angles to the bedrock channel. One joint set is nearly horizontal, while the other crosses the stream at a much steeper angle and forms the face of the falls. Turbulent water in the creek channel has eroded and washed away wedges of rock formed by these intersecting joint sets. Upstream from where these wedges have been removed, steeply dipping flat bedrock faces in the stream channel are left behind. Water rushing down these rocky faces creates the cascading waterfall. Many of the other cascades and waterfalls throughout Gorges State Park formed in a similar way.

### STOP 4B – Mylonites at the Toxaway Gneiss – Tallulah Falls Formation contact

Along the main scarp of the Toxaway River slide on the east side of the Toxaway River, mylonitic rocks mark the thrust fault zone between the Toxaway Gneiss and the Tallulah Falls Formation (see also stop 12S). A mylonite is an extremely granulated and ductilely sheared rock produced through faulting under intense pressure. Around 460 million years ago, oceanic rocks of the Tallulah Falls Formation were shoved up and over continental rocks of the Toxaway Gneiss along a major thrust fault in the Earth's crust at the onset of Paleozoic mountain-building. The best exposures of mylonite are in the steep slopes of the lateral scarp along the southern margin of the slide above the trail. Be careful of rockfall from this area!

In granitic rocks of the Toxaway Gneiss, mylonites near the contact consist of coarser-grained, flaser-structured layers with porphyroclastic potassium feldspar augen, some larger than one centimeter in length. These layers alternate on a scale of several centimeters with finer-grained mylonitic granitic gneiss layers displaying a distinct streaky or finely laminated appearance and containing only a few small potassium feldspar porphyroclasts. At the fault contact, where shearing and granulation were most intense, laminae less than 0.05-0.15 in (1-4 mm) thick, of mica-rich phyllonite alternate with highly sheared quartz- and feldspar-rich mylonitic granitic gneiss with only a few small rotated and flattened potassium feldspar porphyroclasts (fig. 16B).

Mylonite in the adjacent Tallulah Falls Formation is characterized by medium- to coarse-grained feldspar and muscovite porphyroclasts, up to 0.1 in (0.25 cm) in diameter, within a finer-grained, lepidoblastic, mica-rich phyllitic matrix composed of quartz, feldspar, muscovite, and biotite. These rocks are particularly well exposed not only in the weathered-rock slide scarp north of the river, but also in weathered roadcuts on the access road along the ridgeline on the southwestern side of the Toxaway River.

Mylonites along the Toxaway Gneiss – Tallulah Falls Formation fault contact are folded at both outcrop- and map-scales; mylonites are tightly to isoclinally folded in outcrop (figs. 7B and C), suggesting that the fault formed slightly before or simultaneously with peak regional metamorphism, probably in the early to middle Paleozoic. The fault surface is also broadly folded at map-scale; several klippe (erosional remnants of the thrust sheet carrying rocks of the Tallulah Falls Formation) are isolated northwest of the main trace of the fault in the vicinity of Indian Camp Branch and here at the slide.

### STOP 5B – Amphibolite of the Tallulah Falls Formation on Chestnut Mountain

Amphibolite is a common, but minor component in the Tallulah Falls Formation in Gorges State Park. The careful observer can usually find thin interlayers and pods of amphibolite within many of the larger outcrops of metagraywacke and mica schist. Here on Chestnut Mountain, however, large outcrops of amphibolite with just a few interlayers of metagraywacke and mica schist are exposed.

Amphibolite is a fine- to medium-grained rock composed mostly of prismatic crystals of dark greenish black hornblende and lath-shaped, cream-colored grains of plagioclase feldspar. It is also typically well-foliated and nematoblastic; hornblende grains are aligned in a planar orientation.

Basalt that originally formed 500 to 600 million years ago recrystallized into amphibolite during Paleozoic metamorphism 350 to 450 million years ago. Pods of talc schist, commonly called soapstone because it is very soft and easily carved with a knife, can be found in a few bodies of amphibolite in and around the Park. Derived from a body of altered ultramafic rock, talc schist is composed of talc, serpentine, magnesite, chromite, and olivine (a mineral that is most often found in oceanic basalt). Talc, serpentine, and magnesite are minerals that alter from olivine during high-grade metamorphism. These rocks indicate that they, along with other interlayered metasedimentary rocks of the Tallulah Falls Formation, were once on the floor of an ancient ocean, and that sometime later, they were all metamorphosed, or altered by intense heat and pressure, during one or more periods of mountain-building.

Interestingly, amphibolites play a very important role in the present-day ecosystem. Hornblende, the major mineral constituent of amphibolite, carries calcium in its chemical structure. When an amphibolite is exposed to weathering, calcium from hornblende is released into the soil. This raises the pH of the soil and allows nutrients to become more available to plants. Many species of calciphiles (plants requiring a lime-rich, alkaline soil) such as red cedar and spicebush make their home above amphibolites, limestones, marbles, and other calcic rock types.

### STOP 6B – Metagraywacke of the Tallulah Falls Formation on Auger Hole Road

This is a typical exposure of the most common rock type of the Tallulah Falls Formation in Gorges State Park. It is metagraywacke, a type of metamorphosed sandstone. The term "graywacke" is the name given to a muddy, clay- and typically feldspar-rich, sandstone (a rock composed mostly of sand-sized mineral grains). The prefix "meta" means that the sandstone has been metamorphosed. In this case, the clay-rich material in the sandstone recrystallized into flakes of muscovite and biotite during Paleozoic metamorphism.

The rock is composed of quartz, biotite, muscovite, plagioclase feldspar, epidote, apatite, and traces of potassium feldspar, zircon, sphene, and calcite. It is strongly foliated, meaning that many of the constituent mineral grains, particularly the mica minerals biotite and muscovite, were oriented into planar layers during metamorphism; 0.15-0.20 in (4-5 mm) thick zones of quartz and feldspar alternate with zones rich in mica minerals.

Rocks of the Tallulah Falls Formation were deposited some 500 to 600 million years ago on the floor of the ancient Iapetus Ocean. Between 350 to 450 million years ago, the sedimentary rocks were metamorphosed into strongly foliated metagraywackes and mica schists, and interlayered igneous rocks were metamorphosed into amphibolites.

### STOP 7B – The Rosman Fault near the confluence of Maple Springs Branch and Auger Fork Creek

The Rosman fault is well exposed here at the confluence of Maple Springs Branch and Auger Fork Creek. The Rosman fault is the youngest fault within the Brevard fault zone. It developed along the westernmost edge of the fault zone at the very close of Paleozoic mountain-building. Dip-slip thrust faulting along the Rosman fault occurred under less intense heat and pressure than the earlier formed thrust and strike-slip faults within the Brevard zone, so it is the only fault to exhibit brittle deformation.

Several large outcrops of graphitic breccia characterize the Rosman fault at this locality. The breccia consist of broken, angular rock fragments of metagraywacke in a fine-grained matrix of dark-gray, sulfidic, graphitic schist and phyllonite. Graphitic breccia crops out at the base of the Maple Springs Branch waterfall at the confluence of Maple Springs Branch and Auger Fork Creek, and in a high, overhanging outcrop just downstream from the confluence on Auger Fork Creek. Here, Auger Fork Creek flows southwest and parallels the strike of the Rosman Fault.

Auger Fork Creek below the confluence has undercut and eroded much of the graphitic breccia, which is inclined to the east (into the bank of the creek), and created the unstable overhang. Please be very careful at this exposure — rockfall from the overhang occurs without warning!

### STOP 8B – Brevard fault zone rocks at the lime kilns

Some of the most interesting and historically important rocks of Gorges State Park crop out here along Bearwallow Creek, Marble (metamorphosed limestone) of the Brevard fault zone is exposed in a small quarry driven into the hillside. The marble is fine- to medium-grained, granoblastic, and is composed of calcite, quartz, muscovite, feldspar, chlorite, pyrrhotite, and traces of apatite and zircon. This deposit is one of several bodies of marble that crop out within the Brevard fault zone in the Park, but is the most easily accessible.

For this reason, in the late 1800s and early 1900s, the marble here was mined and burned in kilns adjacent to the quarry. The kilns are of simple construction and consist of a mound of stones, about 15 ft (5 m) in diameter and 8 ft ( 2.4 m) high, with four stokeholes accessing the interior of the structure. Within these stokeholes, marble from the quarry was fired in the kilns, probably using timber from the surrounding countryside as fuel. Intense heat from the fire converted the marble into quicklime, which was used by local residents for making mortar, plaster, whitewash, and fertilizer. Please remember that the kilns are more than a hundred years old and very fragile. Do not climb on the structure or remove stones; they are protected under state law.

