DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

PRELIMINARY GEOLOGIC MAP OF THE GREAT SMOKY MOUNTAINS NATIONAL PARK WITHIN THE FONTANA DAM AND TUSKEEGEE QUADRANGLES, SWAIN COUNTY, NORTH CAROLINA

by

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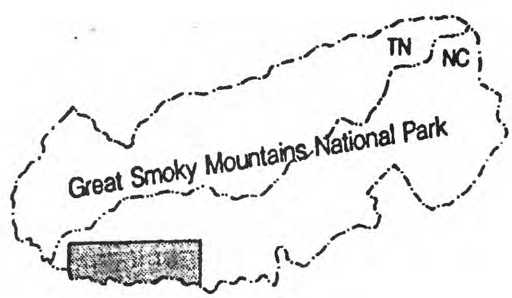
Open-File Report 95-264

Prepared in cooperation with the National Park Service and the National Biological Service



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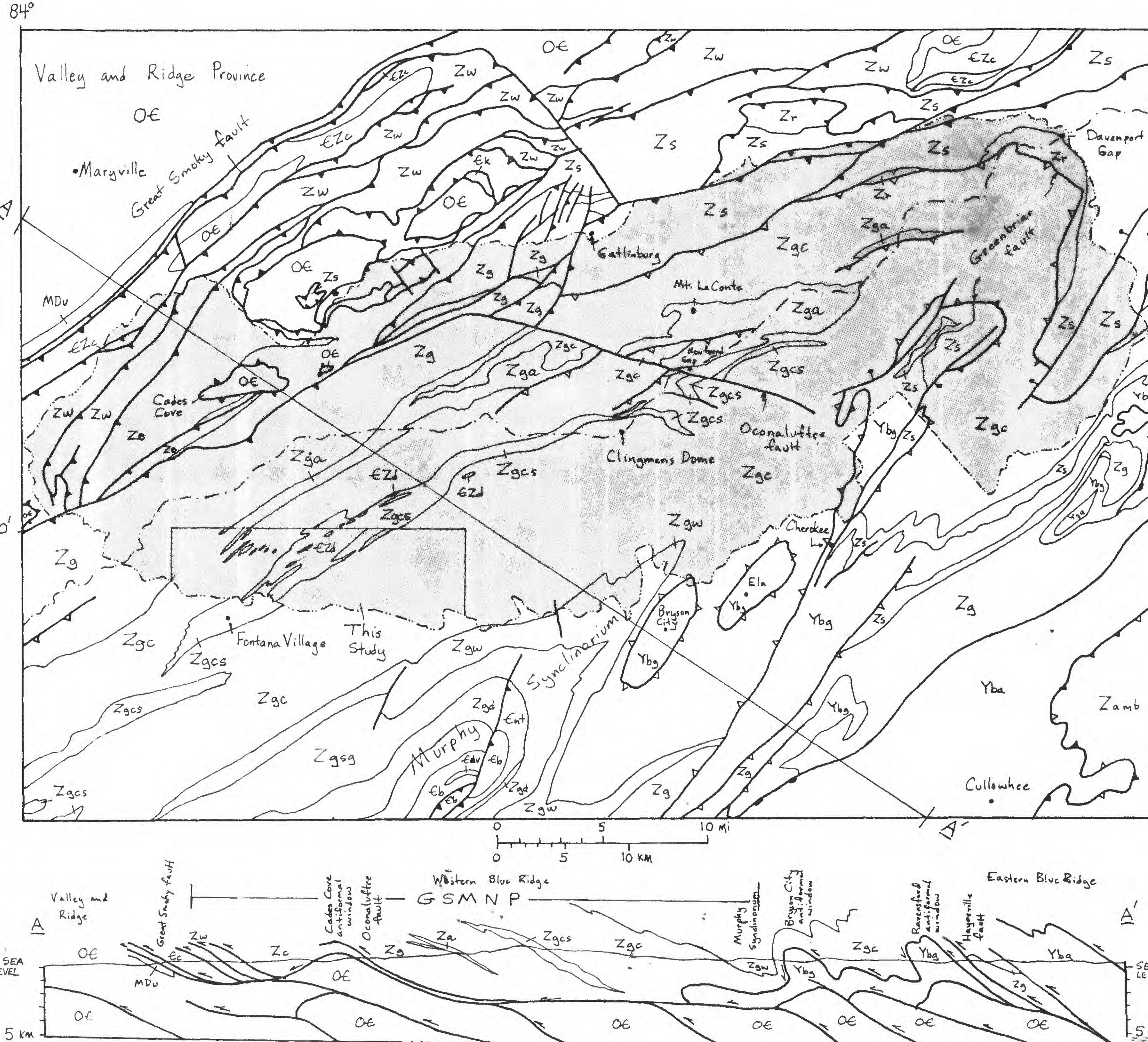
INTRODUCTION AND GEOLOGIC SETTING

The geology of the Great Smoky Mountains National Park (GSMNP) portion of the Fontana Dam and Tuskeegee quadrangles was mapped in 1993 and 1994 under a cooperative agreement between the National Park Service (NPS), National Biological Service (NBS), and the U.S. Geological Survey (USGS). Approximately 27 days were spent mapping in the months of May, June, and October; approximately nine days were spent mapping the north shore of Fontana Lake in November, 1993, when more than 60 vertical feet of steep exposure was provided by seasonal drawn down for flood control.

Keith (1907) first mapped the geology of the area at 1:125,000-scale and part of the area was mapped in 1943 by Espenshade (1963) at 1:24,000-scale. Portland P. Fox mapped the geology of the Fontana Lake region in 1944; this unpublished Tennessee Valley Authority (TVA) map is on file with the North Carolina Geological Survey in Asheville (L.S. Wiener, 1995, written comm.). The creation of Fontana Lake in 1944 by the TVA made the area inaccessible for the 1946 to 1954 USGS mapping project (King, 1964; King and others, 1968). Subsequent regional geologic maps at 1:250,000-scale contain this map area (Hadley and Nelson, 1971; Robinson and others, 1992; Wiener and Merschat, 1992). Some of the most detailed work performed in the region is by Mohr (1972; 1975) in the adjacent (east) Noland Creek quadrangle.

The Fontana Dam and Tuskeegee quadrangles are predominantly underlain by metamorphosed clastic sedimentary rocks of the Ocoee Supergroup (fig. 1). The rocks bear no known fossils and are interpreted to be Late Proterozoic in age. Late Proterozoic, as presently used, ranges from 1000 Million years ago (Ma) to the base of the Cambrian (Plumb, 1991), which is considered to be approximately 545 Ma (Bowring and others, 1993; Landing, 1994). The clastic rocks are dominantly metasandstone, metagraywacke, and metaconglomerate, with lesser graphitic metasiltstone and quartz-muscovite schist. The rocks are interpreted to be turbidites deposited in a deep-water basin (King and others, 1968) during continental rifting. They were presumably derived from the weathering of Middle Proterozoic granitic gneiss similar to that exposed to the east at Bryson City (King and others, 1968).

The metasedimentary rocks contain minor bodies of mafic and felsic igneous rocks and vein quartz. Mafic metaigneous rocks include porphyritic metadiabase and fine-grained greenstone that are interpreted to have been intrusive dikes. Minor metamorphosed felsic pyroclastic volcanic rocks interpreted to represent explosion breccia are spatially associated with the greenstone. The mafic and felsic metaigneous rocks are the first recognized evidence of bimodal volcanism associated with Late Proterozoic continental rifting during Ocoee sedimentation in this region (Rankin and others, 1989). Carbonate-chlorite schist and vein quartz are interpreted to be related to deformation and metamorphic alteration in shear zones near the metaigneous rocks. The massive sulfide deposits of the Fontana Copper mine, as discussed in a later section, are spatially associated with and interpreted to be genetically related to the igneous rocks within the Eagle Creek shear zone.


84°
35°30'
Valley and Ridge Province
Maryville
Great Smoky fault
Cades Cove
Gatlinburg
Mt. LeConte
Clingmans Dome
Oconaluftee fault
Greenbrier fault
Davenport Gap
Fontana Village
This Study
Murphy Synclinorium
Bryson City
Ela
Cherokee
Cullowhee
A
A'
0 5 10 Mi
0 5 10 KM
Valley and Ridge
Great Smoky fault
Cades Cove antiformal window
Oconaluftee fault
Western Blue Ridge
GSMNP
Murphy Synclinorium
Bryson City antiformal window
Ravensford antiformal window
Hayesville fault
Eastern Blue Ridge
SEA LEVEL
5 KM

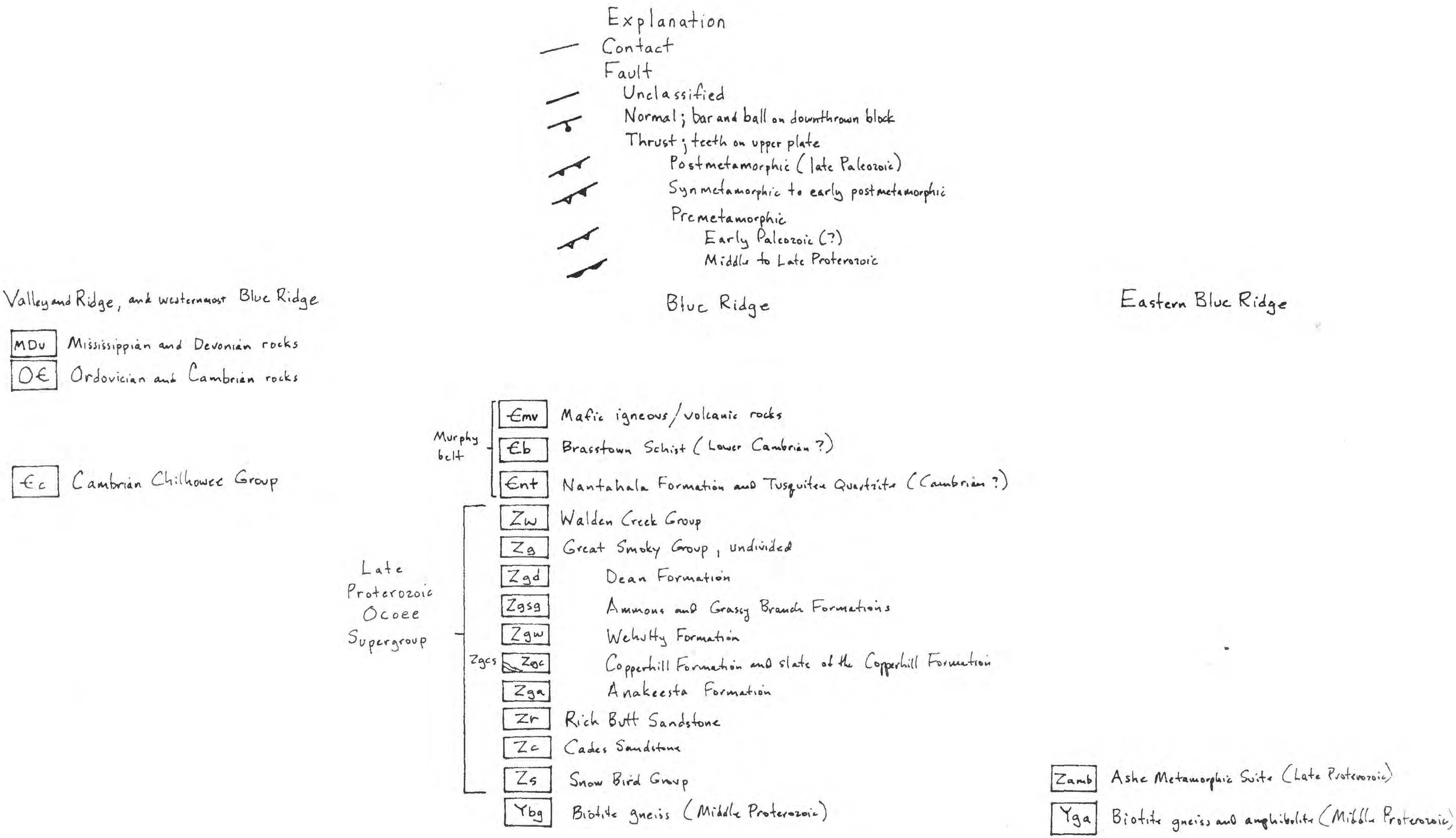


Figure 1. Generalized geologic map and cross-section of the Great Smoky Mountains National Park (GSMNP) (shaded) and environs. Map modified after Robinson and others (1992) and Wiener and Merschat (1992). Rectangular area in lower left outlines the Fontana Dam and Tuskeegee quadrangles of this study.

All of these rocks have been metamorphosed to biotite-garnet-hornblende grade of greenschist-facies during early Paleozoic time (Taconian orogeny?), with later chlorite-grade retrogression during late Paleozoic time (Mohr and Newton, 1983). The prograde minerals are confined to compositional layers (bedding), whereas the retrogressive minerals are associated with intense folding with axial planar cleavage and thrust faulting.

The fluctuating lake shore provides excellent exposure of bedrock in the winter during the annual drawdown of Fontana Lake, but overland the bedrock is poorly exposed in the forest due to extensive vegetation and abundant surficial cover. Deposits of alluvium are along most drainages and locally on adjacent terraces. Diamictons of colluvial debris fill hollows and are locally extensive in upland basins called flats and coves. Elsewhere in the absence of outcrop, a regolith of thin debris and residuum covers bedrock.

BEDROCK LITHOLOGY AND STRATIGRAPHY

In the local study area Keith (1907) mapped conglomerate, sandstone, and graywacke, with beds of slate and schist as "Great Smoky conglomerate," and slate and schist as "Nantahala slate," a revision of his earlier nomenclature (Keith, 1895) for these same units on the adjoining Knoxville folio. Espenshade (1963) mapped feldspathic sandstone, phyllite, diorite, and carbonate-chlorite schist. He observed that the sandstone resembled Thunderhead Sandstone and that the phyllite was similar to rocks of the Anakeesta Formation; names redefined or introduced by King and others (1958). The carbonate-chlorite schist was interpreted to be an altered phase of the intrusive diorite. Along strike to the north in Tennessee, Hadley and Goldsmith (1963), King (1964), and Neuman and Nelson (1965) mapped (in ascending stratigraphic order) Elkmont Sandstone, Thunderhead Sandstone, Anakeesta Formation and unnamed sandstone (fig. 2). Graphitic and sulfidic argillaceous rocks of the Anakeesta Formation were mapped throughout the broad Thunderhead Sandstone at various stratigraphic and structural positions (Hadley and Goldsmith, 1963; King, 1964). Mohr (1975) followed the interpretation of previous workers and mapped metasandstone as Thunderhead Formation and muscovite schist as Anakeesta Formation in the northern part of the adjacent Noland Creek quadrangle. Regional compilations by Robinson and others (1992) (fig. 1) and Wiener and Merschat (1992) show the coarse clastic rocks as Thunderhead and Elkmont Sandstones, undifferentiated, and Copperhill Formation; schist and phyllite units are called Anakeesta Formation, slate of the Copperhill Formation, and Wehutty Formation. In short, lithologically similar graphitic and sulfidic schists and phyllites which are interbedded throughout the entire Great Smoky Group have, in the GSMNP area, been given three different names (Anakeesta, Copperhill, and Wehutty Formations).

For this report, all metasedimentary rocks are simply considered to be Late Proterozoic rocks of the Great Smoky Group of the Ocoee Supergroup. With exception to the Wehutty Formation outside of GSMNP, lithologic units are portrayed without formation names because this work is preliminary; the structural uncertainties and lack of detailed mapping between the Fontana Dam and Tuskeegee quadrangles and the type localities of units require this approach.

