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Geology of the Mesoproterozoic Basement and Younger Cover Rocks in the West Half of the Asheville 100,000 quadrangle, North Carolina and Tennessee—An Updated Look

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Abstract

Bedrock geology of all 7.5-minute quadrangles in the west half of the Asheville 1:100,000-scale map has now been mapped in detail by the North Carolina Geological Survey and other mappers with financial assistance from the STATEMAP program. A preliminary map by the North Carolina Geological Survey is presented here as part of an ongoing compilation project. For this preliminary compilation map, Mesoproterozoic basement rocks are placed into five major units: four highly deformed metamorphic units and the relatively undeformed Max Patch Granite. Contacts between the four metamorphic units are still uncertain but may be either faults, intrusive, or gradual changes of dominant rock type. A newly dated Neoacadian mylonitic shear zone separates Max Patch Granite from the highly deformed metamorphic basement rocks. To the southeast, basement rocks are in fault contact with the Ashe metamorphic suite along the Holland Mountain-Chattahoochee fault. To the northwest, Ocoee Supergroup sedimentary rocks are separated from the basement along unconformities and Paleozoic fault zones. Paleozoic Barrovian metamorphic overprinting intensified from the northwest to southeast but is not observed in all areas of the basement. Granulite-facies rocks are present in localized bodies of the metamorphic basement units and likely preserve Grenvillian foliations.

Introduction

This paper and field trip focus on the history and relationships of the igneous-metamorphic basement rocks in the sixteen 7.5 minute quadrangles that constitute the west half of the Asheville 1:100,000-scale geologic map (Fig. 1). The crystalline basement in this area of western North Carolina comprises part of the Mesoproterozoic metamorphic core of the southern Appalachian Mountains. Geologically, this metamorphic basement core separates the Neoproterozoic Ashe metamorphic suite–Tallulah Falls Formation to the east from Neoproterozoic rocks of the Ocoee Supergroup and stratigraphically overlying early Paleozoic sedimentary units to the west (Fig. 1). Each of the quadrangles that make up the west half of the Asheville sheet has now been mapped in detail (Table 1). This mapping, done at a 1:24,000 scale, provides data that add to, confirm, or modify conclusions of preceding geologists. Our 1:100,000 compilation map is another step in the ongoing effort to decipher the region's geologic history. In this paper we outline the map units, their currently known ages, and our present thinking as to their structural and metamorphic history.

Various map units distinguished during detailed mapping of each individual 1:24,000-scale quadrangle are possibly equivalent but may have different names on different maps. At this stage in the compilation of the 100,000-scale map, formal names for the basement map units are not used except for the Max Patch Granite and Bakersville Metagabbro. We instead use informal names taken from the major rock types that characterize each map unit. All of the many units mapped in the 7.5 minute quadrangles are listed in Figure 1 and are appropriately grouped into the composite units used in the 1:100,000-scale Asheville compilation.

Historical background

Examining and investigating the rocks in an area to determine their mineral composition, economic value, stratigraphy, structure, and ultimately a synthesis of

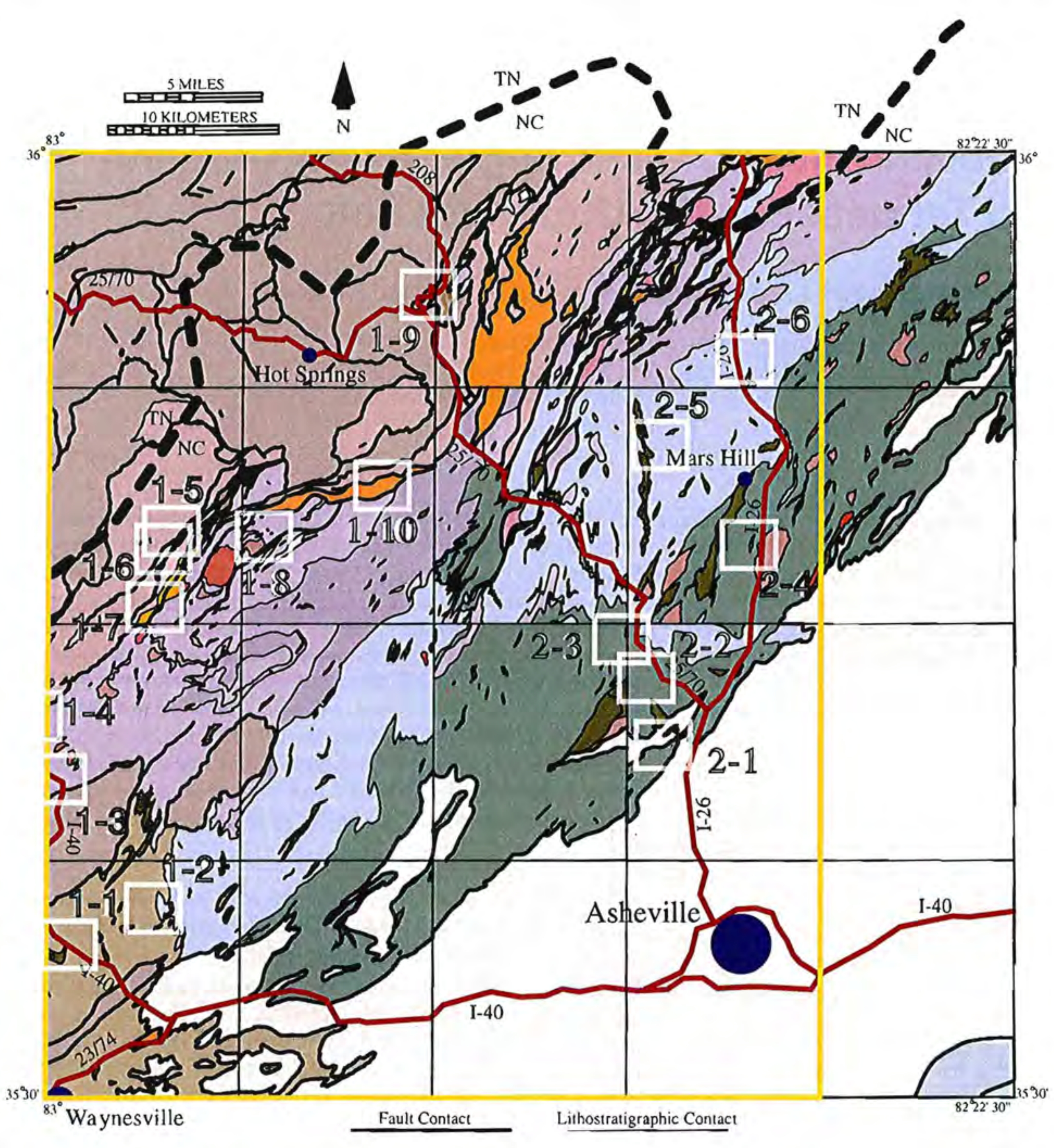
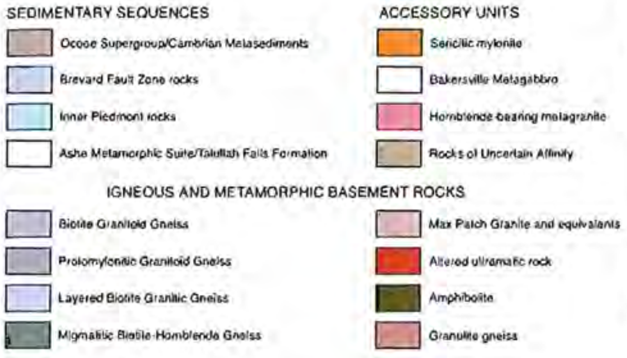


Figure 1. Preliminary compilation of the western portion of the Asheville 1:100,000 scale geologic map (west half shown by yellow box). Labeled boxes correspond to field trip stop locations. Original digital cartography by Mark W. Carter.

the region's geologic history is, of course, the task and goal of geologists. In western North Carolina the earliest formal geologic observations, made during the 19th century, revealed that bedrock in the region was dominated by a great body of ancient-looking rocks. The first published state geologic map (Olmstead, 1825) used Abraham Werner's Neptunist's classification system and labeled these as "Granite-gneiss, Mica-slate, Argyllite, etc." However, for most of the century little systematic attention was paid to the region's "country rock" with most effort being devoted to discovering and promoting the area's mineral wealth, especially iron ore, gems, copper, mica, barite, and other commodities. It was not until near the end of the 19th century that a systematic and comprehensive program of mapping was conceived and begun. This program, undertaken by the U.S. Geo-



Paint Rock Bearce, D.N., (1966) Ferguson, H.W. and Jewell, W.B., (1951) Oriel, S.S., (1950) Merschat, C.E. and Cattanach (2004) STATEMAP	**Hot Springs** Carter, M.W., (2001) STATEMAP	**White Rock** Merschat, C.E. and others, (2001) STATEMAP	**Sams Gap** Merschat, C.E. and others, (2000) STATEMAP	**Bald Creek** Merschat, C.E., (2000) STATEMAP
Lemon Gap Merschat, C.E. and others, (2002) STATEMAP	**Spring Creek** Cattanach, B.L. and others, (2005) STATEMAP	**Marshall** Peterson, V., (2002) Borquist, P.J. (2003) STATEMAP	**Mars Hill** Merschat, C.E., (1977)	**Barnardsville** Merschat, C.E., (1993) STATEMAP
Fines Creek Carter, M.W. and Wiener, L.S., (1999) STATEMAP	**Sandymush** Merschat, C.E. and Wiener, L.S., (1988)	**Leicester** Merschat, C.E. and Cattanach (2005) STATEMAP	**Weaverville** Burr, J.L., (2002) STATEMAP	**Craggy Pinnacle**
Clyde Merschat, C.E. and Wiener, L.S., (1992) STATEMAP	**Canton** Merschat, C.E. and Wiener, L.S., (1988)	**Enka** Burr, J.L., (2000) STATEMAP	**Asheville** Miller, J.W. and Fryer, K.H., (2004) STATEMAP	**Oteen** Nelson, D.O., (1972) Cattanach, B.L. and Merschat, C.E. (2005) STATEMAP

Figure 1, continued. Map explanation, above. Index, right.

logical Survey, was aimed at producing a geologic atlas of the United States. In the Appalachians a remarkable series of folios was ultimately published that covered ground from Alabama to New England. The area of the west half of the present-day Asheville 100,000-scale map is the same as that of Folio 116, the Asheville Folio, by Arthur Keith (1904). This important and impressive pioneer work presented abundant observations and field descriptions, much of which we today can simply acknowledge and reconfirm. As a result of his mapping, Keith concluded that there was a discernable region-wide stratigraphy. The major units in his stratigraphy in the Asheville Folio are:

Cambrian and Ordovician. Sedimentary strata (*conglomerate, quartzite, slate, shale, limestone and dolomite; mostly unmetamorphosed and either unconformably overlying or in fault contact with the older formations*).

Archean. Max Patch Granite (*granite composition, massive; intrusive into all the preceding formations*).

Cranberry Gneiss (*granitic composition; intrusive into both the Roan and Carolina Gneisses*).

Roan Gneiss (*mixed composition, but dominantly hornblende gneiss; intrusive into Carolina Gneiss*).

Carolina Gneiss (*principally mica schist and gneiss; area's oldest unit*).

The 1958 North Carolina Geologic state map (Stuckey, 1958) was published at 1:500,000 scale and includes four major basement units: mica gneiss, hornblende gneiss, Cranberry granite gneiss, and Max Patch granite gneiss. These units are essentially coincident with Keith's (1904) Carolina Gneiss, Roan Gneiss, Cranberry Gneiss, and Max Patch Granite. However, the change in terminology from Carolina Gneiss and Roan Gneiss to the lithologic terms mica gneiss and hornblende gneiss shows that Keith's concept and widespread usage of the Carolina Gneiss and Roan Gneiss as stratigraphic units was no longer fully accepted.

In 1971, the Knoxville 1:250,000-scale geologic map (Hadley and Nelson, 1971) was published. The Knoxville quadrangle presented a significant revision of Keith's work, especially his stratigraphic interpretations, and provided the framework for reinterpreting the area's geologic history. Hadley and Nelson's work in western North Carolina was based primarily on information gained from previous mapping in and around the Great Smoky Mountains National Park (Hadley and Goldsmith, 1963) and on their own rapid reconnaissance throughout the rest of the Knoxville map area (on average, about five days were spent per 7.5 minute quadrangle; Hadley, personal communication). On their map layered gneiss and migmatite were identified as the oldest unit and were succeeded by a redefined Cranberry Gneiss. The layered gneiss and migmatite map unit more or less coincided with Keith's Roan Gneiss and included parts of Keith's Carolina Gneiss, although both those formal terms were by now fully abandoned. The remainder of the Keith's original Carolina Gneiss, the portion characterized by the common presence of muscovite, was depicted as younger than those other units and was identified as being mostly of sedimentary origin. Hadley and Nelson (1971) retained Keith's Max Patch Granite as a significant map unit, although they refined the formation's areal extent. They also agreed with Keith that the Max Patch is the youngest of the granitic and gneissic basement units in the area. The

Basement Rock Summary

Migmatitic Bio-Hbl Gneiss

Bg- Biotite gneiss
Bgn- Biotite gneiss
Bhg- Biotite-horn gneiss
Bhm- Bio/horn migmatite
Hbgn- Hornblende-biotite gniess
Mbg- Magnetite granitic gneiss
Mss- Metasandstone
Yam- Amphibolite
Ybhg- Bio/horn gneiss
Ybhm- Migmatitic biotite-hornblende gneiss
Ybn- biotite gneiss
Ycs- Calc-silicate granofels
Ydn-Biotite dioritic gneiss
Ye- Earlies Gap Biotite Gneiss
Yea- Earlies Gap amphibolite
Yfg- felsic gneiss
Ymbcs- Marble + calc-silicate
Ymg- Magnetite gniess
Ypzpghg- Granitic and bio/horn gneiss
Yr- Richard Russell Bio Gneiss
Yra- Richard Russell Amphibolite
Yrg- Richard Russell Metagraywacke
Yrm- Richard Russell mus-bio gneiss

Layered Bio Granitic Gneiss

bgg- biotite granitic gneiss
Gg- granite gneiss
Ybgg- layered biotite granitic gneiss
Ybggmy- mylonitic layered biotite granitic gneiss
Yea- Earlies Gap amphibolite
Ys- Sandymush felsic gneiss
Ysa- Sandymush amphibolite
Yscs - Sandymush calc-silicate
Ysm- muscovite bearing Sandymush felsic gneiss
Ysp- Sandymush Protomylonite

Protomylonitic Granitoid Gneiss

Ydg- Doggett Gap Protomylonitic Granitoid Gneiss
Ypzpg- Protomylonitic granitic gneiss
Yzcbgg- Cranberry granitic gneiss
Yzkag- K-spar granite/granitic gneiss
Ydgc- Coarse-grained Doggett Gap protomylonite

Biotite Granitoid Gneiss

Hbgn- Hornblende-biotite gneiss
Pzc- cataclasite
Pzfgr- Leucocratic Granite
Ybg- Biotite granitoid gneiss
Ybga- Amphibolite
Ybggf- Aluminous granofels
Ybgh- Hornblende granitoid gneiss
Ybgm- Mylonitic bio granitoid gneiss
Ybgmy- Mylonite gneiss
Ybgmy- Mylonitic biotite granitic gneiss
Ymb- Marble
Ybgn-Feldspar granitoid gneiss
Yggg- Granoblastic granitic gneiss
Ylg- Leucocratic granitoid gniess
Ypzpbg- Biotite granitoid gneiss
Ysc- Spring Creek Granitoid Gneiss
Ysca- Interlayers of amphibolite
Yscm- Protomylonitic Spring Creek Granitoid Gneiss
Yscmy- Mylonitic Spring Creek Granitoid Gneiss
Yscs- Calc-silicate granofels
Yscu- Mylonitic Spring Creek granitic gneiss

Max Patch and equivalents

Pzcpmy- Protomylonite
Ym- Max Patch Granite
Ymfl- Leucocratic granite
Ymmy- Mylonitic granite
Ymp- Protomylonitic granite
Ypzmmp- Mylonitic Max Patch
Zgg- Max Patch
Zggmy- Mylonitic Max Patch
Zggp- Protomylonitic Max Patch
Zm- Max Patch Granite
Zymgm- Protomylonitic monzogranitic gneiss
Zymgu- Mylonitic monzogranitic gneiss

Granulites

Bhgb- Hypersthene metagabbro
Hygg- Hypersthene granitic gneiss
Hyp- Hypersthene plagioclase rock
Ygbg- Granoblasitc biotite granitic gneiss
Yggg- Garnet-rich granulite gneiss
Ygqm- Quartz Monzodioritic Granulite
Ygt- Tonalitic granulite
Yhyp- Pyroxene granulite
Ymg- Mafic granulite

Ultramafic Rocks

Zud- Dunite body
Zua- Altered ultramafic
Yut- Talc body
Um- Ultramafic rocks
Yum- Ultramafic rocks
Du- Dunite body

Miscellaneous

Trondhjemite
Pzm- Mylonite/protomylonite
Pzc- Cataclasite
Pzcf- Ferruginous cataclasite
Pzmy- Paleozoic Mylonite
pegmatite

Bakersville Metagabbro

Zbg- Bakersville metagabbro

Table 1. *List of all 7.5' quadrangle formal and informal basement unit names on the west half of the Asheville 100K initial compilation. Every 1:24,000 scale unit has been grouped within one of the compilation map categories (Fig. 1). Because the compilation is incomplete, some 1:24,000 scale units are in more than one compilation category.*

overlying lightly metamorphosed sedimentary strata of Neoproterozoic and early Paleozoic age were assigned to well defined formations whose original descriptions and definitions mostly trace back to James Safford (1869) and the 19th and early 20th century USGS folio work by Keith and his USGS colleagues. These non-fossiliferous to sparsely fossiliferous strata, of course, correspond to the transition formations recognized and crudely mapped by Olmstead (1823).

A detailed 1:24,000-scale quadrangle mapping program in the Asheville 100,000 sheet was begun in 1968 (more or less at the same time that Hadley and Nelson were working on their Knoxville quadrangle) through cooperation between the North Carolina Survey (then called the Division of Mineral Resources) and the Tennessee Valley Authority. Published maps from this program appeared sporadically over the next 15 years or so until TVA was forced to greatly reduce its geologic unit and eliminate mapping support. Subsequently, with the advent of the National Cooperative Geologic Mapping Program in 1992, especially the STATEMAP component, it was possible for state survey staff and contract mappers to continue detailed quadrangle mapping at an accelerated rate. In addition, maps and reports by several independent workers have contributed to filling in the geology of the Asheville sheet (Fig. 1).

An early significant map resulting from this detailed work is the Mars Hill 7.5 minute quadrangle (Merschat, 1977). This work generally confirmed Hadley and Nelson's major stratigraphic units and also showed that subdivisions and refinements of their large map units were feasible. Also, for the first time in this region, granulite-facies rocks were identified, mapped, and described. The first age date for any rock in this region was a Rb–Sr determination of 1210 Ma obtained from one of the Mars Hill quadrangle map units by Fullagar et al. (1979) and recalculated by Rankin et al. (1983).

The 1985 North Carolina geologic state map, printed at a scale of 1:500,000, was based on the then existing detailed maps, both published and unpublished, on Hadley and Nelson's Knoxville quadrangle (1971), and on supplemental reconnaissance traverses. However, in a few areas, it was still necessary to incorporate Keith's original folio material into the final map. The state map in the Asheville region included four Neoproterozoic basement units: migmatitic biotite hornblende gneisses, biotite granitic gneiss, granodioritic gneiss, and Max Patch Granite. In addition, the 1985 map includes a biotite gneiss unit of questionable Mesoproterozoic age.

In the early to mid 1980s the formal terms Ashe metamorphic suite (Abbott and Raymond, 1984) and Tallulah Falls Formation (Hatcher, 1971) began to be applied to the great expanse of rocks, dominantly aluminous metasedimentary rock with lesser amphibolite, lying southeast of the older basement rocks. About this time the regional terms "eastern Blue Ridge" and "western Blue Ridge" came into use, with eastern Blue Ridge rocks corresponding to the Ashe–Tallulah Falls units. In this terminology, western Blue Ridge rocks within the Asheville quadrangle clearly include sedimentary and metasedimentary formations from the Early Cambrian Chilhowee Group down through the Late Proterozoic Walden Creek, Great Smoky, and Snowbird Groups of the Ocoee Supergroup, along with the unconformably underlying granitic rocks, notably the Max Patch Granite.

Hatcher et al. (2005) used the term "central Blue Ridge" for their Cartoogechaye and Cowrock terranes, rocks cropping out in between western and eastern Blue Ridge units southwest of Asheville. Berquist et al. (2005) used the term central Blue Ridge to include both the Mars Hill terrane of the Asheville 100,000 quadrangle and Hatcher's Cartoogechaye and Cowrock terranes. Neither of these definitions is completely consistent with our present interpretation of the central Blue Ridge. On the west half of the Asheville 100,000 sheet the NCGS now considers the central Blue Ridge to include all rocks east of the Max Patch Granite and west of the Ashe metamorphic suite–Tallulah Falls Formation, as well as rocks of the Cartoogechaye terrane that outcrop in the southwest corner of the map.

Map units

Basement rocks in the west half of the Asheville quadrangle are grouped into five major units (Fig. 1): migmatitic biotite–hornblende gneiss, layered biotite granitic gneiss, protomylonitic granitoid gneiss, biotite granitoid gneiss, and Max Patch Granite and its equivalents. These five units can be put into two broad categories on the basis of age and deformational style: 1) the younger and relatively undeformed Max Patch Granite, and 2) the older but highly deformed rocks of the migmatitic biotite hornblende gneiss, layered biotite granitic gneiss, protomylonitic granitic gneiss, and biotite granitoid gneiss. Minor components of the older units include amphibolite, altered ultramafic rocks, hornblende-bearing granite, calc-silicate bodies and granulite gneisses.

The common rock types associated with the older basement gneisses are found in several map units, thus making it difficult to compile an easily recognizable "stratigraphy" that can be applied to the area. Detailed field mapping at 1:24,000-scale does, however, make it possible to recognize proportional differences between rock types and mineral assemblages within the various units of the compiled map. For example, although it is possible to find biotite-bearing granitic gneisses in all the major basement map units, there is much less of this rock type in the migmatitic biotite-hornblende gneiss unit than in the biotite granitoid gneiss unit.

The protoliths of the complexly deformed basement gneisses are not fully understood but are interpreted to be primarily igneous in nature. New age dates have identified three major time periods of igneous activity: 1020–1080 Ma, 1130–1180 Ma, and 1220–1270 Ma (Berquist et al., 2005). We believe the central Blue Ridge basement units to be an amalgam of the earliest two igneous pulses with each progressively younger phase intruding the older igneous bodies and intermingled pre-1270 Ma country rock. Deciphering this sequence of events is further complicated by at least one and possibly several overprinting high-grade metamorphic events that took place during the long-running Grenville orogenic cycle.

Migmatitic biotite–hornblende gneiss. 1210 Ma (Fullagar et al., 1979; as recalculated by Rankin et al., 1983). This is a strongly metamorphosed and deformed gneiss that contains a higher percentage of amphibolite and hornblende-bearing gneiss than the layered biotite granitic gneiss to the northwest. This unit is commonly migmatized and contains lenses of calc-silicate, altered ultramafic rock, and felsic and mafic granulite gneiss.

It is characteristically a light-brownish-gray to light-pinkish-gray, massive to well-foliated, locally migmatitic gneiss. It consists mostly of interlayered and intergraded biotite–hornblende gneiss and granitic gneiss. The biotite–hornblende layers predominate and may represent thin metamorphosed sills of gabbro or diabase. Locally, biotite–hornblende layers exhibit a chaotic block-in-matrix structure. The granitic layers range from granite to quartz diorite with most of the layers approximating quartz diorite. Migmatization is more prevalent near large bodies of mafic rock.

Layered biotite granitic gneiss. 1270 Ma (Fullagar, 1983). This is a thick, repetitive sequence of layered rocks dominated by biotite granitic gneiss to quartz dioritic gneiss interlayered with biotite gneiss, biotite schist, and amphibolite. Layers range from millimeters to meters thick. Biotite granitic gneiss to quartz dioritic gneiss is composed of quartz, plagioclase, potassium feldspar, biotite, epidote-group minerals, muscovite, opaques, garnet, titanite, apatite, and zircon and is locally migmatitic and mylonitic. Isoclinal folds are prominent. This unit is interpreted to be a highly deformed sequence of predominantly felsic metavolcanic rocks with a minor mafic component.

Protomylonitic granitoid gneiss. This unit consists of medium- to coarse-grained granitoid gneiss exhibiting a protomylonitic fabric consisting of feldspar porphyroclasts in a bioite-rich matrix. It has been mapped on the basis of this fabric and crops out in a northeast trending belt 25 km long and 6 km wide. It is unclear if the protomylonitic fabric is the result of Paleozoic or Grenville deformation. Close association and compositional similarities with the biotite granitoid gneiss raise the possibility that the two map units are the same lithologically, differing only in their deformational fabric.

Biotite granitoid gneiss. 1174–1360 Ma (Officer et al., 2003; Berquist, 2005). This is a highly metamorphosed and deformed gneiss that is typically more massive than the layered biotite granitic gneiss. Biotite granitoid gneiss varies in composition from granitic to granodioritic and consists of potassium feldspar, quartz, plagioclase, biotite, muscovite, epidote group minerals, garnet, and opaques. It is foliated and locally interlayered with biotite gneiss and schist. Layer thickness ranges from decimeters to meters. Along its northwestern margin the biotite granitoid gneiss exhibits a strong mylonitic fabric in middle to late Paleozoic shear zones.

Max Patch Granite and equivalents. 1000–1100 Ma (Officer et al., 2003; Berquist, 2005). This is a large granitic body with an outcrop exposure averaging over 7 km wide and 35 km long on the 100,000 map. Composition ranges from granite to alkali-feldspar granite to granodiorite. It is typically massive to weakly foliated, but is strongly mylonitic in middle to late Paleozoic shear zones. Amphibolite xenoliths are present locally in the unit. The unit is in fault contact with the biotite granitoid gneiss to the southeast and is either unconformably overlain by or in fault contact with Ocoee Supergroup metasedimentary rocks to the northwest.

Units of uncertain affinity. In the southwest corner of the Asheville 100,000 sheet there are rocks originally mapped as being correlative with the migmatitic biotite–hornblende gneiss. They were identified in the Fines Creek and Clyde quadrangles as belonging to the Richard Russell Formation (Merschat and Wiener, 1990; Carter and Wiener, 1999), a group of Mesoproterozoic basement rocks first identified along strike to the southwest in South Carolina (Gillon, 1982). New research suggests that these rocks in the Clyde and Fines Creek quadrangles are part of the Cartoogechaye terrane, a package of Neoproterozoic metasandstone, pelitic schist, altered mafic and ultramafic rocks, and minor Grenville basement (Hatcher et al., 2004).