Along the trail from Auger Hole Road to the marble quarry and lime kilns, one can also observe outcrops of the most characteristic rock type of the Brevard fault zone. Here, "fish scale" schist is composed of lenticular muscovite-aggregate porphyroblasts, as much as 0.75 in (2.0 cm) long and 0.2 in (0.5 cm) thick, that are flattened into the plane of foliation to give rise to its distinctive "fish scale" or "button" appearance (fig. 6H). This texture, fabric, and foliation was developed by shearing (faulting) and metamorphism within the Brevard fault zone during Paleozoic mountain-building.

### STOP 9B – Henderson Gneiss at Lake Jocassee

Exposed along the northwestern shore of Lake Jocassee are excellent water-washed outcrops of the Henderson

Gneiss. These rocks are the youngest in Gorges State Park — they are only about 490 million years old. It is quite likely that the Henderson Gneiss formed initially as a granitic igneous rock, but Paleozoic metamorphism, intense ductile shearing, and extreme granulation during faulting along the Brevard fault zone more than 300 million years ago produced the distinctive mylonitic texture and fabric observed in the rock today.

Rocks of the Henderson Gneiss are distinguished by medium- to coarse-grained, rounded to elongated, rotated and flattened porphyroclasts of feldspar, up to 0.75 in (2 cm) in diameter, which are enveloped in a finer-grained, flaser-structured matrix of quartz, feldspar, biotite, muscovite, and epidote. In a few places, especially in the thrust slice of Henderson Gneiss within the Brevard fault zone to the north, rocks of the Henderson Gneiss are extremely mylonitized. Here, the intense mylonitization produced a fine-grained, distinctly streaked, or finely layered rock with only a few coarser-grained, pea-sized porphyroclasts of feldspar that appear to be rotated within the layers.

Also noteworthy here are sets of northwest-southeast striking, steeply dipping joints. Streams, creeks, and a long stretch of the Toxaway River in this area of the Park follow the trend of these joints. The Toxaway River channel beneath Lake Jocassee, however, parallels the strike of mylonitic foliation in the Henderson Gneiss. Observations of smaller scale structures in outcrop reinforce the concept that features in the underlying bedrock form a template for the overlying surface topography.

#### STOP 10B – Auger Hole

Dramatic bends in the Toxaway River at the Auger Hole are evidence that bedrock structures influence river drainage patterns. The Auger Hole is the S-shaped segment of the Toxaway River near where it is joined by Auger Fork and Bearwallow Creeks (fig. 24). Here the southeast-flowing Toxaway River nearly reverses itself and flows northward toward Chub Line Falls, where it again turns abruptly toward the southeast. In this area, downcutting by these creeks and the Toxaway River has resulted in a deeply eroded notch that can be seen along a topographic profile from Grassy Ridge to Toxaway Creek (cross section A-A', pl. 1).

One possible explanation for the S-shaped river channel relates to easily eroded, fractured and broken rocks along geologic structures that intersect at nearly right angles in this location (fig. 24). Both now, and in the past, the Toxaway River flowed toward the southeast along northwest-southeast fracture zones on either side of the northeast-striking Rosman fault. Although the river cuts across the Rosman Fault at present (fig. 24C), in an earlier stage the river may have turned sharply toward the northeast and flowed along the Rosman Fault for nearly 1,500 ft (460 m) before resuming its southeastward path (fig. 24A). During this early stage, the river's path contained two nearly right-angle bends as it alternately flowed along linear segments of the perpendicular structures.

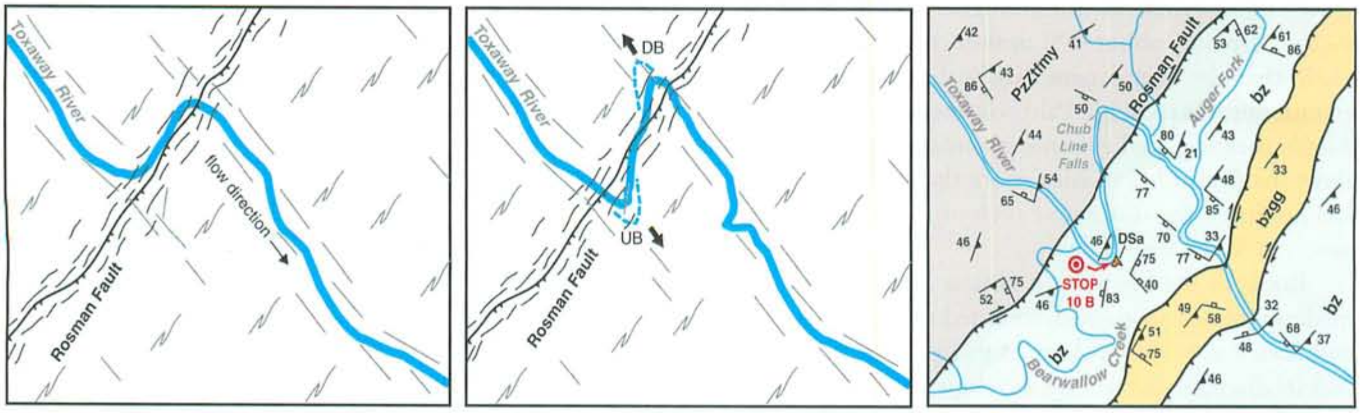
A pervasive fracture zone, or other structure, that parallels the north-northwest flowing part of the river south of Chub Line Falls was not observed in this area; therefore, another phenomena is needed to explain the orientation of this river segment. During an intermediate stage of development, the upstream and downstream bends in the river may have eroded more readily into the intensely fractured and faulted rock where the structures intersect (fig. 24B). In this case, the upstream bend migrated toward the southeast, and the downstream bend migrated toward the northwest.

Over time the river eroded through the rocks at the intersections, and along northwest-southeast fracture zones that extended past the Rosman Fault. More resistant (less fractured) rock beyond the intersection deflected the river northward from the upstream bend. Likewise, more resistant rock redirected the river southeastward from the downstream bend. Eventually this preferential erosion along the upstream and downstream bends would result in the north-northwest flowing reach of the Toxaway River we see today at the Auger Hole (fig. 24C).

#### STOP 11S – 1916 Flood Torrent Deposits along the Toxaway River at Bearwallow Creek

Boulder deposits here form a levee about 300 ft (90 m) long by 200 ft (60 m) wide along the southwest side of the Toxaway River, just upstream from its confluence with Bearwallow Creek. Although partly overgrown with trees and moss, boulders over 5 ft (1.5 m) long are clearly visible. Some of the boulders weigh over an estimated 5,000 lbs (2270 kg), attesting to the enormous force and erosive power of the flood torrent. The top of the levee rises almost 15 ft (5 m) above the present river level where, at this location, it marks the minimum height of the floodwaters that rushed down the gorge. Along the south end of the deposit, boulders appear to be stacked into a crude rock wall. Keep an eye out for copperhead snakes that hide in the empty spaces between some of the boulders!

Tree rings from an increment boring in a large pitch pine (*Pinus rigida*) growing on the crest of the boulder deposit reveal the tree started growing around 1917. This supports the idea that these deposits formed on August 13, 1916, the day the original Toxaway dam failed, and that plants began to colonize the barren deposits soon thereafter.




A - Early stage B - Intermediate Stage C - Present Stage

**Figure 24.** Stages in the development of the Auger Hole. **A.** Early stage of development where the Toxaway River flowed southeast, following northwest-southeast fracture zones, and flowed northeast along the Rosman fault. **B.** Intermediate stage of development when the river cut through the intensely fractured and easily eroded rocks where northwest-southeast fracture zones intersect the Rosman Fault. The river's upstream bend (UB) migrated southeastward through the intersection zone, and is deflected toward the north (across the Rosman fault) once it eroded past the intersection. The river's downstream bend (DB) migrated northwestward through the intersection, and was deflected toward the southeast once it eroded beyond the intersection. **C.** Present stage of the Toxaway River at the Auger Hole showing generalized bedrock map units and structural data. The active debris slide (DSa) on the outside bend of the Toxaway River is evidence of continued southeastward erosion and steepening of slopes along that segment of the river. PzZtfmy = mylonitic metagraywacke and schist of the Tallulah Falls Formation; bz = mylonitic metagraywacke, phyllonite, marble, and metasiltstone of the Brevard fault zone; bzgg = mylonitic granitic gneiss (Henderson Gneiss) within the Brevard fault zone. North is toward the top in all diagrams. Refer to plate 1 for bedrock unit descriptions and explanations for structural symbols.