Metasandstone

The dominant unit in the map area (Zss) is feldspathic metasandstone with lesser conglomeratic metagraywacke and meta-arkose, locally interbedded with graphitic metasiltstone west of Hazel Creek and quartz muscovite schist east of Hazel Creek. From Twentymile Creek eastward to the east boundary of the Tuskeegee quadrangle, the metasandstone unit appears to be the same rock unit. The medium to thick bedded metasandstone with calcareous concretions or calc-silicate granofels (Goldsmith, 1959) ("pseudo-diorite" of Keith, 1913) beneath the schists of the Wehutty Formation (as exposed along the lake-shore in

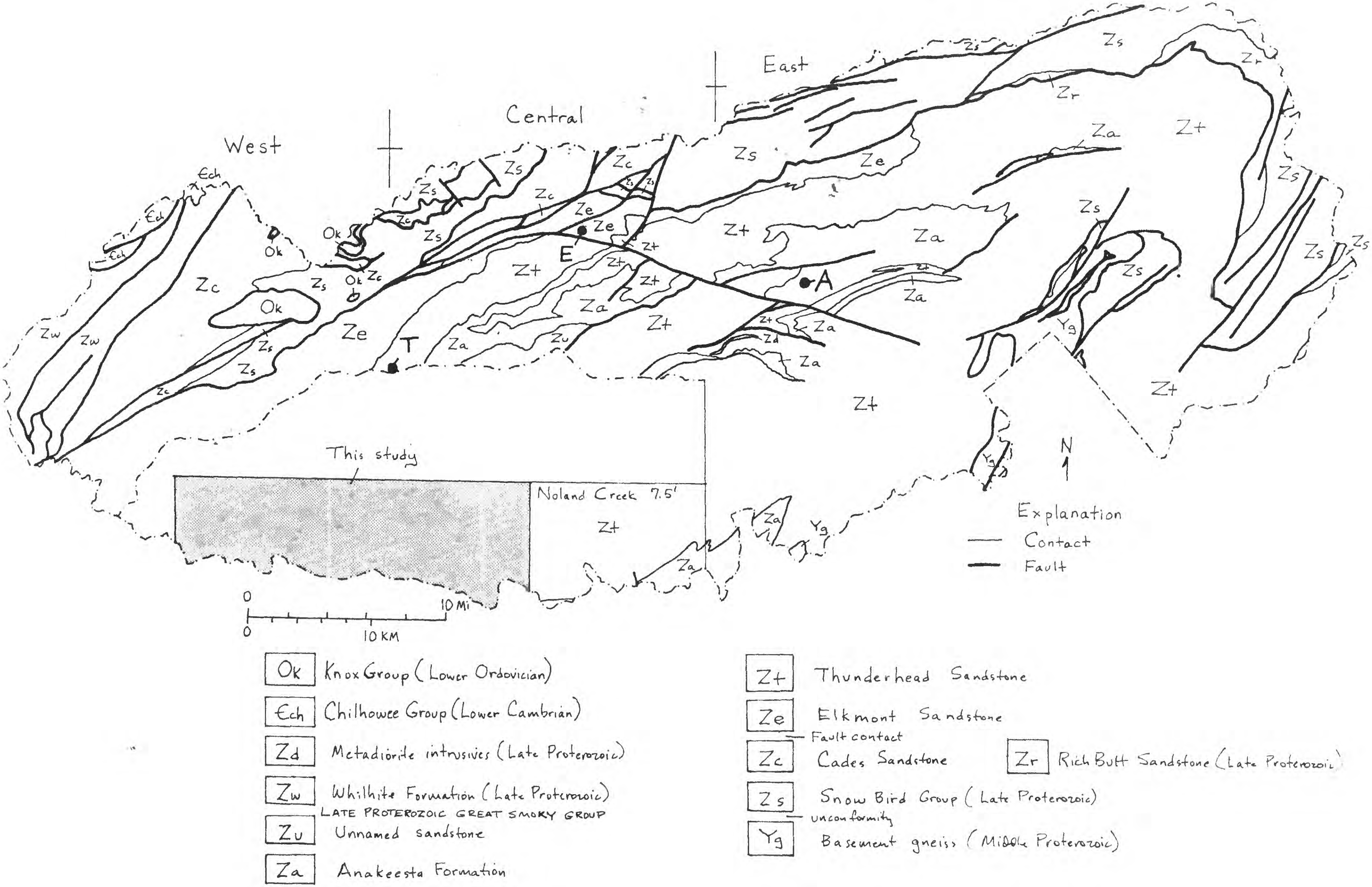


Figure 2. Generalized geologic map of the GSMNP compiled after King and others (1968) and Mohr (1975), showing the unmapped portion of North Carolina and the type localities of the Elkmont sandstone (E), Thunderhead Sandstone (T), and Anakeesta Formation (A). The stipled area was mapped by Espenshade (1963). The west, central, and east portions of GSMNP were mapped by Neuman and Nelson (1965), King (1964), and Hadley and Goldsmith (1963), respectively.

the Noland Creek quadrangle) is similar to the rocks exposed near Chesquaw Branch, Hazel Creek, beneath the Appalachian Trail hut at Fontana Dam, as well as on Long Hungry Ridge north of Twentymile Creek. A distinctive arkosic metaconglomerate with platy clasts of metasiltstone underlies Twentymile Ridge from Shuckstack to Sheep Knob. Collectively, these rocks resemble the Thunderhead Sandstone as mapped along strike to the northeast by Hadley and Goldsmith (1963) and King (1964). The contact of the Thunderhead Sandstone and underlying Elkmont Sandstone as mapped by King (1964) may project into the adjacent Tapoco quadrangle (west) but there is no indication of the contact in this map area (fig. 2). The contact of the Thunderhead Sandstone with the overlying Anakeesta Formation (King, 1964) (fig. 1) projects southwestward into the northwest part of the Fontana Dam quadrangle but there are only thin units of dark graphitic metasiltstone in this region (fig. 2). Using the interpretation of Wiener and Mershat (1992), the metasandstone unit east of Twentymile Creek may be the Copperhill Formation. The Thunderhead Sandstone may be either beneath the Copperhill Formation or equivalent to the basal part of it. In either case, the formations were not distinguishable from each other in the field.

Metasiltstone

Metasiltstone and metashale with lesser phyllite, schist, slate, and thin beds of metasandstone, undifferentiated (Zsl), are found west of Hazel Creek where they are interbedded with the metasandstone unit. The argillaceous strata are graphitic and sulfidic, they host the massive sulfide deposits of the Fontana copper mine, and they locally are stained rusty-orange due to iron sulfides (Flohr and others, 1995). The largest occurrence of this unit is within the Eagle Creek shear zone. Here, the rocks resemble some of the rocks of the Anakeesta Formation as mapped by Hadley and Goldsmith (1963) from Newfound Gap to the type locality at Anakeesta Ridge (fig. 2). At several localities along Eagle Creek the metasiltstone displays soft-sediment slump folds. Immediately east of Shuckstack are rusty graphitic and sulfidic phyllite and metasiltstone that closely resemble both Anakeesta Formation and some of the rocks of the Wehutty Formation as exposed along the "Road to Nowhere" in the Bryson City and Noland Creek quadrangles to the east. Although these rocks are lithologically similar, they occupy different stratigraphic and structural levels, and they cannot be traced to the type locality of the Anakeesta Formation.

The schists that underlie Meetinghouse Mountain in the southeast corner of the map area are on the west limb of the Murphy synclinorium and they are considered to be Wehutty Formation (Hernon, 1969) by Wiener and Merschat (1992), as opposed to Anakeesta Formation as suggested by Hadley and Goldsmith (1963) and Mohr (1975). The metasiltstone unit along Eagle Creek is called the slate of the Copperhill Formation by Wiener and Merschat (1992) and Robinson and others (1992), yet these rocks are identical to their Anakeesta Formation in the Fontana Dam and southernmost Cades Cove quadrangles. When the right-lateral offset along the Oconaluftee fault is restored, the thin units of graphitic metasiltstone in the northwest part of the map area suggests that they can be traced to the type locality of the Anakeesta Formation (fig. 2). The metasiltstone unit along Eagle Creek suggests that this unit is at a higher stratigraphic level than the type Anakeesta rocks.

Carbonate-Chlorite Schist

Highly foliated carbonate-chlorite schist (Zc; fig. 3) is exposed in the Eagle Creek shear zone adjacent to thrust faults, as float adjacent to metadiabase at Flint Gap on Pinnacle Ridge, as small pods of float west of Fontana Copper mine, and as float west of Soapstone Gap. The rock was interpreted by Espenshade (1963) and Hadley and Goldsmith (1963) to be an altered variety of metadiorite as it locally is spatially associated with it. Along Ecoah Branch and west of it, the carbonate-chlorite schist is in the footwall of

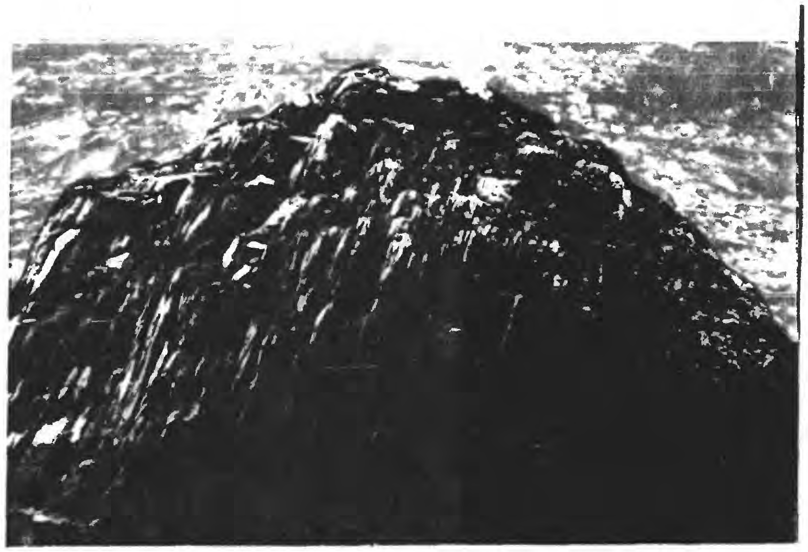


Figure 3. Well-foliated carbonate-chlorite schist exposed along Eagle Creek, photo locality 3, pl. 1.

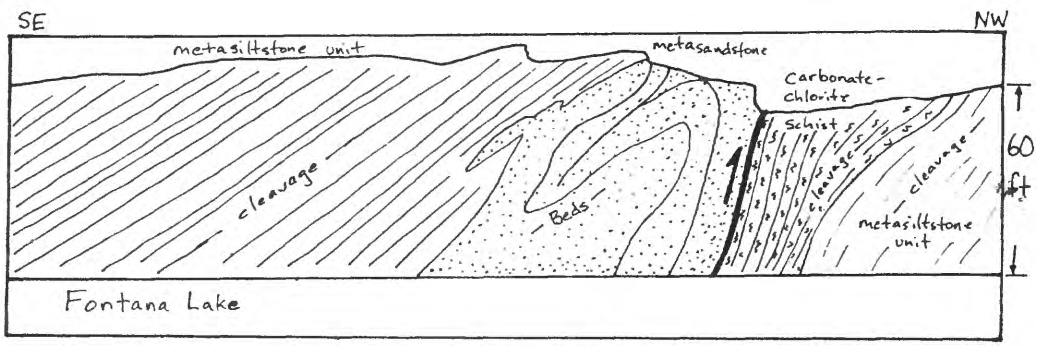


Figure 4. Tracing of photograph showing carbonate-chlorite schist in footwall of thrust fault as exposed along Eagle Creek, photo locality 4, pl. 1. Figure 3 shows the same carbonate-chlorite schist approximately 1300 feet along strike to the northeast.

thrust faults well exposed in low-water conditions (fig. 4). The rock is characteristically vuggy, containing rhombehedral cavities as much as 0.2 in diameter due to dissolution of dolomite (ankerite?) that is seen in fresh specimens. The rock is composed predominantly of chlorite with lesser quartz and minor talc. The quartz content of the carbonate-chlorite schist is greater than that of the metadiabase so the protolith of this rock may not be the metadiabase. The protolith of the rock may have been an impure limestone. However, it has been altered by contact metamorphism near the dikes followed by retrogressive metamorphism and deformation. The high chlorite content and minor talc makes a lustrous, greasy rock that can be scratched with a fingernail, and probably is the namesake for "Soapstone Gap" on Pinnacle Ridge.

Quartz-Muscovite Schist

The quartz-muscovite schist unit (Zs) is interbedded with the metasandstone unit from Hazel Creek eastward to Meetinghouse Mountain where rocks of the Wehutty Formation are found. The quartz-muscovite schist was described as gray to dark-gray muscovite schist within the Thunderhead Formation by Mohr (1975); the unit was not mapped by Hadley and Goldsmith (1963) or King (1964) to the northeast. The lustrous schist has diagnostic porphyroblasts of garnet, biotite, and muscovite. The protolith of this unit is interpreted to have been an aluminous, clay-rich metasiltstone. The lack of graphite and iron-sulfides suggests that this unit is not the equivalent of the metasiltstone unit to the west.

Wehutty Formation

Rocks of the Wehutty Formation (Zw) (Hernon, 1969) underlie Meetinghouse Mountain in the extreme southeast portion of the map area. These rocks are outside of GSMNP but are included for structural and stratigraphic control. These rocks include muscovite schist and metasandstone (Mohr, 1975) as well as lesser metasiltstone and phyllite. They contain abundant graphite and sulfide minerals and they physically resemble rocks of the Anakeesta Formation, as they were mapped and described by Hadley and Goldsmith (1963) and by Mohr (1975). Cross sections (Hadley and Goldsmith, 1963) demonstrate that rocks of the Wehutty Formation occupy a higher stratigraphic and structural position relative to the Anakeesta Formation at its type locality.

Late Proterozoic Metadiabase Dikes

Mafic igneous rocks that intrude the metasedimentary rocks of GSMNP were recognized by Laney (1907), Espenshade (1963), Hadley and Goldsmith (1963), and King (1964), and further mapped during this study (fig. 5). The rocks were initially classified as metadiorite and metadiabase based on the modal composition of two samples from Clingmans Dome (Hadley and Goldsmith, 1963). Chemical analyses (table 1) of these two samples, in addition to ten others within GSMNP, show the composition of subalkalic basaltic rocks (fig. 6), thus they are herein classified as metadiabase (Zd).