The sediments of the Cartoogechaye terrane contain Grenvillian detrital zircons, a discovery that precludes them from being part of the Grenville basement complex (Hatcher et al., 2005). In addition to the apparent differences in age and protolith, Cartoogechaye terrane rocks contrast with the Grenvillian high-grade metamorphic and deformational fabrics of the Asheville 100,000-sheet basement in that the dominant foliation and upper amphibolite- to granulite-facies metamorphism is Taconic in age (Moecher and Miller, 2000; Moecher et al., 2004).

Minor map units. These units include amphibolite, altered ultramafic rocks, granulite gneisses, Bakersville metagabbro, sericitic mylonite, and hornblende-bearing metagranite.

Structure

All basement map units follow the northeast trend prominent in this part of the Appalachian orogen. To the southeast, the basement is in fault contact with the Ashe metamorphic suite–Tallulah Falls Formation. To the northwest it is both in fault contact with and unconformably overlain by the Ocoee Supergroup. A major shear zone of variable thickness separates the older, more deformed basement units of the central Blue Ridge from the western Blue Ridge Max Patch Granite (Fig. 2).

The vast majority of foliation measurements in the Asheville 100,000 align with outcrop patterns and are oriented to the northeast. Within the granulite bodies, however, most foliations trend northwest and are only locally overprinted by northeast-trending Paleozoic foliations. Merschat and Wiener (1990) suggested that these granulite-facies northwest-trending foliations

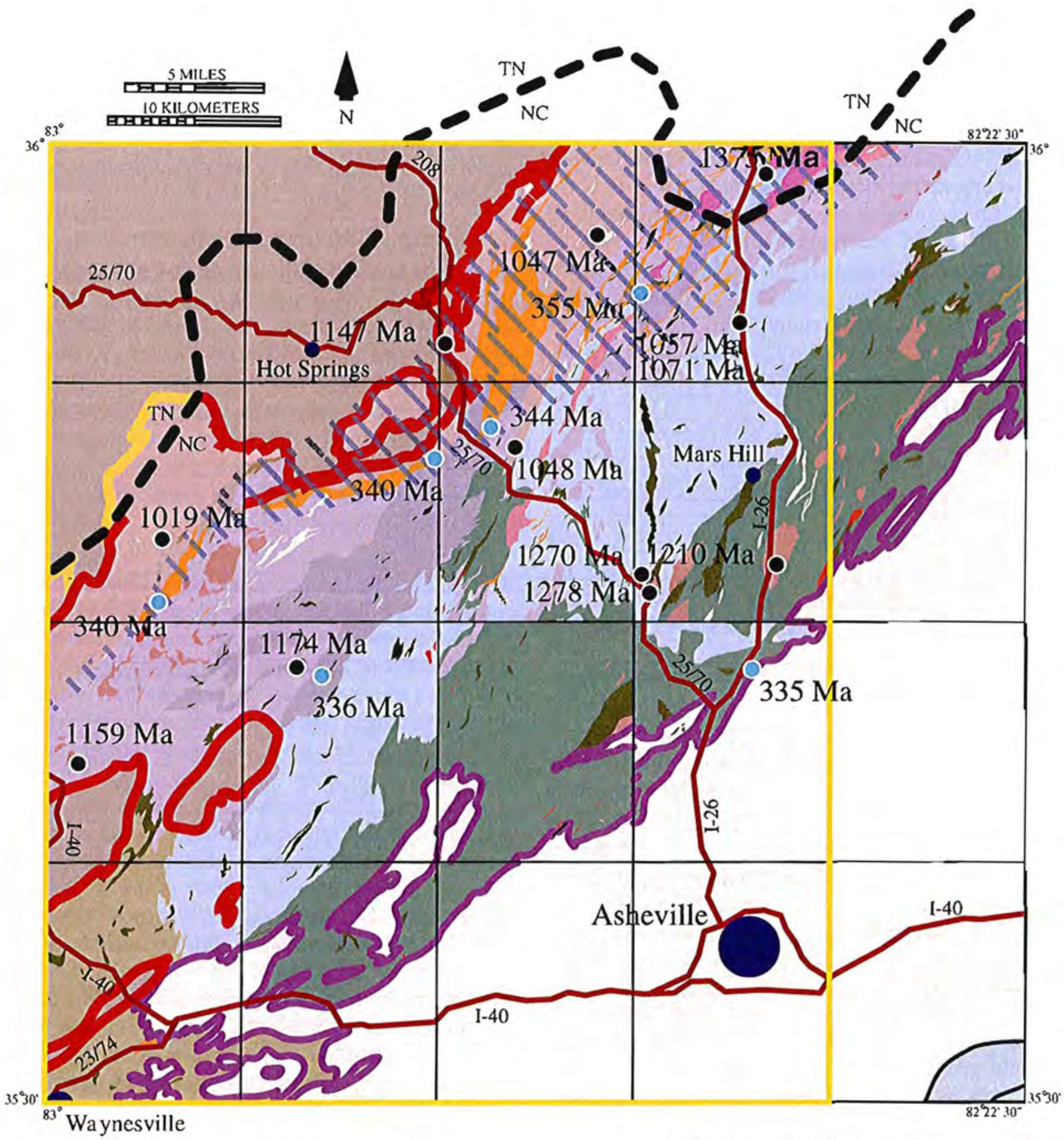


Figure 2: Map showing major structural boundaries, crystallization ages, and deformation ages for basement r ocks of the west half of the Asheville 1:100,000 scale geologic map.

Holland Mountain Fault

Basement-Sediment Fault Contact

Basement-Sediment Unconformity

Zone of Neoacadian Mylonitization

Deformation Age

Crystallization Age

were formed during the Grenville orogeny. Recent geochronologic studies by Berquist (2005) support this interpretation. Northwest foliations found in non-granulite assemblages elsewhere in the basement may also preserve this relict Grenville fabric. Such foliations are more common to the northwest (Cattanach et al., 2004; Merschat and Carter, 2004).

Southeastern boundary

The dominantly metasedimentary Ashe metamorphic suite–Tallulah Falls Formation rocks are separated from the migmatitic biotite–hornblende gneiss and layered biotite granitic gneiss by the Holland Mountain fault. The Holland Mountain fault is likely a syn- to post-metamorphic Taconic thrust fault that has subsequently been folded, thus producing isolated klippen of Ashe metamorphic suite–Tallulah Falls Formation surrounded by older basement rocks (Merschat and Wiener, 1988). Hatcher (2004) correlated the Holland Mountain fault with the Chattahoochee fault and interpreted this contact to be a Neoacadian or Alleghanian thrust fault. Farther to the northeast, Stewart et al. (1997) and Trupe et al. (2003) interpreted the Burnsville shear zone to be an Acadian reactivation of the Holland Mountain fault with dextral strike-slip offset. Final compilation of the west half of the Asheville 100,000 map demands reexamination of the Holland Mountain fault to better determine its extent and geologic history.

Southwestern Boundary

Basement rocks are in contact with rocks of uncertain affinity in the southwestern corner of the Asheville 100,000 quadrangle that were originally mapped as Richard Russell Formation and believed to be correlative with the migmatitic biotite–hornblende gneiss (Merschat and Wiener, 1990; Carter and Wiener, 1999). Recent workers, however, place these rocks in the predominantly Neoproterozoic Cartoogechaye terrane (Hatcher et al., 2004; Hatcher et al., 2005). Although there are many lithologic and structural similarities between the Grenville basement rocks and Richard Russell Formation–Cartoogechaye terrane rocks, metamorphic and geochronologic data suggest that they have contrasting geologic histories.

The boundary between these bodies is therefore significant to the understanding of the geology of the west half of the Asheville quadrangle. It has been mapped on the Clyde and Fines Creek quadrangles as a concordant, folded contact between the Richard Russell Formation–Cartoogechaye terrane and units of the layered biotite granitic gneiss and biotite granitoid gneiss (Merschat and Wiener, 1990; Carter and Wiener, 1999). In light of new data suggesting a possible correlation with the Cartoogechaye terrane, this contact will be reexamined during compilation of the Asheville 100,000 sheet.

Northwestern boundary

The contact between the Max Patch Granite and the Neoproterozoic Ocoee Supergroup in the western portion of the Asheville 100,000 sheet is a nonconformity that is locally overprinted by Neoacadian mylonitization. To the northeast, this contact is mapped as a series of Paleozoic thrust faults.

Intra-basement unit boundaries

Internal boundaries between the four older, highly deformed basement units are much less distinct and have been delineated on the basis of the relative percentages of the major rock types. The overall map pattern exhibits a progressive trend from the high-grade mafic-rich biotite–hornblende migmatitic gneiss in the southeast to the more felsic-rich biotite granitoid gneiss in the northwest. It is unclear if this progression is representative of stacked thrust sheets or a complex heterogeneous intrusive sequence.

The contact separating the protomylonitic granitoid gneiss and biotite granitic gneiss from the Max Patch Granite is more distinct. Middle to late Paleozoic mylonitic shear zones place highly deformed basement rocks on the relatively undeformed and weakly metamorphosed Max Patch Granite. Shear-sense indicators and mineral stretching lineations indicate northwest directed thrusting. New Ar–Ar dating on sericitic muscovite in these shear zones yields ages of 355 to 336 Ma, suggesting that the deformation is Neoacadian (Southworth et al., 2005; Kunk et al., 2006). An interesting feature of this mylonitization is that it affects a much wider area in the north-central part of the 100,000 map than farther to the southwest. To the southwest, most of the deformation associated with Neoacadian thrusting is confined to a subkilometer-wide ductile shear zone. This shear zone increases in width to the northeast and joins an east-trending shear zone along a lateral ramp bordering the Hot Springs window. Farther northwest, the mylonite zone is more than 10 km wide in the White Rock and Sams Gap quadrangles. Mylonitic effects have also been mapped within the basement suite away from unit contacts. These mylonites form an anastomosing network of ductile deformation that locally overprints earlier foliations.

Several workers have termed a group of high-grade, pre-1270 Ma rocks within the central Blue Ridge the Mars Hill terrane. The boundaries of the Mars Hill terrane, traditionally viewed as the extent of the biotite–hornblende migmatitic gneiss, will be examined to further define this important geological feature that is the focus of much new research. Preliminary findings suggest that outcroppings of Mars Hill terrane rocks in the Asheville 100,000 sheet are discontinuous and more widespread than previously thought.

Age

U–Pb zircon ages have been reported by several workers that reinforce the two-fold division of the basement rocks (Fig. 2). The Max Patch crystallization age of 1019 Ma is slightly younger than those of the highly deformed basement gneisses and granulite bodies (1057–1375 Ma) (Berquist, 2005). We believe the Max Patch Granite was intruded after peak Grenville metamorphism or in a location distant from the Mesoproterozoic deformation affecting the other basement gneisses. In this scenario, the highly deformed and metamorphosed central Blue Ridge basement rocks were only juxtaposed with the pristine western Blue Ridge Max Patch Granite during the Neoacadian. Alternatively, it is possible that some of the relatively undeformed granite bodies in the biotite granitic gneiss could be related to the slightly post-Grenville intrusion of Max Patch Granite or even younger intrusions.

Metamorphism

The basement rocks of the Asheville 100,000 quadrangle have a complex metamorphic history dating back to at least 1300 Ma. Unfortunately, it has been difficult to interpret the metamorphic history for many of the map units because they do not contain readily diagnostic field identifiable index minerals.

Three major periods of metamorphism have been identified. The earliest is Grenvillian granulite-facies metamorphism that produced garnet-hypersthene gneisses. These are present along the northwest margin of the deformed gneiss–Max Patch contact and in scattered bodies in the migmatitic biotite–hornblende gneiss near the eastern margin of the basement rocks. We believe this grade of metamorphism was widespread in the basement gneisses, but few unaltered bodies persist because of later metamorphic overprinting. It is also possible, however, that the basement gneisses and amphibolites did not reach granulite-facies conditions in all areas.

The second period of metamorphism, a Barrovian event, is interpreted to be Taconic. Metamorphic intensity drops from sillimanite grade to the southeast (Ashe metamorphic suite) to biotite grade to the northwest (Max Patch Granite). Locally, metamorphic conditions were not sufficient to significantly retrograde the Grenvillian granulite assemblages. This could be related to lower temperatures and pressures or a lack of metamorphic fluids in dry granulite bodies.

The final metamorphic event reached chlorite grade and was associated with Neoacadian mylonitization. Effects of this event include sericitization and saussuritization and are limited to the areas of ductile shearing.

Summary

Table 2 provides a chronological order of events shaping the geology of the area.

The Mesoproterozoic basement rocks of the west half of the Asheville 100,000 map consist of a series of highly deformed and metamorphosed gneiss and the relatively undeformed Max Patch Granite. These map units were juxtaposed along Neoacadian mylonitic fault zones. The northwestern boundary of the basement rocks is a Neoproterozoic nonconformity in some places and a middle to late Paleozoic fault in others. To the southeast, basement rocks are in fault contact with the Ashe metamorphic suite–Tallulah Falls Formation along the Holland Mountain–Chattahoochee–Burnsville faults.

Grenvillian granulite-facies deformation is preserved in localized domains and commonly displays northwest-trending foliations. These fabrics were overprinted during lower-grade Taconic or Neoacadian metamorphism. Finally, chlorite-grade metamorphism occurred in areas affected by middle to late Paleozoic shearing.

Although the basic foundation is in place, many questions remain unanswered in the Blue Ridge basement rocks of the western half of the Asheville 100,000 sheet. Once synthesis is completed, the compilation along with the detailed quadrangle maps will provide solid geologic data on which further work and interpretation can be based.

Acknowledgments

Much of this research was supported by the STATEMAP component of the National Cooperative Geologic Mapping Program under multiple grants to the North Carolina Geological Survey, since 1995. Scott Williams, Lauren Hewitt, Jon Burr, Virginia Peterson, and Pete Berquist made significant mapping contributions. Although not directly used in the new compilation, other workers have completed important mapping projects contributing to the geologic interpretation of the Asheville sheet (Finlayson, 1957; Brewer, 1986; Burton, 1996). Pete Berquist, Steven Ownby, and Calvin Miller provided age dates for several map units. M. J. Kunk and

Table 2. Sequence of events for the west half of the Asheville 100,000 Map

Quaternary	Erosion and formation of surficial deposits; continued regional uplift and joint development.
Tertiary and Mesozoic	Subaerial erosion; variably active epeirogenic uplift.
Pennsylvanian–Permian	Alleghanian deformation (320 Ma to 270 Ma). Culmination of northwestward thrusting of the Blue Ridge allochthon. Typically brittle deformational style with characteristic breccias to near gouge along fault planes.
Mississippian	Neoacadian mylonitization characterized by low grade metamorphism and the development of sericite and/or muscovite that has been dated at 355 to 330 Ma (Kunk et al., 2006) and typically associated with northwest directed thrusting. A major zone, up to several mi. wide, of mylonitization occurs along the western boundary of the basement rocks and affects both the basement and the Max Patch. Similar mylonites occur scattered throughout the basement rocks. This coincides with the sub-Chattanooga Shale Late Devonian–early Mississippian unconformity in the Valley and Ridge.
Late Silurian–Early Devonian	Intrusion of Trondjhemite dikes at about 420–405 Ma (Miller et al., 2000 and Mapes, 2002) that crosscut dominant foliations and structures in both metasediments and basement gneisses.
Early Paleozoic	Orogenic deformation and metamorphism attributed to the Taconic orogeny, median age of about 470 Ma. Primary metamorphic minerals and structural features develop in the sediments. Major and minor folds with corresponding cleavage in the low grade metasediments and foliation in the higher grade metasediments. Syn- to post-metamorphic thrusting (i.e., Holland Mountain fault) occurs. Total movement is unknown but must be many kilometers. Kyanite and sillimanite conditions of Barrovian metamorphism were reached. Effects in the basement are retrogressive, less pervasive, and of local significance. For example, excluding the formation of biotite, metamorphic overprinting is difficult to recognize in both the low grade metamorphic rocks to the northwest and in dry granulite rocks throughout the basement. Coeval with the Early-Middle Ordovician unconformity and change in sedimentation pattern in the Valley and Ridge.
Late Neoproterozoic through Early Odovician	The Snowbird and Walden Creek Groups of the Ocoee Supergroup were deposited in marine rift basins much closer to the continent than were the AMS–TFF. Great Smoky sediments were deposited conformably with the other units of the Ocoee, although the Great Smoky is usually found to be in fault contact with the other units except in the Hot Springs and White Rock quadrangles. Walden Creek strata are succeded conformably by the early Paleozoic platform rocks (Chilhowee Group through Knox Dolomite).
Middle Neoproterozoic	Intrusion of ultramafic rocks. Deposition of Late Proterozoic AMS–TFF sedimentary and volcanic materials in a more distal seaward basin or basins.
Middle Neoproterozoic	Intrusion of Bakersville mafic dikes at about 734 Ma (Goldberg et al., 1986) and associated felsic plutons (i.e., hornblende bearing metagranite near Big Bald on Sams Gap quadrangle).

Table 2. Sequence of events for the west half of the Asheville 100,000 Map (continued)

Early Neoproterozoic or Late Mesoproterozoic	Post Grenville mylonitization of variable intensity formed an overprinting foliation that locally changed the character of the basement rocks making them more layered to thinly layered than their protoliths. Intrusion of the Max Patch Granite and correlatives at about 1020 Ma (Berquist et al., 2005). The Max Patch Granite exhibits no apparent Grenville metamorphism. In fact the only recognizable deformation in these units may be Neoacadian.
Mesoproterozoic	The Grenville orogenic cycle (1000 to 1200 Ma). Granulite or at least upper amphibolite facies metamorphic and deformational event or events that produced complexly deformed gneissic rock.
Mesoproterozoic	Intrusion of biotite granitoid gneiss and correlatives at about 1170 Ma (Berquist et al., 2005). Formation of protoliths of variable origin and composition for the following map units: migmatitic biotite-hornblende gneisses, layered biotite granitic gneisses, amphibolite, altered ultramafic rock, and granulite gneiss.
Early Mesoproterozoic	Formation of the protolith of the granitic gneiss dated at 1.38 Ga on the Sams Gap quadrangle (Berquist et al., 2005). This rock may occur as a xenolith within younger intrusives.

Scott Southworth of the United States Geological Survey dated the muscovite mica in selected shear zones. R. D. Hatcher, Jr., and Nancy Meadows of the University of Tennessee improved the original manuscript with editorial and review comments. We are responsible for any misinterpretations and errors.

Road Log and Stop Descriptions

Safety and stop etiquette

Caution, common sense, and consideration for fellow field trip participants should be observed at all times. Three of the stops are on or near an interstate highway and are to be treated with extra care and considerable caution. The other stops are along secondary paved roads and private driveways with relatively low motor vehicle use, but please be careful at all stops. Motor vehicles are not the only safety issue on this field trip. Many of the roadcuts and quarry walls are at least several meters high and have the potential for rock falls at any time. Other concerns include poor footing on loose rubble, rock hammering issues, and noxious plants. Please follow the instructions of the field trip leaders.

We hope everyone has a productive and enjoyable experience examining the geology of these Blue Ridge basement outcrops.

Day 1

(Figure 1 shows stop locations on the preliminary compilation map).

Cumulative mileage	Incremental mileage	
0.0	0.0	Field trip begins at the Holiday Inn Asheville–Biltmore East headquarters hotel (1450 Tunnel Rd., Asheville, NC). Right turn out of entrance to hotel on to US 70. Immediate left turn at stop light on to Porter's Cove Road.
0.3	0.3	Right turn at entrance ramp to I-40 west. Scattered rock exposures along next 21 mi. are in the Ashe metamorphic suite/ Tallulah Falls Formation (AMS–TFF).
8.6	8.3	Cross French Broad River.
18.9	10.3	Buncombe-Haywood County Line.
19.2	0.3	Ascend Holland Mountain. Exposures on north side of the interstate are sillimanite grade metagraywackes and sillimanite schists of the AMS–TFF.
20.5	1.3	End good exposure of the AMS–TFF.
22.2	1.7	Cross the Holland Mountain-Chatahoochee thrust fault with AMS–TFF in the hanging wall to the east and Mesoproterozoic Earlies Gap Biotite Gneiss of the Migmatitic biotite-hornblende gneiss map unit to the west and north in the footwall. The trace of this fault is very irregular through the Canton area.
25.8	3.6	View of Chambers Mountain with towers on top ahead. The AMS–TFF rocks underlying Chambers Mountain are in the hanging wall of the Holland Mountain–Chatahoochee thrust fault.
31.2	5.4	Cross Pigeon River.
31.3	0.1	Leave I-40 at exit 24.
31.6	0.3	At end of exit turn left onto NC 209.
32.0	0.4	Turn right onto Iron Duff Road (SR 1364).
33.0	1.0	Bear left onto Coleman Mountain Road (SR 1364).

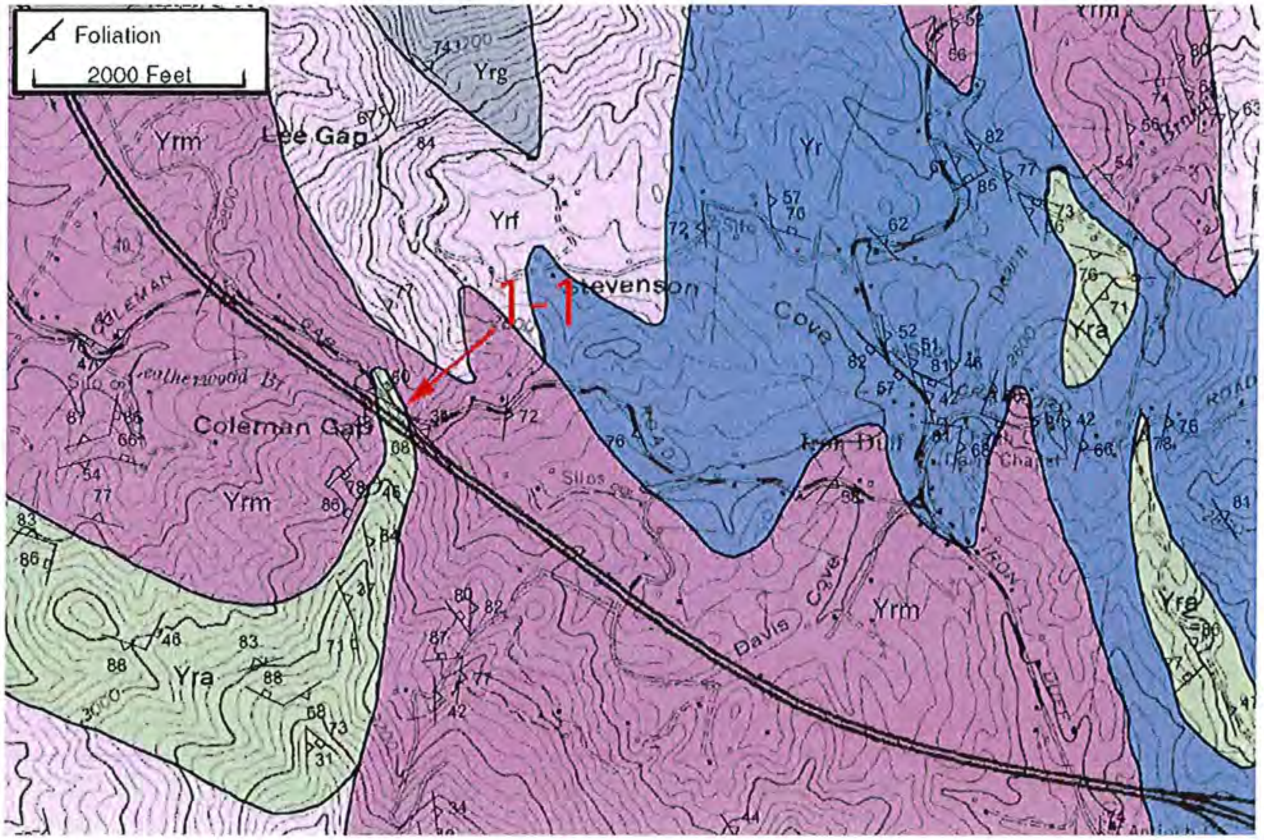


Figure 1-1-1: Local geologic map of Stop 1-1. Yrm - Richard Russell migmatite. Yra - Richard Russell amphibolite. Yrf - Richard Russell felsic gneiss. Yr - Richard Russell biotite gneiss. Yrg - Richard Russell metagraywacke.

STOP 1-1: Migmatitic gneisses along roadcut in Coleman Gap. 25 minutes.

Location: STATE ROAD 1364—Clyde quadrangle (NCGS Manuscript Geologic Map, Merschat and Wiener 1992; Fig. 1-1-1).

GPS Location: 35° 34' 52" N; 82° 59' 11" W.

Purpose: To examine granoblastic textures and different lithologies within migmatitic gneisses of the Richard Russell Formation-Cartoogechaye terrane, a component of the compilation map's migmatitic biotite-hornblende gneiss (Fig. 1-1-2).

Description: The bench on Coleman Mountain Road provides excellent exposures above the traffic and noise of Interstate 40 in Coleman Gap. The eastern portion of the outcrop is composed chiefly of migmatitic biotite gneiss with minor lenses of coarse-grained amphibolite. The western part of the outcrop is dominated by coarse-grained, migmatitic amphibolite. Leucocratic zones within the migmatitic amphibolite exhibit a granoblastic texture of quartz, feldspar, amphibole, and garnet. Amphibolite layers are commonly boudined and broken, creating blocky mafic segregations within more leucocratic migmatite and biotite gneiss layers. Coarse-grained (>2 cm) garnet porphyroblasts overprint the primary foliation throughout the outcrop and appear to be at least synkinematic, to postkinematic.

Approximately 100 m from the eastern end of this roadcut, primary migmatitic foliation and outcrop-scale layering (which trends northeast and dips northwest) is crosscut by a small ductile shear zone that trends northwest and dips to the northeast. Nearby, there is also a steeply dipping crosscutting trondjhemite dike about 15 cm thick that appears to be unaffected by metamorphism and deformation.

Arthur Keith (1904) placed this outcrop within his Carolina Gneiss. He also showed a small sliver of Roan Gneiss here, which is equivalent to amphibolite in the outcrop. Merschat and Wiener (1990) interpreted these rocks as belonging to the Richard Russell Formation (RRF), and tentatively correlated them with similar lithologies in Mesoproterozoic basement rocks to the northeast. In contrast, Hatcher et al. (2005) included them in their

Figure 1-1-2. Boudinaged garnet amphibolite layer within migmatitic biotite gneiss.

Cartoogechaye terrane (CT), a package of rocks containing high-grade Neoproterozoic metasedimentary sequences and minor Mesoproterozoic basement gneiss.