#### STOP 12S – Toxaway River slide

Features exposed at the Toxway River slide record a number of the important geologic events that have shaped the Park's landscape from over a billion years ago to the present. Along the main scarp, mylonitic rocks mark the fault zone between the granitic basement rocks of the Toxaway Gneiss where they are overthrust by metasedimentary rocks of the Tallulah Falls Formation. In the main scarp of the slide, uplift and erosion has preserved an isolated remnant of the Tallulah Falls Formation above the folded fault surface. This remnant of the Tallulah Falls Formation surrounded by the Toxaway Gneiss is called a "klippe." Outcrops of the Toxaway Gneiss in the river below the slide reveal northwest-striking faults and joints that parallel the river's course. These fractures, and similar ones found in rocks in the slide are pathways for water to infiltrate underground.

The hurricanes that tracked over the Blue Ridge in July and August 1916 produced record setting rains, which saturated slopes and triggered widespread debris flows in Transylvania County, and the catastrophic failure of the Lake Toxaway Dam. As the flood torrent from the dam failure raced down the Toxaway River gorge, floodwaters scoured the hillside in the area of the slide and oversteepened the valley wall. This torrent probably triggered the first movement on the slide, as it began to move toward the river along pre-existing planes of weakness in the rock. Slopes that once buttressed the hillside dropped down and created scarps and the stair-stepped, hummocky ground surface.

Giant conifers, descendants of boreal, ice-age forests, tilt with the still-moving ground, and then grow straight, always recording the seasons with annual growth rings (figs. 15 and 17). The rise in the trail and the bent saplings mark where a lobe of slide debris continues to advance toward the river. The river erodes the toe of the lobe, removing more support from the hillside. Now bowl-shaped, the moving hillside collects infiltrating rain that creates pressure along planes of weakness and pushes apart interlocking grains of soil, and layers of weathered rock causing parts of the slide to continue to move and adjust. As the process continues, old scarps grow, new scarps form and open pathways for water to infiltrate.

#### STOP 13S – 1916 Flood Torrent Deposits along the Toxaway River near Panther Creek

The largest boulder found to date in the flood torrent deposits of 1916 is just above Panther Creek along the northeast side of the Toxaway River. This boulder is nearly 40 ft (12 m) long and weighs over an estimated 600,000 lbs (2720 kg). Further upstream, the top of the boulder deposits rise nearly 40 feet above the present river level. Along this reach of the river, many of the boulders in jumbled piles are larger than 3 ft (1 m) long. In some areas, the levee creates an elongate trough along the toe of the hillside that diverts small creeks and streams that orginally flowed directly into the Toxaway River.

Just below Panther Creek, an area of active erosion and sliding from a steep soil-covered slope marks what is most likely an area that was scoured and oversteepened by the flood torrent. The arc-shaped head scarp of this feature is nearly 20 ft (6 m) higher than the trail elevation and possibly marks the high water line of flood torrent.

**STOP 13S – Debris Fan Deposits on the east side of Lake Jocassee**

Excellent examples of extensive debris fan deposits occupy the lower hillslopes, or foot slopes, below the northwest-facing cliffs in the Henderson Gneiss that rise above the east side of Lake Jocassee. Boulders deposited by the August 1916 flood torrent are also visible near the outlet of Toxaway Creek. The debris that forms an apron-like deposit along the gentle foot slopes above the trail is actually a composite accumulation of material from numerous debris flows, debris slides, rockfalls and stream action over thousands, perhaps tens of thousands of years. Lobes of debris, or fans, form near the outlets of individual drainage ways, and as the fans grow they coalesce to form the composite apron of debris along the foot slopes.

Some of the more recent additions to the fan deposits are boulders, some as much as 8 ft (2.5 m) long, that are scattered about and stand in relief on the forest floor. These boulders bounced and rolled to their present location from cliffs nearly 700 ft (215 m) upslope. Steep banks, eroded by wave action near the lakeshore, expose the internal parts of some of the fans. Here, round and angular rock particles, as well as silt- and sand-sized sediment show the variety of shapes and sizes of the particles making up the debris fan. Rounded rock particles indicate the smoothing effect of past stream action. Accumulations of angular rock fragments indicate rapidly deposited material from debris slides and debris flows.

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## LIST OF PLATES, FIGURES, TABLES, AND APPENDICES

# APPENDIX A: SLOPE MOVEMENT NAMES

Slope movements were classified using two-part names depending on the type of movement (e.g., slide, flow, or fall), and the type of material in the source area that moved (e.g., earth, debris, or rock) in general accordance to the classification system of Varnes (1978) and Cruden and Varnes (1996).

The term "rock" designates hard or firm bedrock that was intact and in place before the movement occurred. Loose, unconsolidated aggregates of soil, sediment, and rock particles are divided into two categories, debris and earth. Debris is coarse-grained material in which over 80 percent of the particles are sand sized or greater. Earth is fine-grained material in which more than 80 percent of the particles are silt and clay sized; however, slope movements made up of this type of material were not found during the inventory of the Park. Although debris and earth flows can also contain uprooted trees and other vegetation, and other materials and structures on the ground surface (i.e., buildings, etc.), the terms "debris" and "earth" are based only on the size of the soil and rock particles in the source material.

The modifiers "active," "past-active," and "potential movement" are included in the names to categorize the relative activity of the movements. Active movements show evidence of recent movement such as curved trees, unvegetated scarps, and freshly exposed rock surfaces. Evidence of past-active movements includes vegetated scarps and deposits, and moss- or lichen-covered rock surfaces. Evidence of potential future movement includes dilated or favorably oriented joints (fractures) in rock cliffs and overhangs. The modifiers "translational" (planar failure surface) or "rotational" (curved failure surface) are suffixed where the style of slide movement was readily observable. Table 1 lists the types and characteristics of slope movements found in Gorges State Park.

# APPENDIX B: DESCRIPTION OF ROCK SAMPLES OF CHARACTERISTIC ROCK TYPES FOUND IN GORGES STATE PARK

The following is a listing and description of rock samples of characteristic rock types found in Gorges State Park. The samples are archived at the Park office.

## ROCKS OF THE TOXAWAY GNEISS

**Megacrystic Granitic Gneiss**
**Locality: Roadside outcrop along U.S. Highway 64 at Toxaway Dam.**

Many rocks of the Toxaway Gneiss exhibit a flaser, or wavy structure defined by abundant mica minerals that enclose megacrysts of feldspar. In this sample, these large megacrysts of potassium feldspar, up to 0.60 in (1.5 cm) in diameter, are enveloped in a finer-grained, flaser-structured matrix of biotite, quartz, feldspar, muscovite, epidote, and traces of apatite and zircon. This characteristic fabric was most likely imparted on the rock when it was metamorphosed (for a second time in its history) during Paleozoic mountain-building.

**Layered Granitic Gneiss**
**Locality: Roadside outcrop along U.S. Highway 64 at Toxaway Dam.**

Distinct compositional banding is a common fabric in rocks of the Toxaway Gneiss. In this sample, 0.5 in (approx. 1 cm) thick, light-colored bands of mostly feldspar and quartz alternate with darker-colored, biotite-rich layers. A few large megacrysts of potassium feldspar are also scattered throughout the rock. Metamorphism 350 to 450 million years ago gave this rock its "gneissic," or banded, appearance.

**Mylonitic Toxaway Gneiss**
**Locality: Headscarp of large rock slide along the Toxaway River.**

Alternating, 1.5 to 2 in (4 to 5 cm) thick layers of mylonitic Toxaway Gneiss attest to the tremendous pressure exerted on these rocks during Paleozoic thrust faulting about 460 million years ago. Extreme granulation and ductile shearing during faulting produced the mylonitic foliation observed in this sample. Coarser-grained layers consist of porphyroclasts of potassium feldspar, some larger than one centimeter in length, in a finer-grained, flaser-structured matrix of feldspar, quartz, biotite, and muscovite. Finer-grained mylonitic granitic gneiss layers display a distinct streaky or finely laminated appearance.