The metadiabase dikes were intruded into rocks of the Great Smoky Group, Snowbird Group, and Rich Butt Sandstone (Hadley and Goldsmith, 1963) and they clearly predate metamorphism and deformation since they are altered and foliated. The linear northeast-trend of the dikes from the Fontana Dam quadrangle to Clingmans Dome (samples CD) is partly the result of transposition into foliation, locally within shear zones. The largest body is a 350-foot thick and 2-mile long dike which follows cleavage rather than beds (Hadley and Goldsmith, 1963). Several bodies north-northeast of Clingmans

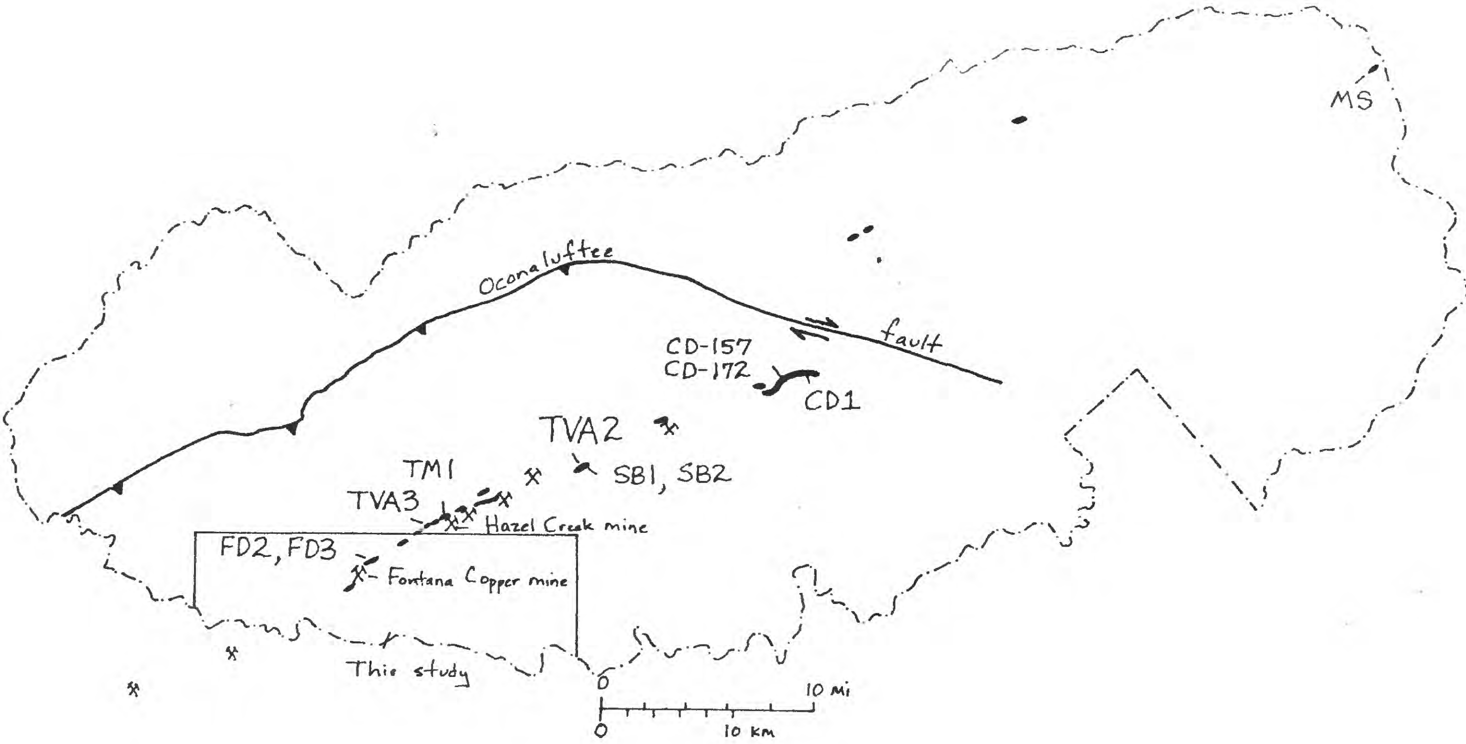


Figure 5. Index map of GSMNP showing Late Proterozoic metadiabase dikes, sample locations of analyzed rocks listed in table 1 and plotted in figures 6, 8, and 9, and the spatially associated copper mines and prospects. See Espenshade (1963) and Robinson and others (1992) for details on the mines.

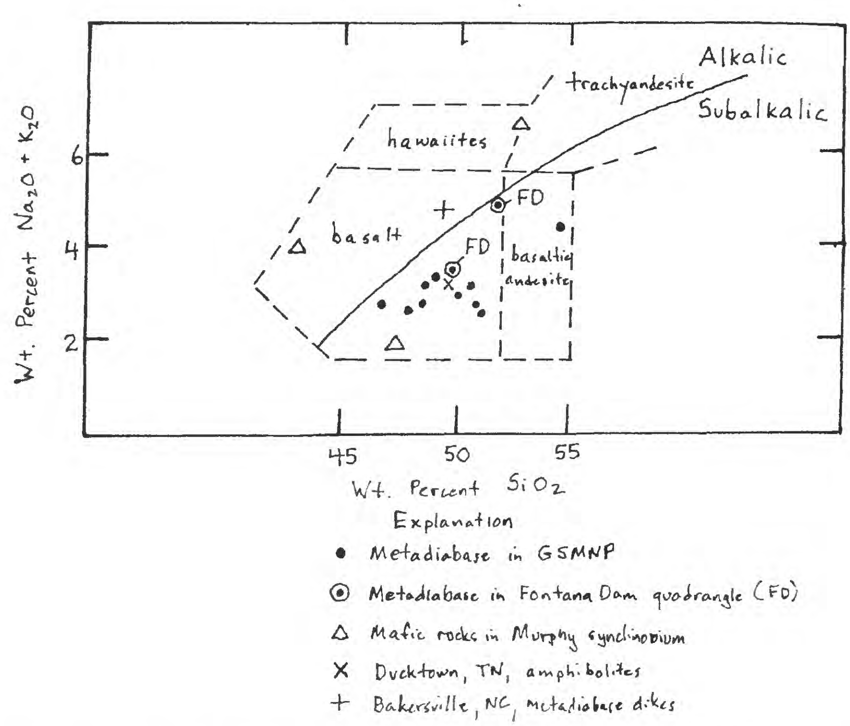


Figure 6. SiO_2 versus Na_2O+K_2O (total alkalies) diagram of metadiabase shown in table 1. Compositional fields from Cox and others (1979).

Dome may be dikes of the same generation. However, if the right-lateral offset along the Oconaluftee fault is restored, these bodies are not consistent with the regional trend of the other metadiabase dikes.

Metadiabase dikes are also found near Ducktown, Tennessee (Misra and Lawson, 1988) and Bakersville, North Carolina (Goldberg and others, 1986; Goldberg and Butler, 1990), Linville, North Carolina (Bryant and Reed, 1970), and within the Cranberry Gneiss in Virginia (Rankin and others, 1972) (fig. 7). The Bakersville metadiabase dikes intrude Middle Proterozoic gneiss and they yield a 734 ± 26 whole-rock Rb-Sr isochron based on eight samples (Goldberg and others, 1986). No metadiabase dikes have been reported in the basement gneiss in and around GSMNP. Amphibolite sills associated with the massive sulfide deposits at Ducktown are metamorphosed tholeiitic basalts of oceanic affinity (Misra and Lawson, 1988) (fig. 8). Rare-earth element (REE) plots (fig. 9) suggests that the metadiabase dikes in GSMNP are most similar to the undated amphibolites at Ducktown, yet on a Ti/100-Zr-Yx3 tectonomagmatic diagram (fig. 8) they do not cluster within the field of ocean floor basalt as do the Ducktown samples.

The only other known mafic igneous rocks in this region is a metadiorite-metagabbro sill within the Late Proterozoic(?) to lower Cambrian(?) Brasstown Formation of the Murphy synclinorium (Van Horn, 1948) (fig. 7). Chemical analysis of this rock (field No. NG, table 1) (figs. 6 and 8) suggests that it may not be associated with the intrusive rocks in the GSMNP. To the south in the Murphy synclinorium amphibolite and mafic dikes/sills are found above and below the Murphy marble (Kish and others, 1991) within the Mission Mountain (Thompson and Tull, 1991) and Nantahala Formations (Aylor and Kish, 1991).

Greenstone

On the southeast bank of Ecoah Branch opposite the Fontana Copper mine greenstone (Zg) with masses of epidosite outcrops in low-water conditions. The greenstone is adjacent to carbonate-chlorite schist and felsic pyroclastic rocks within the broader metasiltstone unit. The greenstone is fine-grained and is composed principally of plagioclase (sausseritized), quartz, actinolite, epidote, and chlorite; locally the rock is vesicular with quartz-filled amygdules. Masses of epidosite (quartz and epidote nodules) as much as 1 foot diameter occur in the greenstone. The greenstone is interpreted to be an altered variety of the porphyritic metadiabase; it was not chemically analyzed.

Metamorphosed Felsic Pyroclastic rock

Adjacent to the greenstone along Ecoah Branch is a light gray, fine-grained, laminated, quartz-plagioclase rock that contains angular blocks and fragments as much as one foot across. The blocks and fragments are composed of medium to coarse grained porphyritic metarhyolite(?) having equant feldspar phenocrysts as much as 0.2 in. in diameter (Zf) (fig. 10). Elsewhere the angular blocks of metarhyolite occur as breccia in a fine-grained quartz-plagioclase laminated matrix. These rocks are here interpreted to be explosion breccia of a felsic igneous intrusion. The spatial association of the felsic pyroclastic rocks to the greenstone unit (Zg) suggests that they may be related. If this interpretation is correct, these rocks are the first evidence of bimodal volcanic rocks recognized in the Ocoee Supergroup. It cannot be determined whether the greenstone and felsic pyroclastic rocks were emplaced during sedimentation of the metasiltstone unit because strong deformation has made evidence obscure.

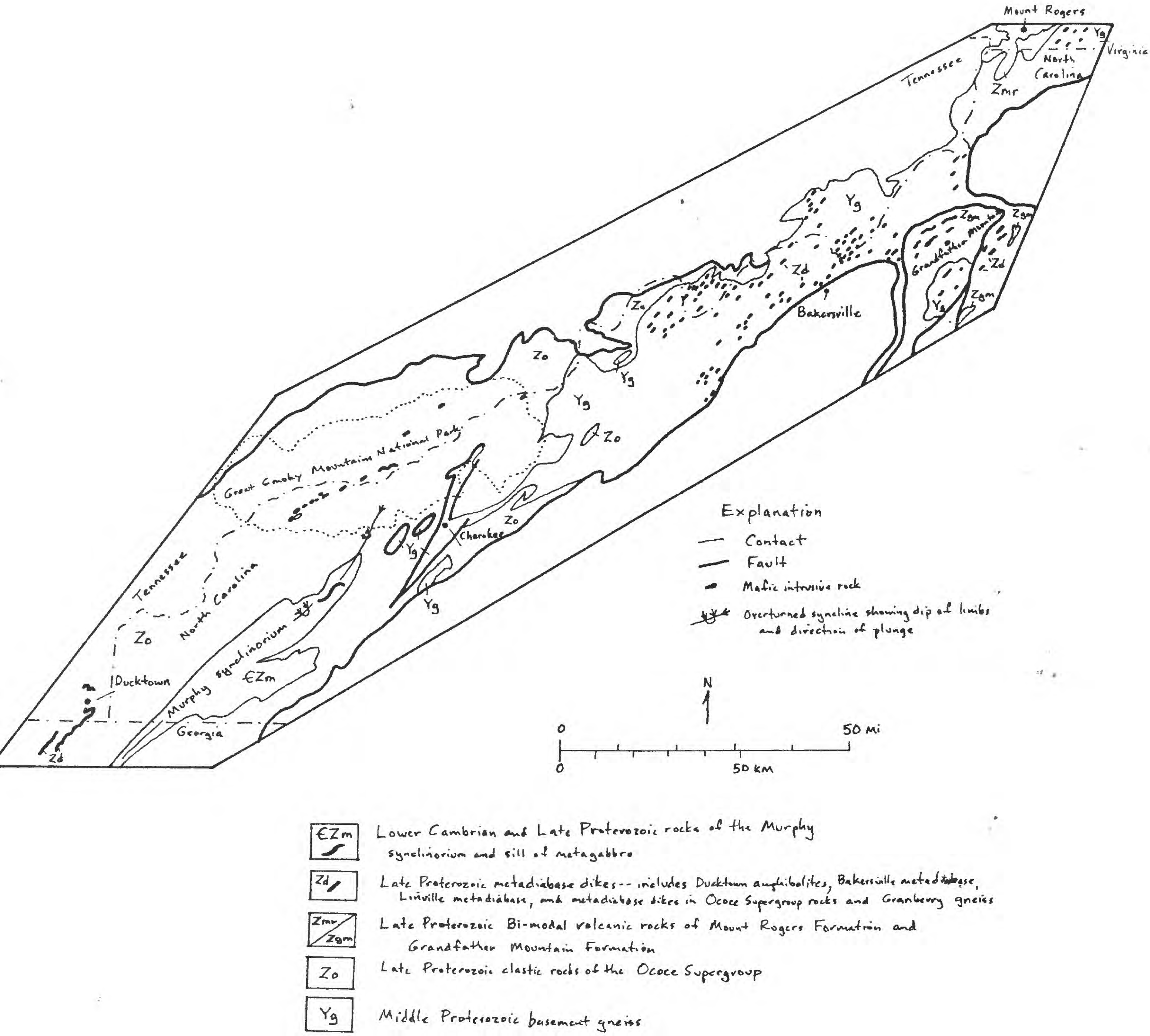


Figure 7. Regional geologic map (modified after Rankin and others, 1989) showing the distribution of mafic intrusive rocks, and mafic and felsic volcanic complexes in the southern Appalachian Blue Ridge. Mafic intrusive rocks include Bakersville metadiabase (Goldberg and others, 1986), Linville metadiabase (Bryant and Reed, 1970), metadiabase dikes in Middle Proterozoic Cranberry Gneiss in Virginia (Rankin and others, 1972), amphibolite at Ducktown, Tennessee (Misra and Lawson, 1988), and metadiabase in GSMNP (Espenshade, 1963; Hadley and Goldsmith, 1963; King, 1964; and this study). Extrusive bi-modal metavolcanic complexes include Mount Rogers Formation (Rankin, 1993) and Grandfather Mountain Formation (Bryant and Reed, 1970). Mafic rocks in the Murphy synclinorium are from Van Horn (1948) and Thompson and Tull (1991).