If the rocks in this outcrop are part of the CT, the major metamorphic event that affected them would be Taconic (Moecher et al., 2004; Hatcher et al., 2004; Hatcher et al., 2005). If they are correlative with basement gneisses to the northeast, however, the primary metamorphic event should be Grenville. What we attempt to show at other stops on this field trip is that the major granulite-facies metamorphic event in basement gneisses on the west half of the Asheville 100,000 sheet is either pre-Grenville or Grenville, and that Taconic metamorphism has only weakly overprinted the basement gneisses. Although we do not rule out a possible connection between the basement gneisses in the Asheville 100,000 area and the rocks in the Cartoogechaye terrane shown as basement by Hatcher et al. (2005) there is a significant difference in the timing of high-grade metamorphism between these two areas of Grenville basement.

The contact between CT rocks and basement gneisses in the west half of the Asheville 100,000 sheet is therefore an important piece of a complex puzzle. Detailed geologic mapping of the Clyde quadrangle (Merschat and Wiener, 1992) and the Fines Creek quadrangle (Carter and Wiener, 1999) locates and shows the contact between the rocks at this stop and the basement gneisses (Sandymush Felsic Gneiss) to be concordant.

34.5	0.4	Continue west and turn around at intersection with Maple Spring Drive (SR 1398). Back track to NC 209.
37.2	2.7	Turn Left on to NC 209.
38.4	2.2	Cross Pigeon River.
40.2	1.8	STOP 1-2: White mica-bearing rocks in basement gneisses.

STOP 1-2: White mica-bearing rocks in basement. 20 min.

Location: NC Highway 209—Clyde quadrangle (NCGS Manuscript Geologic Map, Merschat and Wiener 1992; Fig. 1-2-1).

GPS Location: 35° 36' 13" N; 82° 56' 14" W.

Purpose: To examine rocks originally mapped as metagraywacke of the Richard Russell Formation.

Description: Rocks in this outcrop are northwest of the Holland Mountain–Chattahoochee fault (which contains Ashe metamorphic suite–Tallulah Falls Formation (AMS-TFF) in its hanging wall), and southeast of the Hayesville fault, (containing rocks of the Great Smoky Group). This outcrop consists of sulfidic, garnet-muscovite-biotite

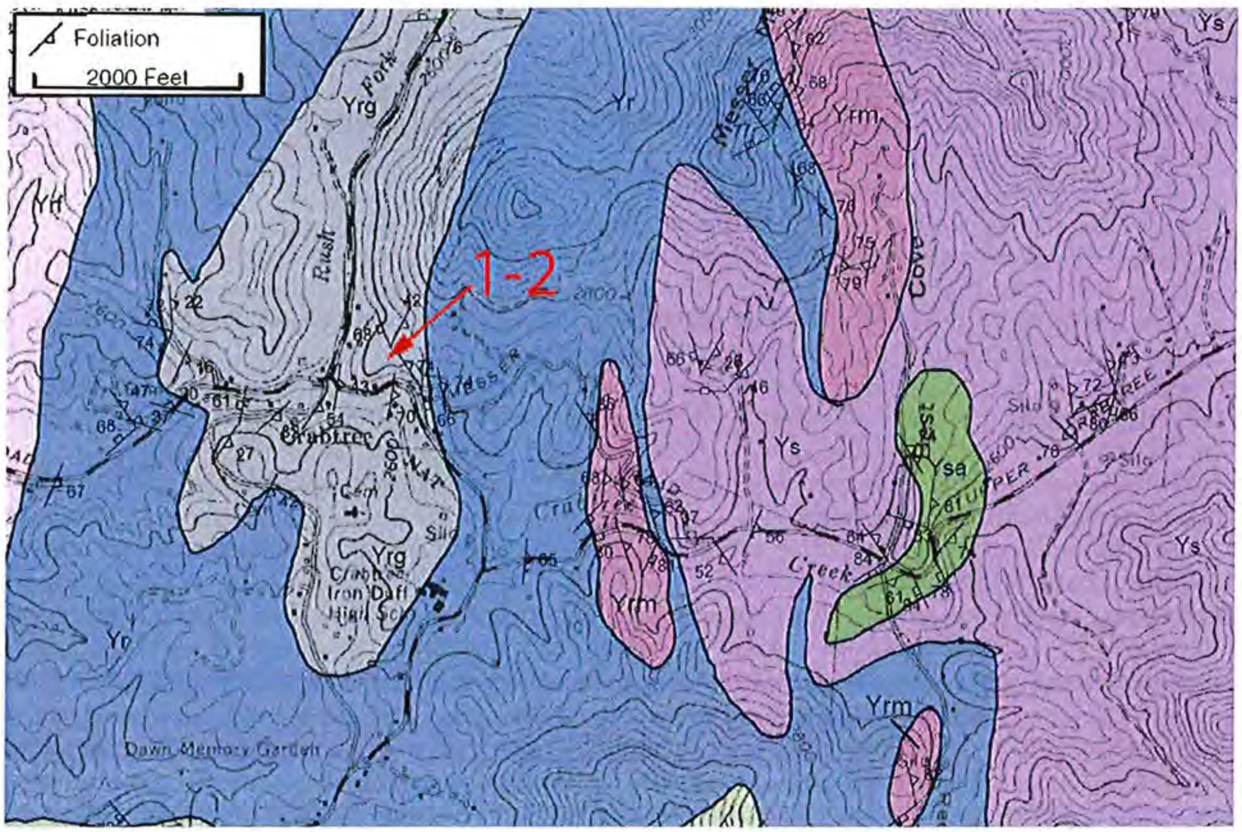


Figure 1-2-1: Local geologic map of Stop 1-2. Yrg - Richard Russell metagraywacke. Yr - Richard Russell biotite gneiss. Yrm - Richard Russell migmatite. Yrf - Richard Russell felsic gneiss. Ys - Sandymush felsic gneiss. Ysa - Sandymush amphibolite.

gneiss and schist, and is locally migmatitic. This rock type is common throughout the AMS–TFF, but is nearly absent in the Grenville basement to the northeast.

White mica-bearing metagraywackes of this outcrop presented a dilemma as to what to correlate them with when first discovered in 1989 during detailed mapping on the Clyde quadrangle. Although quite similar to AMS–TFF rocks to the east, they lack kyanite and could not be demonstrably mapped into the AMS–TFF. A folded or downfaulted option was considered, but not chosen. A few years earlier during the mapping of the Canton and Sandymush quadrangles biotite gneiss and amphibolite, commonly migmatitic, were correlated with similar basement rocks in north Georgia, the Richard Russell Formation (Merschat and Wiener, 1988). When mapping commenced in the Clyde quadrangle, the white mica-bearing metagraywackes of this outcrop were mapped as a subdivision within the Richard Russell Formation. At the time it seemed most plausible to choose a stratigraphic option, since both metagraywacke and granitic gneiss (preliminary concordant Pb–Pb age for zircons of 1,035 Ma, Nelson et al. 1998) are important constituents of the Richard Russell Formation in Georgia. This interpretation makes the Richard Russell Formation potentially correlative with basement rocks to the northeast.

Since the early 1980s, R. D. Hatcher, Jr. and his students have mapped similar rock types in quadrangles to the southwest. In their most recent synthesis (Hatcher et al., 2005), these rock types are included in the Cartoogechaye terrane, a tectonostratigraphic package within the Hayesville thrust sheet. Rocks of the Cartoogechaye terrane consist of metasandstone, pelitic schist, assemblages of altered mafic and ultramafic rocks, and Grenville basement. Sediments of the Cartoogechaye contain Grenvillian detrital zircons that were affected by the Taconic deformational event (Hatcher et al., 2005). Thus, the upper amphibolite- to granulite-facies metamorphism, and the dominant foliation in these rocks should be Taconic in age. Mapping on the Clyde and adjoining Fines Creek quadrangles shows the contact between rocks of the Cartoogechaye terrane and basement gneisses to the northeast (Sandymush Felsic Gneiss) to be concordant. The nature of this contact will be re-examined before final synthesis of the Asheville 100,000 sheet.

43.1	2.9	Make a 180-degree turn. Backtrack south on NC 209. Right turn and return to I-40 west.
47.1	4.0	Cross Hayesville fault into Copperhill Formation metagraywackes of the Great Smoky Group in footwall of the fault.
48.1	1.0	Cross Pigeon River.
51.1	3.0	Large roadcuts to the SW are in the Copperhill Formation.
51.9	0.8	Cross the Hayesville fault (?) back into basement.
52.0	0.1	Cross Pigeon River.
52.3	0.3	Take Exit 15 and at the end of the exit go straight ahead and park on right side of entrance ramp. Stop 1-3: Grenville granitic gneisses and mylonites.

STOP 1-3: Grenvillian granitic basement gneisses, pervasively deformed amphibolite, and mylonites. 20 min.

Location: I-40, Exit 15—Fines Creek quadrangle (published geologic map, Carter and Wiener 1999; Fig. 1-3-1).

GPS Location: 35° 40' 07" N; 82° 59' 42" W.

Purpose: To examine granoblastic textures within migmatitic biotite granitoid gneiss and selective overprinting of mylonitic deformation.

Description: Complexly folded migmatitic granitic gneisses dominate the western end of this outcrop. Some of the granitic rocks exhibit a granoblastic texture. The eastern portion of the outcrop consists of well-foliated fine-grained amphibolite. Undulatory migmatitic foliation in the granitic gneisses generally strikes northwest, a common orientation found in relic Mesoproterozoic granulites. There is also a strong northeast oriented mylonitic overprint that is present in localized, meter-scale zones in the granitic gneisses. Pervasive deformation becomes more widespread and better defined within amphibolites in the eastern portion of the outcrop. An interesting

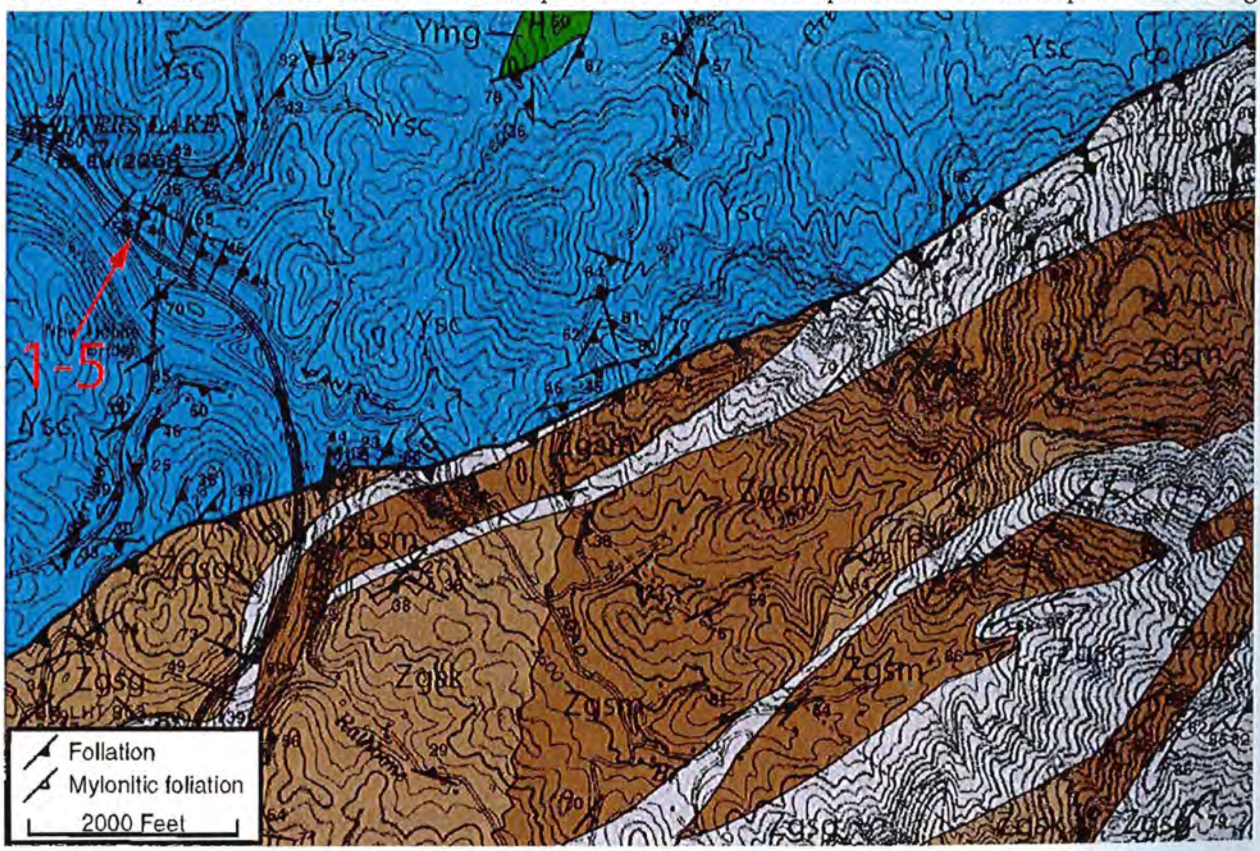


Figure 1-3-1: Local geologic map of Stop 1-3. Ysc - Spring Creek granitoid gneiss. Ymg - metagabbro. Zgsg - Great Smoky metagraywacke. Zgsm - Great Smoky garnet-mica schist. Zgsk - Great Smoky kyanite garnet-mica schist.

feature to note in this outcrop is the strain partitioning between mafic and felsic rock units—mafic rocks developed a much more uniform pervasive foliation than felsic rocks.

Both granitic gneiss and amphibolite are interpreted to be basement rocks here. Granitic gneiss apparently preserves a high-grade Grenville-age metamorphic fabric, which was then overprinted by later (Grenville?) mylonitization.

54.2 1.9 Continue along entrance ramp to merge with I-40 West. Drive 1.9 mi. and pull off on right shoulder. STOP 1-4: Unconformity between Max Patch Granite and basal Neoproterozoic Snowbird Group. CAUTION! Dangerous stop because of high volume and speed of interstate traffic. NC Highway Patrol permission required!

STOP 1-4: Unconformity between Max Patch Granite and Neoproterozoic basal Snowbird Group. 30 min.

Location: I-40—Cove Creek Gap quadrangle (adjacent to the Fines Creek quadrangle; Fig. 1-4-1).

GPS Location: 35° 40' 31" N; 83° 01' 16" W.

Purpose: To examine the contact between Neoproterozoic basal metasediments of the Snowbird Group with the underlying Mesoproterozoic Max Patch Granite.

Description: This stop revisits one from a previous field trip along I-40 for the Tennessee Academy of Sciences (Hadley et al., 1974). One difference from the 1974 stop is that we interpret the Mesoproterozoic basement complex of Hadley et al. to be Max Patch Granite. The Mesoproterozoic Max Patch is granodiorite here and consists mostly of saussuritized plagioclase, quartz, pink potassium feldspar, hornblende, and biotite. Resting unconformably on the Max Patch is the Wading Branch Formation, the lowermost unit of the Neoproterozoic Snowbird Group. The contact strikes N10°E and dips about 45° southeast. Slaty cleavage in the Wading Branch Formation dips more steeply southeast. According to Hadley et al. (1974), the lower 70 ft. of the Wading Branch Formation here consists of strongly foliated chlorite schist underlying a dark, medium-bedded, chloritic metagraywacke con-

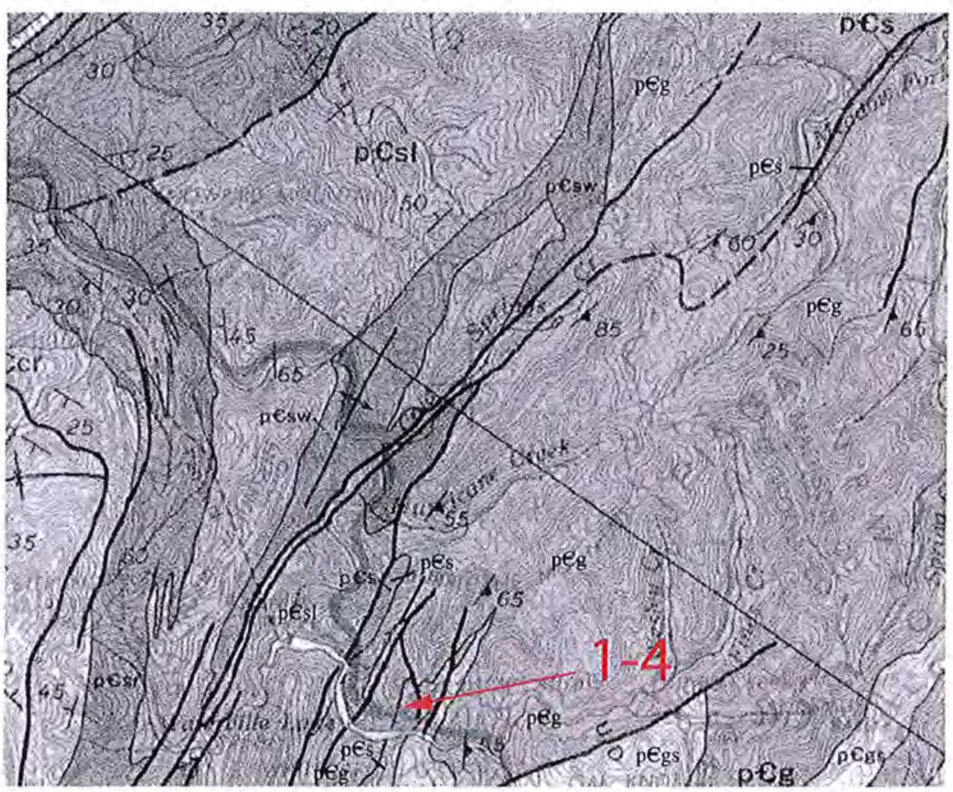


Figure 1-4-1: Local geologic map of Stop 1-4 from Hadley and Nelson (1971). pCg - Max Patch Granite and Cranberry Gneiss. pCs - Roaring Fork Sandstone, Long Arm Quartzite, and Wading Branch Formation (Undivided). pCsw - Wading Branch Formation. pCsl - Long Arm Quartzite. pCsr - Roaring Fork Sandstone. pCgs - Great Smoky Group Undivided.

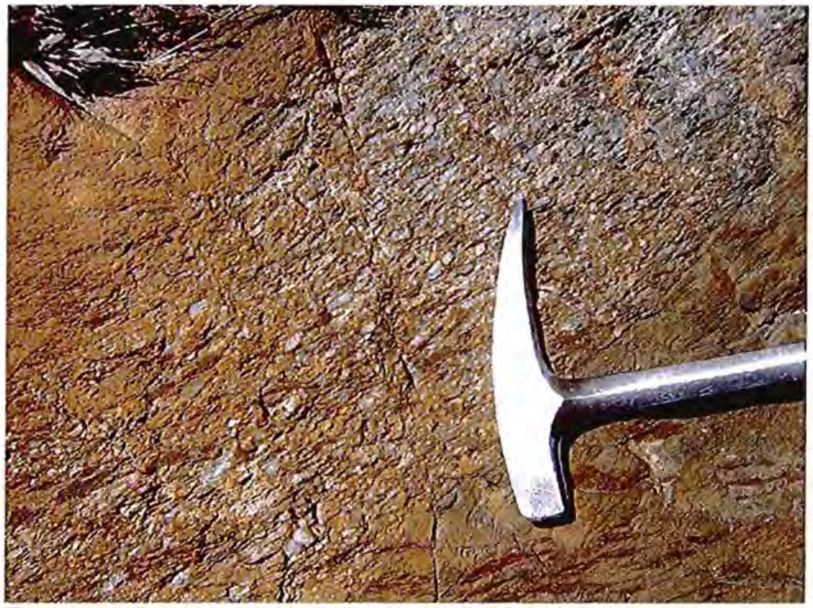


Figure 1-4-2. Conglomeratic interlayer in the Wading Branch Formation. Note the flattened pebbles.

taining several 1 ft.-thick pebble conglomerate beds (Fig. 1-4-2). Large detached blocks of granodiorite occur within the chlorite schist. Wading Branch metagraywacke beds become sandier and less chloritic toward the contact with the overlying Longarm Quartzite.

The well-exposed contact between the Wading Branch Formation and Long Arm Quartzite is sharp. The Longarm Quartzite consists of light tan to grayish pink, current bedded meta-arkose, metasubgraywacke, feldspathic quartzite, and meta-arkosic conglomerate, with thin interbeds of chloritic, sericite schist.

The Snowbird Group in this area was metamorphosed to greenschist facies in the Paleozoic. Biotite is the highest Barrovian index mineral observed in any of the Snowbird units mapped in the west half of the Asheville 100,000 sheet. A short distance to the southeast on the adjoining Clyde (Merschat and Wiener, 1992) and Fines Creek quadrangles (Carter and Wiener, 1999), kyanite-bearing rocks were mapped as the Copperhill Formation of the Great Smoky Group (Merschat and Wiener, 1990), and occur in an early Paleozoic thrust sheet.

There are at least two explanations for the rapid increase in metamorphic grade over such a short distance. Hadley and Goldsmith (1963) show the metamorphic isograds overprinting major structures and unit boundaries to converge in the vicinity of the outcrop. Another possibility is that the units were juxtaposed along syn- to post-metamorphic faults. This has not been confirmed by detailed mapping but would explain the rapid increase in metamorphic grade, and the apparent thinning of the Snowbird Group, over such a short distance. Note that in these exposures the Longarm Quartzite is succeeded by Great Smoky Group strata with no hint or room for the younger Snowbird Group formations that normally overlie the Longarm. The fault interpretation may explain the prominent deflection of Hadley and Goldsmith's (1963) isograds in this area.

56.7	2.5	Continue west on I-40. Entrance to I-40 West Rest area. BREAK. Return to I-40 West. Roadcuts are in the Longarm Quartzite of Snowbird Group for about a mile.
60.5	3.8	Depart I-40 West at Exit 7, Harmon Den. Turn right on Cold Springs Creek Road (National Forest Road 1148). Lower portion of NFS Road 1148 has great exposures of the Cold Springs mylonite zone (in Wading Branch formation of Snowbird Group). Hadley and Goldsmith (1963) initially placed the mylonites in the basement complex.
67.0	6.5	Turn left toward Max Patch on Fines Creek Road (SR 1182). This intersection is on the divide between the French Broad River drainage basin and Pigeon River drainage basin.
67.3	0.3	Right turn on Little Creek Road (SR 1181).
69.2	1.9	Left turn on to Poplar Gap Road (SR 1180).
70.8	1.6	STOP 1-5: Max Patch Granite along Poplar Gap Road. Outcrops on left side of the road.

STOP 1-5: Max Patch Granite along Poplar Gap Road. 15 min.

Location: STATE ROAD 1180—Lemon Gap quadrangle (NCGS Manuscript Geologic Map, Merschat, Cattanach, and Carter, 2002; Fig. 1-5-1).

GPS Location: 35° 47' 46" N; 82° 55' 10" W.

Purpose: To observe undeformed Max Patch Granite.

Description: Here is a typical exposure of undeformed Max Patch Granite. The massive, well-jointed granite is coarse-grained, granoblastic, and consists mostly of pink potassium feldspar, plagioclase feldspar that has been saussuritized to epidote and sericite, quartz, hornblende, and minor biotite. It contains mafic schlieren composed mainly of biotite and hornblende, which are interpreted as xenoliths. Uncommon felsic xenoliths also occur locally within the Max Patch. Complex deformation and folding have not been observed within the Max Patch Granite, although many outcrops within the main body of the unit exhibit varying degrees of mylonitization.

Recent zircon geochronologic data from the Max Patch Granite indicate a crystallization age of 1020 Ma, with metamorphic rims of approximately 1000 Ma (Berquist et al., 2005).

71.3 0.5 Continue along Poplar Gap Road 0.5 mi.. Outcrops are on left. STOP 1-6: Mylonitic Snowbird Max Patch Granite and Metasediments.

STOP 1-6: Mylonitized Snowbird Group and Max Patch Granite rocks on Poplar Gap Road. 25 min.

Location: STATE ROAD 1180—Lemon Gap quadrangle (NCGS Manuscript Geologic Map, Merschat, Cattanach, and Carter, 2002; Fig. 1-5-1).

GPS Location: 35° 47' 37" N; 82° 54' 53" W.

Purpose: To examine the effects of Neoacadian mylonitization on the Max Patch Granite and the Snowbird Group (Fig. 1-6-1).

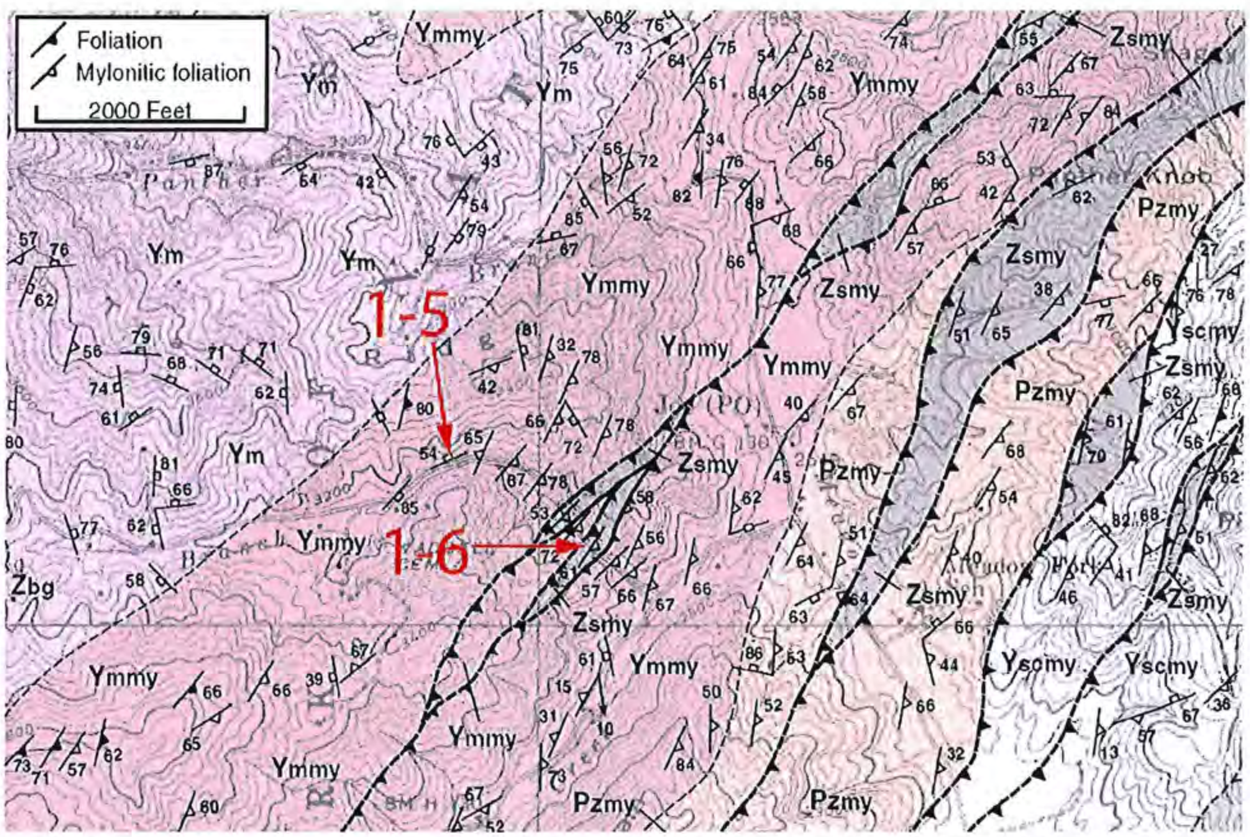


Figure 1-5-1: Local geologic map of Stops 1-5 and 1-6. Ym - Max Patch Granite. Ymmy - mylonitic Max Patch Granite. Pzmy - Paleozoic mylonite. Yscmy - mylonitic Spring Creek Granitoid Gneiss. Ysc - Spring Creek Granitoid Gneiss. Zsmy - mylonitic Snowbird Formation.