**Mylonite**
**Locality: Big Spice Cove.**

Paleozoic thrust faulting around 460 million years ago shoved oceanic rocks of the Tallulah Falls Formation up and over continental rocks of the Toxaway Gneiss along a huge fault in the Earth's crust. This is a sample of mylonite, a granulated and sheared rock produced through faulting under intense pressure, from the contact zone between the Toxaway Gneiss and Tallulah Falls Formation along the Toxaway River. In it, one can see alternating, 0.05 in to 0.15 in (1mm to 4mm) thick laminae of mica-rich phyllonite and quartz- and feldspar-rich mylonite with a few small potassium feldspar porphyroclasts.

## ROCKS OF THE TALLULAH FALLS FORMATION

**Altered Ultramafic Rock**
**Locality: Flat Creek Valley (outside of the Park boundary).**

This fine- to medium-grained, lepidoblastic rock is a talc schist. It is very soft and easily carved with a knife. This sample came from an abandoned mine on privately owned land just outside the Park boundary. In the 1930s, talc schist sawn from this mine was used locally for building stone and fireplace hearths.

This sample is composed of olivine, serpentine, magnesite, talc, chromite, and magnetite. Olivine is a mineral that is most often found in oceanic basalt. Serpentine, talc, and magnesite are minerals that form from olivine during metamorphism. This rock tells us that it and other rocks of Tallulah Falls Formation were once on the floor of an ancient ocean, and that sometime later, it was metamorphosed, or altered by intense heat and pressure, during a period of mountain-building.

Although this sample was collected from outside of the Park, another small deposit of talc schist occurs in the Park along the Toxaway River about 1 mile (approx. 1.6 km) below Wintergreen Falls.

**Porphyroclastic Schist**
**Locality: From a flood deposit boulder near the ford of Auger Hole Road on the Toxaway River.**

This sample was collected from a large boulder that was transported about a mile down river during the flood of 1916 when the Lake Toxaway dam failed. The rock unit it comes from occurs along the fault contact between the Toxaway Gneiss and Tallulah Falls Formation. It is a schistose rock characterized by medium- to coarse-grained feldspar and muscovite porphyroclasts, up to 0.1 in (0.25 cm) in diameter, within a finer-grained, lepidoblastic, mica-rich phyllitic matrix composed of quartz, feldspar, muscovite, and biotite. Its unique fabric is the product of shearing (faulting) and metamorphism along the contact between the two major rock units during Paleozoic mountain-building.

**Garnet Mica Schist**
**Locality: Outcrop on the northeast side of Chestnut Mountain above Bearwallow Creek.**

Translucent, reddish-pink garnet porphyroblasts up to 0.12 in (3mm) that weather to a red-brown color characterize this rock. Finer-grained muscovite, with lesser amounts of black biotite and clear quartz make up the silver-gray matrix that envelops the garnet. Progressive shearing during mountain-building produced the two foliations visible in this sample. The garnet porphyroblasts are rotated in the plane of the dominant foliation (S-surface), that is cross-cut by a shear foliation (C-surface). Together these two foliations create what is known as an S-C fabric. This fabric forms in ductile shear (fault) zones, and imparts a "fish-scale" or "button" appearance similar to that found in rocks of the Brevard fault zone. This sample comes from near the fault contact between the Toxaway Gneiss and the Tallulah Falls formation.

**Amphibolite**
**Locality: From a flood deposit boulder near the ford of Auger Hole Road on the Toxaway River.**

Amphibolite is a fine- to medium-grained, nematoblastic rock composed mostly of aligned prismatic crystals of dark greenish-black hornblende and cream-colored laths of feldspar. This sample, transported down river during the flood of 1916 when the Lake Toxaway dam failed, is also composed of epidote, quartz, sphene, clinopyroxene, biotite, and traces of zircon, apatite, and muscovite. It is strongly foliated (the grains of hornblende are arranged in a planar orientation) and layered; 0.08-0.25 in (2-6 mm) thick zones of feldspar- and quartz-rich material define layering. Amphibolite in the Tallulah Falls Formation most likely recrystallized from 500-to 600-million-year-old basalt during Paleozoic metamorphism 350 to 450 million years ago.

**Metagraywacke**
**Locality: Roadside outcrop along Auger Hole Road near Chestnut Branch.**

This is a sample of the most common rock type of the Tallulah Falls Formation in Gorges State Park. It is a metagraywacke, a type of metamorphosed sandstone. When it was originally deposited on the floor of an ancient ocean some 500 to 600 million years ago, it consisted of both sand-sized grains of quartz and feldspar, and clay-rich mud. The sand grains and mud soon hardened (lithified) into "muddy" sandstone, and later, during Paleozoic metamorphism, the clay-rich material re- crystallized into flakes of muscovite and biotite. This sample of metagraywacke is fine- to medium-grained, granoblastic, and composed of quartz, feldspar, biotite, muscovite, garnet, epidote, and traces of apatite. It is also strongly foliated (flakes of muscovite and biotite lie flat in a planar orientation) and layered; 0.15-0.02 in (4-5 mm) thick zones of quartz and feldspar alternate with zones rich in mica minerals.

**Pegmatite**
**Locality: From stream boulders on Chestnut Branch.**

Pegmatite is a coarse- to very coarse-grained rock composed mostly of quartz, feldspar, and mica. In these samples, large phenocrysts and porphyroclasts of feldspar and books of muscovite dominate the fabric of the rocks. One of the samples is strongly foliated; feldspar porphyroclasts are rotated and flattened into the plane of the foliation.

Pegmatite within Gorges State Park probably formed during high-grade Paleozoic metamorphism, sometime between 350 and 450 million years ago. As metagraywacke and mica schist of the Tallulah Falls Formation stewed in hot metamorphic fluids, some of the quartz, feldspar, and mica within the rocks actually melted and recrystallized into very coarse-grained pegmatites. In the late 1800s and early 1900s, books of transparent to translucent muscovite were mined from a shallow pit driven into a body of pegmatite at the head of Chestnut Branch. At that time, one of the many uses for large sheets of muscovite mica was to make window panes for wood- and coal-burning stoves.

## BREVARD FAULT ZONE ROCKS

**Siliceous Marble**
**Locality: Lime kilns near the confluence of Bearwallow Creek and the Toxaway River.**

This fine- to medium-grained, granoblastic, metamorphosed limestone is composed of calcite, quartz, muscovite, feldspar, chlorite, pyrrhotite, and traces of apatite and zircon. It was deposited in an oceanic environment after deposition of the Tallulah Falls Formation, around 500 to 600 million years ago. In the late 1800s and early 1900s, this rock was mined and burned in kilns at the quarry for use as building lime and fertilizer.

**Phyllonite**
**Locality: Along Bearwallow Creek near the lime kilns.**

This schistose rock is characterized by lenticular muscovite-aggregate porphyroblasts, as much as 0.75 in (2.0 cm) long and 0.2 in (0.5 cm) thick, which are flattened in the plane of foliation to give rise to a distinctive "fish scale" or "button" appearance. Originally a mica schist, its distinctive fabric and foliation developed by shearing (faulting) within the Brevard fault zone during Paleozoic mountain-building.

## ROCKS OF THE HENDERSON GNEISS

**Protomylonitic Granitic Gneiss**
**Locality: Eastern shore of Lake Jocassee.**

Rocks of the Henderson Gneiss are some of the youngest in Gorges State Park — they are only about 490 million years old. This sample exhibits its characteristic mylonitic fabric. Medium- to coarse-grained, rounded to elongated, rotated and flattened megacrystic porphyroclasts of feldspar, up to 0.75 in (2 cm) in diameter, are enveloped in a finer-grained, flaser-structured matrix of quartz, feldspar, biotite, muscovite, and epidote. Intense shearing (faulting) along the Brevard fault zone during Paleozoic mountain-building produced the distinctive fabric observed in rocks of the Henderson Gneiss today.