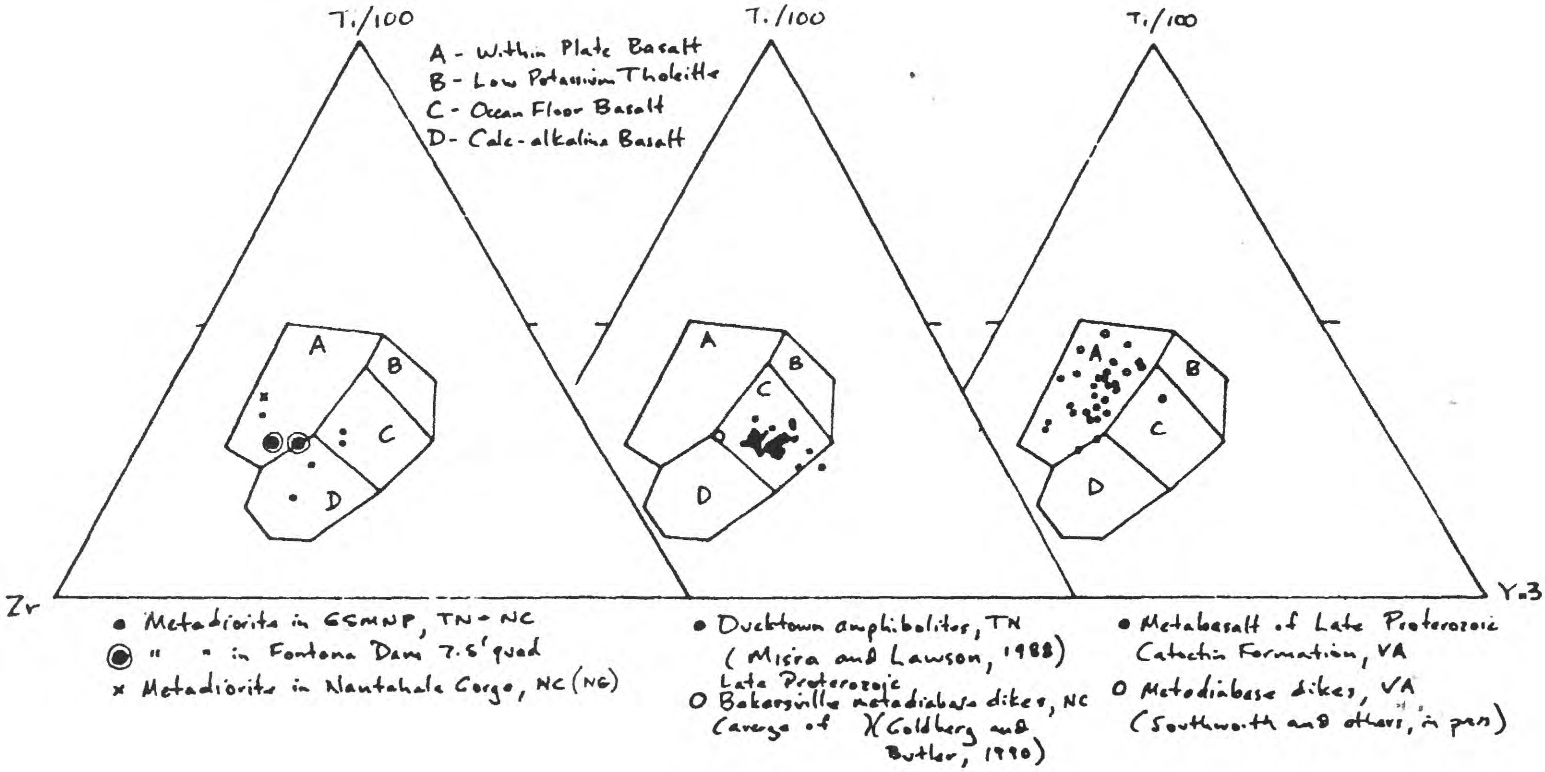


Figure 8. Ti/100-Zr-Yx3 diagram (Pearce and Cann, 1973) of metadiabase shown in table 1.

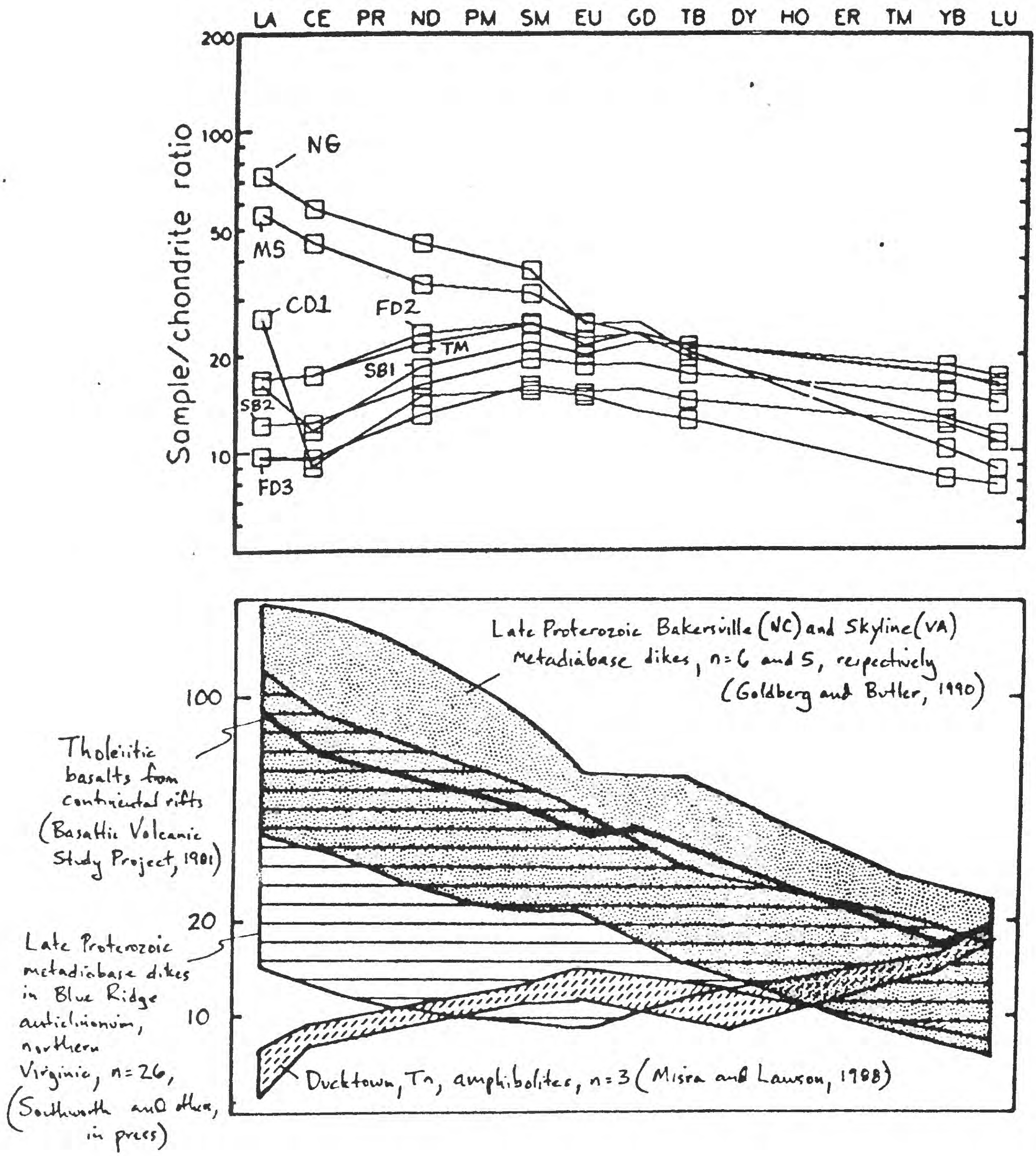


Figure 9. A, Rare-earth element (REE) diagrams of metadiabase, metadiorite, and metagabbro shown in table 1 and B, REE patterns of Ducktown amphibolite (Misra and Lawson, 1988), Bakersville and Skyline metadiabase (Goldberg and Butler, 1990), metadiabase dikes of Blue Ridge-South Mountain anticlinorium, Virginia (Southworth and others, in press) and typical pattern of tholeiitic basalts from continental rifts (Basaltic Volcanic Study Project, 1981).

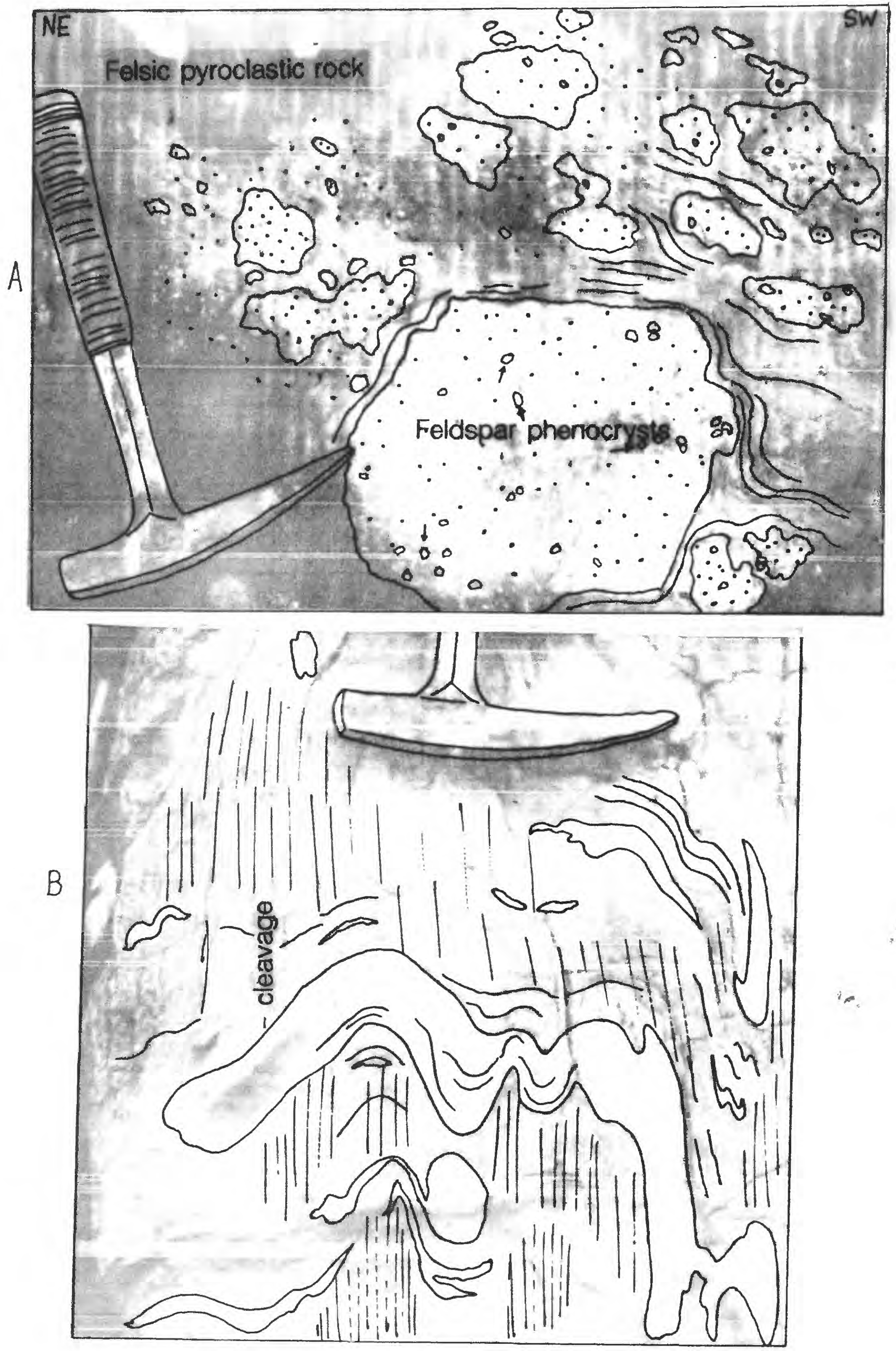


Figure 10. Photographs and tracings of interpreted explosion breccia of metamorphosed felsic pyroclastic rock exposed along Ecoah Branch. A shows coarse grained metarhyolite with feldspar phenocrysts with finely-laminated quartz-plagioclase matrix wrapped around the block. B shows fine grained subangular clasts of metarhyolite in quartz-plagioclase matrix that are folded with axial planar cleavage. Photo locality 10, pl. 1.

The closest occurrence of similar felsic metavolcanic rock is over 120 miles northeast in the Grandfather Mountain area, N.C. and 140 miles northeast at Mount Rogers, Virginia (fig. 7), where rhyolites of the Grandfather Mountain Formation (Bryant and Reed, 1970) and Mount Rogers Formation erupted about 758 ± 12 Ma (Aleinikoff and others, 1995). The rhyolitic rocks of the Mount Rogers Formation are related to an early aborted episode of Iapetan continental rifting (Rankin, 1993).

QUATERNARY SURFICIAL DEPOSITS

Quaternary surficial deposits in the map area are alluvium (Qa), alluvial terrace deposits (Qt), and diamicton (Qd). Alluvium is along most drainages and is most obvious along meanders of Eagle Creek and Hazel Creek. The active channels of most tributaries and creeks are large boulders and bedrock, as shown by map symbols of planar features on plate 1. Fine alluvium is actively moved and deposited along meanders as overbank deposits during storms and floods, such as in March-April, 1994, when foot bridges as much as 15 feet above Eagle Creek were washed out.

Alluvial terrace deposits as much as 160 feet above the present channel are recognized along Eagle Creek and locally along the drowned Little Tennessee River (Fontana Lake). These deposits typically are recognized as rounded metasandstone boulders that float on a yellow and orange weathered sand and clay horizon on flat benches. The boulders have a weathering rind and occasionally they are friable due to in situ physio-chemical weathering.

Diamicton deposits are concentrated in narrow hillside channels as well as upland basins that are locally called flats, fields, hollows, and coves. The most impressive deposits are at Proctor Field Gap (Fontana Dam quadrangle) and Deep Gap, Coot Cove, and Kirkland Branch (Tuskeegee quadrangle). The diamicton deposits are comprised of blocks and boulders of subangular to subrounded metasandstone that float in a sandy clay matrix, as exposed along Hazel Creek at "The Horseshoe." The surface of the deposits are open-framework boulders that rest on a nearly flat terrace. Locally there are multiple terraces that step down-slope as seen at Coot Cove. The terraces are incised by tributaries that reveal cross sections of the deposits as much as 40 feet thick (fig. 11). The microtopography of the deposits far exceeds the resolution of the 40-foot contour interval map and consists of ridges and swales, wet depressions, and topographic inversions produced by gully gravure (Mills, 1981) (fig. 12). Narrow hillside channels and steep valleys that lack streams are locally filled with diamicton deposits. Where streams and springs are transporting fine-grained material on the steep channels, the deposits are instead classified as alluvium.

The diamicton is interpreted to be the result of a combination of debris flow, colluviation, and freeze-thaw processes related to gravity, water, and ice. These deposits are not as extensive as those mapped in Tennessee by Hadley and Goldsmith (1963) and King (1964). The huge deposits there are a function of orographic effect (north-facing slope) and cliffs of thick-bedded massive Thunderhead Sandstone on the scarp face or outcrop slope. Approximately 60 miles to the east along the Blue Ridge Parkway, Shafer (1988) describes thermoluminesence dates of 11,900 and 10,100 yBP from diamicton as marking the change from colluvial to alluvial processes.

The density of map symbols for planar elements can be used as an approximate indicator of the amount of regolith that covers bedrock. Diamicton in hillslope depressions is more extensive than portrayed on the map because not all of the area was traversed. However, many hollows, as seen on the Appalachian Trail from Fontana Dam to Shuckstack, have no diamicton. These hollows are incised into residuum as are

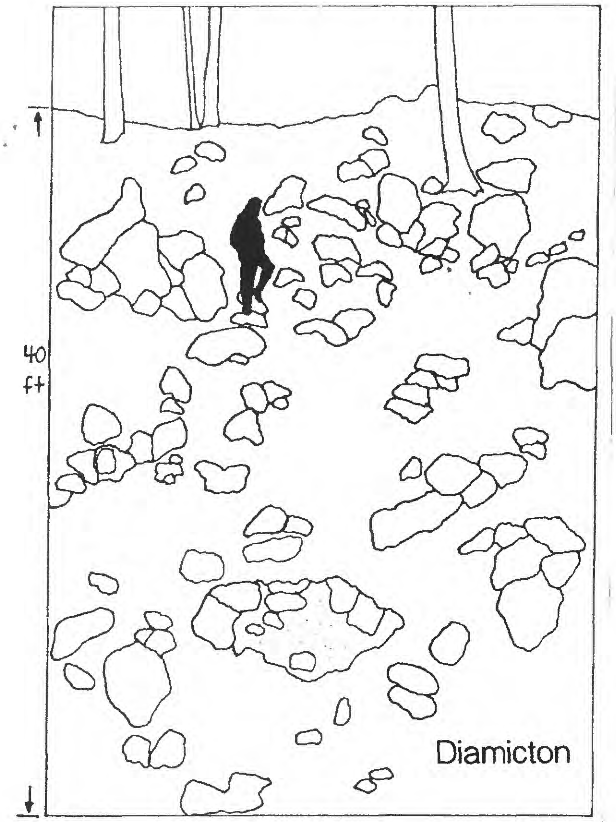


Figure 11. Tracing of photograph of diamicton exposed at Coot Cove, photo locality 11, pl. 1. The cross section of the diamicton is the result of stream incision on the terraced deposit; the photographer is positioned in the stream.