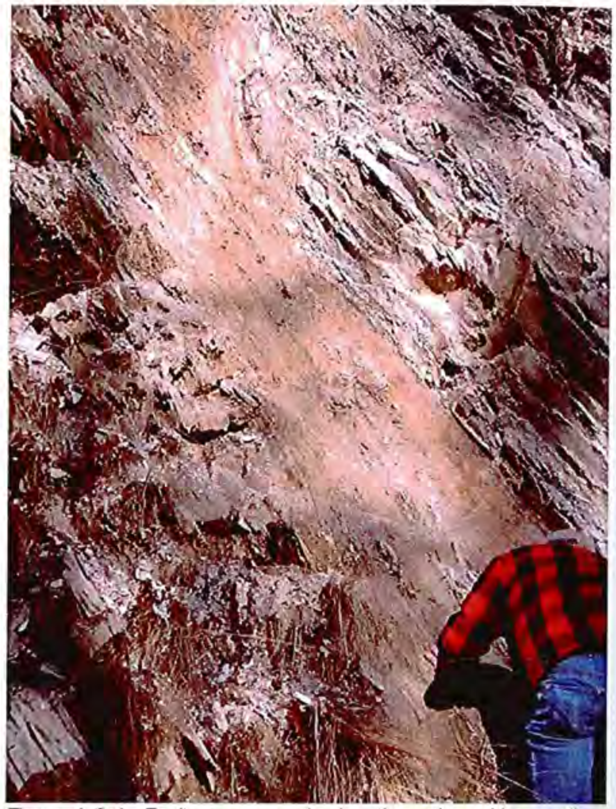


Figure 1-6-1. Fault gouge marks location where Neoacadian mylonitic fabric is disrupted by later brittle faulting. Mapping geologist for scale.

Description: The roadcuts here show a progression of Neoacadian mylonitization across the contacts between the Max Patch Granite and several thin slivers of metasedimentary rocks correlated with the Snowbird Group. A hundred meters south, at the intersection of Poplar Gap Road and Little Creek Road (SR 1181), outcrops of massive Max Patch Granite are nearly pristine, but the effects of mylonitization become increasingly more intense as one traverses northward to this outcrop. In places, mylonitization is so intense that it is difficult to determine whether the rocks are ultramylonitized granite or mylonitic metasediments, but a lighter color due to a higher quartz content helps distinguish metasediments from mylonitic Max Patch Granite. Making an accurate distinction was a common problem while mapping in this part of the Asheville 100,000 sheet. Note also the prominent fault gouge that could either be a younger brittle reactivation of the fault, or an indication of brittle-ductile transition during Neoacadian thrusting. A similar feature can be observed at Stop 1-7 in the Meadow Fork shear zone.

Mylonitic foliation in both the granite and metasedimentary slivers dip southeast and is cut by a thin, post-mylonitic brittle fault. At least three structural interpretations can be proposed for the geometry of these slivers in this outcrop: 1) they are fault-bounded slices of Snowbird Group rocks which have been transported an unknown distance within a Neoacadian fault zone, 2) they are isoclinally down-folded remnants of the unconformable contact between the Max Patch Granite and Snowbird Group that have been overprinted by later Neoacadian mylonitization, or 3) they are Snowbird Group sediments resting unconformably on the Max Patch Granite that have been thoroughly dissected by the Neoacadian mylonitization.

The nature and timing of prominent shear zones in the northwestern part of the Asheville 100,000 sheet is complex. In 1980 Merschat initially mapped strongly mylonitic rocks on the Huntdale quadrangle north of the Asheville 100,000 (Merschat, 2001). Later, Carter et al. (1998) coined the name "Pigeonroost-Fines Creek mylonite zone" for a broad, anastomozing zone of late Paleozoic mylonitization that extends over 70 km from the Huntdale quadrangle southwest to the Fines Creek quadrangle (Carter and Wiener, 1999). This zone of mylonitization is characterized by retrograde sericite and chlorite growth at the expense of feldspar and mafic minerals, respectively. Sericite and muscovite have yielded Ar-Ar ages of 355 to 336 Ma (Southworth et al., 2005). Shear-sense indicators and mineral stretching lineations indicate northwest directed thrusting. Mylonitization within the zone varies in intensity. It typically progresses from non-mylonitic to protomylonitic to mylonitic over variable distances. The progression can occur many times within a map unit and in places is not continuous along strike. The zone also exhibits a change in map pattern along strike. To the northeast, it is depicted as a broad anastomosing series of mylonite units, but narrows and becomes more linear to the southwest. This change may reflect an evolving mapping style and interpretation along strike, or a real change in structural character within the zone.

71.4	0.1	Continue down hill to stop sign. Turn left onto Little Creek Road (SR 1181).
71.7	0.3	Turn right onto Meadow Fork Road (SR 1175).
75.1	3.4	Outcrops on right. STOP 1-7: Mylonitic Max Patch in the Meadow Fork shear zone along Meadow Fork Road.

STOP 1-7: Mylonitic Max Patch Granite in the Meadow Fork shear zone along Meadow Fork Road. 20 min.

Location: STATE ROAD 1175—Lemon Gap quadrangle (NCGS Manuscript Geologic Map, Merschat, Cattanach, and Carter, 2002; Fig. 1-7-1).

GPS Location: 35° 45' 34" N; 82° 55' 43" W.

Purpose: To examine strong mylonitic fabrics within a Neoacadian shear zone and possible brittle overprinting.

Description: This outcrop is part of the Paleozoic mylonite (Pzmy), a highly sheared unit within a high-strain zone associated with Neoacadian thrusting along the Meadow Fork fault. These rocks are characterized by alteration of feldspars, plagioclase in particular, to sericite and alteration of mafic minerals to chlorite. Rocks within the Meadow Fork shear zone may have undergone a large amount of flattening and in places are phyllonitic. This exposure is somewhat atypical because the protolith can be identified as Max Patch Granite. Elsewhere along the fault mylonitic overprinting is too strong to make a positive identification of the protolith.

A down-dip mineral lineation defined by mica alignment and preferred grain-shape orientation is consistent with northwest-directed thrust faulting. The Meadow Fork shear zone was stated to be a Paleozoic structure of Taconic or later age (Oriel, 1950). New Ar-Ar ages, combined with field relationships that show a similarity in structural style, metamorphic grade, and orientation suggest that most Paleozoic mylonites within the basement on the west half of the Asheville 100,000 sheet are Neoacadian. Further studies are needed to confirm this new interpretation, however.

Note the prominent fault gouge that could either be a younger brittle reactivation of the fault, or an indication of brittle-ductile transition during Neoacadian thrusting. No shear-sense indicators have been identified within this zone.

Neoacadian thrusting within the basement contrasts with Acadian strike-slip deformation reported to the east along the Burnsville shear zone (Stewart et al., 1997; Trupe et al., 2003). This raises the possibility that younger Neoacadian thrust fabrics have overprinted older Acadian strike-slip fabrics.

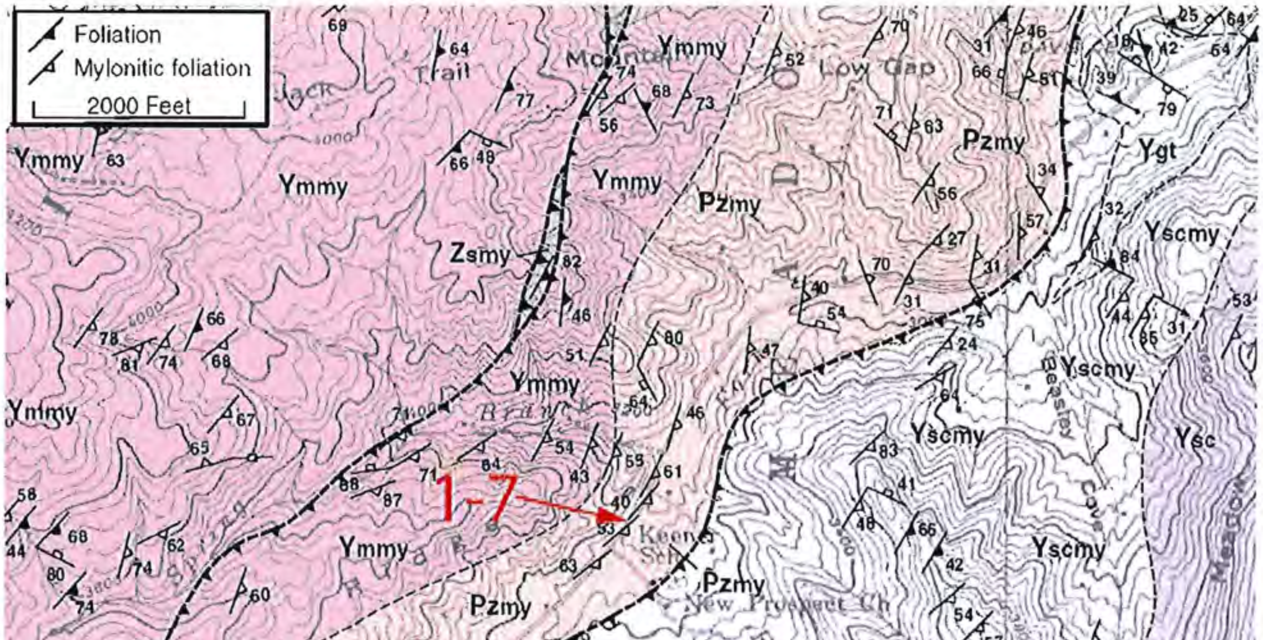


Figure 1-7-1: Local geologic map of Stop 1-7. Ymmy - mylonitic Max Patch Granite. Pzmy - Paleozoic mylonite. Yscmy - mylonitic Spring Creek Granitoid Gneiss. Ysc - Spring Creek Granitoid Gneiss. Zsmy - mylonitic Snowbird Formation. Pzc - Paleozoic cataclasite.

75.1	0.0	Turn around and head north on Meadow Fork Road.
76.8	1.7	Turn right at Caldwell Mountain Road (SR 1165).
78.9	2.1	Turn left on to NC 209.
81.1	2.2	Turn left on to Freedom Lane (a private drive).
81.4	0.3	STOP 1-8: Mylonitic foliation overprinting a Grenvillian foliation. A small weathered outcrop just beyond intersection with Mountain Valley Road on right.

STOP 1-8: Neoacadian mylonitic foliation overprinting Grenville foliation. 15 min.

Location: Private drive from NC Highway 209—Spring Creek quadrangle (NCGS Manuscript Geologic Map, Cattanach, Merschat, Carter, 2003; Fig. 1-8-1).

GPS Location: 35° 47' 59" N; 82° 51' 28" W.

Purpose: To examine northwest-trending foliations in a Grenville granulitic rock that has been clearly overprinted by Neoacadian mylonitization.

Description: A small weathered outcrop of garnet-rich granulite gneiss in the Spring Creek Granitoid Gneiss (a component of the compilation map's biotite granitoid gneiss), exhibiting a well-developed, northwest-striking layering, occurs on a private drive along N.C. 209. Northwest-striking foliations are common in this area, especially in garnet-rich granulite gneiss and associated quartz monzodioritic and tonalitic granulite (Merschat, Cattanach, and Carter, 2002). A northeast-striking, southeast-dipping mylonitic foliation overprints the northwest-striking foliation. Merschat and Wiener (1990) suggested that northwest-trending foliations in the Mars Hill area are Grenville-age relicts that survived Taconic overprinting during the early Paleozoic. We interpret the overprinting foliation at this stop to be Neoacadian because it is similar in orientation and mineral composition to the

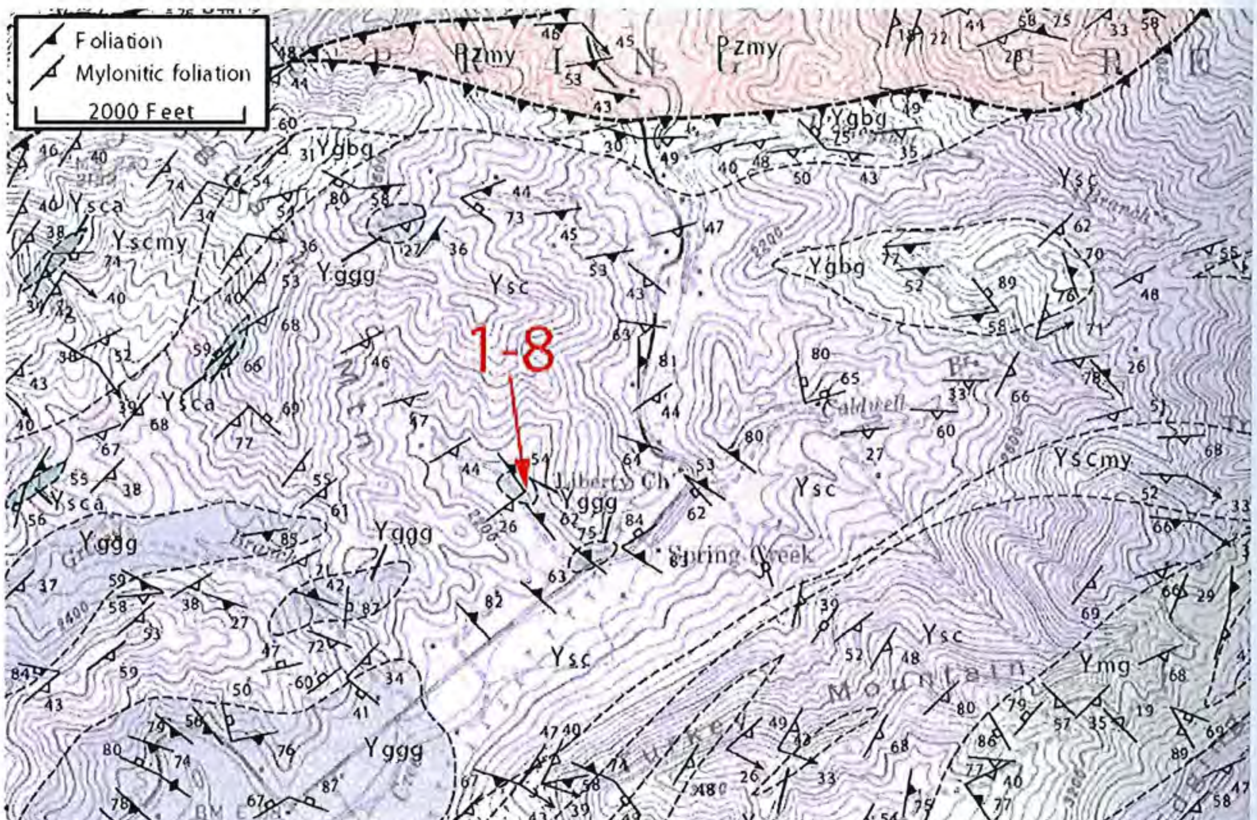


Figure 1-8-1: Local geologic map of Stop 1-8. Pzmy - Paleozoic mylonite. Ysc - Spring Creek Granitoid Gneiss. Yscmy - mylonitic Spring Creek Granitoid Gneiss. Ysca - Spring Creek amphibolite. Ygbg - granoblastic biotite granitic gneiss. Yggg - garnet-rich granulite gneiss. Ymg - metagabbro.

dated, sericitic Neoacadian shear zones along strike. In addition, the outcrop is most likely too far northwest to have been significantly affected by the low-grade Taconic metamorphism.

81.4	0.0	Turn around and backtrack to NC 209.
81.7	0.3	Turn Left on to NC 209 north.
86.4	4.7	Enter Hot Springs window. Begin in the Roaring Fork Formation of the Snowbird Group and continue to move up section into the Walden Creek Group.
91.1	4.7	Base of Chilhowee Group in stratigraphic contact with Sandsuck Formation of the Walden Creek Group.
92.4	1.3	Continue straight through Intersection NC 209 and US 25-70 on US 25-70 east through Hot Springs, North Carolina.
92.6	0.2	Cross French Broad River.
97.3	4.7	Cross Laurel River.
97.4	0.1	Turn Left on to NC 208 North.
98.6	1.2	STOP 1-9 Basement window within the Snowbird Group on Highway 208. Outcrops on right before bridge.

STOP 1-9: Basement klippe on Highway 208. 20 min.

Location: NC Highway 208—Hot Springs quadrangle (NCGS Manuscript Geologic Map, Carter, 2001; Fig. 1-9-1).

GPS Location: 35° 55' 21" N; 82° 45' 06" W.

Purpose: To observe a brittle fault klippe showing basement resting on rocks of the Snowbird Group.

Description: Cataclastic basement gneisses structurally overlie rocks of the Pigeon Formation (Snowbird Group) at this outcrop. Basement rocks in this area consist of a mixed array of mafic and felsic breccias, mylonite and

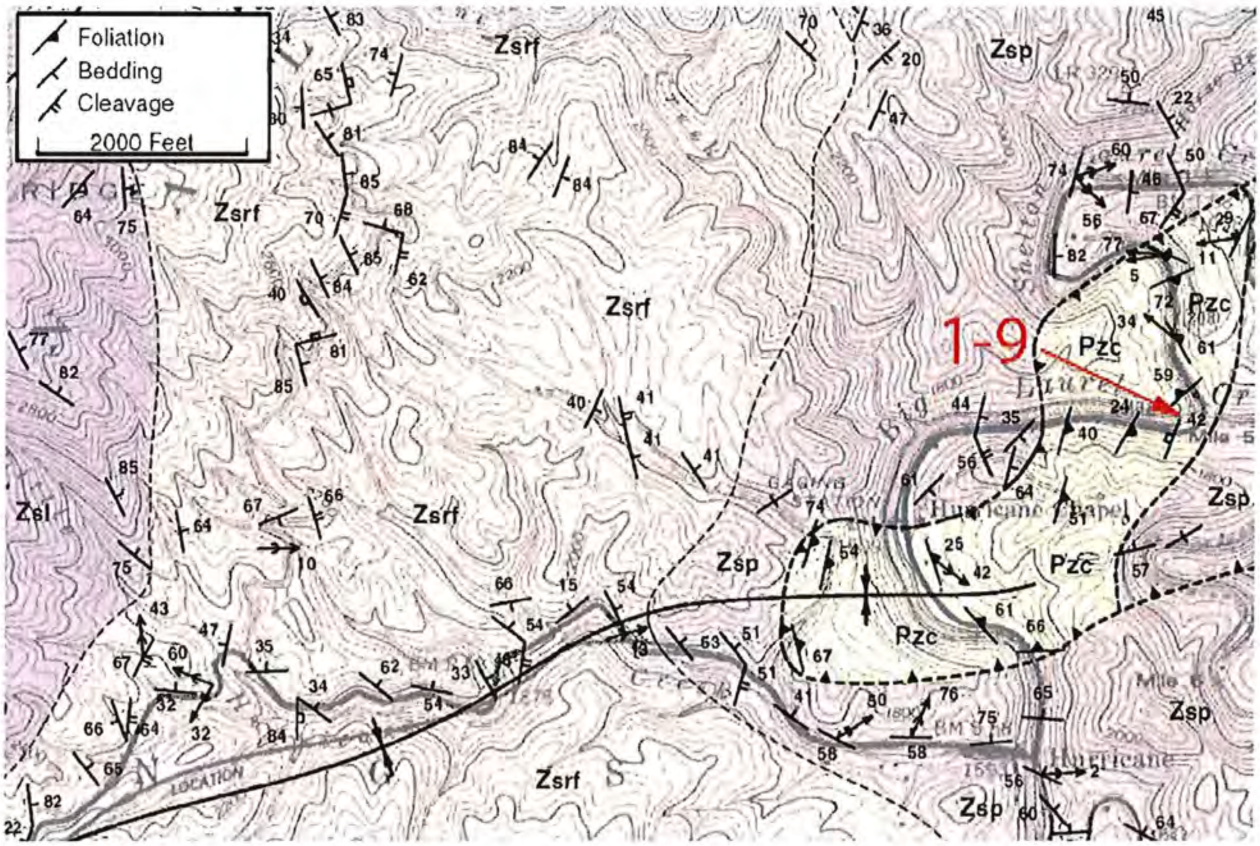


Figure 1-9-1: Local geologic map of Stop 1-9. Pzc - Paleozoic cataclasite. Zsp - Pigeon Siltstone. Zsrf - Roaring Fork Metasandstone. Zsl - Long Arm Quartzite.

Figure 1-9-2: Zone of quartz veins mark fault contact between Mesoproterozoic Max Patch Granite and Neoproterozoic Pigeon Siltstone.

locally undeformed granitic rock. We speculate that their protolith is Max Patch Granite, as undeformed granitic rocks in this area resemble Max Patch rocks to the south. Here, the Pigeon Formation is mostly slate, interbedded with feldspathic metagraywacke. A zone of quartz veins approximately three meters thick marks the contact between the Pigeon Formation and basement rocks (Fig. 1-9-2). Although a minor cataclastic fabric overprints metasedimentary rocks near the contact, the bulk of cataclastic deformation appears to have affected the basement rocks. The brittle nature of the deformation leads us to believe that its age is most likely Alleghanian.

105.9	7.3	Turn around and backtrack heading south on NC 208 for 7.3 mi.. Turn right on to Sharp Hollow Road (SR 1145).
107.0	1.1	Left turn on to SR 1151 towards Barnard.
108.3	1.3	Cross French Broad River at Barnard .
110.9	2.6	Right turn on to private bridge and road called Crooked Ridge lane.
111.3	0.4	Stop 1-10: Grenville amphibolite and granitic gneiss and Neoacadian mylonite. Outcrops are to the north in the low roadcut and to west in the creek bed above the tight turn in the road.

STOP 1-10: Grenville amphibolite and Neoacadian mylonites. 25 min.

Location: Crooked Ridge Lane (private) leading off STATE ROAD 1151 - Spring Creek quadrangle (NCGS Manuscript Geologic Map, Cattanach et al., 2003; Fig. 1-10-1).

GPS Location: 35° 49' 30" N; 82° 47' 17" W.

Purpose: To view Neoacadian mylonites and undeformed Grenville basement placed in the sericitic mylonite unit of the compilation map.

Description: Here, mylonites derived from basement granitic gneisses are juxtaposed against amphibolite and granitic gneiss that preserve a northwest trending Grenville foliation. Mylonitic overprinting is absent in the amphibolite and associated granitic gneiss. Most of the rocks in this region show a consistent northeast-southwest trending mylonitic overprint. Ar-Ar dating of muscovite within these shear zones yields Neoacadian ages of 355 to 336 Ma (Kunk et al., 2006). Sericite-chlorite-epidote mineral assemblage suggests that deformation

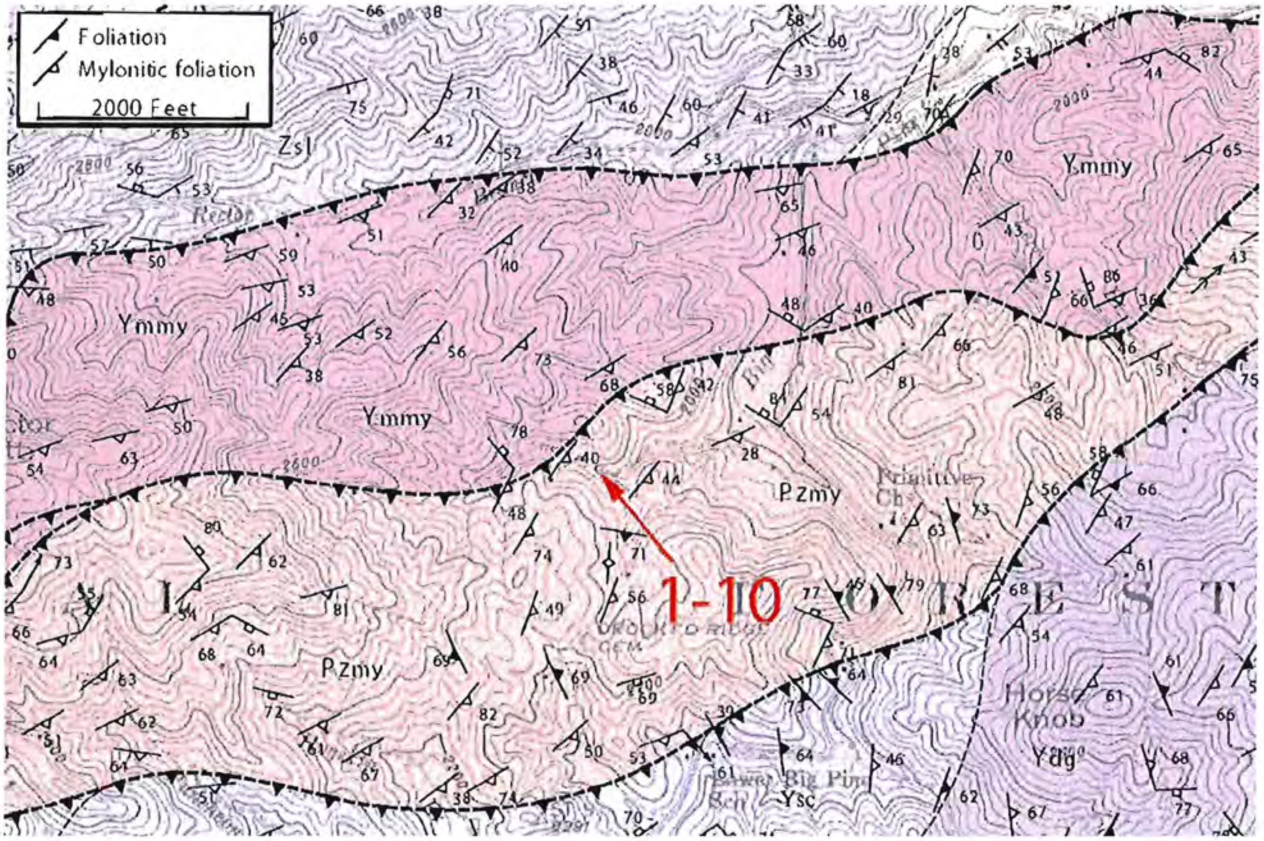


Figure 1-10-1: Local geologic map of Stop 1-10. Zsl - Long Arm Quartzite. Ymmy - mylonitic Max Patch Granite. Pzmy - Paleozoic mylonite. Ysc - Spring Creek granitoid gneiss. Ydg - Doggett Gap protomylonite.

took place at greenschist facies and down-dip mineral stretching lineations are consistent with a top-to-northwest sense of movement within the shear zones.