# Types and Characteristics of Slope Movements Commonly Found in Gorges State Park

| Slope Movement Type | Definition | Appearance | Geomorphic Setting | Hazard |
|---|---|---|---|---|
| **Debris Slide** | ♦Regolith displaced along well-defined failure surface.<br>♦Translational (planar) or rotational (curved) failure surface.<br>♦Displaced mass deformed but coherent .<br>♦Water content to low for displaced mass to liquefy. | ♦Elliptical outline.<br>♦Arc-shaped main scarp with concave ground surface below.<br>♦Convex ground surface where material accumulated.<br>♦Size varies - most <65ft x 80ft, few 100ft x 300ft.<br>♦Failure surface at regolith-bedrock contact. | ♦Steep slopes (>35°).<br>♦Mainly on scarp and oblique slopes (e.g., Chestnut Mtn.).<br>♦ Some on dip slopes along steeply incised rivers and streams. | ♦Movement rates rapid (ft/sec) to slow (ft/year).<br>♦Usually moves over short distances (<100ft).<br>♦Can mobilize into debris flow with increased water content.<br>♦Displaced mass can block roads and trails.<br>♦Typically occurs during periods of heavy rainfall. |
| **Debris Flow** | ♦Water content sufficient for displaced regolith to mobilize (liquefy).<br>♦Displaced mass is incoherent fluid mixture of soil, rock and vegetation. | ♦Typically follows drainage course.<br>♦Scar at, or near, initiation zone.<br>♦Elongate eroded track.<br>♦Displaced material accumulates in fan-shaped deposit near drainage outlet. | ♦ Typically initiates in hillslope depressions on steep (>35°) scarp and oblique slopes.<br>♦Initial failure surface at sharp contact between regolith and bedrock in drainage headwalls.<br>♦Past debris flows originated upslope of debris and debris fan deposits. | ♦Movement very rapid (ft/sec) over long distances (>500ft).<br>♦Debris can bury, damage or destroy structures; can cause injury and death.<br>♦Typically occurs during periods of heavy rainfall. |
| **Weathered-rock slide (Toxaway River Slide)** | ♦Displaced mass is mainly deformed but coherent blocks of weathered rock (saprolite).<br>♦Movement is mainly translational, with subordinate rotational component. | ♦Nearly vertical scarps up to 30ft high.<br>♦Large (~4 acre) area.<br>♦Stair-stepped, hummocky ground surface.<br>♦Curved and tilted trees. | ♦Footslope oblique to bedrock dip.<br>♦At contact between Toxaway gneiss and Tallulah Falls formation. | ♦Slow movement (ft/year).<br>♦Rockfall hazard at south end of main scarp above trail.<br>♦Movement probably occurs after extended periods of above average rainfall.<br>♦Periodic trail maintenance probably required. |
| **Rockfall** | ♦Free fall of rock blocks detached from cliff face or overhang.<br>♦Rock blocks (boulders) can bounce and roll downslope. | ♦Boulder accumulation below cliff face or overhang.<br>♦Fresh, unweathered faces along cliffs and overhangs. | ♦Well-jointed rock cliffs and overhangs along Toxaway River, and lower Auger Fork Creek.<br>♦Northwest-facing cliffs along scarp slopes. | ♦Very rapid movement (ft/sec) of large boulders.<br>♦Can occur with little or no warning at any time, especially during freeze-thaw cycles. |
| **Rockslide** | ♦Translational movement of rock blocks along plane(s) of weakness (e.g., foliation, joint). | ♦Planar bedrock surface above detached blocks at slope toe. | ♦Mainly along southeast-facing dip and oblique slopes in exposed bedrock. | ♦Moderate (ft/week) to rapid (ft/min) movement.<br>♦Known occurrences limited to remote reaches of the Toxaway River and Auger Fork Creek. |

**Table 1.** Types and characteristics of slope movements commonly found in Gorges State Park. Refer to generalized map of slope movements and related surficial deposits (pl. 2) for locations.

## GLOSSARY

The following is a geologic glossary of terms and concepts used in this Information Circular. Many of the definitions are modified from the America Geologic Institute *Glossary of Geology*, edited by Bates and Jackson (1987). Some of the terms below have multiple, non-geologic meanings; definitions provided stem from their usage in geology.

**abyssal plain** — A flat region of the ocean floor at the base of the continental rise formed by the deposition of sediments and usually underlain by oceanic crust.

**aggregate** — (a) A mass or body of rock particles, mineral grains, or a mixture of both. (b) Rock material, such as crushed stone, used for mixing with a cementing agent to form concrete.

**alluvium** — Clay, silt, sand, gravel or similar unconsolidated detrital material deposited during relatively recent geologic time by a stream or other body of running water. Alluvium usually contains rounded particles and usually collects in the channels and floodplains of creeks, streams, rivers, and lakes (*adj* **alluvial**).

**amphibole** — A group of dark, mafic, rock-forming ferromagnesian silicate minerals having the general formula $A_{2\text{-}3}B_5(Si,Al)_8O_{22}(OH)_2$, where A = Mg, Fe, Ca, or Na, and, B = Mg, Fe, or Al. Amphiboles are a common constituent in many igneous rocks, but are especially prevalent in metamorphic rocks.

**amphibolite** — A rock consisting mainly of amphibole and plagioclase with little or no quartz.

**amphibolite facies** — Medium- to high-grade regional metamorphism under moderate to high pressures (in excess of 3000 bars), at temperatures between 450° and 700°C, and characterized by the metamorphic mineral assemblage: hornblende + plagioclase in mafic rocks.

**antiform** — A fold whose limbs close upward in strata for which the stratigraphic sequence is not known.

**apatite** — A group of minerals in both igneous and metamorphic rocks consisting of calcium phosphate together with fluorine, chlorine, hydroxyl, or carbonate in varying amounts and having the general formula $Ca_5(PO_4CO_3)_3(F,OH,CL)$.

**apron** — An extensive blanket-like deposit of alluvial, colluvial, or other unconsolidated material derived from an identifiable source, and deposited at the base of a mountain.

**aquifer** — a permeable body of consolidated or unconsolidated rock that contains and transmits ground water that is yielded to wells and springs.

**assimilation** — The incorporation and digestion of solid or fluid foreign material, i.e., wall rock, in magma (*vb* **assimilate**).

**augen** — In foliated metamorphic rocks, large lenticular mineral grains or mineral aggregates having the shape of eyes (*augen* in German) in cross section.

**axial surface** — A surface that connects the hinge lines of the strata in a fold.

**axial trace** —The intersection of the axial surface of a fold with the surface of the earth.

**basalt** — A general term for dark-colored mafic igneous rocks, commonly extrusive (e.g., basalt flows), but locally intrusive (e.g., sills, dikes), composed chiefly of calcic plagioclase and pyroxene.

**basement** — Rocks that formed or were deformed during an earlier episode of mountain-building, and are older than all of the rocks above them.

**bedding** — The arrangement of a sedimentary rock into layers.

**bedrock** — Rock that underlies soil or other unconsolidated, surficial material.

**biotite** —A widely distributed and important, dark-colored, rock-forming mineral of the mica group having the formula $K(Mg,Fe)_3(Al,Fe)_3(Al,Fe)Si_3O_{10}(OH)_2$. It is a common constituent in both igneous and metamorphic rocks.

**borrow pit** — An excavated area where fill material has been obtained.

**boulder** — A detached rock mass larger than a cobble, having a diameter greater than 10 in (256 mm).

**breccia** — A coarse-grained sedimentary rock composed of angular and broken rock fragments, and held together by mineral cement or in a finer-grained matrix.

**brittle** — Said of a rock that easily fractures.

**calcic** — Said of minerals and rocks containing much calcium.

**calciphile** — A plant requiring lime-rich soil.

**calcite** — A common, colorless, white to pale gray or yellow, rock-forming mineral having the formula $CaCO_3$. It is the principle constituent of limestone, but is also found in both igneous and metamorphic rocks.

**carbonate** — A mineral compound characterized by $CO_3$. Calcite, $CaCO_3$, is the most common carbonate mineral.

**chlorite** — A group of platy, mica-like, usually greenish minerals of the general formula $(Mg,Fe)_6AlSi_3O_{10}(OH)_8$ that are common in low-grade metamorphic rocks.

**chromite** — A brownish-black to iron-black mineral with the formula $(Fe,Mg)(Cr,Al)_2O_4$, found in certain igneous and metamorphic rocks.

**clay** — A rock or mineral fragment or a detrital particle of any composition smaller than a very fine silt grain, having a diameter less than 0.00002 in (0.004 mm).

**clinometer** — An instrument used to measure angles of slope, elevation, or inclination.

**cobble** — A rock fragment larger than a pebble and smaller than a boulder, having a diameter in the range of 2.5 in (64 mm) to 10 in (256 mm).

**colluvium** — Any loose, heterogenous, and unconsolidated mass of soil and rock particles deposited by rainwash, sheetwash, or slow, continuous downslope creep. Colluvium usually contains angular to subrounded rock particles and usually collects at the base of gentle slopes or hillsides.