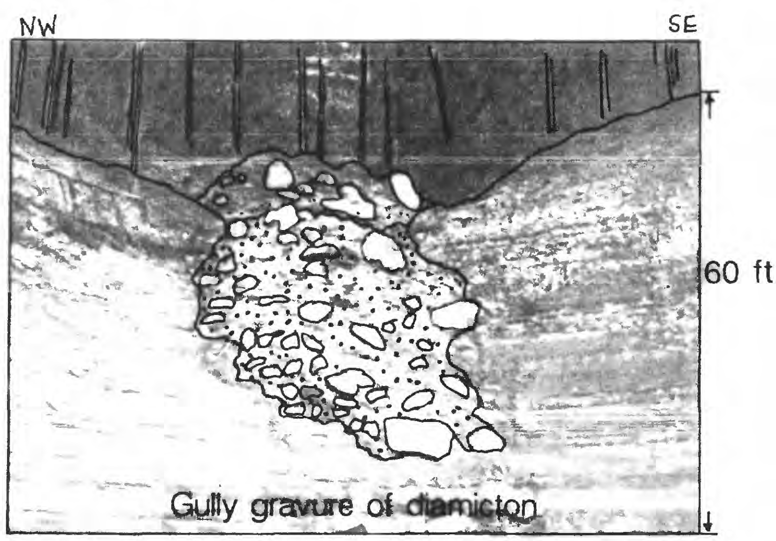


Figure 12. Photograph and tracing of diamicton exposed along Cable Branch west of Hazel Creek, photo locality 12, pl. 1. Fluctuating water level of Fontana Lake has removed fine matrix material exposing coarse boulders. Convex-upward cross section at forest line is the result of "gully gravure"; the topographic inversion formed by subsequent fluvial erosion along the lateral margins of the diamicton.

many trails and abandoned railbeds. During construction of Fontana Dam, Moneymaker (1947) reported residual mantle ranging from a few feet to 70 feet thick, with deeply weathered bedrock below this mantle. As impressive as the bedrock exposure is along the Fontana Lake shore, much of the bedrock is weathered and saprolitized and can be cut with a knife. Hand dug graves in cemeteries on knolls underlain by metasandstone along Hazel Creek and Sugar Fork, for example, show that the bedrock is friable and the regolith is deep. Residuum and diamicton along North Carolina Highway 28 west of Fontana Dam is prone to debris flow and landslides as evidenced by the many landslides caused by torrential storms of March-April, 1994.

METAMORPHISM

Rocks within GSMNP record a Barrovian-type metamorphism that increases southeastward from sub-chlorite grade to kyanite grade (Hadley and Goldsmith, 1963; Connelly and Dallmeyer, 1993). The rocks within the map area are at greenschist-facies with a composite metamorphic mineral assemblage of garnet, hornblende, chlorite, muscovite, biotite, albite, epidote, and chloritoid(?). The garnet (almandine in) isograd was located at one place west of Fontana Dam. A garnetiferous graphitic phyllite within the metasandstone unit exposed along Lewellyn Branch provides locational control for the isograd and reasonably conforms to generalized isograds of King (1964) and Lesure and others (1977) to the northeast and southwest, respectively. These isograds are generalized because the distribution of garnets in this area is a function of rock composition (Mohr and Newton, 1983) as well as exposure and sampling sites. The folded isograds at the northern end of the Murphy synclinorium support the hypothesis of post-metamorphic folding in this region, as described by Nesbitt and Essene (1982) to the south.

The metasiltstone and quartz-muscovite schist units contain porphyroblasts of garnet and biotite that are retrograded to chlorite and sericite. The metasandstone unit typically has biotite and chlorite, but calc-silicate granofels (Goldsmith, 1959) concretions ("pseudo-diorite" of Keith (1913) preserve clusters of randomly-oriented garnet-hornblende-biotite (fig. 13) crystals visible to the naked eye. The porphyroblasts are confined to compositional layers that are bedding (fig. 13). There is no recognized structural foliation associated with the minerals. The carbonate-chlorite schist and greenstone within the Eagle Creek shear zone is interpreted to be the product of retrogressive metamorphism and deformation.

K-Ar and $^{40}Ar/^{39}Ar$ radiometric dating of biotite, hornblende, muscovite, and whole rock specimens suggests a complex metamorphic history (Kish, 1991; Connelly and Dallmeyer, 1993). As summarized by Connelly and Dallmeyer (1993), the polymetamorphic history is interpreted to record a 460 to 440 Ma (Middle to Late Ordovician) event (Taconian orogeny) that was overprinted by a 380 to 360 Ma (Middle to Late Devonian) event (Acadian orogeny?). In the map area, the peak of thermal metamorphism produced randomly oriented porphyroblasts. These cannot be demonstrated to be associated with any foliation or planar feature other than bedding. Cleavage that is axial planar to folds contains chlorite and sericite that cut across and retrograde the garnet and biotite porphyroblasts.

To the east and southeast, Mohr (1973) and Power and Forrest (1971) described garnet porphyroblasts that overgrew an earlier foliation. Mohr (1973) described one or more retrograde events, and Power and Forrest (1971) described subsequent folding that was followed by growth of sillimanite, staurolite, and biotite.

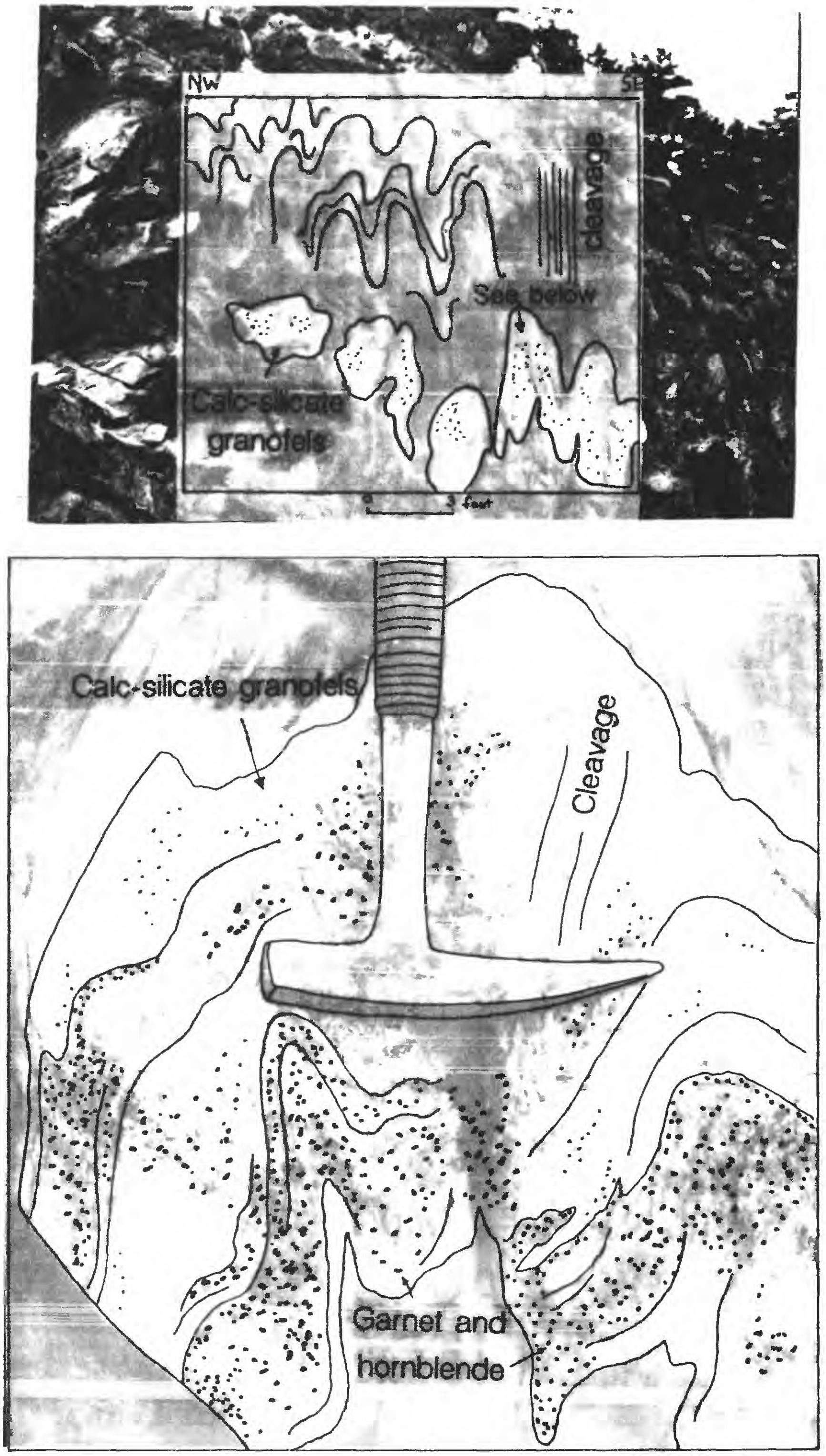


Figure 13. Photographs and tracing of A, argillic metasandstone with concretions of calc-silicate granofels parallel to bedding showing folds with axial plane cleavage, and B, enlargement of A showing folded calc-silicate granofels with crystals of garnet and hornblende (dark spots). Photo locality 13, pl. 1.

STRUCTURE

Tectonic Setting

The rocks of the GSMNP are allochthonous above the Great Smoky fault (fig. 1) that is part of the Blue Ridge thrust system of the late Paleozoic Alleghanian orogeny (Hatcher and others, 1989). The Oconaluftee fault, interpreted to be a splay of the Great Smoky fault, forms a profound fault escarpment south of Cades Cove, as well as a right-lateral tear fault roughly parallel to the Newfound Gap road. The enigmatic Greenbrier fault is interpreted to be a Late Proterozoic to lower Paleozoic young-on-old fault that predates regional metamorphism (Hadley and Goldsmith, 1963; Milton, 1983). Subsequent folding has produced antiformal domes and windows through the Greenbriar thrust sheet exposing Middle Proterozoic gneiss at Bryson City, Ela, and north of Cherokee (fig. 1). Duplex of underlying Cambrian and Ordovician rocks (Woodward, 1985) folded the structurally higher Greenbrier and Great Smoky faults and erosion has exposed the parautochthonous rocks in the classic tectonic windows of Cades Cove, Tuckaleechee Cove, and Wear Cove (southwest to northeast) (Keith, 1927). The northernmost part of the southwest-plunging Murphy synclinorium is just north of Bryson City; the synclinorium extends over 110 miles into Georgia. GSMNP is within the eastern Tennessee seismic zone that is defined by the crustal "Ocoee block" (Powell and others, 1994) beneath the Great Smoky thrust sheet.

Foliation

In this map area, the predominant foliations are (1) bedding in the metasandstone and metasiltstone units and (2) schistosity in the metadiabase dikes and schist units.

Bedding

The metasandstone unit has graded beds (fig. 14), rare cross beds, and beds marked by rip-up accumulated clasts of dark argillaceous rocks as well as light concretions (fig. 15). The light concretions, interpreted to be calcareous material, contain macroscopic crystals of garnet, hornblende, and biotite. Often the concretions are aligned parallel to cleavage so individual concretions can be a false indicator of bedding attitude. Bedding is recognized in virtually all of the rocks of the metasiltstone unit with the exception of the phyllitic and sheared rocks along Eagle Creek. Elsewhere bedding in the metasiltstone is recognized as graded beds, microlaminations, and color changes related to primary minerals. Topping direction of beds is difficult to determine in the fine-grained and conglomeratic rocks.

Schistosity

Pervasive schistosity is the dominant foliation in the metadiabase dikes, carbonate-chlorite schist, quartz-muscovite schist, as well as schist of the Wehutty Formation. The schistosity is a metamorphic foliation that appears to be parallel to beds in adjacent metasandstone; no bedding in the schist units was recognized. The metadiabase dikes range from massive to schistose greenstone. The carbonate-chlorite schist is the most highly foliated rock observed (fig. 3) with the schistosity being defined by quartz and chlorite domains suggestive of a mylonitic foliation. The quartz is recrystallized; lenticular and elongated enclaves of chlorite are retrograde.

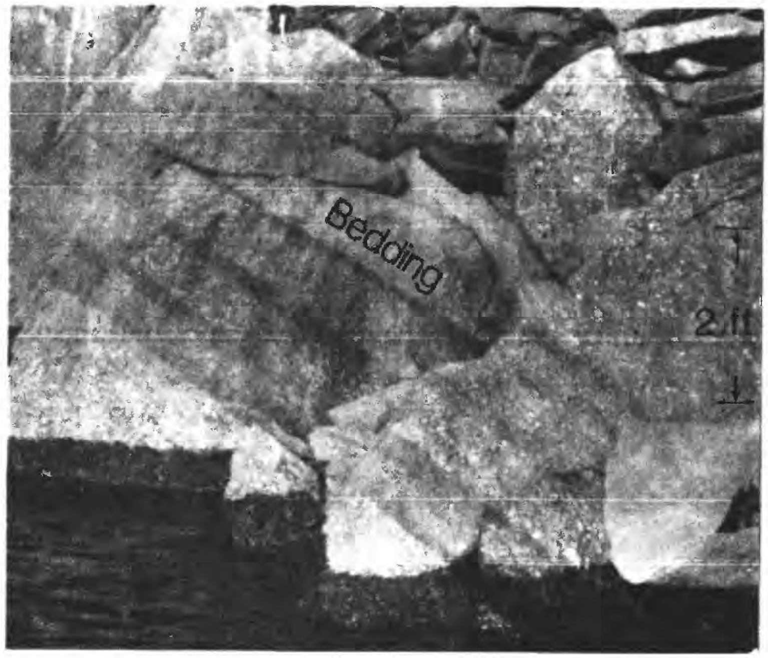


Figure 14. Photograph of graded-beds of metasandstone defined by quartz and feldspar grains, photo locality 14, pl. 1.