Turn around and retrace to SR 1151. Turn left on to SR 1151. Cross French Broad River and retrace trip route to US 25-70 east. Turn right on US 25-70 and return to Asheville. Holiday Inn is 36.4 mi. distant.

End of Day 1.

Day 2

Cumulative Mileage	Incremental Mileage	
0.0	0.0	Field trip begins at the Holiday Inn Asheville-Biltmore East headquarters hotel (1450 Tunnel Rd., Asheville, NC). Right turn from motel entrance on to US 70. Immediate left turn at stop light on to Porter's Cove Road.
0.3	0.3	Right turn at entrance ramp to I-40.
2.3	2.0	Take I-240 west at Exit 53B.
3.7	1.4	Turn right onto I-26 West, US 19-23 North and US 70 West toward Weaverville.
5.9	2.2	Take Weaverville/New Stock Road exit (Exit 21).
6.1	0.2	Turn left at the bottom of the exit ramp onto New Stock Road (SR 1740).
6.9	0.8	Left turn onto Aiken Road (SR 1720).

7.2 0.3 Right turn onto Goldview Road (SR 1718). Looking Southwest across Asheville Basin.
8.2 1.0 STOP 2-1: Turn right to enter Grove Stone's North Buncombe Quarry, a division of Hedrick Industries. Enter quarry only with official permission. Safety equipment required.

STOP 2-1: BV Hedrick North Quarry. 30 min.

Location: STATE ROAD 1918—Weaverville quadrangle (NCGS Manuscript Geologic Map, Burr, 2002; Fig. 2-1-1).
GPS Location: 35° 41' 15" N; 82° 36' 30" W.
Purpose: To examine the Holland Mountain fault and discuss age relationships between Grenville basement and rocks of the Ashe metamorphic suite.
Description: This crushed stone quarry contains good exposures of the Holland Mountain fault. Here, the fault separates rocks of the Neoproterozoic Ashe metamorphic suite–Tallulah Falls Formation (AMS–TFF) from those of the Mesoproterozoic Earlies Gap Formation (part of the migmatitic biotite-hornblende gneiss compilation unit). AMS–TFF rocks consist of migmatitic muscovite-bearing schists and metagraywackes and minor amphibolite. Basement rocks are predominantly migmatitic layered biotite gneisses and amphibolites. The contact between the two units is a zone of steeply dipping mylonite.

Undeformed trondjhemite bodies crosscut units on both sides of the fault. Trondjhemite sills and dikes are widespread in both basement and AMS–TFF rocks in the Asheville 100,000 sheet. They show no evidence of metamorphism or deformation, and thus define the minimum age of deformation within the AMS–TFF. Age dates from regional trondjhemites range from 420 to 400 Ma (Mapes, 2002; Miller et al., 2000; Kish et al., 1975), which support a Taconian age for deformation and metamorphism.

These data contrast with studies to the northeast that indicate the Acadian strike-slip Burnsville shear zone overprints the Holland Mountain fault (Trupe et al., 2003). To the southwest, studies suggest that the Holland Mountain–Chatahoochee fault system is an Alleghanian feature (Hatcher et al, 2005).

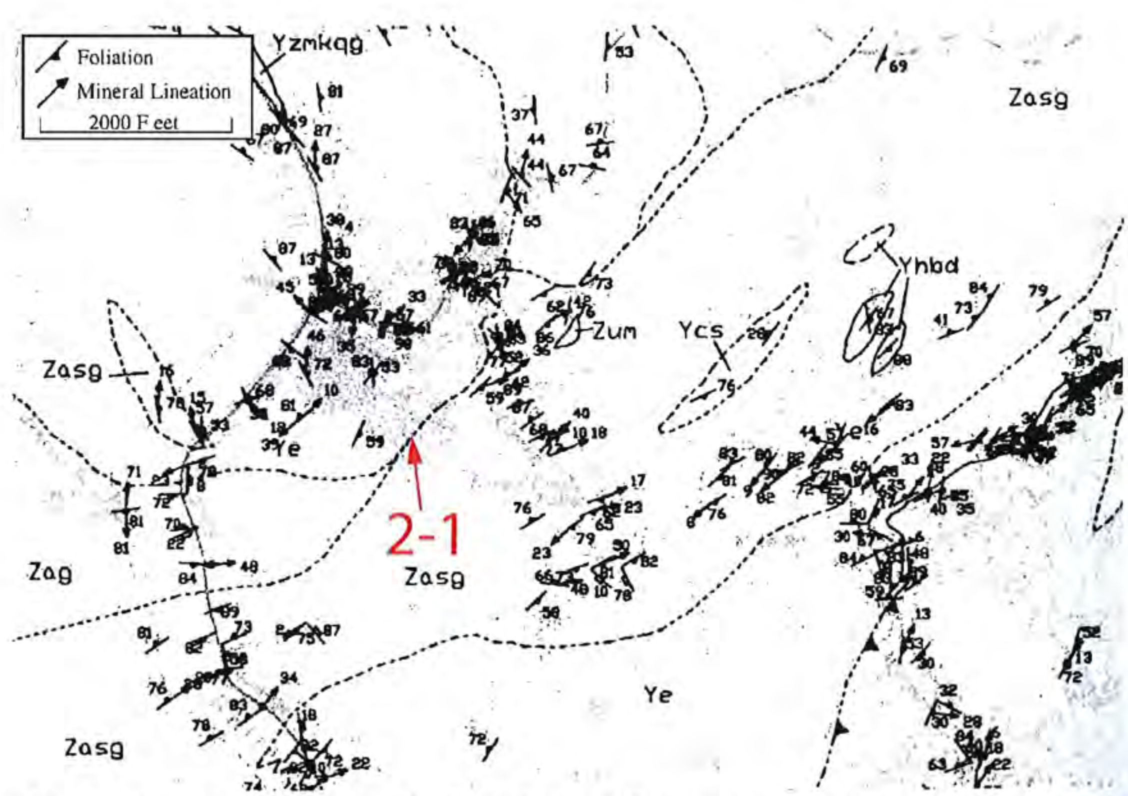


Figure 2-1-1: Local geologic map of Stop 2-1. Ye - Earlies Gap Biotite Gneiss and migmatitic biotite-hornblende gneiss. Zasg - Ashe Metamorphic Suite interlayered 2-mica schist and schistose gneiss, and biotite gneiss. Zag - Ashe Metamorphic Suite biotite gneiss/metagraywacke with subordinate 2-mica schist. Ycs - calc-silicate gneiss and amphibolite. Yhbd - Hornblendite. Yzmkqg - magnetite K-feldspar quartz gneiss. Geology by Burr (2002).

8.8	0.6	Turn right out of quarry entrance road on to Goldview Road (SR 1718). Entering the incised river valley of the French Broad River. Turn right on to NC 251 North.
10.8	2.0	Migmatites in roadcuts on the right are in the Earlies Gap Amphibolite.
11.4	0.6	Turn right on to Lower Flat Creek Road.
12.7	1.3	Turn right on to Lower Shepards Branch Road.
12.9	0.2	Right turn on to Martin Ford Road (SR 1717)
13.8	0.9	STOP 2-2: Agmatitic texture within Earlies Gap amphibolitic gneiss on Martin Ford Road. Outcrops on left.

STOP 2-2: Agmatitic texture within migmatitic biotite-hornblende gneiss on Martins Ford Road. 20 min.

Location: STATE ROAD 1717—Weaverville quadrangle (NCGS Manuscript Geologic Map, Burr, 2002; Fig. 2-2-1).
GPS Location: 35° 43' 20" N; 82° 36' 27" W.
Purpose: To examine local agmatitic textures within the basement rocks (Fig. 2-2-2).
Description: This outcrop is dominated by coarse-grained migmatitic amphibolite and lies in the migmatitic biotite-hornblende gneiss unit on the compilation map. Amphibolite layers are boudinaged into discrete blocks that appear to have behaved as cohesive units within the surrounding migmatite. Prominent within the outcrop is a northwest striking foliation, typical of many Grenville-aged metamorphic gneisses. Biotite is present in the rocks, and may indicate Paleozoic retrogression.

This outcrop is part of the Earlies Gap amphibolitic gneiss unit that has been dated on the adjoining Leicester quadrangle at 1260 Ma by Owenby et al. (2004). We interpret this outcrop to be part of the "Mars Hill terrane" rocks that have intruded and intermingled with older crust (Monrad and Gulley, 1983; Carrigan et al., 2003; Ownby et al., 2004). Bodies of migmatitic biotite-hornblende gneiss and layered biotite granitic gneiss have magmatic

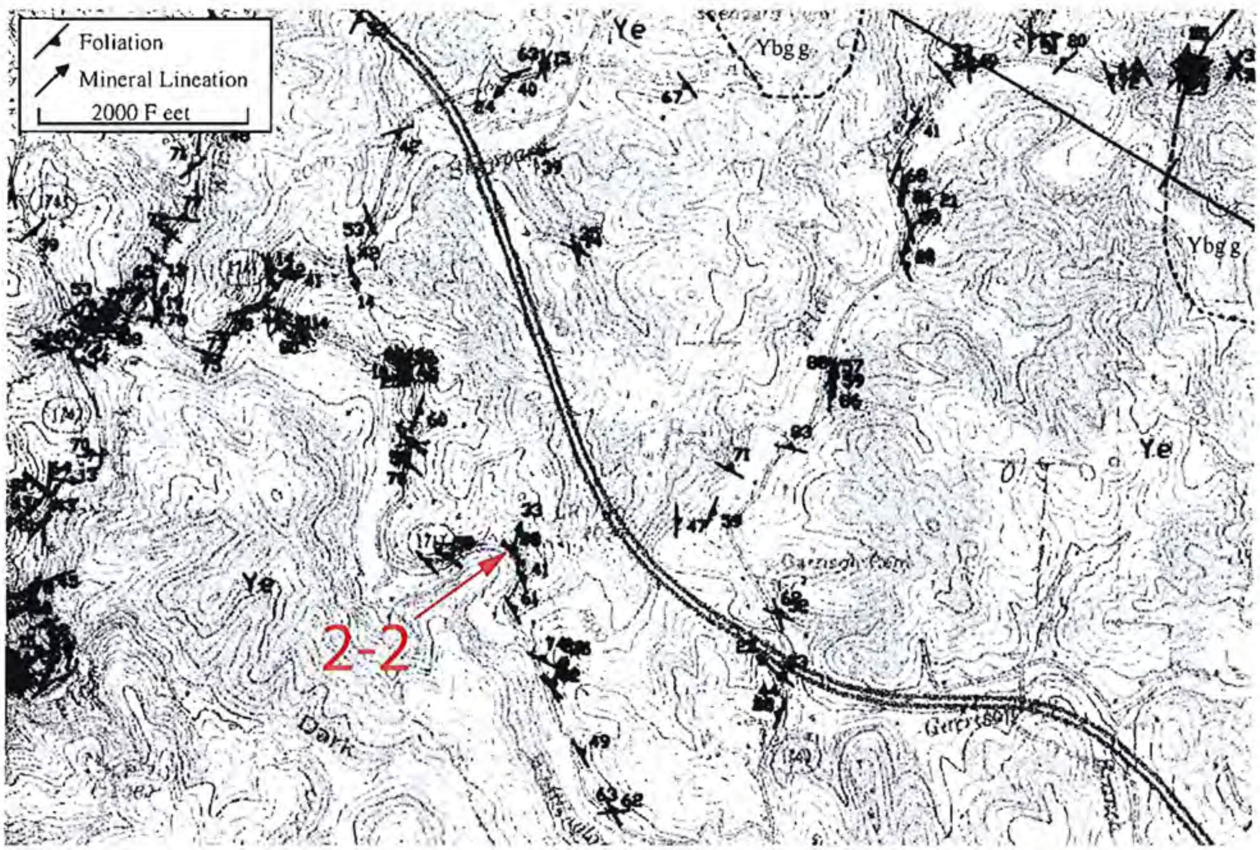


Figure 2-2-1: Local geologic map of Stop 2-2. Ye - Earlies Gap Biotite Gneiss and migmatitic biotite-hornblende gneiss. Ybgg - biotite granitic gneiss.

Figure 2-2-2. Agmatite within the migmatitic biotite–hornblende gneiss.

ages spanning 1380-1214 Ma (Fullagar et al., 1979; Officer et al., 2003; Ownby et al., 2004; Berquist et al., 2005) and pre-date younger intrusive bodies such as the 1170 Ma Spring Creek Granitoid Gneiss (Berquist et al., 2005).

13.9	0.1	Right turn into driveway to turn around and retrace path to French Broad River.
14.9	1.0	Left turn on to Lower Shepard Branch Road.
15.1	0.2	Left turn on to Lower Flat Creek Road, continue retracing route to French Broad River.
16.4	1.3	Right turn on to NC 251 North.
18.4	2.0	Right turn on to Panther Branch Road, SR 1745.
18.7	0.3	Turn right and enter Buncombe County Landfill. STOP 2-3: Granulites along the entrance to the Buncombe County Landfill. Pull off on right shoulder immediately after entering gate. PLEASE be careful of landfill traffic.

STOP 2-3: Granulites along the entrance to the Buncombe County Landfill. 25 min.

Location: STATE ROAD 1745—Leicester quadrangle (Merschat and Cattanach, 2005; Fig. 2-3-1).

GPS Location: 35° 43' 42" N; 82° 38' 26" W.

Purpose: To examine a typical exposure of Grenvillian granulites and their relationship with later features (Fig. 2-3-2).

Description: This roadcut on the east side of the entrance to the Buncombe County Landfill contains felsic and mafic granulite, and several thick, variably migmatitic amphibolite interlayers. Grenville foliation strikes approximately N50W and dips to the southwest. Rocks from this exposure yielded a preferred magmatic age of 1260 Ma (Ownby et al., 2004) using Sm-Nd isotope geochemistry.

Rocks of this outcrop were mapped as pyroxene granulite within the Earlies Gap Amphibolitic Gneiss (Merschat and Cattanach, 2005). These rocks are part of the granulite gneiss compilation unit. Similar granulites are observed, and have been mapped on the Mars Hill, Leicester, Marshall, Weaverville, Fines Creek, Lemon Gap, and Spring Creek quadrangles on the west half of the Asheville 100,000 sheet, and in the Barnardsville and Bald Creek quadrangles on the east half of the Asheville 100,000 sheet. Earlier regional reconnaissance and compilation for the 1985 State Geologic Map of North Carolina placed all known granulites from Mars Hill northeast to Roan Mountain into a migmatitic biotite-hornblende gneiss unit. Because granulites have more recently been mapped outside of this belt on the Fines Creek, Lemon Gap, and Spring Creek quadrangles, the originally proposed model that a single belt or terrane contains all of the Mesoproterozoic granulites does not fit our expanded database.

Several zones of post-Grenville mylonite locally cut this long roadcut. The mylonites strike northeast, but do not produce the fine mineralogic layering observed in mylonites at the next stop. In addition, at the northern

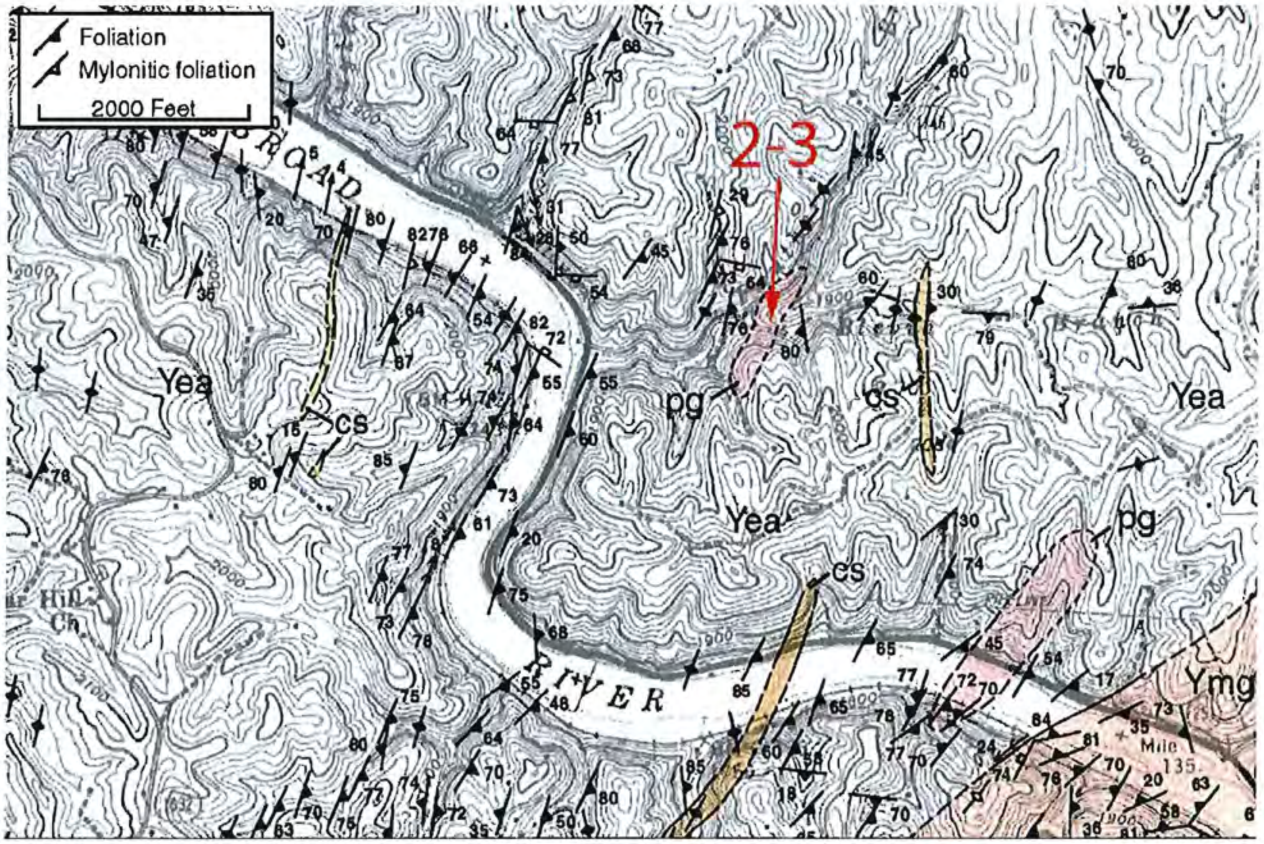


Figure 2-3-1: Local geologic map of Stop 2-3. Yea - Earlies Gap amphibolitic gneiss. cs - calc-silicate. pg - pyroxene granulite. Ymg - Interlayered mafic gneiss.

Figure 2-3-2. Typical granoblastic texture of the granulite gneisses on the west half of the Asheville 100,000.

(entrance) end of the exposure, one of the mylonite zones truncates a Bakersville Metagabbro dike, implying a Paleozoic age for mylonitic deformation (Fig. 2-3-3).

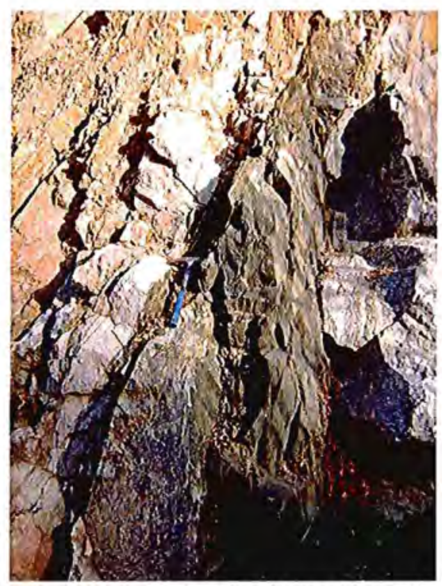


Figure 2-3-3. Bakersville Metagabbro dike crosscutting basement granulites. Both units are truncated by later shearing.

20.3 0.0 Turn around and return to Panther Branch Road. Turn right.

20.3 1.6 Turn left on Flint Hill Road (SR 1743).

21.1	0.8	Continue straight after stop sign to Jupiter Road (SR 1756).
21.9	0.8	Cross US 25-70 and continue on Jupiter Road (SR 1756).
27.2	5.3	Turn left on entrance ramp to I-26 West/US 19-23 North.
28.7	1.5	Take Exit 13 (Forks of Ivy). Turn right and then immediately left onto old 19-23 North.
29.7	1.0	Turn left onto old NC 213 (SR 1557) and cross Little Ivy River.
30.0	0.3	Take left on to Forks of Ivy Road (SR 1556).
30.2	0.2	Park at east side of abandoned quarry. Walk along road for over a half mile to see typical exposures. STOP 2-4: Granulites along Ivy River west of Forks of Ivy.

STOP 2-4: Granulites along Ivy River west of Forks of Ivy. 35 min.

Location: STATE ROAD 1556—Mars Hill quadrangle (Merschat, 1977; Fig. 2-4-1).

GPS Location: 35° 47' 34" N; 82° 32' 47" W.

Purpose: To examine relatively unretrograded granulites and their relationship to post-Grenville mylonites and Bakersville Metagabbro.

Description: In this abandoned quarry and along State Road 1556 are exposures of Mesoproterozoic felsic granulite. Recent road improvements have exposed fresher and more extensive roadcuts not available during initial field mapping in 1972 (Merschat, 1977). These exposures have allowed new observations of previously unrecognized granulitic assemblages and textures.

Weathered outcrops in the quarry and along the road were originally mapped as variably layered biotite and hornblende-bearing granitic gneisses within migmatitic biotite-hornblende gneiss (Merschat, 1977). The new exposures reveal foliated felsic granulites that are characterized by a granoblastic texture, light brown to grayish-red purple andesine, blue quartz, and hypersthene. They are generally dioritic in composition, consisting of andesine, quartz, potassic feldspar, hypersthene and diopside. Accessory and alteration minerals include biotite, hornblende, magnetite, and zircon. Thin sections show alteration rims of hornblende and biotite surrounding hypersthene and diopside. The felsic granulites are locally migmatitic. Similar rocks approximately 1.8 km east of

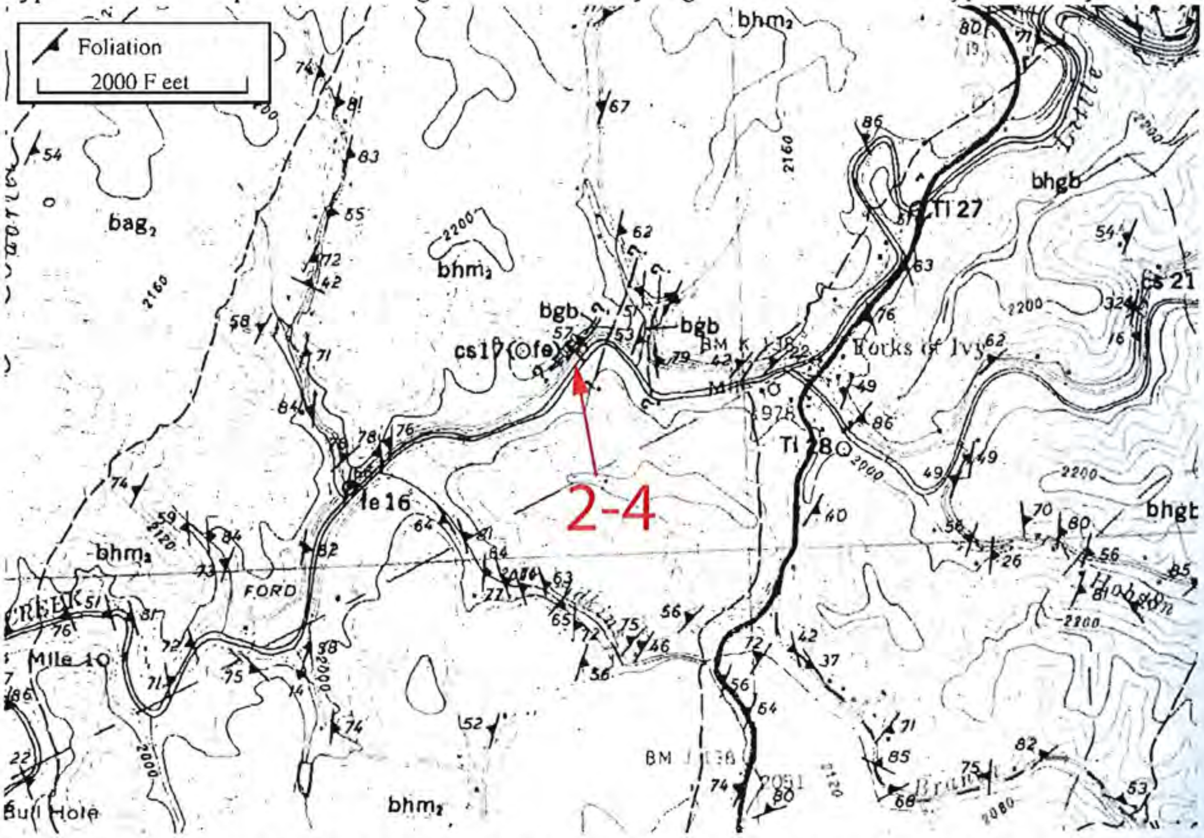


Figure 2-4-1: Local geologic map of Stop 2-4. bhm 2 - biotite hornblende migmatite. bgb - Bakersville Metagabbro and Metadiabase. bag 2 - biotite augen gneiss. bhgb - Bakersville Hypersthene Metagabbro

Figure 2-4-2. Mylonitic zone transposing Grenville foliation within the migmatitic biotite-hornblende gneiss.

this outcrop were dated at 1214 Ma (Fullagar et al., 1979; as recalculated by Rankin et al., 1983).

At the eastern edge of the quarry two Neoproterozoic Bakersville Metagabbro dikes 1.5–2 m thick crosscut strong foliation in the granulite rocks. The dikes exhibit only a weak foliation defined by subparallel alignment of hornblende grains where there was incomplete metamorphic recrystallization of pyroxene to amphibole. Kuckenbuch (1979) recognized four different levels of metamorphic recrystallization in the Bakersville dikes in the Mars Hill quadrangle. Incomplete recrystallization of Bakersville dikes in granulite-facies rocks has been attributed to the lack of available fluids during metamorphism (Wilcox and Poldervaart, 1958; Merschat, 1977; Kuckenbuch, 1979; Merschat and Wiener, 1990).

Crystallization ages of the Bakersville Metagabbro are 734 Ma by Goldberg et al. (1986) and 728 Ma by Ownby et al. (2004). We therefore interpret the weak metamorphic overprint within the dikes to be Taconic and attribute the strong penetrative deformation within the country rock to be Grenvillian. This suggests that Taconic metamorphism was not a major overprinting event throughout the entire region.