**composition** — The chemical or mineral make-up of a rock.

**continental margin** —The ocean floor that is between the shoreline and the abyssal plain.

**continental rise** — Part of the continental margin that is between the continental slope and abyssal plain.

**continental shelf** — Part of the continental margin that is between the shoreline and continental slope.

**continental slope** — Part of the continental margin that is between the continental shelf and continental rise.

**country rock** — The rock intruded by and surrounding an igneous intrusion or mineral deposit.

**creep** — The slow, more or less continuous downslope movement of mineral, rock, and soil particles by gravity.

**crest** — The highest point or line of a landform, from which the surface slopes downward in opposite directions.

**crust** — The outermost layer or shell of the earth.

**debris** — Regolith that contains a significant proportion of coarse material in which 20% to 80% of the particles are greater than sand sized (0.08 in or 2 mm). Debris is a general term used to classify the coarser-grained material in the source area of a slope movement (e.g., debris flow or debris slide).

**debris avalanche** — The very rapid and usually sudden sliding and flowage of incoherent, unsorted mixtures of soil and weathered bedrock.

**debris flow** — A type of slope movement in which the water content in the displaced mass is sufficient for the material to liquefy and resemble a viscous fluid. Flows involve the movement of unconsolidated earth materials (i.e., earth and debris) in a semifluid state.

**debris slide** — Slope movements initiated by slippage along a well-defined failure surface that is usually planar or curvi-planar. Slides are divided into two classes, rotational and translational. Slides usually consist of displaced and deformed blocks of material.

**debris fan** — A fan-shaped accumulation of debris typically along the lower gentle slope of a hillside.

**deformation** — A term for the processes of folding, faulting, shearing, compression, or extension of rocks as a result of various Earth forces.

**deposit** — (a) Earth material of any type that has acumulated by some natural process or agent (*vb* **deposited**). (b) An accumulation of ore or other valuable earth material.

**detritus** — A term for loose rock and mineral material that is eroded by mechanical means (*adj* **detrital**).

**dike** — A tabular igneous intrusion that cuts across the bedding or foliation of the country rock.

**dip** — The angle that a sloping surface makes with a horizontal plane.

**dip slope** — A slope of the land surface, roughly determined by, and conforming with, the direction and angle of dip of the underlying rock.

**dip-slip fault** — A fault along which the movement or slip is parallel to dip of the fault surface.

**displacement** — The relative movement of the two sides of a fault; also the specific amount of such movement.

**ductile** — Said of a rock that can withstand some deformation before fracturing and faulting.

**earth** — Regolith in which about 80% or more of the particles are smaller than 2 mm. Earth is a general term used to classify the finer-grained type of material in the source area of a slope movement (e.g., earth flow or earth slide).

**en echelon** — Said of geologic features that are in an overlapping or staggered arrangement.

**eolian** — Erosion, deposition, and sedimentary accumulations accomplished by the wind.

**epidote** — A yellowish-green, pistachio-green, or blackish-green mineral with the formula $Ca_2(Al,Fe)_3Si_3O_{12}(OH)$ that is common in low-grade metamorphic rocks.

**erosion** — The loosening, dissolution, wearing away, and simultaneous transport of earth materials from one place to another.

**exfoliation** — The weathering process of spalling or stripping away of concentric scales, plates, or shells of rock from the bare surface of a large rock mass.

**extrusive** — Said of an igneous rock that has been erupted onto the Earth's surface.

**fabric** — An all-encompassing term that describes the shapes and characteristics of all the components that make up a deformed rock.

**fault** — A fracture or zone of fractures along which there has been displacement of the sides relative to one another parallel to the fracture.

**feldspar** — A group of abundant rock-forming minerals of the general formula $MAl(Al,Si)_3O_8$, where M = K, Na, Ca, Ba, Rb, Sr, or Fe. Feldspars are the most widespread of any mineral group and occur in all kinds and types of rocks.

**felsic** — Said of an igneous rock having abundant light-colored minerals (chiefly feldspar and quartz) in its composition; also, said of those minerals.

**ferromagnesian** — Containing iron and magnesium.

**flaser structure** — A structure in a metamorphic rock in which crystals, lenses, and layers of original minerals are surrounded by a matrix of highly sheared and crushed material.

**floodplain** — The surface or strip of relatively smooth land adjacent to a river channel, and built of alluvium carried and deposited by the river during floods.

**fold** — A curve or bend of rock strata or foliation.

**foliation** — The planar arrangement of textural or structural features in a metamorphic rock that results from flattening of the constituent mineral grains.

**footwall** — Rock beneath an inclined fault.

**foot slope** — The lower gentle slope of a hillside below a steep rock face or escarpment including lower slopes of diminishing steepness.

**formation** — A body of rock identified by its unique lithologic characteristics and stratigraphic position.

**fracture** — A general term for any break in a rock, whether or not it causes any displacement. Fracture includes cracks, joints, and faults.

**garnet** — A group of minerals of the formula $A_3B_2(SiO_4)_3$, where A = Ca, Mg, Fe, Mn, and B = Al, Fe, Mn, V, and Cr. Garnet occurs in igneous rocks, but is most common in metamorphic rocks.

**geomorphology** — The study of the classification, description, nature, origin, and development of present landforms and their relationships to underlying bedrock structures.

**glacial** — Of or relating to the presence and activities of ice.

**gneiss** —A coarsely foliated metamorphic rock segregated into alternating bands of granular and flaky minerals.

**gradient** — A degree of inclination, or a rate of ascent or descent, of an inclined part of the Earth's surface.

**granitic rock** — A term applied to any light-colored, coarse-grained plutonic igneous rock containing quartz and feldspar as essential components, along with accessory minerals.

**granoblastic** — A type of texture in a metamorphic rock in which equidimensional, interlocking crystals predominate.

**granulite facies** — High-grade regional metamorphism at temperatures in excess of 650°C and characterized by the metamorphic mineral hypersthene.

**graphite** — A naturally occurring crystalline form of carbon (*adj* **graphitic**).

**gravel** — A rock or mineral fragment or a detrital particle of any composition smaller than a sand and larger than a cobble, having a diameter between 0.08 in (2 mm) and less than 2.5 in (64 mm).

**greenschist facies** — Low-grade regional metamorphism at temperatures in the range of 300° to 500°C, characterized by the metamorphic minerals chlorite, muscovite, and biotite in pelitic rocks.

**ground water** —Water below the surface of the Earth. Also spelled: groundwater, ground-water.

**groundmass** —The finer-grained material between the phenocrysts of a porphyritic igneous rock, or the matrix of a sedimentary rock.

**hanging wall** — The wall rock above an inclined fault.

**headwall** — A steep slope at the head of a valley.

**headward erosion** — The lengthening and downcutting of a young valley or gully above the original source of its stream.

**hinge line** — a line connecting the points of maximum curvature of the strata in a fold.

**hornblende** — The most common mineral of the amphibole group, with the formula: $(Ca,Na)_2(Mg,Fe,Al)_5(Al,Si)_8O_{22}(OH)_2$. Hornblende is usually black, dark green, or brown. It is a primary constituent of certain igneous rocks, and is a very common medium- to high-grade metamorphic mineral.

**hypersthene** — A common rock-forming pyroxene mineral with the formula: $(Mg,Fe)SiO_3$. It is an essential constituent of certain igneous rocks, and a high-grade metamorphic mineral.

**igneous rock** — A rock that solidified from molten or partly molten magma.

**imbricated** — Overlapping, as tiles on a roof or scales on a bud of a plant.

**interfluvial** — Lying between streams.

**intrusive** — Igneous rocks crystallized from magma beneath the surface of the Earth.

**isostasy** — A condition of equilibrium, comparable to floating, of the two outermost layers of the Earth. Crustal loading by ice, water, sediments, or volcanic accumulations leads to isostatic depression, whereas removal of the load (as by erosion) leads to isostatic uplift.

**joint** — A fracture or parting in a rock, without displacement.

**klippe** — An isolated rock unit that is an erosional remnant of a thrust sheet.

**kyanite** — A blue or light-gray bladed mineral, formed at medium temperatures and high pressures during regional metamorphism, with the formula $Al_2SiO_5$.

**lamina** — The thinnest recognizable layer in a rock (*pl* **laminae**).

**landform** — Any physical, recognizable form or feature on the Earth's surface, having a characteristic shape, and produced by natural causes.