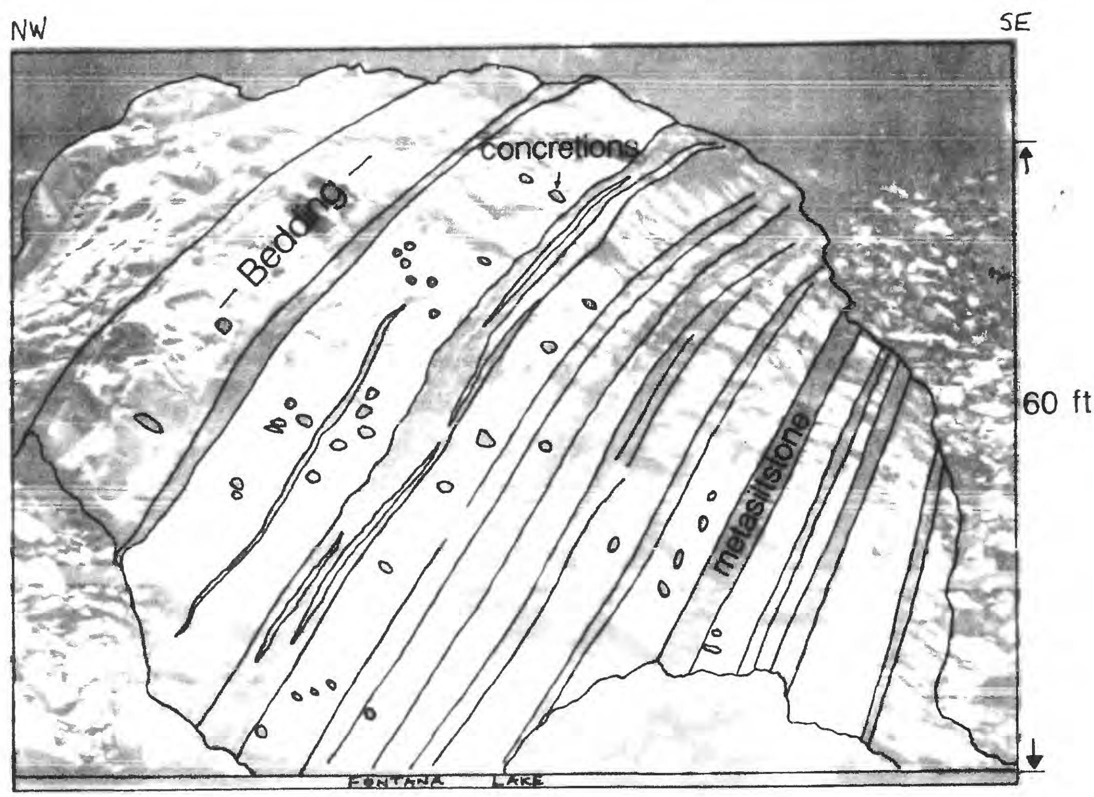


Figure 15. Photograph and tracing of graded and rhythmically bedded metasandstone and argillic metasiltstone (dark) interpreted to constitute turbidite deposits. Dark spots are concretions of argillite. Photo locality 15, pl. 1.

Cleavage

Cleavage that is axial planar to a single phase of folding is recognized in the metasandstone and metasiltstone units (fig. 16). The cleavage fans about the folds and contains chlorite and sericite crystals that cut and replace garnet, muscovite, and biotite porphyroblasts. Iron-oxide film in the cleavage plane suggests that locally it is a pressure solution cleavage. Much of the foliation portrayed by Espenshade (1963) was reclassified as cleavage. Cleavage is best developed in the argillaceous rocks but locally it is also well developed in the metasandstone. The outcrop habit of isolated bodies of metasandstone in the forest is often controlled by cleavage rather than bedding. Elongate outcrops of metasandstone that are inclined to the southeast show horizontal to northwest beds when examined.

Crenulation Cleavage

The phyllitic rocks and the quartz-muscovite schist exhibit a late crenulation cleavage that crinkles the earlier cleavage and schistosity. The crenulation cleavage exhibits various orientations and is probably related to late minor folding.

Eagle Creek Shear Zone and Associated Foliations

The Eagle Creek shear zone is here named for sheared rocks exposed along Eagle Creek (Espenshade, 1963) that exhibit fault fabrics of mylonitic, phyllonitic, and transposition foliations and shear band cleavage. The Eagle Creek shear zone may link with the Mingus fault of King (1964) as portrayed by Hadley and Nelson (1971).

The fine-grained metasandstone beds, the metamorphosed felsic pyroclastic rocks, and the carbonate-chlorite schist exhibit grain-size reduction and dynamic recrystallization as a result of mylonitization. The sheared argillaceous rocks locally are phyllonites containing asymmetric top-to-the-northwest shear band cleavage indicative of thrusting. In these rocks, bedding is obliterated and transposed into the dominant cleavage. Thin layers of metasandstone and vein quartz within argillaceous rocks are also transposed into the cleavage as a result of high strain (fig. 17).

Lineations

The dominant lineation in the rocks is a conspicuous bedding-cleavage intersection lineation best developed in the metasiltstone unit. These lineations show that folds plunge both gently to moderately to the northeast and southwest. Locally there is a strong stretching lineation that plunges steeply southeastward in the highly deformed rocks of the Eagle Creek shear zone. Crinkle folds formed by the intersection of cleavage and(or) schistosity with crenulation cleavage in the schists are upright and plunge gently.

Folds

The earliest folds recognized in the metasiltstone unit along Eagle Creek are interpreted to be slump folds related to soft sediment deformation (fig. 18).

Exposure along Fontana Lake shows highly folded strata that have not been portrayed (Espenshade, 1963; Hadley and Nelson, 1971) since Keith's cross sections (1907). The folded beds of metasandstone

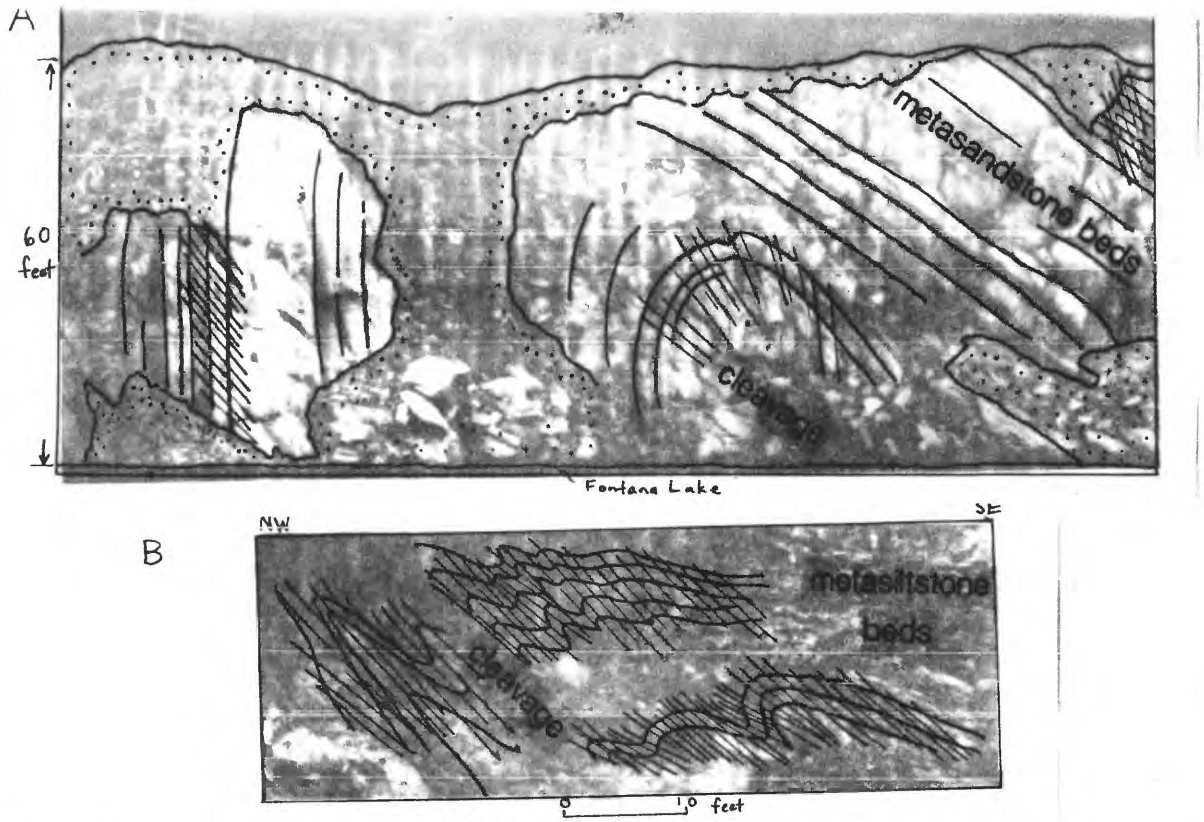


Figure 16. Photographs and tracings of folds and fanning axial planar cleavage in A metasandstone and B metasiltstone. Photo locality 16 A and B, pl. 1.

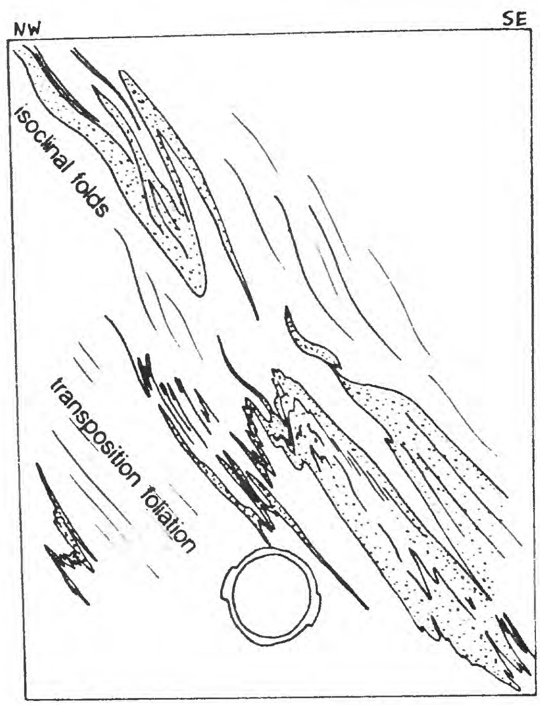


Figure 17. Tracing of photograph of isoclinal folds with transposed beds of metasandstone in the metasiltstone unit within the Eagle Creek shear zone. Lens cap is 5 cm. Photo locality 17, pl. 1.

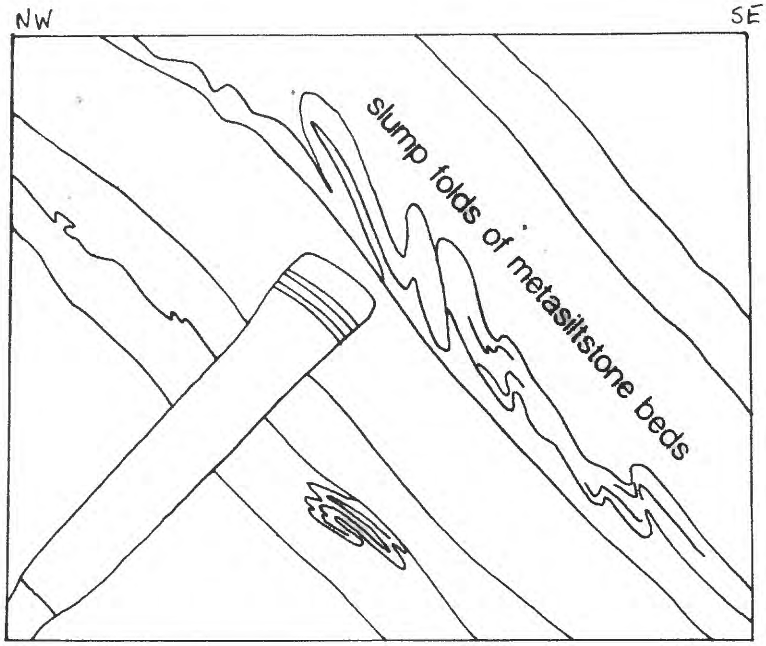


Figure 18. Tracing of photograph of folds interpreted to be synsedimentary gravitational slump folds in metasiltstone along Eagle Creek. Photo locality 18, pl. 1.

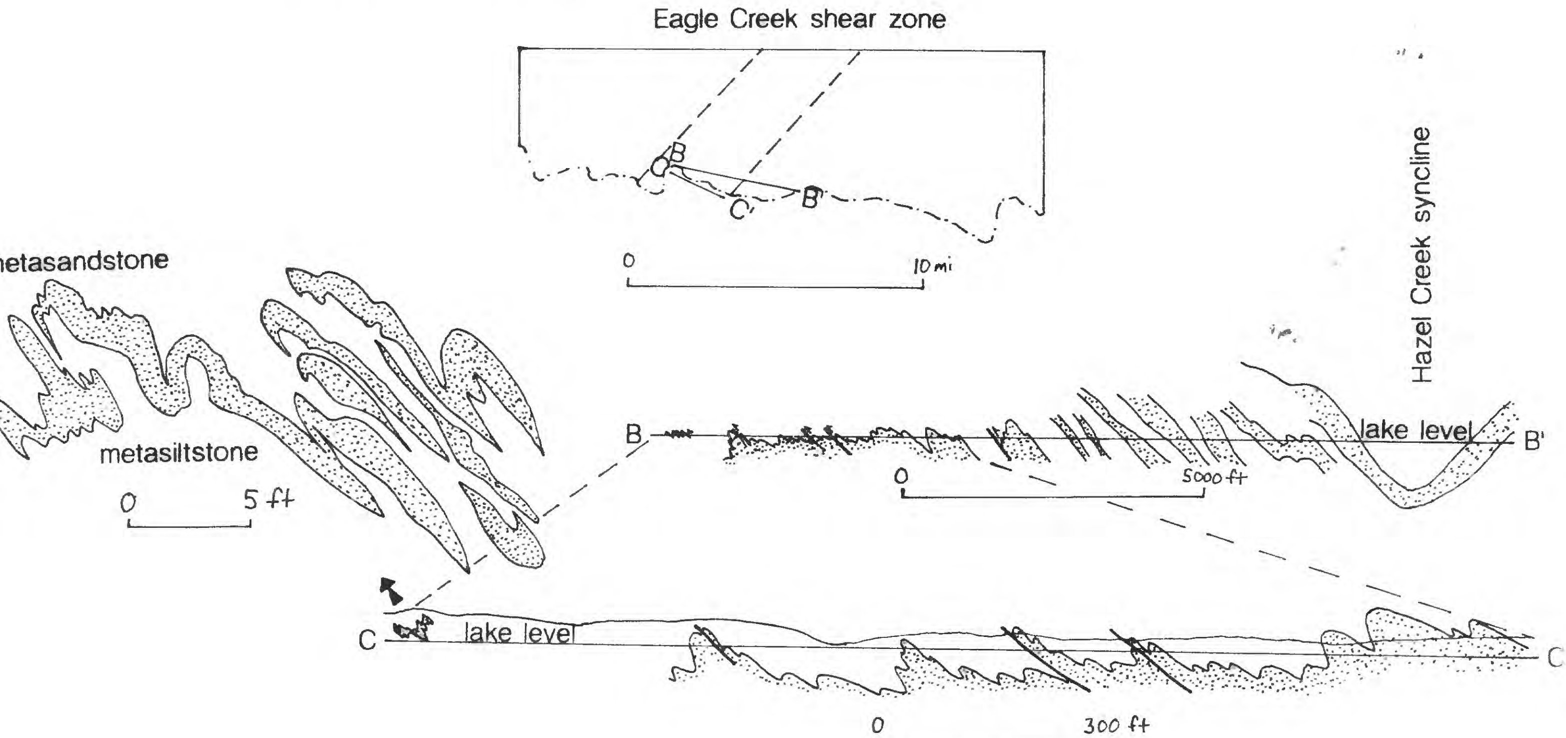


Figure 19. Schematic cross sections of the Eagle Creek shear zone based on tracing from inverted photomosaics of the north shore of Fontana Lake (see pl. 1, B-B' and C-C').

and metasiltstone have an axial planar cleavage related to a single fold phase (figs. 13 and 16). There are at least three orders of upright to inclined, gently plunging folds. Large second-order folds are mapped west of the first-order Murphy synclinorium (Meetinghouse Mountain). The second-order folds verge westward, and they can be mapped from Meetinghouse Mountain to the syncline at Hazel Creek. The deformation in the Eagle Creek shear zone precludes determining whether the metasiltstone rocks are synformal above the metasandstone unit. The graphitic and sulfidic argillaceous rocks near Shuckstack are highly folded and are interpreted to be the erosional remnant of a doubly-plunging syncline. Third-order folds parasitic to the limbs of the second-order folds are numerous and verge both northwest and southeast depending on their limb position.