New exposures along the road west of the quarry consist of granulites, granitic gneisses, and migmatites. These rock types were locally mylonitized (Fig. 2-4-2), producing a strongly overprinting foliation that transposed the primary Grenville foliation. Mylonitization has locally changed the character of the basement rock to a very thinly layered, well-foliated, flaser gneiss. Muscovite, a characteristic mineral of Neoacadian mylonitization in other parts of the Mesoproterozoic basement, is absent here. Bakersville Metagabbro at this locality is not mylonitized, suggesting a post-Grenville mylonitization age prior to intrusion of the metagabbro.

30.8	0.6	Turn around at next intersection and retrace route back to I-26 West.
32.5	1.7	Turn right on entrance ramp to I-26 at Exit 13 (Forks of Ivy).
34.8	2.3	Turn left on to NC 213.
36.0	1.2	Pass through Mars Hill College campus, founded 1856.
39.9	3.9	Turn right onto Petersburg Road (SR 1370).
41.2	1.3	Turn right onto East Fork Road (SR 1364).
41.8	0.6	Turn right onto Morgan Branch Road (SR 1367).
42.0	0.2	STOP 2-5: Layered biotite granitic gneiss intruded by the Spring Creek Granitoid Gneiss. Small roadcut opposite driveway with mail boxes 296 & 298.

STOP 2-5: Layered biotite granitic gneiss intruded by Spring Creek Granitiod Gneiss. 15 min.

Location: STATE ROAD 1367—Mars Hill quadrangle (Merschat, 1977; Fig. 2-5-1).

GPS Location: 35° 50' 36" N; 82° 36' 18" W.

Purpose: To examine relationships between massive granitic gneiss, layered granitic gneiss, and later Proterozoic mylonitization.

Description: This small, partly weathered roadcut along State Road 1367 contains a dike-like body of Mesoproterozoic Spring Creek Granitoid Gneiss intruding more layered biotite granitic gneiss. The Spring Creek Granitoid Gneiss at this outcrop is coarse-grained, augen-rich, and has a pronounced protomylontic fabric. It is composed primarily of plagioclase feldspar, potassium felpdspar, quartz, biotite, and minor hornblende. Coarse-grained microcline augen commonly have euhedral grains of magnetite at their cores.

Keith (1904) originally mapped these rocks as Max Patch Granite, presumably because the augen gneiss character of these rocks is very distinctive and resembles exposures near the top of Max Patch Mountain. Merschat (1977) mapped them as augen granitic gneiss within biotite granitic gneiss. The fabrics in each unit in the outcrop are puzzling in that although they are parallel, the layered biotite granitic gneiss shows a much stronger mylonitic overprint than the protomylonitic augen gneiss. Because the protomylonitic fabrics contain no recrystal-

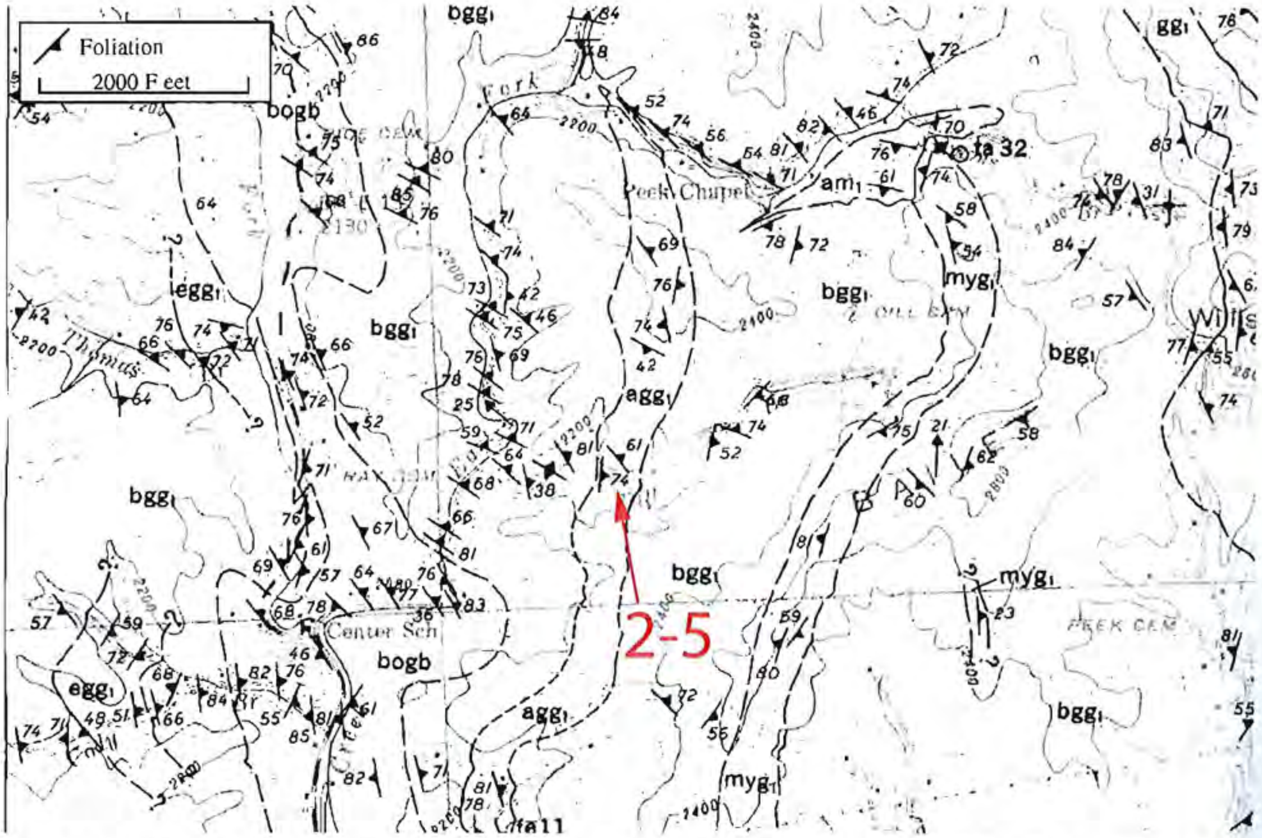


Figure 2-5-1: Local geologic map of Stop 2-5. agg 1 - augen granitic gneiss. bgg1 - biotite granitic gneiss. bogb - Bakersville Metaolivine Gabbro. myg 1 - mylonite (flaser) gneiss. egg1 - epidote-veined granitic gneiss. am1 - amphibolite. gg1 - granitic gneiss.

lized sericite or muscovite (a common characteristic of Neoacadian deformation in this region) a Proterozoic age is suggested for this mylonitization.

At its type locality in the Sandymush quadrangle (Merschat and Wiener, 1988), the Spring Creek Granitoid Gneiss is a massive, weakly foliated gneiss with widely spaced compositional layers. It has a crystallization age of 1170 Ma (Berquist et al., 2005). In contrast, biotite granitic gneiss is commonly very well layered. Fullagar (1983) dated exposures of layered biotite granitic gneiss along US 25/70 (about three miles southwest of this stop) to be about 1270 Ma. The concept that two Mesoproterozoic units with distinct ages are present here contrasts with earlier thought, and reflects the evolving hypothesis that basement on the Asheville 100,000 sheet consists of an amalgamation of various plutons and older metamorphic country rock. All were assembled and deformed during the long-lasting Grenville orogeny.

42.3	0.3	Turn around in private driveway and backtrack to I-26 West. Turn left on to East Fork Road (SR 1364). Continue to backtrack.
42.9	0.6	Turn left onto Petersburg Road.
44.2	1.3	Turn left onto NC 213.
49.2	5.0	Turn right onto entrance ramp for I-26 West.
55.0	5.8	STOP 2-6: Roadcut on I-26. Park on right shoulder behind guard rail.

STOP 2-6: Roadcut on I-26. 30 min.

Location: I-26—Sams Gap quadrangle (Merschat, Carter, and Hewitt, 2002; Fig. 2-6-1).

GPS Location: 35° 53' 08" N; 82° 32' 54" W.

Purpose: To examine basement gneisses and crosscutting Bakersville Metagabbro.

Description: This is a new roadcut that was not available during the detailed geologic mapping of the Sams Gap quadrangle in 2002. The outcrop lies within the layered granitic gneiss compilation unit. The locality was origi-

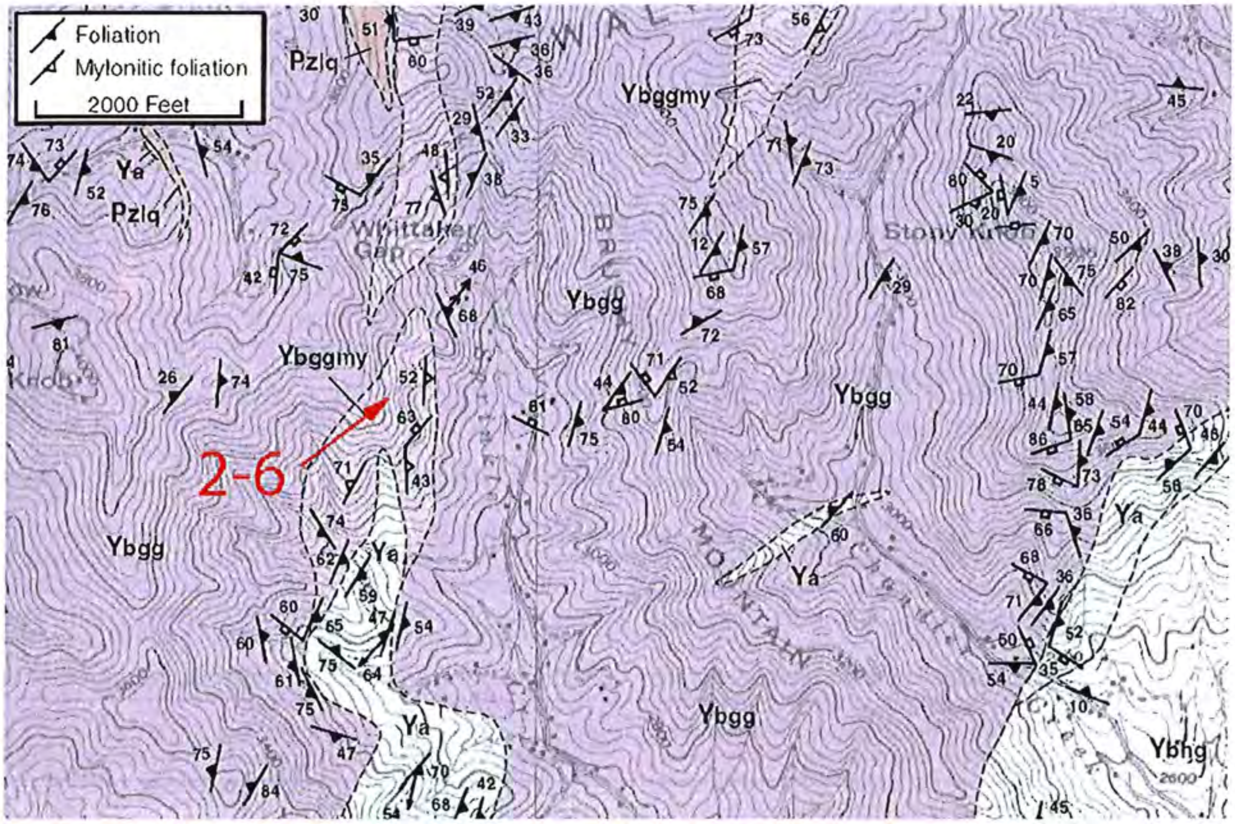


Figure 2-6-1: Local geologic map of Stop 2-6. Ya - amphibolite. Ybggmy - mylonitic layered biotite granitic gneiss. Ybgg - layered biotite granitic gneiss. Ybhg - migmatitic biotite-hornblende gneiss. Pzlq - leucocratic quarto-feldspathic rock.

nally mapped as biotite granitoid gneiss and mylonitic biotite granitoid gneiss and amphibolite. Subsequently, A.J. Merschat et al. (2005) mapped this outcrop at a large scale, identifying Bakersville Metagabbro in addition to migmatitic amphibolite and granitoid gneisses. Their observations and interpretations fit nicely with the working hypothesis we have developed for the different basement units.

Biotite granitoid gneiss, tentatively correlative with the 1170 Ma (Berquist, et al., 2005) Spring Creek Granitoid Gneiss, appears to be intrusive into migmatitic amphibolite and migmatitic biotite-hornblende gneiss. Biotite granitoid gneiss dominates the outcrop and contains numerous mafic enclaves. An alternative explanation for the genesis of the biotite granitoid gneiss is that it is migmatite formed coeval with Grenville deformation and is not a separate intrusive body. All of these units were deformed during Grenville upper amphibolite facies metamorphism.

Bakersville Metagabbro dikes crosscut these rocks (Fig. 2-6-2), but are only weakly foliated. Bakersville dike crystallization ages of 734 Ma and 728 Ma (Goldberg et al., 1986; Ownby et al., 2004) restrict the timing of foliation development to the Paleozoic. Development of this later weak foliation in the Bakersville dikes is interpreted to be Taconian and coeval with thrusting along the Holland Mountain fault, which is present only seven miles to the southeast. Ashe metamorphic suite-Talullah Falls Formation rocks in the

Figure 2-6-2. Bakersville Metagabbro crosscutting Mesoproterozoic basement gneisses.

hanging wall of the Holland Mountain fault are complexly deformed and exhibit Taconic age kyanite grade metamorphism. Within the basement gneisses, however, no textural overprint is recognized and the Bakersville Metagabbro is only weakly affected, suggesting that Paleozoic metamorphism did not play a significant role in deforming rocks in this outcrop and by extension, other basement rocks of the Asheville 100,000 sheet.

Return to Asheville by proceeding North on I-26 West to Wolf Laurel exit (Exit 3). Exit I-26. Left on to Bear Creek Road and under I-26, another Left turn up entrance ramp to I-26 East. Return to Asheville via I-26 East (31.2 mi.)

End of Day 2 and field trip.

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Geologic excursion across part of the Southern Appalachian foreland fold–thrust belt in northeastern Tennessee

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Introduction—Trip Overview

The aim of this field trip is to provide an overview of the geology in the northeastern part of the Tennessee Valley and Ridge Province. In particular, the two main themes of this trip are: (1) the types of structures that form in a foreland fold-thrust belt; and (2) how the Middle Ordovician Chickamauga Group deposits record a major change in the regional tectonic regime and the beginning of mountain building to the southeast. Additionally, we will discuss regional geologic hazards and touch upon mineral resources.

The field trip starts at a road cut through the Copper Creek fault along War Ridge, approximately 13 mi (21 km) northwest of Rogersville, TN (Fig. 1). We will then traverse toward the southeast and examine 13 additional sites in the Copper Creek thrust sheet, Greendale syncline, Saltville thrust sheet, Bays Mountain synclinorium, Mosheim anticline and Sevier basin. The field trip ends on a farm 10 mi (16 km) southwest of Greenville, TN, where there is an occurrence of quartz crystals, also known as, Tennessee field diamonds. In addition to examining typical foreland fold-thrust belt structures, the stops follow a time-line from northwest to southeast across the Appalachian basin during the Middle and Late Ordovician.

The following is a brief summary of the geology we will see today. Morning stops focus on the stratigraphy and mesoscopic structures within the Copper Creek thrust sheet and correspond to the well-known Thorn Hill exposure along US Highway 25E (Fig. 1). At the first stop, the Lower Cambrian Rome Formation, which is the oldest rock unit we will examine, is in fault contact with the Middle Ordovician Moccasin Formation. This is the first of four exposures we will see of the Moccasin Formation or its stratigraphic equivalent the Bays Formation. Each exposure is within a different thrust sheet and taken together represents the change in the environment of deposition that occurred across the Appalachian basin during Middle and Late Ordovician time. Stops 2 through 6 include an intraformational duplex in the Moccasin Formation, folds in the Martinsburg Formation, and the cover rock units composing the northwest limb of the Greendale syncline.

Between Stops 7 and 8 we will be crossing the Greendale syncline (Fig. 1). This is the only area in Tennessee where the overturned southeast limb of the Greendale syncline is exposed. At Thorn Hill, this limb of the syncline is buried below the Saltville thrust sheet, but it is exposed here because of an erosional reentrant through the thrust sheet. Stop 7 is within the overturned limb of the syncline in the Clinch Sandstone. The Saltville fault is exposed at Stop 8 and is the floor thrust of a duplex of Middle Cambrian Conasauga Group rocks mapped in Caney Valley. At Stop 9, we will examine a splay of the Saltville fault, called the Town Knobs fault, which is the roof thrust of the duplex.

After lunch in Rogersville or at the John Sevier Steam Plant Campground, we will spend the rest of the day in the Saltville thrust sheet (Fig. 2). Rodgers (1953) was the first to point out the change in structural style from faulting to the northwest to dominantly folding southeast of the Saltville fault. This difference in structural style is accompanied by a significant change in the Middle Ordovician Chickamauga Group rocks where the carbonate shelf facies seen in the Copper Creek thrust sheet are replaced by deep flysch deposits of the Sevier basin. We will make two stops in Middle and Upper Ordovician rocks exposed in the Bays Mountain synclinorium. Stop 10 is an exposure of the mudstone- and sandstone-rich Bays Formation, which is stratigraphically equivalent to the more limestone-rich Moccasin Formation (Fig. 5). The Bays Formation deposits are part of a clastic wedge of material derived from the southeast that overlies deepwater shales and turbidite sandstones of the Sevier Shale. The contact between the Bays Formation mudstone and sandstones and overlying fossiliferous Martinsburg Formation is seen at Stop 11. The Martinsburg Formation at this stop is very similar to Stop 5 in the Copper Creek thrust sheet. The purpose of Stop 12 is to examine the Lower Ordovician post-Knox unconformity on the southeast limb of the

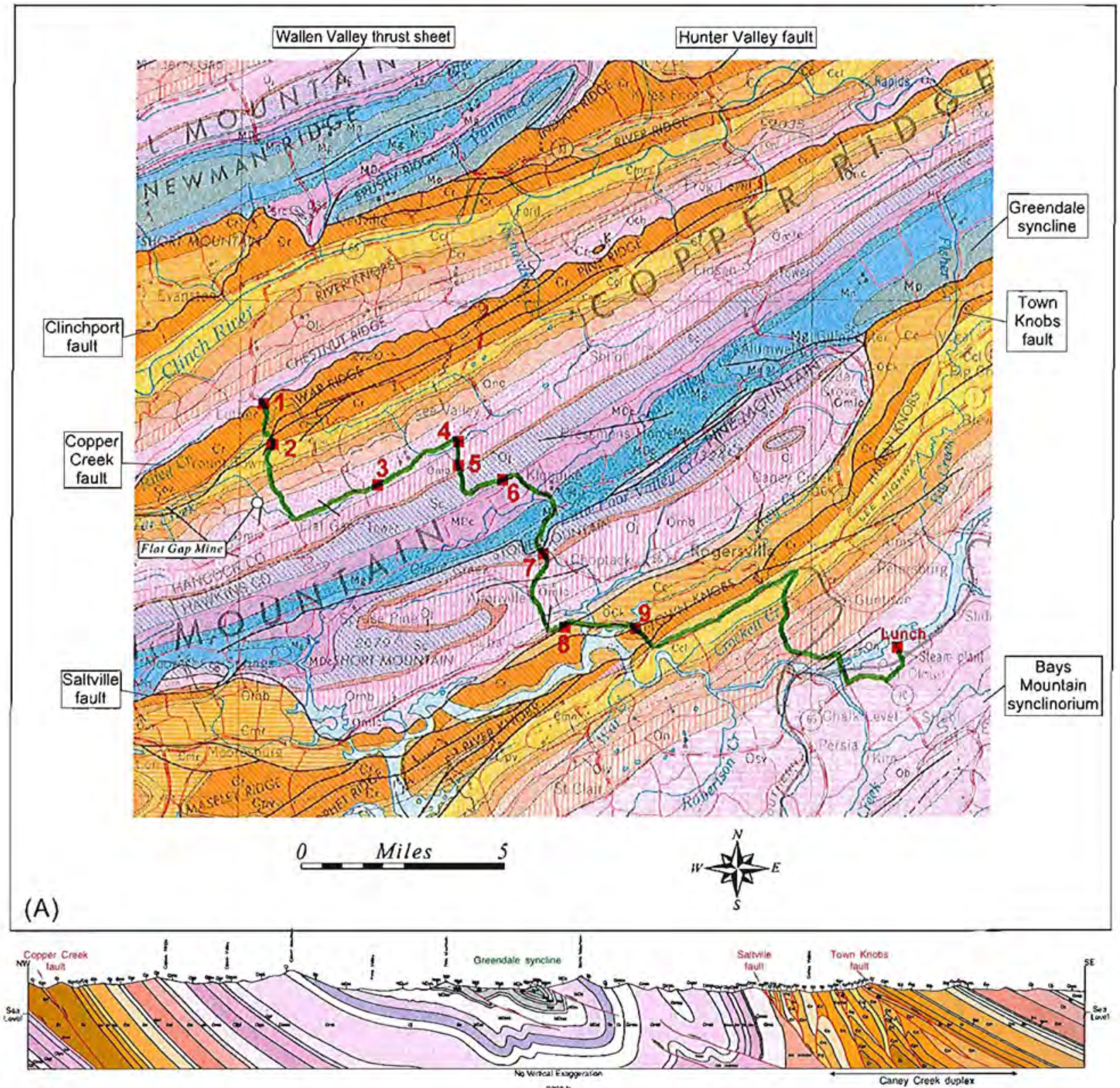

Figure 1. (A) Tennessee state geologic map with the location of morning field trip stops (Hardeman, 1966). (B) Northwest-southeast cross section across the area based on recent mapping of the Camelot quadrangle. (C) Explanation for the geologic map.

Mosheim anticline. Here, a thin sequence of Mosheim/Lenoir Limestone lithofacies rocks was deposited on the post-Knox unconformity before being inundated by the Sevier Shale clastic wedge. The purpose of this stop is to emphasize that within the Saltville thrust sheet the Sevier Shale is the predominant rock unit between the Lower Ordovician post-Knox unconformity and Middle Ordovician Bays Formation. Stop 13 is an outcrop of cleaved and deformed rocks in the upper part of the Sevier Shale. The last stop is in the Oven Creek anticline, which is an open fold cored by Knox Group rocks in the footwall of the Pulaski fault. Although we will examine a small outcrop of a collapse breccia in the upper part of the Knox Group here, the purpose of the last stop is to collect quartz crystals in the surface regolith.

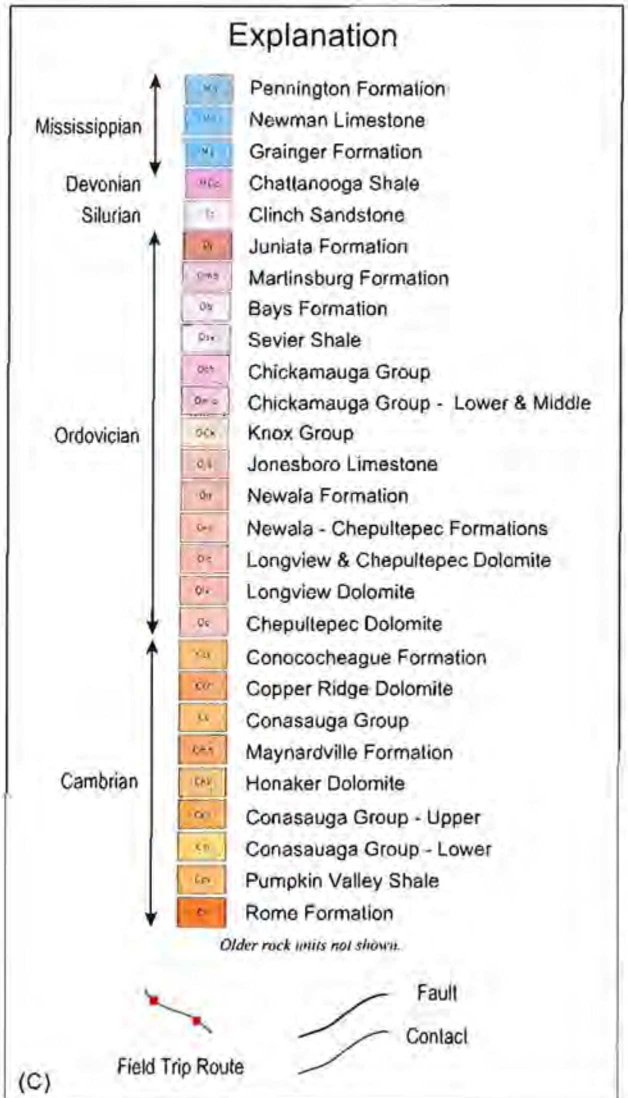

Figure 1, continued.

Regional Paleozoic tectonic history and structural setting

Although deeply eroded, the southern Appalachians preserve most of the features that characterize a collisional orogen formed at a convergent plate tectonic boundary. From east to west these features include a plutonic-volcanic belt (Carolina superterrane), a high-grade metamorphic core (central to eastern Blue Ridge and western Piedmont), and a foreland fold-thrust belt (Valley and Ridge and Cumberland Plateau) (Fig. 3). The fold-thrust belt that we will examine today formed during the Late Carboniferous to Permian Alleghanian orogeny. The Alleghanian orogeny represents the subduction and final closure of a major ocean basin (Rheic ocean) resulting in continent-continent collision between North America and Africa (Hatcher, 1987). During the collision and suturing of the two continents, the Blue Ridge-Piedmont crystalline thrust sheet was detached from the North American crust and transported to the northwest. The relatively rigid crystalline thrust sheet bulldozed the Precambrian to Paleozoic rocks that filled the Appalachian basin and formed the fold-thrust belt.

Thrust faults within the Valley and Ridge Province strike northeast-southwest and most all dip to the southeast (Fig. 4). Faults and folds are responsible for at least 50% horizontal shortening of the Paleozoic sedimentary rocks (Hatcher, 1989). Detailed geologic mapping and structural analysis supports the interpretation that the regional sequence of thrust fault development is from the hinterland (southeast) toward the foreland (northwest) (e.g., Lemiszki and Hatcher, 1992). This interpretation is consistent with mechanical models for the growth of a foreland fold-thrust belt (e.g., Davis et al., 1983). However, certain map patterns require that some of the faults either formed out-of-sequence or were reactivated. This is necessary in order to internally thicken (strengthen) the thrust belt wedge, so that it could continue to advance toward the northwest. Deciphering the sequence of regional thrust fault development is important because one's viewpoint will influence the way cross sections and map patterns are drawn where poorly constrained by geologic and geophysical data.