**landscape** —The distinct association of landforms that can be seen in a single view.

**landslide** — A wide variety of mass movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock material en masse.

**lava** — Molten extrusive material, or rock solidified from it.

**lava flow** — A lateral, surficial outpouring of molten lava from a volcanic vent or fissure.

**layer** — A tabular body of rock, essentially parallel to the surface or surfaces on or against which it was formed.

**lepidoblastic** — A type of texture in a metamorphic rock that is due to the parallel orientation during recrystallization of minerals with a flaky or scaly habit.

**levee** — An embankment of sediment bordering one or both sides of a stream or river.

**limestone** — A sedimentary rock consisting chiefly of calcium carbonate ($CaCO_3$).

**lithification** — The conversion of a newly deposited, unconsolidated sediment into coherent, solid rock (*vb* **lithified**).

**lithology** — The description of rocks, especially in hand specimen and in outcrop, on the basis of such characteristics as color, mineral composition, and grain size (*adj* **lithologic**).

**mafic** — An igneous or metamorphic rock composed chiefly of one or more ferromagnesian, dark-colored minerals; also, said of those minerals.

**magma** — molten rock material.

**magnesite** — A white to grayish, yellow, or brown carbonate mineral with the formula: $MgCO_3$. It is a common alteration mineral of rocks rich in magnesium-silicate minerals.

**marble** — A metamorphic rock consisting predominantly of fine- to coarse-grained recrystallized calcite.

**matrix** — The finer-grained material enclosing larger grains or particles of a rock.

**megacryst** — A crystal or grain in an igneous or metamorphic rock that is significantly larger than the surrounding matrix (*adj* **megacrystic**).

**metagraywacke** — A field term for a metamorphosed, dark, clayey, impure sandstone.

**metamorphic grade** — The intensity or degree of metamorphism.

**metamorphic rock** — A rock derived from metamorphism of a pre-existing rock.

**metamorphism** — Solid-state recrystallization of a pre-existing rock by heat and pressure.

**metasedimentary rock** — A metamorphosed sedimentary rock.

**metavolcanic rock** — A metamorphosed volcanic rock.

**mica** — A flaky, scaly, or platy group of minerals with the general formula: $(Mg,Fe,Li,Al)_{2\text{-}3}(Al,Si)_4O_{10}(OH,F)_2$. Micas are common rock-forming constituents of igneous, metamorphic, and sedimentary rocks.

**migmatite** — A composite rock formed during metamorphism when felsic portions of the rock melt and crystallize, and other portions of the rock recrystallize without melting, producing a new rock with both igneous and metamorphic components.

**mine** — An underground excavation for the extraction of minerals of value.

**mineral** — A naturally occurring, inorganic substance having an orderly internal crystalline structure, characteristic chemical composition, and physical properties.

**monadnock** — A hill or mountain rising conspicuously above the general level of the surrounding landscape that represents an isolated erosional remnant of a former higher topography.

**muscovite** — A colorless to silvery gray mineral of the mica group having the formula: $KAl_2(AlSi_3)O_{10}(OH)_2$. It is common in igneous, metamorphic, and sedimentary rocks.

**mylonite** — A strongly foliated or banded rock produced by extreme granulation and shearing during faulting.

**nematoblastic** — A type of texture in a metamorphic rock due to the development during recrystallization of slender, parallel, prismatic crystals.

**normal fault** — A fault in which the hanging wall appears to have moved downward in relation to the footwall.

**oblique slope** — A relatively steeper face of a hillslope, facing in a direction at an angle to the dip of the rock layers. An oblique slope faces a direction that lies between a dip slope and a scarp slope.

**olivine** — An olive-green, grayish-green, or brown rock-forming igneous mineral with the formula $(Mg,Fe)_2SiO_4$.

**orogeny** — The process of mountain-building, accompanied by deformation of the crust, resulting from subduction, terrane accretion, and continent-continent collision.

**outcrop** — A rock appearing at the surface of the Earth that is part of a larger geologic formation or structure at depth.

**overturned fold** — a fold with one limb tilted past the vertical.

**pavement** — A bare rock surface that suggests a paved road in smoothness, hardness, horizontality, and surface extent.

**pebble** — A general term for a small, rounded, waterworn stone; specifically, a rock fragment larger than a granule and smaller than a cobble, having a diameter in the range of 0.16 in (4 mm) to 2.5 in (64 mm).

**pegmatite** — An exceptionally coarse-grained igneous rock, with interlocking crystals, usually found as irregular dikes, lenses, or veins.

**phenocryst** — A large, conspicuous crystal in a porphyritic igneous rock.

**phyllite** — A metamorphic rock, intermediate in grade between slate and mica schist.

**phyllonite** — A rock that resembles a phyllite, but is formed by mylonitization of pre-existing rocks, some of which may be coarse-grained.

**physiographic province** – A region of similar landforms and geomorphic history.

**plagioclase** — A group of feldspars with general formula $(Na,Ca)Al(Si,Al)Si_2O_8$. Plagioclase is among the most common rock-forming minerals on Earth.

**plutonic rock** — An igneous rock that crystallized below the Earth's surface.

**pore water** — Subsurface water in the voids of rock, sediment, or soil.

**porphyritic** — The texture of an igneous rock in which larger crystals (phenocrysts) are set in a finer-grained groundmass.

**porphyroblast** — A large mineral crystal in a metamorphic rock, formed during metamorphism (*adj* **porphyroblastic** texture).

**porphyroclast** — A large phenocrystic mineral crystal in a metamorphic rock that is pre-existing and not formed during metamorphism (*adj* **porphyroclastic** texture).

**premetamorphic** — Said of a structure that formed prior to peak regional metamorphism.

**prograde metamorphism** — Metamorphic changes in a rock in response to higher temperatures and pressures than that to which the rock last adjusted itself.

**prospect** — An area that has been explored for a potential mineral deposit, but unlike a mine, is nonproducing.

**pyroclastic deposit** — An accumulation of material formed by a volcanic explosion.

**pyroxene** — A group of dark-colored, mafic, rock-forming silicate minerals found in both igneous and metamorphic rocks and having the general formula: $ABSi_2O_6$, where A = Ca, Na, Mg, Fe, and B = Mg, Fe, Cr, Mn, Al.

**pyrrhotite** — A common, red-brown to bronze-colored, iron sulfide mineral with the formula: FeS. It is darker-colored and softer than pyrite, and forms at higher metamorphic grades.

**quadrangle** — A rectangular area bounded by parallels of latitude and meridians of longitude.

**quarry** — A surface mine.

**quartz** — An important rock-forming mineral with the formula $SiO_2$. It is, next to feldspar, the most common mineral found in most rocks in the Earth's crust.

**rainwash** —The washing-away of loose surface material by rainwater.

**regolith** — A general term for the layer or mantle of fragmental and unconsolidated rock material that nearly everywhere forms the surface of land and overlies or covers bedrock. It includes alluvium, colluvium, residuum, debris, earth, and soil.

**retrograde metamorphism** — Metamorphic changes in a rock in response to lower temperatures and pressures than that to which the rock last adjusted itself.

**rift** — A long, narrow, continental trough that is bounded by normal faults.

**rifting** —The formation of a rift by tectonic processes.

**rock** — An aggregate of one or more minerals, undifferentiated mineral matter, or solid organic material.

**rock fall** — A type of slope movement in which a single mass of rock of any size is detached from a steep slope or cliff along a surface on which little or no shear displacement occurs. The detached material descends mostly through the air by free fall, bounding, or rolling.

**rock pavement** — A smooth, bare, rock surface.

**rock type** — A particular kind of rock having a specific set of characteristics.

**rotational movement** — A term used to describe the type of movement in a slide in which the displaced material has moved along a curved, concave upward, failure surface.

**sand** — A rock or mineral fragment or a detrital particle of any composition smaller than a granule and larger than a coarse silt grain, having a diameter between 0.00002 in (0.004 mm) and 0.08 in (2 mm).

**sandstone** — A sedimentary rock composed of abundant sand-sized fragments.

**saprolite** — A soft, earthlike, completely decomposed (or weathered), in-place rock material typically formed in humid environments. Saprolite is characterized by the preservation of structures that were present in the unweathered rock.

**scar** — A cliff, precipice, or other steep slope.

**scarp** — A relatively straight, cliff-like face or slope that breaks the general continuity of the land surface.

**scarp slope** — A relatively steeper face of a hillslope, facing in a direction opposite the dip of the rock strata or layers.

**schist** — A strongly and finely foliated metamorphic rock that can be readily split into thin flakes or slabs (e.g., **mica schist** is a strongly foliated rock dominated by mica minerals).