Some of the most impressive folds are those associated with the Eagle Creek shear zone. Large west-verging folds of metasandstone exposed along the bluff beneath the Appalachian Trail hut at Fontana Dam are illustrated in figure 19 by tracing an inverted photomosaic (see plate 1, cross sections, B-B' and C-C'). Small thrust faults suggests that these are fault propagation folds (Suppe, 1985). Exposed on the north-facing side of the island northeast of Fontana Dam are ptygmatic folds of a metasandstone bed in argillic metasiltstone, shown as an enlarged inset (fig. 19). Along Eagle Creek are mesoscopic ptygmatic folds (fig. 20), and isoclinal to intrafolial folds (fig. 17).

Few mesoscopic folds are recognized away from Fontana Lake due to limited exposure. Exceptions are high amplitude, upright folds of metasandstone exposed in the abandoned quarry southwest of Fontana Dam along Highway 28 (fig. 21). Deformation decreases westward so that along Highway 28 opposite the substation at Rymers Ferry is a small low amplitude anticline. The map pattern of metasiltstone and quartz-muscovite schist units may reflect folds, stratigraphic tongues, or both.

Faults

Faults recognized in the map area are almost exclusively northwest-directed thrust faults exposed in the Eagle Creek shear zone. Several minor thrust faults were mapped east of Hazel Creek. The thrust faults are intraformational and amounts of offset are undetermined. The entire Eagle Creek shear zone contains numerous map-scale thrust faults (fig. 4). Folding, the development of cleavage and mylonitic, phyllonitic, and transposition foliations, and thrust faulting within the Eagle Creek shear zone are interpreted to be a continuum of deformation (fig. 20). The deformation in the Eagle Creek shear zone is post-peak metamorphism as it is characterized by retrogressive mineral assemblages. Small thrust faults mapped in the folded metasandstone on the bluffs east of Fontana Dam are related to the folding of these strata. Mappable bodies of vein quartz (Pzq and Q) and the carbonate-chlorite schist indicate substantial migration of fluids during deformation. Whether or not the Eagle Creek shear zone links up with the Mingus fault (King, 1964) as suggested by Espenshade (1963) and portrayed by Hadley and Nelson (1971), it cannot be traced as a single thrust fault.

Where Augerhole Branch meets Eagle Creek, a down-to-the-south, east-west striking normal fault cuts a metasandstone bed within the metasiltstone unit (fig. 22). The normal fault is a late structure that cuts both beds and cleavage. This fault is sub-parallel to large east-west trending lineaments in the region (such as Fontana Lake and Yellow Creek to the south).

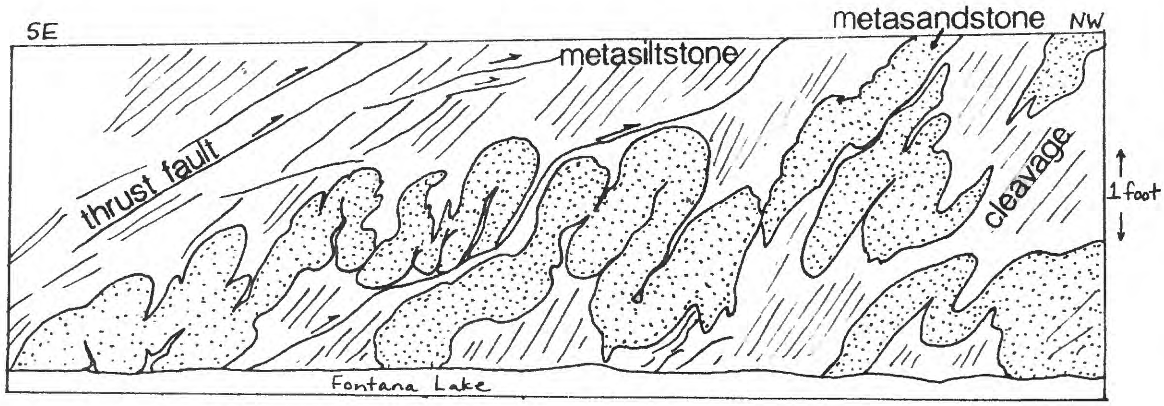


Figure 20. Tracing of photograph of ptygmatic folds of metasandstone bed within metasiltstone unit within the Eagle Creek shear zone. Photo locality 20, pl. 1.

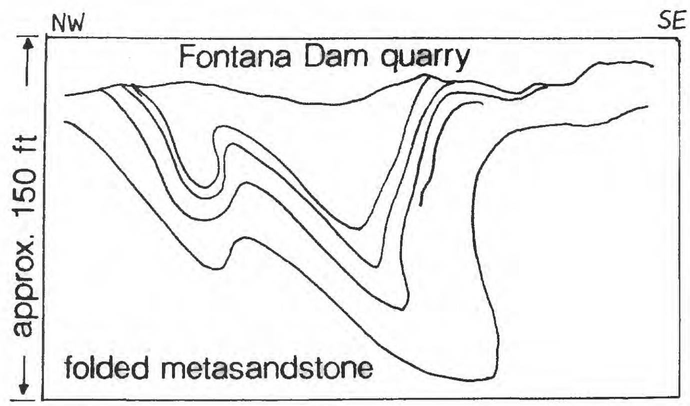


Figure 21. Tracing of photograph of folded metasandstone exposed in the abandoned quarry west of Fontana Dam, photo locality 21, pl. 1.

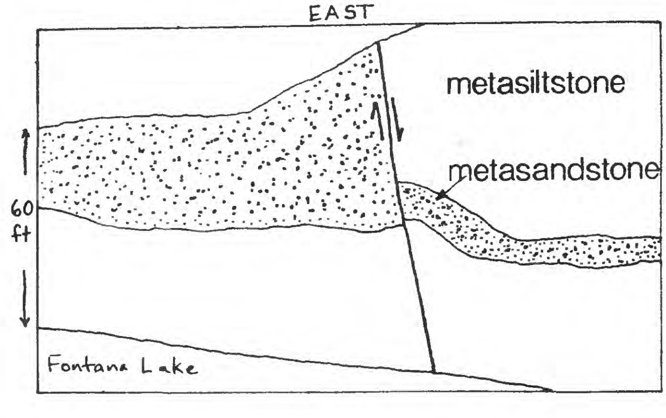


Figure 22. Tracing of photograph of down-to-the-south normal fault exposed along Eagle Creek, photo locality 22, pl. 1.

FONTANA COPPER MINE

Metamorphosed stratabound massive sulfide deposits of probable Besshi-type (Fox, 1984) were mined for copper and zinc with traces of lead, silver, and gold between 1926 and 1944 at the Fontana Copper mine, north of the confluence of Ecoah Branch and Eagle Creek (Espenshade, 1963; Robinson and others, 1992). Like the massive sulfide deposits at Ducktown, Tennessee, the host rock of the Fontana mine is the graphitic and sulfidic metasiltstone unit that is mapped as the Copperhill Formation by Wiener and Merschat (1992). Besshi-type massive sulfide deposits are interpreted to be related to extensional marine basins filled with clastic sediments and variable amounts of tholeiitic basalt (Fox, 1984) and are compatible with the local geologic setting here. Hypabyssal metadiabase dikes and sills are common here, near the Hazel Creek mine and prospects along strike to the northeast (fig. 5), and near similar sulfide deposits (Fox, 1984; Gair and Slack, 1984; Misra and Lawson, 1988). Metadiabase dikes and greenstone are near all of these deposits yet they were not encountered in the mines (Espenshade, 1963). The association of the dikes, carbonate-chlorite schist, and massive sulfide deposits have long been recognized (Laney, 1907; Espenshade, 1963) but their relationship to one another is still unresolved. They all occur within a shear zone that has transposed and aligned all units into the foliation. Specimens of folded sulfide ore shows that the ore preceded deformation.

The property shown on the base map lying outside the broken line marked "National Park Boundary" around the Fontana Copper mine was transferred to the NPS in 1983. Chemical analyses of rocks, soil, and ash of forest litter of the Fontana Copper mine area is provided by Lesure and others (1977).

WATER RESOURCES

McMaster and Hubbard (1970) provide data on spring discharge, stream flow, and chemical analyses of ground-water and surface water. Springs at approximately 5000 feet altitude (Newfound Gap and Indian Gap within the Clingmans Dome quadrangle) yielded a maximum range of 51.2 to 62.5 gpm in August, 1966, with minimum discharge of 12.7 gpm in July, 1966. Springs are numerous throughout the map area but none exhibit discharge comparable to these. The drainage basins of Twentymile Creek, Eagle Creek, and Hazel Creek are 8.15, 22.3, and 44.4 sq. mi. in size yet they all record approximately 3.1 cfsm (cubic feet per second per square mile of drainage basin) average flow with minimum flow of .47, .42, and .70 cfsm, respectively (McMaster and Hubbard, 1970). Hazel Creek and Eagle Creek drain southwestward into Fontana Lake and Twentymile Creek drains southwestward into Lake Cheoah. Fontana Lake and Lake Cheoah were created by dams built on the Little Tennessee River to provide hydroelectric power. Fontana Lake contains a volume of water estimated to be $1.78 \times 10^9 m^3$ (Tennessee Valley Authority, 1965). The only water well record is from the Twentymile Ranger Station: the well is 186 feet deep in metasandstone and yields an estimated 4 gpm maximum pumping rate (McMaster and Hubbard, 1970).

The effect of sulfidic-bearing rocks on surface water quality was demonstrated by Bacon and Maas (1979) where Beech Flats Creek flows through artificial fill of rocks of the Anakeesta Formation along U.S. 441 in the Clingmans Dome quadrangle. In that area, the acidity of surface water increased 100-fold (pH 6.7 to 4.7) within several hundred meters. Silsbee and Larson (1982) sampled water along Twentymile Creek, Eagle Creek, and Hazel Creek, and concluded that "the bedrock influences pH, alkalinity, conductivity, and hardness," yet no specific data was provided. Sediments dredged in Fontana Lake at the mouth of Hazel Creek and Eagle Creek (16 and 22 m depth, respectively) shows elevated Cu indicating the input of metal compounds from the Fontana mining district (Abernathy and others, 1984).

During this study, stream samples collected along Sugar Fork (Hazel Creek mine), the tributary adjacent to Fontana Copper mine, and springs discharging from Wehutty Formation in the Noland Creek quadrangle, show moderate pH values (5.6 pH) with the most acidic affluent (2.7 pH) from rocks of the Wehutty Formation (Geoff Plumlee, U.S. Geological Survey, 1994, oral comm.).

ACKNOWLEDGEMENTS

Field mapping was accomplished through the able assistance of "Volunteers For Science" Charles Southworth, Stan Southworth, Hap Dashiell, and Mike Hoffman. The logistical support provided by the following made the work possible: Keith Langdon, Glenn Martin, Robbie Robinson, Frank Hyatt, Clyde Laws, and Garl Holder of NPS; Chuck Parker of NBS, and especially Luther Turpin of the Fontana boat dock. The previous work of Gilbert Espenshade (1963) was invaluable to this study. Technical review by J. Wright Horton, Jack Epstein (USGS) and Leonard S. Wiener (North Carolina Geological Survey) improved this report.

References Cited

Abernathy, A.R., Larson, G.L., and Mathews, R.C., Jr., 1984, Heavy metals in the surficial sediments of Fontana Lake, North Carolina: Water Resources, v. 18, no. 3, p. 351-354.

Aleinikoff, J.N., Zartman, R.E., Walter, Marianne, Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, Central and Southern Appalachians: Evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428-454.

Aylor, J.G., and Kish, S.A., 1991, Supplemental Stop 2 in Studies of Precambrian and Paleozoic Stratigraphy in the western Blue Ridge: Carolina Geological Society, Kish, S.A., ed., p. 159-161.

Bacon, J.R., and Maas, R.P., 1979, Contamination of Great Smoky Mountains Trout streams by exposed Anakeesta Formations: Journal of Environmental Quality, v. 8, no. 4, p. 538-543.

Basaltic Volcanism Study Project, 1981, Basaltic volcanism on the terrestrial planets: Pergamon Press, Inc., New York, 1286 p.

Bowring, S.A., Grotzinger, J.P., Isochsen, C.E., Knoll, A.H., Pelechaty, S.M., and Kolosav, P., 1993, Calibrating rates of Early Cambrian evolution: Science, v. 261, p. 1293-1298.

Bryant, Bruce, and Reed, J.C., Jr., 1970, Geology of the Grandfather Mountain window and vicinity, North Carolina and Tennessee: U.S. Geological Survey Professional Paper 615, 190 p.

Connelly, J.B., and Dallmeyer, R.D., 1993, Polymetamorphic evolution of the western Blue Ridge: Evidence from $^{40}Ar/^{39}Ar$ whole-rock slate/phyllite and muscovite ages: American Journal of Science, v. 293, p. 323-359.

Cox, K.G., Bell, J.D., and Pankhurst, R.J., 1979, The interpretation of igneous rocks: London, Allen and Unwin, 450 p.

Espenshade, G.H., 1963, Geology of some copper deposits in North Carolina, Virginia, and Alabama: U.S. Geological Survey Bulletin 1142-I, p. I1-I50.

Flohr, M.J.K., Dillenburg, R.G., and Plumlee, G.S., 1995, Characterization of secondary minerals formed as the result of weathering of the Anakeesta Formation, Alum Cave, Great Smoky Mountains National Park, Tennessee: U.S. Geological Survey Open-File Report 95-477, 22 p.

Fox, J.S., 1984, Besshi-type volcanogenic sulfide deposits--a review: Canadian Institute of Mining and Metallurgy Bulletin, v. 77, p. 57-68.

Gair, J.E., and Slack, J.F., 1984, Deformation, geochemistry, and origin of massive sulfide deposits, Gossan lead district, Virginia: Economic Geology, v. 79, p. 1483-1520.

Goddard, E.N., Trask, P.D., DeFord, R.K., Rove, R.N., Singewald, J.T., and Overbeck, R.M., 1948, Rock-color chart: Washington, D.C., National Research Council, 6 p., reprinted by Geological Society of America, 1951, 1963, 1970.

Goldberg, S.A., and Butler, J.R., 1990, Late Proterozoic rift-related dykes of the southern and central Appalachians, eastern U.S.A. in Mafic Dykes and Emplacement Mechanisms, Parker, Richwood, and Tucker, eds., Balkema, Rolterdam, p. 131-144.

Goldberg, S.A., Butler, J.R., and Fullager, P.D., 1986, The Bakersville dike swarm: Geochronology and petrogenesis of Late Proterozoic basaltic magmatism in the Southern Appalachian Blue Ridge: American Journal of Science, v. 286, p. 403-430.

Goldsmith, Richard, 1959, Granofels: a new metamorphic rock name: Journal of Geology, v. 67, p. 109-110.

Hadley, J.B., and Goldsmith, Richard, 1963, Geology of the eastern Great Smoky Mountains, North Carolina and Tennessee: U.S. Geological Survey Professional Paper 349-B, 118 p.

Hadley, J.B., and Nelson, A.E., 1971, Geologic map of the Knoxville quadrangle, North Carolina, Tennessee, and South Carolina: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-654, scale 1:250,000.

Hatcher, R.D., Jr., Thomas, W.A., Geiser, P.A., Snoke, A.W., Mosher, Sharon, and Wiltshko, D.V., 1989, Alleghanian orogen in The Geology of North America, v. F-2, The Appalachian-Ouachita Orogen in the United States: The Geological Society of America, Boulder, CO, p. 233-318.