At least two earlier Paleozoic compressional orogenic events have been identified throughout the Appalachians (Hatcher, 1987). The first orogenic event is the Taconic orogeny, which spanned the Middle Ordovician to Silurian Periods. The Taconic orogeny occurred when the Piedmont island arc collided with North America. The Piedmont terrane consists of Late Proterozoic to early Paleozoic sedimentary, volcanic, and plutonic rocks. The Greenbrier, Hayesville, and Brevard faults in the Blue Ridge probably formed at this time. Although there is no deformation associated with the Taconic orogeny in the Valley and Ridge of East Tennessee, the Middle Ordovician and Silurian sedimentary rocks record a major change in source area and depositional environment.

The second orogenic event, known as the Acadian orogeny, is even more elusive in the southern Appalachians. The Acadian orogeny occurred during the Devonian to Early Carboniferous and is associated with the collision of the Avalon island arc. The Avalon arc is considered a truly exotic terrane with respect to North America and is an assemblage of volcanic and volcaniclastic rocks (Hatcher, 1987). Although well documented in the northern Appalachians, there is no deformation, and only a thin stratigraphic (Devonian to Mississip-

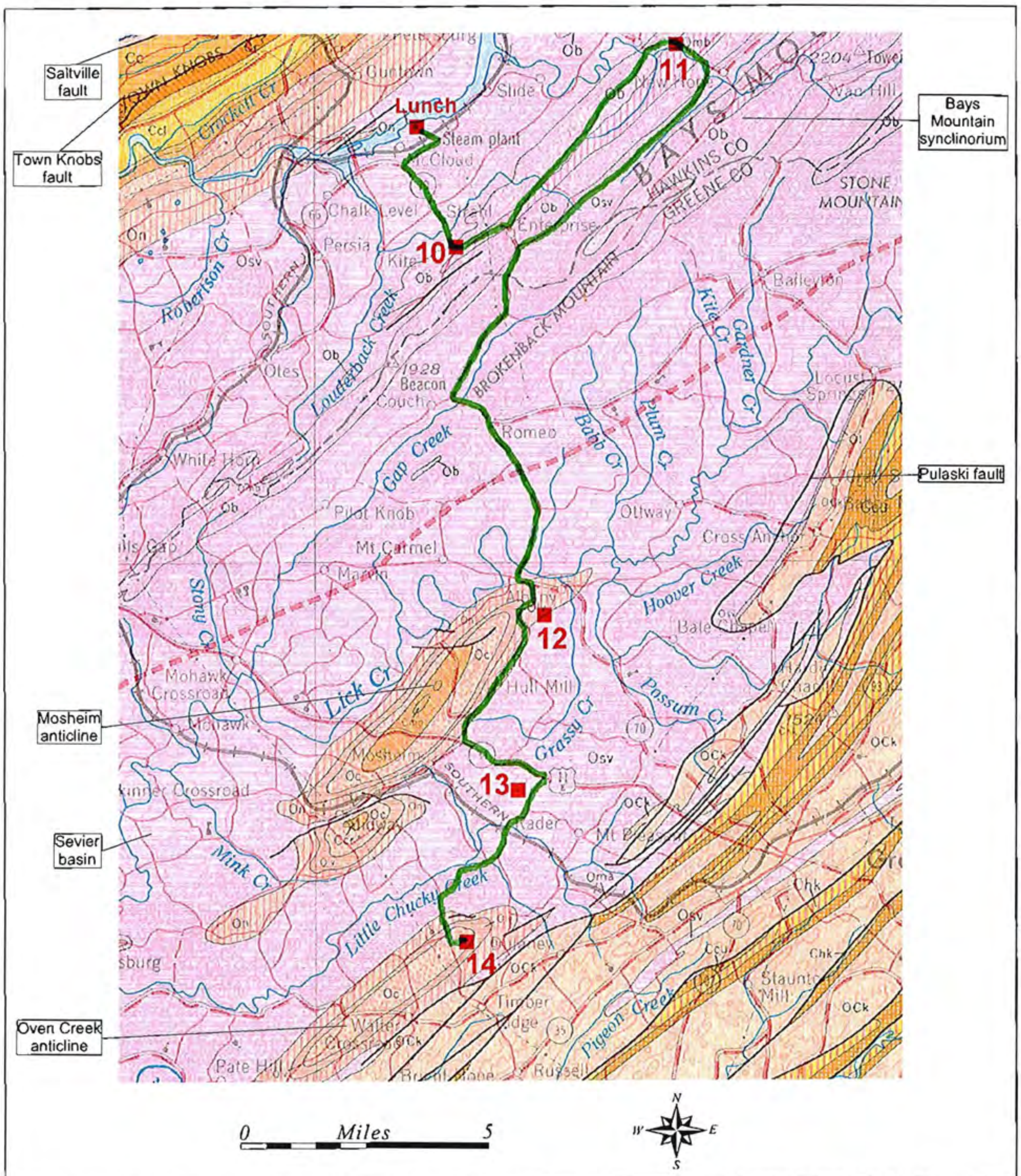

Figure 2. Tennessee state geologic map with the location of afternoon field trip stops (Hardeman, 1966). See Figure 1C for explanation of rock unit colors.

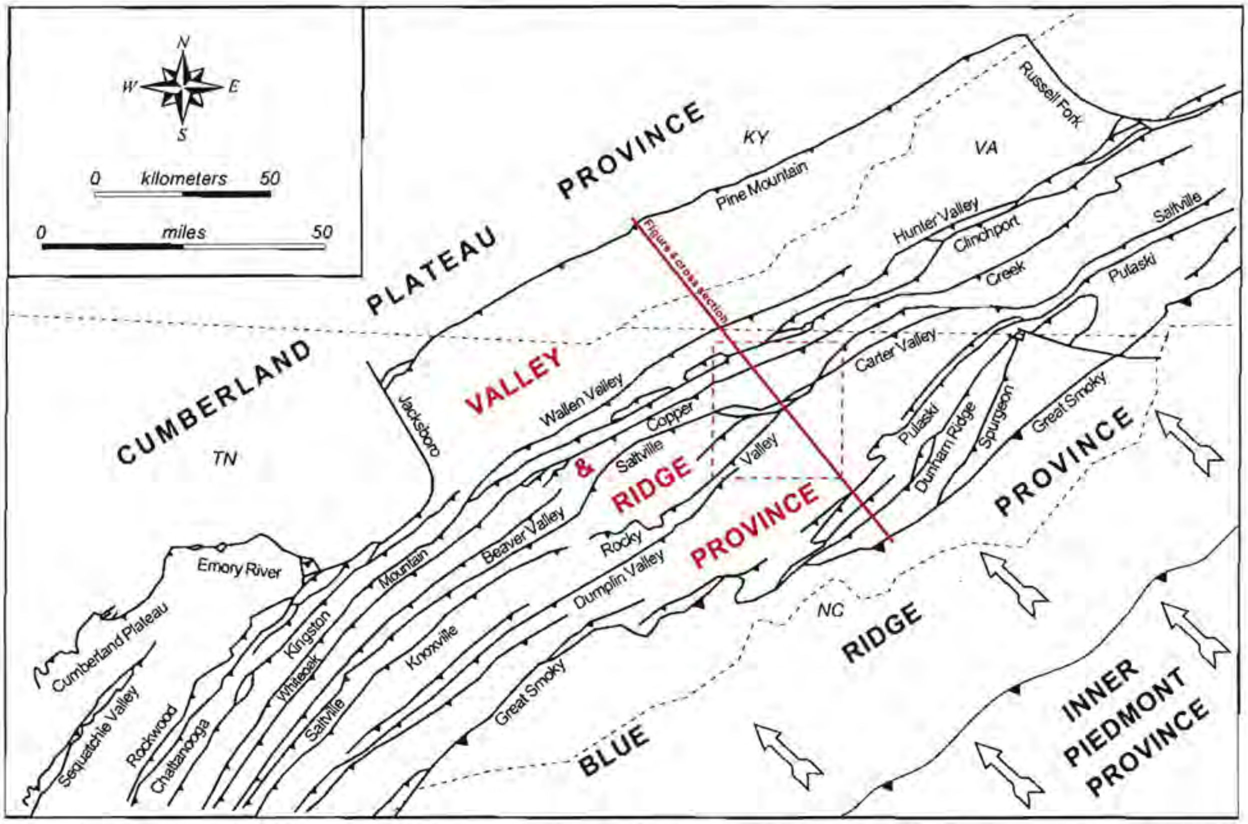

Figure 3. Tectonic–geomorphic provinces of the southern Appalachian orogen. White arrows define the direction of emplacement of the Blue Ridge–Inner Piedmont crystalline thrust sheet. Dashed outline is the area covered during the field trip. Line of cross section shown in Figure 4.

pian) record related to this orogeny in the Valley and Ridge Province of East Tennessee.

Regional stratigraphy

The Paleozoic geologic history of the Valley and Ridge Province in East Tennessee encompasses more than the collisional orogenic events described above (Fig. 5). Prior to any mountain building, the Lower Cambrian to Early Ordovician rocks we will see today record deposition on a passive continental margin. The present-day Atlantic Ocean shelf, slope, and rise are an example of a passive margin, because the closest plate tectonic boundary is the Mid-Atlantic Ridge.

The basement unconformity defines the base of the rift-to-drift and overlying passive margin sedimentary sequences and formed during the erosional beveling of the 1.1 Ga Grenville orogen and Late Proterozoic rifting of the continental margin between 690 and 570 Ma (Fig. 6; Odom and Fullagar, 1984). This event resulted in the formation of discontinuous rift basins, volcanic centers, isolated basement blocks, and an irregular continental margin (Thomas, 1977). The Ocoee Supergroup and Chilhowee Group were deposited during the rifting and initial development of the passive margin (Fig. 6).

The overlying Lower Cambrian to Lower Ordovician Shady Dolomite, Rome Formation, Conasauga Group, and Knox Group sequence was deposited in a shelf environment with an open ocean to the east and continental sediment source to the west. This passive margin sequence terminates at the post-Knox unconformity, which marks a major change in the tectonic regime. Mountain building to the east along an encroaching convergent plate boundary is converting the passive margin to a foreland basin, with rising mountains forming a new eastern sediment source. The post-Knox unconformity formed when loading of the crust in the east during the Taconic orogeny caused the migration of a foredeep basin and peripheral bulge (Fig. 7; Finney et al., 1996). The bulge caused subtle uplift of the passive margin sequence and exposed the upper part of the Knox Group to erosion. The unconformity extends from Alabama to Newfoundland, but passes into a conformable sequence in Pennsylvania. The widespread, global distribution of the unconformity suggests eustatic sea level fall (Mussman and Read, 1986), but it is synchronous with the conversion of the passive margin to a convergent plate boundary.

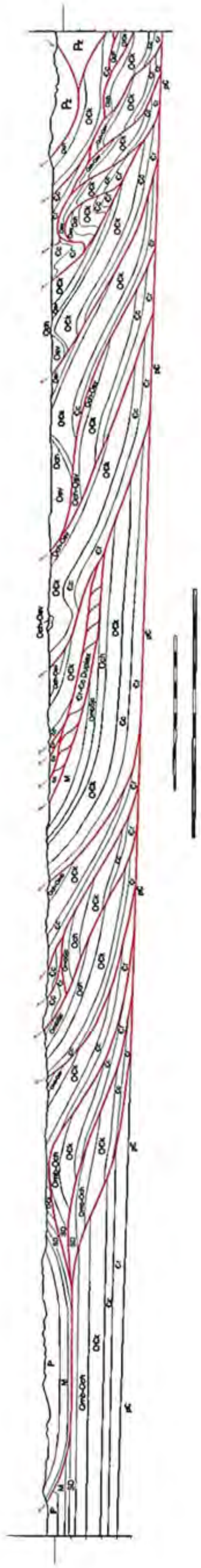

Figure 4. Regional cross section (modified from Woodward, 1985).

The Middle Ordovician Chickamauga Group rocks were deposited on top of the post-Knox unconformity and cover more than 50% of the ground surface in the East Tennessee Valley and Ridge Province. This sequence records the shift in source area and the westward progradation of the Taconic clastic wedge into the new foreland basin (Fig. 8). The Middle to Upper Ordovician sequence contains numerous facies changes both parallel and perpendicular to depositional strike. The most conspicuous is the change from shallow water shelf carbonates (Fleanor, Hogskin, Benbolt, Wardell, Witten and Moccasin (?)) to deep-water clastics (Sevier Shale) (Fig. 8). Capping the Taconic clastic wedge sequence is the Lower Silurian Clinch Sandstone.

The post-Clinch Sandstone unconformity removed all vestiges of the Middle Silurian to Middle Devonian sedimentary sequence (Fig. 5). It too is interpreted to have formed during regional uplift producing erosion and nondeposition associated with the Acadian orogeny (Driese, 1988; Fig. 6). The Upper Devonian-Lower Mississippian Chattanooga Shale and Mississippian Grainger Formation compose the 1365 ft (416 m) of clastic wedge material deposited as a result of the Acadian orogeny in this area. We will pass by, but not examine, these formations during this field trip.

Geologic hazards in east Tennessee

The three most significant geologic hazards in East Tennessee are karst, mass movement (landslides), and radon (Fig. 9).

Topography formed over limestone or dolomite and characterized by closed depressions (sinkholes), caves, and underground drainage, is termed karst. Such topography is common in both Middle and East Tennessee where many carbonate rock units are present. In such areas much of the drainage is below ground. These areas present numerous problems related to land-use planning, such as sinkhole subsidence and collapse, moderate to high shrink and swell soils, flooding within sinkholes, and pollution of ground water. In many cases, problems arise when storm water runoff and drainage are improperly controlled during and after construction, or when there is a break in water or sewer lines. The Knox Group is the major bedrock unit that develops karst in the Valley and Ridge Province. The orientation of fractures and bedding has a strong control on both vadose canyon and phreatic tube cave development (Rubin and Lemiszki, 1992).

Natural landslides that cause property damage are rare in this region. Resistant sandstone beds in the Clinch Sandstone and Bays Formation form relatively

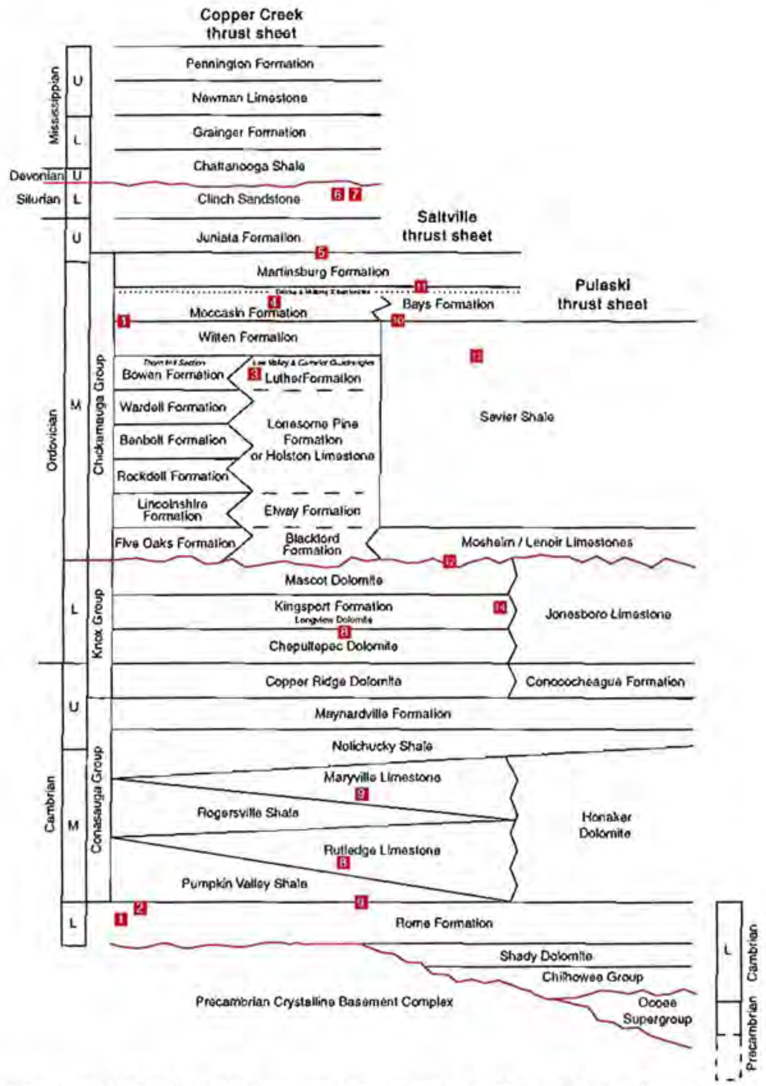

Figure 5. Stratigraphic nomenclature in the field trip area correlated across the Copper Creek, Saltville, and Pulaski thrust sheets. Vertical colored columns outline the stratigraphic units present in that thrust sheet. Magenta colored lines are unconformities. Red numbered squares are field trip stops.

steep topography that produces significant colluvial deposits. Quite often human-induced landslides occur as a result of improper development related to undercutting slopes and poor management of surface water runoff. We have documented human-induced landslides in all the rock units in the region regardless of topography.

The Chattanooga Shale is considered a potential radon source as are all the other shales in the area. Even in the carbonates, karst conduits provide open pathways that can respond to atmospheric pressure changes and either pump or concentrate radon gas. The EPA warns that the radon risk in this area is high enough that regardless of the underlying bedrock all buildings should be tested.

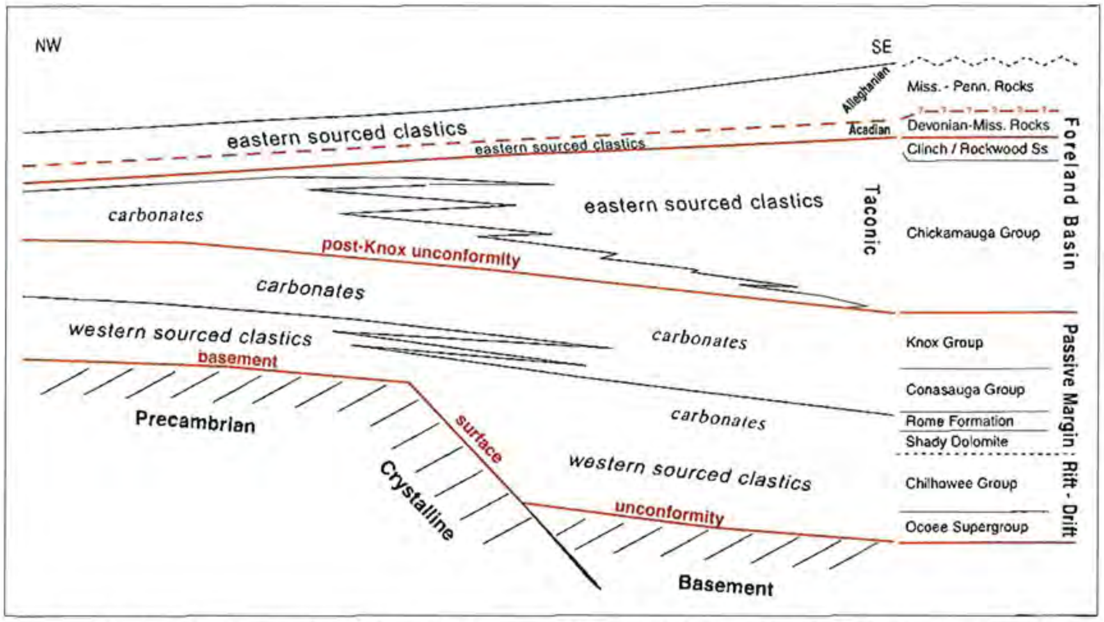

Figure 6. Schematic stratigraphic section depicting the change in lithology and location of unconformities across the basin when deformation is restored. The rocks between the basement and post-Knox unconformities are part of the passive margin sequence and faced an open ocean to the east. The Taconic, Acadian, and Alleghanian orogenic events created a new source area that shed clastic sediments toward the west into the foreland basin. Regional unconformities in red.

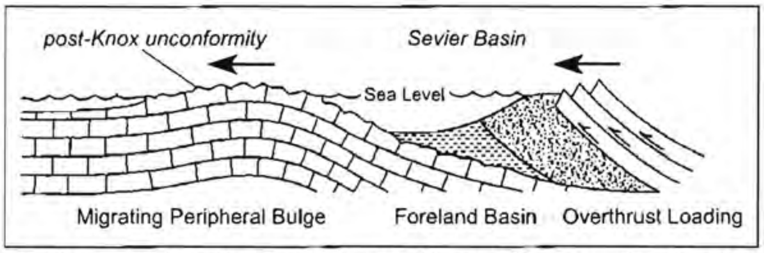

Figure 7. Tectonic setting associated with the development of the post-Knox unconformity and Sevier basin during the Middle Ordovician to Silurian Taconic orogeny (from Finny et al., 1996).

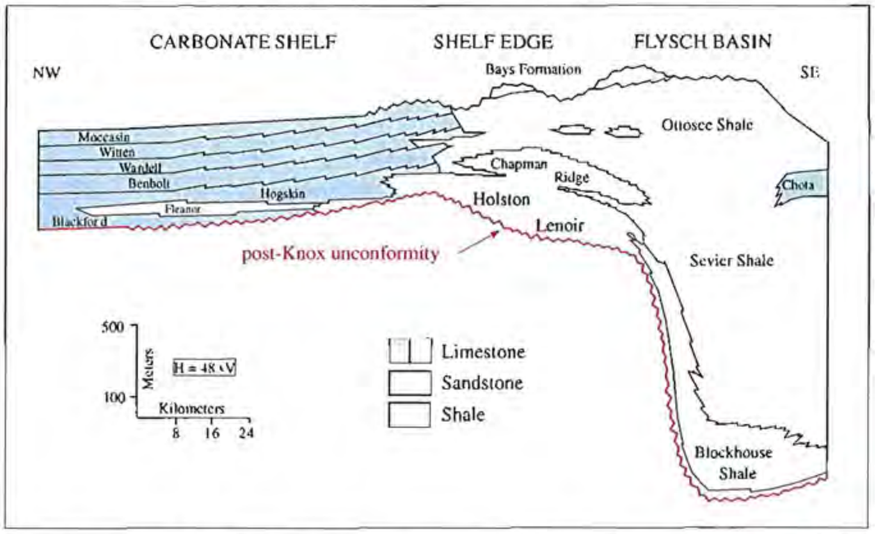

Figure 8. Stratigraphic cross-section of the Chickamauga Group across the Valley and Ridge in Tennessee. Note the vertical exaggeration. Shallow water limestone facies (Fleanor, Hogskin, Benbolt, Wardell, Witten and Moccasin (?)) and shelf edge reefs (Holston, Lenoir) become deep water shale and turbidite facies (Sevier) sourced from the southeast that coarsen upward into the Chapman Ridge Sandstone and Bays Formation (based on Walker et al., 1983).

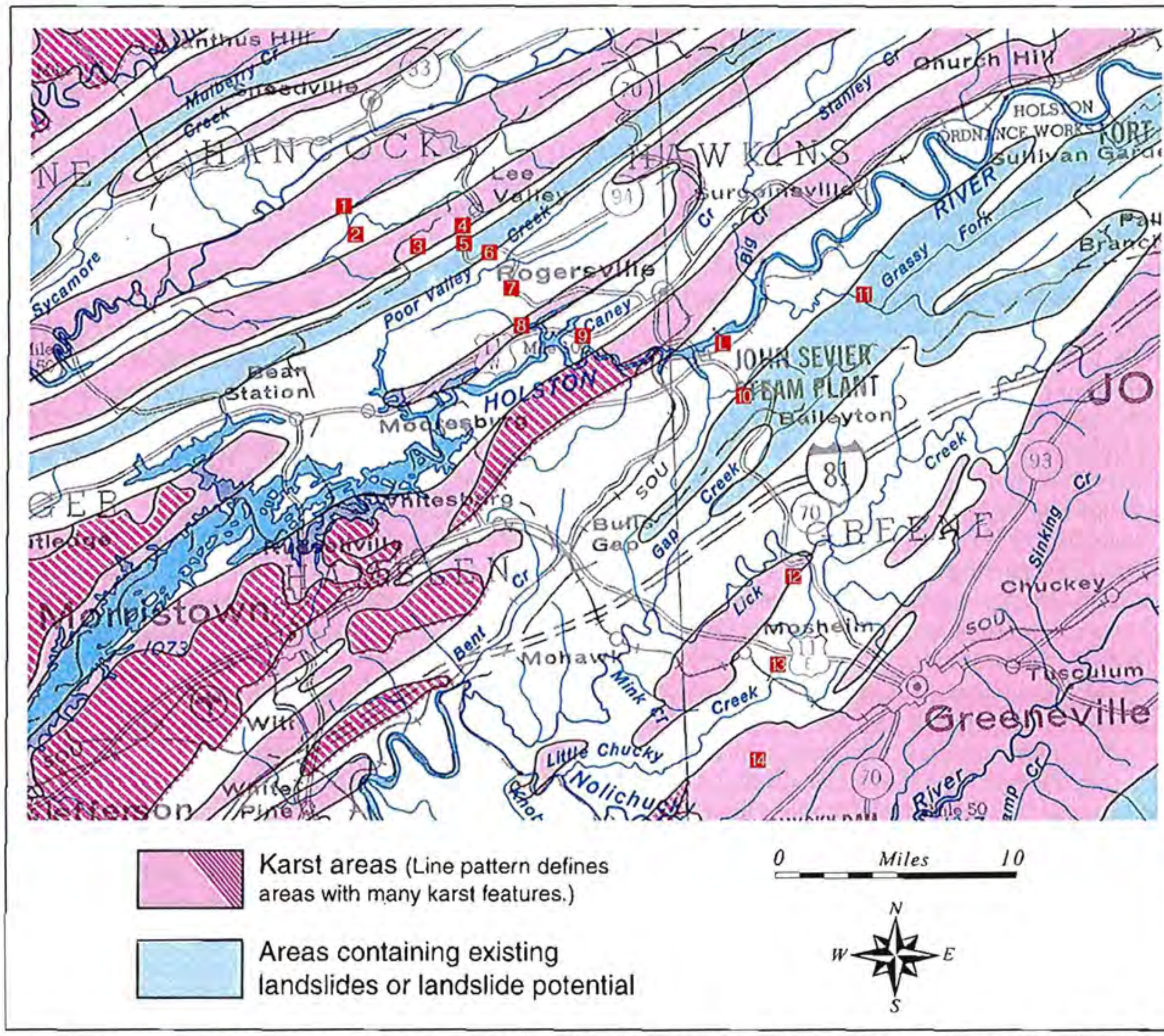

Figure 9. Tennessee state geologic hazards map with location of field trip stops (Miller, 1977). Major geologic hazards in the area are related to karst development, landslides in mountainous topography and radon (not shown).