**schistose** — Said of rock displaying schistosity.

**schistosity** — Foliation in schist.

**scour** — The powerful and concentrated clearing and digging action of flowing air, water, or ice.

**sediment** — Loose, unconsolidated, fragmental material that originates from weathering of rocks and is transported or deposited by air, water, or ice.

**sedimentary rock** — A rock resulting from the consolidation of loose sediment that has accumulated in layers; also a rock formed by precipitation from solution, or an organic rock consisting of the remains or secretions of plants and animals.

**serpentine** — A group of green, greenish-yellow, or greenish-gray, rock-forming minerals with the formula: $(Mg,Fe)_3Si_2O_5(OH)_4$, that have a greasy or silky luster and a slight soapy feel, and are derived from the alteration of magnesium-rich silicate minerals, especially olivine.

**shale** — A fine-grained sedimentary rock formed by the consolidation of clay or mud.

**shear** — A deformation resulting from stresses that cause adjacent parts of a rock mass to slide relative to each other in a direction parallel to their plane of contact (*vb* **shearing**).

**shear strength** — The internal resistance of a body to shear stress.

**shear zone** — A tabular zone of rock that has been crushed, brecciated, and mylonitized by shearing.

**sheet joint** — A joint formed by exfoliation.

**sheetwash** — A broad expanse of storm-borne water moving and spreading out over the ground surface.

**silicate** — A mineral compound whose crystal structure contains $SiO_4$.

**sill** — A tabular igneous intrusion that parallels the planar structure of the surrounding rock.

**silt** — A rock or mineral fragment or a detrital particle of any composition smaller than a very fine sand grain and larger than coarse clay, having a diameter between 0.004 mm and 0.06 mm.

**siltstone** — A sedimentary rock composed of mineral grains of silt size.

**slate** — A compact, fine-grained metamorphic rock formed from shale.

**slope movement** — The gradual or rapid downslope movement of soil or rock by gravity.

**soapstone** — A soft, metamorphic rock composed mostly of talc.

**sphene** — A yellow or brown mineral of the formula $CaTiSiO_5$ occurring in granitic igneous rocks and calcium-rich metamorphic rocks.

**stratified** — formed, arranged, or laid down in layers.

**stratigraphic** — The succession and age of rock units and layers.

**stratum** — A tabular or sheetlike body or layer of sedimentary rock (*pl* **strata**).

**strike** — the direction or trend taken by a structural surface, e.g., a bedding, foliation, or fault plane, as it intersects the horizontal.

**strike-slip fault** — A fault on which the movement is parallel to the fault's strike.

**structure** — A feature in the rock that results from rock deformation.

**sulfide** — A mineral compound containing sulfur and a metal, such as pyrite: $FeS_2$.

**surficial deposit** — Unconsolidated and residual, alluvial, or glacial deposits lying on bedrock or occurring on the Earth's surface.

**synform** — A fold whose limbs close downward in strata for which the stratigraphic sequence is unknown.

**synmetamorphic** — Said of a structure that formed during peak regional metamorphism.

**talc** — An extremely soft, light-green or gray mineral with the formula $Mg_3Si_4O_{10}(OH)_2$ that has a characteristic soapy or greasy feel, and is derived from the alteration of magnesium-rich silicate minerals, especially olivine.

**tectonics** — A branch of geology dealing with the study of large structural or deformational features of the Earth's crust, and their mutual relations, origins, and historical evolution.

**terrace** — Any long, narrow, relatively level or gently inclined surface bounded by steeper descending and ascending slopes on either side.

**texture** — The size, shape, and arrangement of the constituent minerals of a rock.

**thrust fault** — A shallow fault along which the hanging wall appears to have moved upward relative to the footwall.

**thrust sheet** — The body of rock above a large-scale thrust fault.

**thrust slice** — a relatively thin body of rock bounded above and below by thrust faults within a zone of thrusting. Variation: slice.

**toe** — The lowest part of a slope.

**topographic map** — A map showing the topographic features of the land surface.

**topography** — The general configuration of the land surface (*adj* **topographic**).

**translational movement** — A term used to describe the type of movement in a slide in which the displaced material has moved along a generally planar failure surface.

**ultramafic** — Said of an igneous rock composed almost entirely of mafic minerals.

**vein** — A thin, sheetlike igneous intrusion.

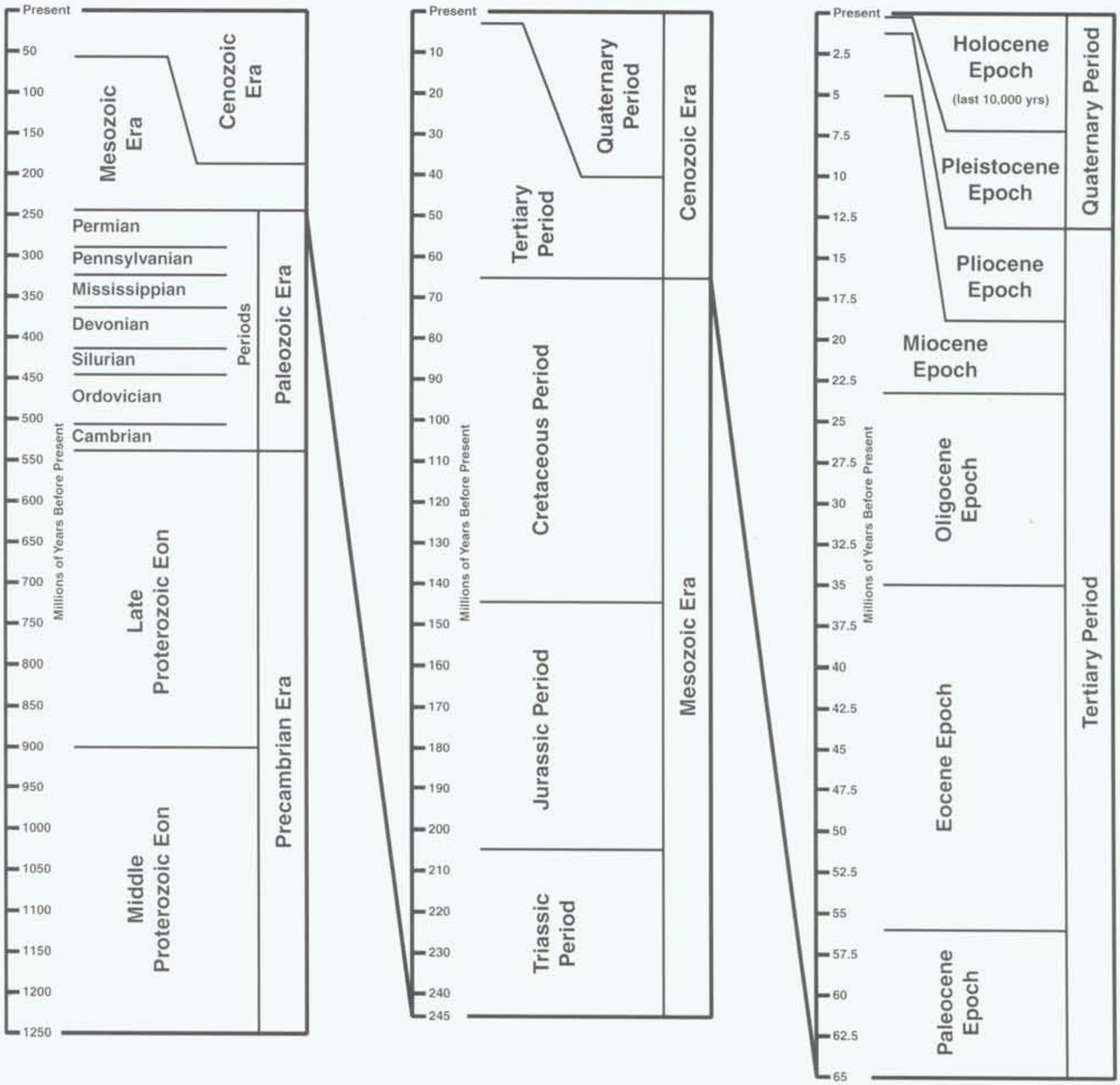
**volcanic rock** — An igneous rock resulting from volcanic action at or near the Earth's surface.

**weathering** — The physical disintegration and chemical decomposition of rock at the Earth's surface.

**xenolith** — A foreign inclusion in an igneous rock.

**zircon** — A common mineral in igneous and metamorphic rocks with the formula $ZrSiO_4$.

# Geologic Time Scale




Adapted from MacRae (1996)