Hatcher, R.D., Jr., and Goldberg, S.A., 1991, The Blue Ridge Province, in Horton, J.W., Jr., and Zullo, V.A., eds., The Geology of the Carolinas--Carolina Geological Society 50th Anniversary Volume: Knoxville, University of Tennessee Press, p. 11-35.

Hernon, R.M., 1969, The Wehutty Formation of North Carolina in Changes in Stratigraphic Nomenclature by the U.S. Geological Survey 1967: U.S. Geological Survey Bulletin 1274-A, p. A49-A52.

Keith, Arthur, 1895, Description of the Knoxville quadrangle (Tennessee-North Carolina): U.S. Geological Survey Geologic Atlas Folio 16, 6 p.

_____1907, Description of the Nantahala quadrangle (North Carolina-Tennessee): U.S. Geological Survey Geologic Atlas Folio 143, 11 p.

_____1913, Production of apparent diorite by metamorphism: Geological Society of America Bulletin, v. 24, p. 684-685.

_____1927, Great Smoky overthrust [abs.]: Geological Society of America Bulletin, v. 38, p. 154-155.

King, P.B., 1964, Geology of the central Great Smoky Mountains, Tennessee. U.S. Geological Survey Professional Paper 349-C, 148 p.

King, P.B., Hadley, J.B., Neuman, R.B., and Hamilton, W.B., 1958, Stratigraphy of the Ocoee Series, Great Smoky Mountains, Tennessee and North Carolina: Geological Society of America Bulletin, v. 69, no. 8, p. 947-966.

King, P.B., Neuman, R.B., and Hadley, J.B., 1968, Geology of the Great Smoky Mountains National Park, Tennessee and North Carolina: U.S. Geological Survey Professional Paper 587, 23 p., and 1:125,000-scale map.

Kish, S.A., 1991, Potassium-argon dating in the western Blue Ridge of North Carolina and Tennessee, in Kish, S.A., ed., Studies of Precambrian and Paleozoic Stratigraphy in the western Blue Ridge: Carolina Geological Society Field Trip Guidebook, p. 69-77.

Kish, S.A., Campbell, S.K., Groszos, M.S., and Tull, J.F., 1991, Geochemistry and petrology of metaigneous rocks in Murphy syncline, Tate, Georgia: Geological Society of America Abstracts with Programs, v. 23, no. 1, p. 53.

Landing, Ed, 1994, Precambrian-Cambrian boundary global stratotype ratified and a new perspective of Cambrian time: Geology, v. 22, p. 179-182.

Laney, F.B., 1907, Copper deposits of Swain County in Pratt, J.H., The mining industry in North Carolina during 1906: North Carolina Geological and Economical Survey, Economic Paper 14, p. 72-79.

Lesure, F.G., Force, E.R., Windolph, J.F., and Hill, J.J., 1977, Mineral resources of the Joyce Kilmer-Slickrock Wilderness, North Carolina-Tennessee: U.S. Geological Survey Bulletin 1416, 89 p.

McMaster, W.M., and Hubbard, E.F., 1970, Water resources of the Great Smoky Mountains National Park, Tennessee and North Carolina: Hydrologic Investigations Atlas HA-420, 2 sheets, scale 1:125,000.

Mills, H.H., 1981, Boulder deposits and the retreat of mountain slopes, or, "Gully Gravure" revisited: Journal of Geology, v. 89, p. 649-660.

Milton, D.J., 1983, Garnet-biotite geothermometry confirms the premetamorphic age of the Greenbriar fault, Great Smoky Mountains, North Carolina: Geological Society of America Abstracts with Programs, v. 15, p. 90.

Misra, K.C., and Lawson, J.S., 1988, Paleotectonic setting of massive sulfide deposits of the Ducktown mining district, Tennessee, in Zachrisson, Ebbe, ed., Proceedings of the Seventh Quadrennial IAGOD Symposium: Stuttgart, E., Schweizerbait'sche Verlagsbuchhandlung, p. 685-692.

Mohr, D.W., 1972, Stratigraphy, structure, and metamorphism of the eastern part of the Fontana Lake Reservoir, Great Smoky Mountains, North Carolina [Ph.D. dissertation]: Chicago, University of Chicago, 284 p.

_____1973, Stratigraphy and structure of part of the Great Smoky and Murphy belt Groups, western North Carolina: American Journal of Science, v. 273-A, p. 41-71.

_____1975, Geologic map of the Noland Creek quadrangle, North Carolina: North Carolina Geological Survey Geologic Map GM 158-NE, scale 1:24,000.

Mohr, D.W., and Newton, R.C., 1983, Kyanite-staurolite metamorphism in sulfidic schists of the Anakeesta Formation, Great Smoky Mountains, North Carolina: American Journal of Science, v. 283, p. 97-134.

Moneymaker, B.C., 1947, Geologic conditions at Fontana Dam (abs.): Geological Society of America Bulletin, v. 58, no. 12, pt. 2, p. 1209-1210.

Nesbitt, B.E., and Essene, E.J., 1982, Metamorphic thermometry and barometry of a portion of the southern Blue Ridge province: American Journal of Science, v. 282, p. 701-729.

Neuman, R.B., and Nelson, W.H., 1965, Geology of the western Great Smoky Mountains, Tennessee: U.S. Geological Survey Professional paper 349-D, 81 p.

Pearce, J.A., and Cann, J.R., 1973, Tectonic setting of basic volcanic rocks determined using trace element analysis: Earth and Planetary Science Letters, v. 19, p. 290-300.

Plumb, K.A., 1991, New Precambrian time scale: Episodes, v. 14, no. 2, p. 139-140.

Powell, C.A., Bollinger, G.A., Chapman, M.C., Sibol, M.S., Johnson, A.C., and Wheeler, R.L., 1994, A seismotectonic model for the 300-kilometer-long eastern Tennessee seismic zone: Science, v. 264, p. 686-688.

Power, W.R., and Forrest, J.T., 1971, Stratigraphy and structure of the Murphy belt, North Carolina: Carolina Geological Society field trip guidebook, 29 p.

Rankin, D.W., 1993, The volcanogenic Mount Rogers Formation the the overlying glaciogenic Konnarock Formation--Two Late Proterozoic units in southwestern Virginia: U.S. Geological Survey Bulletin 2029, 26 p.

Rankin, D.W., Espenshade, G.H., and Neuman, R.E., 1972, Geologic map of the west half of the Winston-Salem quadrangle, North Carolina, Virginia, and Tennessee: U.S. Geological Survey Miscellaneous Geologic Investigations, Map I-709-A, scale 1:250,000.

Rankin, D.W., Drake, A.A., Jr., and Ratcliffe, N.M., 1989, Geologic map of the U.S. Appalachians showing the Laurentian margin and the Taconic orogen, plate 2, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita orogen in the United States: Geological Society of America, The Geology of North America, Boulder, v. F-2, scale 1:2,000,000.

Robinson, G.R., Jr., Lesure, F.G., Marlow, J.I., II, Foley, N.K., and Clark, S.H., 1992, Bedrock geology and mineral resources of the Knoxville 1°x2° quadrangle, Tennessee, North Carolina, and South Carolina: U.S. Geological Survey Bulletin 1979, 73 p. with 1:250,000-scale map.

Shafer, D.S., 1988, Late Quaternary landscape evolution at Flat Laurel Gap, Blue Ridge Mountains, North Carolina: Quaternary Research, v. 30, p. 7-11.

Silsbee, D.G., and Larson, G.L., 1982, Water quality of streams in the Great Smoky Mountains National Park: Hydrobiologia, v. 89, p. 97-115.

Southworth, Scott, Burton, W.C., Schindler, J.S., and Froelich, A.J., in press, Geologic map of Loudoun County, Virginia: U.S. Geological Survey Miscellaneous Investigations Map I-2553, scale 1:50,000.

Suppe, John, 1985, Principles of Structural Geology: Englewood Cliffs, N.J., Prentice-Hall, Inc., 537 p.

Tennessee Valley Authority, 1965, Fontana Dam: Knoxville, TVA Bulletin No. F6516R, 4 p.

Thompson, T.W. and Tull, J.F., 1991, Stratigraphy of the Minerals Bluff Group, Southwestern North Carolina in Studies of Precambrian and Paleozoic stratigraphy in the western Blue Ridge, Carolina Geological Society, Kish, S.A., ed., p. 97-110.

Van Horn, E.C., 1948, Talc deposits of the Murphy Marble belt: North Carolina Division of Mineral Resources Bulletin 56, 54 p.

Wiener, L.S., and Merschat, C.E., 1992, Geologic map of southwestern North Carolina including adjoining southeastern Tennessee and northern Georgia: North Carolina Geological Survey, scale 1:250,000.

Woodward, N.B., ed., 1985, Valley and Ridge thrust belt: balanced structural sections, Pennsylvania to Alabama: Appalachian Basin Industrial Associates, University of Tennessee Department of Geological Sciences Studies in Geology no. 12, 64 p.

Table 1. Major and minor element chemical analyses of Late Proterozoic(?) metadiabase, metadiorite, metagabbro, and amphibolite. See figures 5 and 7 for location of field number samples. FD2 and FD3 are from Flint Gap in the Fontana Dam quadrangle (see map). Analyses CD-157, CD-172, and TVA-3 are from Hadley and Goldsmith (1963), analyses TVA-1 and TVA-2 are unpublished TVA data (L.S. Wiener, NCGS, written comm., 1995), analyses of mafic rocks of the Murphy synclinorium are NG and HRD from Aylor and Kish (1991) and MMF from Thompson and Tull (1991), analyses of Ducktown amphibolite are from Misra and Lawson (1988), and analyses of Bakersville metadiabase are from Goldberg and Butler (1990). [For the first eight samples, major elements determined by x-ray spectroscopy by D.F. Siems and J.S. Mee; minor elements by Instrumental Neutron Activation Analysis (INAA) by M. Pickering and G.A. Wandless, in laboratories of the U.S. Geological Survey]

					Great Smoky Mountain National Park								----Murphy Synclinorium----			Bakersville, NC	Ducktown, TN
Field No.	TM 1	CD 1	MS	SB1	SB 2	FD 2	FD 3	CD-157	CD-172	TVA-1	TVA-2	TVA-3	NG	HRD	MMF	(Avg of 90)	(Avg of 10)
Lab No.	D-533742	D-533743	D-533744	D-533746	D-533747	D 533748	D-533749	E2150	E2151	91030	91031	88200	D-533745		(Avg of 4)		
SiO_2	48.8	49.1	46.5	50.3	48.3	51.9	49.9	55.45	50.29	48.3	48.8	50.9	52.6	43.1	47.3	49.16	49.55
Al_2O_3	15.3	21.7	15.2	15.4	16.0	15.5	15.6	15.28	18.90	15.3	15.6	15.2	14.3	14.3	16.3	14.16	15.30
Fe_2O_3	2.05	1.16	3.4	1.63	1.81	1.45	2.19	.97	.78	2.2	2.7	1.6	1.49	3.41	15.6	—	11.87
FeO	8.16	4.68	9.19	6.80	7.92	6.42	6.68	7.34	6.14	8.1	7.2	8.4	8.21	9.54	—	13.62	—
MgO	7.64	5.92	6.46	7.43	8.35	7.21	8.78	5.58	7.69	9.0	7.8	7.5	5.51	6.57	5.7	5.38	7.31
CaO	9.76	10.2	9.55	11.5	9.71	8.24	8.75	8.07	9.58	9.3	10.8	10.8	4.56	10.4	5.85	8.16	11.43
Na_2O	2.69	3.02	2.26	2.78	2.52	4.31	3.44	4.06	2.83	2.6	2.9	2.4	4.36	1.59	0.99	3.01	2.39
K_2O	0.11	0.09	0.61	0.18	0.17	0.08	0.06	.16	.09	0.24	0.24	.2	2.20	2.49	1.07	1.55	0.56
H_2O+	2.33	2.56	3.39	1.38	2.46	2.01	2.88	1.23	2.41	—	—	.85	2.42	—	—	—	—
H_2O-	0.43	0.34	0.19	0.14	0.64	0.22	0.12	.12	0.17	—	—	—	0.04	—	—	—	—
TiO_2	1.84	0.72	2.38	1.40	1.48	2.09	1.16	1.38	.83	1.7	1.7	1.7	1.92	1.91	4.14	2.66	1.48
P_2O_5	0.16	0.09	0.29	0.13	0.13	0.19	0.10	.12	.08	0.09	0.10	.20	0.25	0.22	0.49	0.66	0.18
MnO	0.17	0.09	0.18	0.15	0.16	0.12	0.13	.14	.12	0.19	0.17	—	0.11	0.3	0.13	0.18	0.27
CO_2	0.11	0.04	<0.01	0.44	0.06	0.03	<0.01	—	.02	—	—	—	1.13	—	—	—	—
Sum	99.55	99.71	99.61	99.66	99.71	99.77	99.80	99.90	99.93	97.02	98.01	99.75	99.10	93.83	95.57	98.54	100.34
SC	45.7	18.3	26.6	41.1	43.3	41.1	43.7						21.5			—	—
CR	233	251	83.1	354	344	83.9	343						115		764	—	365
CO	35.9	29.3	48.7	46.5	42.6	12.39	37.3						31.8		72	—	—
NI	30	81	85	57	63	<60	60						43		319	—	56
ZN	58	36	89	38.9	52.6	35.9	44						86		152	—	—
AS	<1	2.8	8.2	3.2	1.9	<2	1.6						<0.9			—	—
SE	<0.6	0.61	<0.9	<0.6	<0.6	1.12	<0.6						<0.8			—	—
RB	<6	<12	22	<5	<5	<4	<5						66			40	11.4
SR	310	443	580	210	264	320	340						550			390	240
ZR	142	<90	<240	<240	106	<250	140						191		261	223	185
MO	<5	<4	<4	<4	<4	4.0	<6						<4			—	—
SB	0.20	0.24	0.78	<0.1	0.17	0.23	<0.4						0.35			—	—
CS	<0.2	<0.1	1.83	<0.2	<0.2	<0.2	<0.2						4.56			1.1	—
BA	98	33	164	63	<100	<30	<40						664			565	—
LA	5.24	8.07	17.1	5.04	3.74	5.17	2.97						22.5			36.1	—
CE	13.7	7.3	36.5	9.4	9.9	14.2	7.7						46.5			70	—
ND	13.1	8.9	20.4	11.4	9.7	13.7	7.8						27.4			—	—
SM	4.86	3.03	6.07	4.27	3.80	4.93	3.14						7.20			9.3	—
EU	1.65	1.09	1.86	1.47	1.36	1.57	1.12						1.83			—	—
TB	0.99	0.58	0.91	0.99	0.81	0.99	0.67						0.95			—	—
YB	3.59	1.68	2.58	3.83	3.14	3.63	2.53						2.10			3.7	—
LU	0.52	0.25	0.36	0.55	0.45	0.51	0.34						0.28			—	—
HF	3.19	1.16	4.00	2.40	2.47	3.68	1.87						4.47			7.3	—
TA	0.22	0.13	1.17	0.14	0.17	0.29	0.16						1.10			2.5	—
AU	<5	<4	<5	<4	<4	<5	<5						<6			—	—
TH	0.38	0.16	1.57	<0.1	<0.1	0.36	0.14						4.51			3.1	—
U	<0.4	<0.2	0.31	<0.4	<0.3	<0.4	<0.4						0.89			0.9	—