Road Log and Stop Descriptions

Leave Knoxville heading east on I-40 to the I-40/I-81 split. Continue on I-81 to Exit 8 and head north on US 25E. At mile 4.2 we cross Highway 160, where a series of folds is exposed in the Nolichucky Shale 0.5 mi. to the east. Continue 11.2 mi. on US 25E to US 11-W north and exit. Go 3.6 mi. northeast on 11-W to TN Hwy 31. Turn left. Follow TN Hwy 31 for the next 8.7 mi. over Clinch Mountain. Along the way are exposures of Grainger Formation and the thick tripartite Chattanooga Shale on the southeast side of Clinch Mountain. The Clinch Sandstone, Juniata Formation, and Martinsburg Formation are well exposed on the mountain itself. Cross intersection with TN Hwy 131 (Mountain Valley Road) and continue heading northwest on TN Hwy 31. The Flat Gap Zinc Mine is on the left approximately 0.5 mi. past Mountain Valley Road. Continue an additional 2.4 mi. on TN Hwy 31 to Stop 1 and park on the right just past Big War Creek.

STOP 1. Copper Creek Fault-Lower Cambrian Rome Formation and Middle Ordovician Moccasin Formation (Lee Valley quadrangle: 36.4616°N, 83.2405°W).

The purpose of this stop is to examine an exposure of a major foreland thrust fault in the Valley and Ridge Province and use it to demonstrate a hinterland (southeast)-to-foreland (northwest) thrusting progression between the Copper Creek and Clinchport faults. One of the main points we want to demonstrate is that the present dip of the fault is not the same as when the fault was active.

According to the Tennessee state geologic map, the fault here differs from its regional structural style and consists of three hanging-wall imbricate splay faults in the Rome Formation (Fig. 1). Based on a restored cross section, the displacement along the fault is a minimum of 7.5 mi (12 km). We cannot better determine displacement because erosion has removed where the Copper Creek fault cut through the hanging wall rock units, which is needed to tie them to the footwall stratigraphic cutoffs.

At this location, the Copper Creek thrust sheet is the hanging wall and the Clinchport thrust sheet is the footwall. The fault and bedding in the footwall and hanging wall strike N40E and dip 20SE at this erosion level. Because bedding in the Lower Cambrian Rome Formation in the hanging wall is nearly parallel to the fault, this suggests that the fault here is a hanging wall flat. Furthermore, bedding in the Middle Ordovician Moccasin Formation is nearly parallel to the fault and is interpreted to be a footwall flat (Fig. 10). The bedding-parallel geometry of the Copper Creek fault can also be traced into the subsurface on seismic reflection profiles.

The Moccasin Formation is a mid-level detachment horizon where the Copper Creek fault propagated nearly parallel to bedding after it ramped upward from the basal décollement (Rome Formation) and cut diagonally

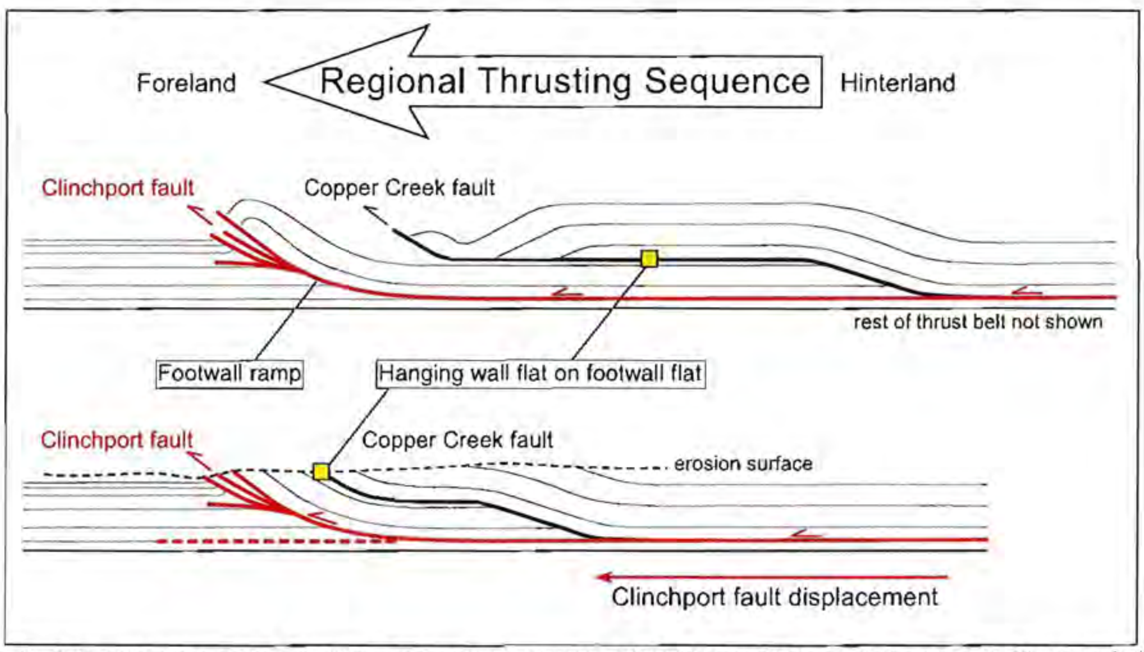

Figure 10. Schematic cross section depicting the piggyback transport of the Copper Creek thrust sheet by the Clinchport fault. The Copper Creek fault was emplaced first followed by displacement along the Clinchport fault, which caused the passive clockwise rotation of both thrust sheets as they climbed a footwall ramp.

through the overlying Conasauga Group, Knox Group, and most of the Chickamauga Group. The present southeast dip of the fault and bedding occurs because the Copper Creek thrust sheet was carried piggyback by the Clinchport thrust sheet over a footwall ramp. As both thrust sheets moved over the ramp they were passively rotated to the southeast (Fig. 10). This interpretation is consistent with an overall hinterland to foreland progression of thrust fault development during the growth of the fold–thrust belt.

The amount of deformation in the hanging wall and footwall surrounding the fault is relatively minor. Fractures and small-scale faults brecciated the rock and formed cataclasite adjacent to the fault. This differs from the development of a lower broken formation zone and upper fractured zone documented along the Cumberland Mountain fault (at Dunlap) and the Copper Creek fault (at Bull Run) (Harris and Milici, 1970). The lack of deformation seen here suggests that, although this is the fault with the greatest stratigraphic offset, the imbricate faults that are mapped within the Rome Formation on War Ridge may have formed in a break-back manner and accommodated most of the regional displacement.

The Rome Formation is the location of the major basal décollement in the fold–thrust belt. The Lower Cambrian Shady Dolomite underlies the Rome Formation in the eastern part of the Valley and Ridge. How far the Shady Dolomite extends westward is not clear, and the Rome may have been deposited directly on top of crystalline basement (Fig. 5). The Rome Formation in this exposure consists of massively bedded dolomite adjacent to the fault that is overlain by thin- to medium-bedded sandstone, siltstone, and shale. We will examine a better exposure of the Rome Formation at Stop 2.

The Moccasin Formation consists of thin- to medium-bedded, light- to medium-gray, micritic limestone. Some of the limestone is argillaceous and has a reddish color. Fossils and other typical sedimentologic features of this unit, such as mud cracks, are difficult to identify here. Underlying the Moccasin Formation is the Witten Formation, which is predominately thin- to medium-bedded limestone.

Also visible in this outcrop is a landslide scar. The landslide probably occurred after the road was widened. All of the material transported by the landslide has been removed.

Turn around and proceed southeast 0.9 mi. along Hwy 31 to Stop 2.

STOP 2. Lower Cambrian Rome Formation Imbricate (Lee Valley quadrangle: 36.4509°N, 83.2355°W).

The purpose of this stop is to examine some of the sedimentologic and outcrop-scale structures that occur in the Rome Formation. In particular, we thought this might be a good place to discuss the concept of fold vergence and its usefulness for mapping and regional structural analysis.

The Lower Cambrian Rome Formation at this stop contains many sedimentologic features typical of this unit. Although all these features have not been seen here, the presence of halite hoppers, mud cracks, algal laminated dolostone, and relict evaporite features indicate that deposition occurred in a supratidal to shallow subtidal environment. Mudflats in an intertidal environment can be inferred from red beds of laminated shale and siltstone, ripple marks, and bioturbation. All of the sediment had a westward source with an open ocean to the east (Samman, 1975).

The color of the rock is variegated shades of red, green, gray, and tan. The red is iron oxide resulting from weathering in a tropical to subtropical environment in both the sediment source area and depositional environment, and the green color is mostly due to glauconite. Bedding varies from thin to thick, with bed bottoms that are either sharp (erosional) or gradational. Rock types consist of repeated sequences of shale-siltstone-sandstone-dolomite/limestone.

Deposition during Rome time is associated with the Cambrian explosion of new life forms that has been well documented elsewhere. The Rome Formation, however, typically contains few body fossils, but it is bioturbated and contains various trace fossils, including *Planolites* and *Cruziana*. Trilobites are the only fossils that have been found in the Rome Formation here (Fig. 11).

Starting at the southeast end of the exposure the strike and dip of bedding are approximately N50E/55SE. Overall, the rocks are undeformed except for two steeply dipping thrust faults that bound a small horse (a horse is a fault-bounded slice of rocks). Continuing to the northwest, down section, the ratio of shale to sandstone increases in conjunction with the number of folds and faults. Structurally this is the most interesting interval in this exposure and contains folds of various shapes ranging from concentric folds to chevron-hinged buckle folds and kink folds. Many of these folds have axial planes with dips that vary within 5° from vertical. However, recall that at the first stop we discussed how the frontal edge of the Copper Creek thrust sheet has been passively rotated to

Figure 11. Olenellid trilobite cephalons on a siltstone bedding surface from the Rome Formation.

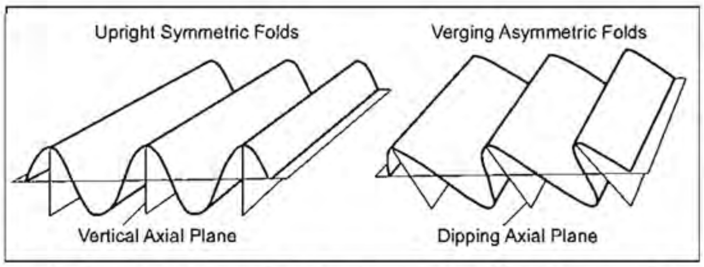

Figure 12. Example of symmetric and asymmetric folds. Upright symmetric folds have no vergence direction. The sense of vergence of an asymmetric fold is based on the dip of the axial plane when looking down the plunge of the fold axis. In this example the sense of vergence of the asymmetric folds is toward the left (from Ramsay and Huber, 1987).

the southeast by about 20° and when this rotation is removed most of the fold axial planes dip to the southeast.

Recording the orientation of the fold axial plane and fold axis, and describing the shape of the folded surface is a useful way to evaluate the vergence of structures in an area (Fig. 12). Structural vergence is then used to deduce the overall shortening direction caused by a deformational event. In addition, the vergence of outcrop scale structures can also be used to infer the location of larger structures that may be important at the map scale.

How do you determine the vergence of a fold? If the fold axial plane is a plane of symmetry, then the fold shape is said to be symmetric, if not, then the fold is asymmetric (Fig. 12). Another way to make the distinction is that symmetric folds have nearly equal limb lengths and asymmetric folds do not. For asymmetric folds the sense of asymmetry is a measure of vergence. When viewed down the plunge of the fold axis the sense of asymmetry is often described as clockwise or anticlockwise, which is related to the dip direction of the fold axial plane. At this location, the southeast dip of the axial planes indicate that most of the folds have a northwest vergence. The overall northwest vergence of map scale structures in the fold-thrust belt is consistent with regional shortening associated with the Alleghanian orogeny.

As we continue to the northwest along the outcrop there is a poorly exposed interval with a number of folds with a southeast vergence (i.e., axial planes dip moderately to the northwest). This location is also associated with a decrease in the overall dip of bedding to about 30°SE. Furthermore, there is a thick-bedded carbonate that underlies this interval and changes dip from about 20°SE to 75°SE. The folding of this carbonate bed, change in overall dip of the overlying shale and siltstone beds, and southeast vergence of the folds has been used to infer the location of a northwest dipping thrust fault or back-thrust. Chances are that the displacement along the back-thrust is small and is being accommodated, in part, by the development of the southeast vergent folds. The back-thrust must either end or continue out of the top of the outcrop, because overlying carbonate beds are undeformed.

Brief History of the Flat Gap Zinc Mine

On the way to Stops 1 and 2, we will pass the New Jersey Zinc Company's Flat Gap Mine, which was closed in 1972 for economic reasons (Fig. 1). This was one of two mines and a number of zinc prospects referred to as the Copper Ridge District. The Idol Mine (Clinch Valley Mine) lies about 10 mi (16 km) to the southwest, and significant quantities of ore have been proven elsewhere along the ridge. The following account is taken from the Mineral Resources Summary of the Lee Valley quadrangle (Brent, 2000).

The occurrence of sphalerite (ZnS) in rocks of the Knox Group underlying Copper Ridge northwest of Clinch Mountain has long been known. Mineralization with economic potential is restricted to the Kingsport Formation and the lower part of the overlying Mascot Dolomite. Paleokarst breccia bodies are the host-rock to commercial occurrences of sphalerite in this area. At the Flat Gap Mine, galena is fairly common, but was not recovered. Other minerals present include pyrite, barite, fluorite, calcite, anhydrite, and gypsum.

Production began in 1958. Access to the underground workings of the Flat Gap Mine was provided by a vertical shaft on the west side of State Highway 31, and by an inclined subterranean roadway with an entrance on the east side of that highway. A 2,000 ton (1,800 mt) per day flotation mill was operated at the mine site. In 1968 and 1969, peak production reached about 2,000 tons of ore per day, with a grade of about 2.5% zinc. Ore concentrates were sent by truck to Morristown, Tennessee, and from there shipped by rail to smelters. During the life of the Flat Gap Mine, total ore production was 4.6 million tons (4.2 million mt), with an average grade of 2.8% zinc. Ore reserves remaining in place have been estimated at 11.1 million tons (10.1 million mt), with an average grade of about 3.7% zinc.

Continue heading southeast on TN Hwy 31 for 2.1 mi. and turn left on Mountain Valley Road (TN Hwy 131). Stop 3 is 2.2 mi. northeast on TN Hwy 131. The road is narrow with no safe place to park completely off the road. Leave blinkers on and use caution.

STOP 3 (Optional). Middle Ordovician Chickamauga Group Luther Formation Mud Cracks (Lee Valley quadrangle: 36.4369°N, 83.1908°W).

The purpose of this stop is to view some well-developed mud cracks in the Middle Ordovician Luther Formation. Mud cracks are indicative of deposition in a subaerial tidal flat setting and are seen in all the variously named red-bed sequences in the Chickamauga Group. Although we are in the same strike belt (valley) of the Chickamauga Group as Thorn Hill, this red-bed unit below the Witten Formation is equivalent to the red-bed unit called the Bowen Formation at Thorn Hill (Fig. 5). We do not know the reason for the change in name. Limestone of the overlying Witten Formation is exposed in the pasture across the road.

Although not seen here, underlying the Luther Formation is the Lonesome Pine Formation (Fig. 5). The Lonesome Pine Formation has been subdivided into lower and upper units and is equivalent to the Rockdell, Benbolt, and Wardell Formations at Thorn Hill. Near Rogersville, rocks below the Luther Formation that are equivalent to the Lonesome Pine Formation are mapped as Holston Limestone. The Holston Limestone is very different lithologically and consists of pink, tan, and gray, coarse-grained, fossil-rich, limestone "marble," that is thick- to very thick-bedded with bedding plane stylolites. This signifies an increase in water depth and the development of a reef facies along the shelf margin, which all occurred within the Copper Creek thrust sheet on either side of the Greendale syncline. As we will see today, the predominantly limestone and red-bed sequence composing the Chickamauga Group in the Copper Creek thrust sheet becomes a deep water shale and turbidite sequence in the Saltville thrust sheet.

The desiccation polygons in this exposure are deformed and can be used as strain markers. A strain marker is a feature with a fairly well-known original shape. Based on their slightly squished shape, the polygons appear flattened parallel to bedding, and probably record a layer-parallel-shortening strain that occurred prior to rotation of bedding to its present orientation.

The mud cracks can also be used to determine if the beds are upright. Although not always developed, the cross sectional shape and upward bending of bedding laminations adjacent to a mud crack points toward the top of bedding.

Continue 2.3 mi. northeast on Hwy 131 and turn right on Hwy 66. Stop 4 is immediately ahead on left. Park on right.

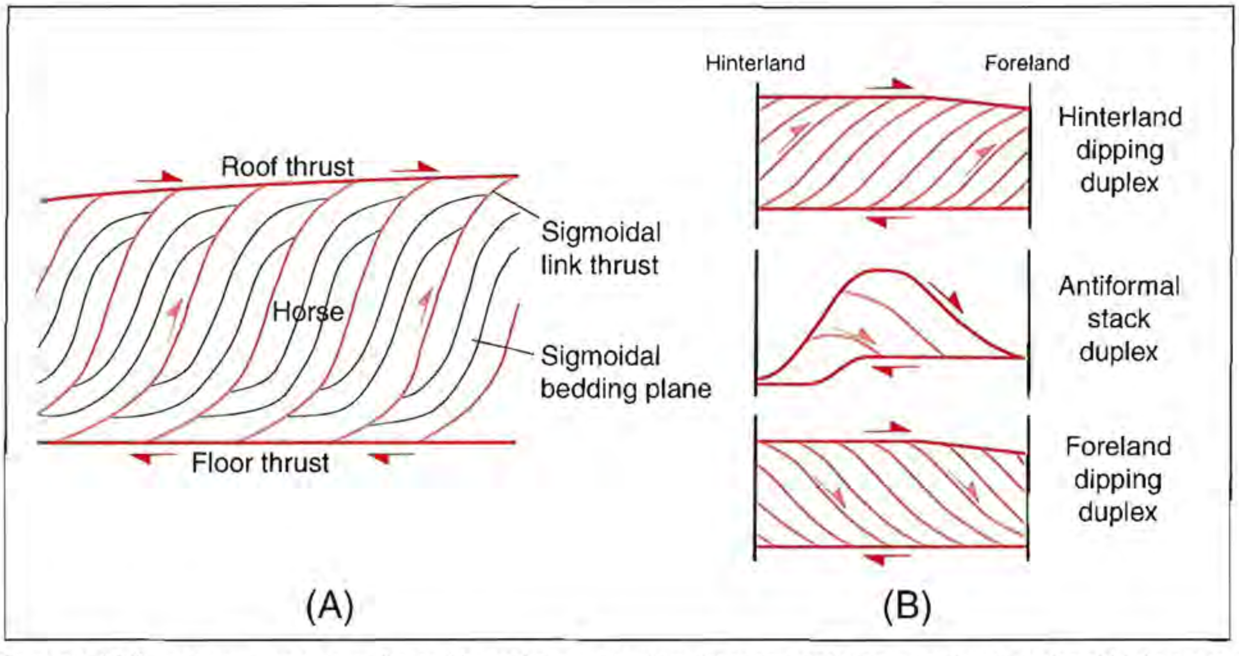

Figure 13. (A) Terminology used to describe an idealized duplex structure. Floor and roof thrusts are linked by sigmoidal thrusts that bound individual horses. (B) Terminology to describe the stacking arrangement of horses in a duplex (from Boyer and Elliott, 1982).

STOP 4. Middle Ordovician Chickamauga Group Moccasin Formation Intraformational Duplex (Lee Valley quadrangle: 36.4506°N, 83.1554°W).

Here we will examine the upper part of the Moccasin Formation in the Copper Creek thrust sheet and see an example of a mesoscopic duplex. Duplexes represent an important mechanism of shortening in a fold-thrust belt and are characterized by repetitions of strata on sigmoidal faults that are linked to a floor thrust and to a roof thrust (Fig. 13). There are numerous examples of strike-parallel to bedding-parallel deformation features in the Chickamauga Group and younger rocks in Clinch Valley. These features have little stratigraphic displacement, however, and would probably go unnoticed during detailed mapping if it were not for road cut exposures. The Lee Valley quadrangle geologic map does not indicate that the Moccasin Formation is any thicker here because of this duplex than anywhere else along strike (Brent, 2000).

Simonson (1985) indicated that the Moccasin Formation represents part of a broad tidal flat environment. At Thorn Hill he described three members in the Moccasin Formation: a lower red bed unit, a middle limestone unit, and an upper red bed unit. The duplex is near the upper boundary of the limestone member. This member consists of medium-gray to tannish-gray, well-bedded limestone with chert nodules that is recognizable over considerable distances because of its cherty residuum. Several of the characteristic brown chert nodules can be observed both in the duplex and in the adjacent rock.

Bedding in both the hanging wall and footwall of the duplex approximates N55E/45SE, somewhat steeper to the northwest, becoming less steep to the southeast (Fig. 14). Superimposed on this subtle synclinal bend is a local anticlinal flexure directly over the duplex, visible as a shallowing of dip in the upper part of the exposure. A very weak foliation dipping steeply northwest can also be observed. The duplex itself occupies the space between the floor and roof thrusts and is composed of horses of cherty limestone. Within the duplex, bedding orientations range from steeply southeast-dipping to slightly overturned, suggesting that during their emplacement, the slices were rotated about 45°. Later, passive rotation of the Copper Creek thrust sheet brought the structure to its present orientation.

Calcite veins are common in the limestone but not in the surrounding red beds. Typical orientations are E-W/45N, but other bed-perpendicular orientations are common. There are also bedding plane slickensides within the duplex and a folded chert pod.

Continue 0.9 mi. southeast up the mountain to Stop 5. There is an old quarry on the left. Pull off into very restricted space used as dumping ground.

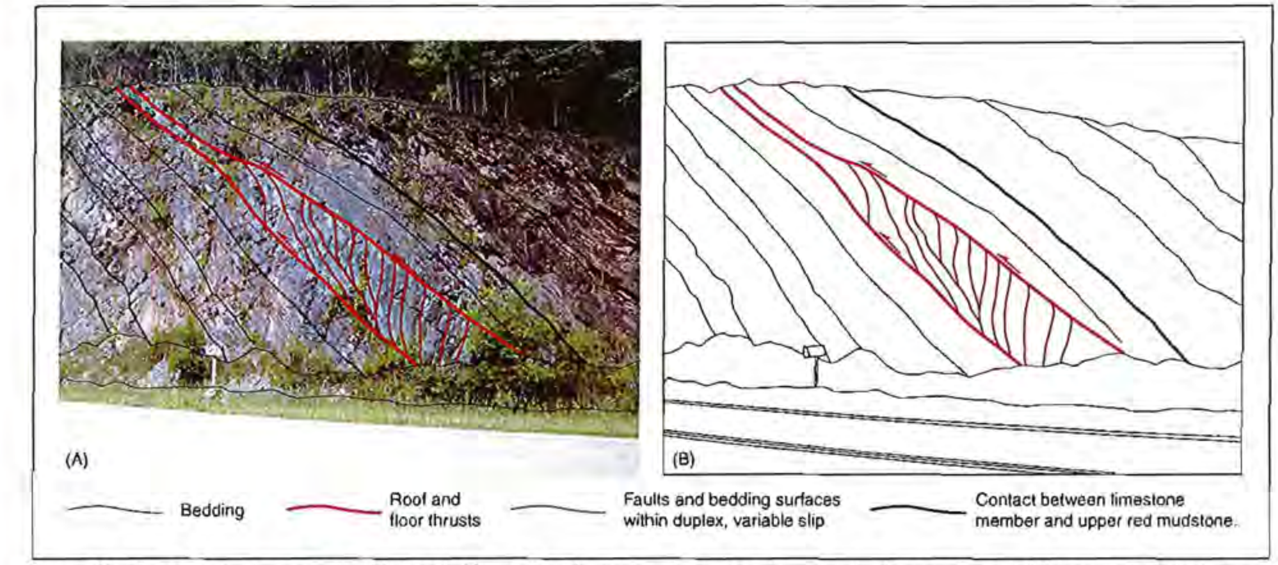

Figure 14. Mesoscopic duplex in the Moccasin Formation cherty limestone member, view looking northeast. (A) Interpreted photograph. (B) Sketch of the structures exposed at this stop.

STOP 5. Middle and Upper Ordovician Martinsburg Formation & Upper Ordovician Juniata Formation (Lee Valley quadrangle: 36.4373°N, 83.1519°W).

This stop is located on the northwest side of Clinch Mountain, which is the upright northwest limb of the Greendale syncline. One purpose of this stop is to examine the Martinsburg Formation in the Copper Creek thrust sheet so that we can compare it with the Martinsburg Formation in the Saltville thrust sheet at Stop 11. The similarity of the Martinsburg Formation at each of these stops indicates that the major facies changes in the Chickamauga Group between these two thrust sheets were gone by the time the Martinsburg was deposited. The second reason for this stop is to examine fold and fault development in an area where there are no large-scale structures shown on the Lee Valley quadrangle geologic map. Even more intriguing is that many of the folds verge southeast and southwest, which may indicate the presence of a hidden map-scale structure in this area (Fig. 15).

The Martinsburg Formation in the Copper Creek thrust sheet overlies the Moccasin Formation and is the youngest formation in the Chickamauga Group. This exposure represents a mixed carbonate-clastic facies of the upper part of the Martinsburg Formation and consists of thin-bedded shale, siltstone, and limestone. Limestone beds are fossiliferous packstone, which contain a basal fossil lag (hash) grading upward into bioturbated shale. Fossils include brachiopods, bryozoans, pelcypods and gastropods, echinoderms, and trilobites (Byerly et al., 1986). In this area, the Martinsburg Formation is about 1936 ft (590 m) thick and contains evidence for an initial deepening event followed by a shallowing-upward sequence culminating in deposition of peritidal rocks of the Juniata Formation (Walker and Diehl, 1980). The contact between the Martinsburg and overlying Juniata Formation is gradational but is placed at the appearance of the first maroon siltstone bed. The attitude of the rocks is N60E/30SE and is consistent throughout the Juniata portion of the outcrop.

The Upper Ordovician Juniata Formation (note that where it is more carbonate-rich it is called the Sequatchie Formation) consists mainly of medium-bedded, maroon and gray, calcareous siltstone and shale with minor amounts of sandstone. It is about 400 ft (122 m) thick. Although difficult to see here, the lower part of the formation contains mud cracks, ripple cross-laminations, flaser bedding, and vertical burrows, which suggest a tidal flat or deltaic depositional environment.

The folds exhibited here range from concentric to chevron with a parallel fold style forming in the competent (siltstone and limestone) layers and a similar fold style forming in the incompetent (shale) layers. Most folds have an inclined plunging attitude with subhorizontal to gently plunging fold axes and gently to moderately inclined axial surfaces (Fig. 15). The photo in Figure 15 is an example of a fold with a curviplanar axial surface that becomes recumbent.

Besides the unusual vergence of these folds, we thought this might be a good place to discuss that the strain state within a folded layer cannot be deduced by its shape, but instead by the types of secondary structures that formed within it. The two end-member strain states are flexural-slip–flow folds and tangential-longitudinal strain folds (Fig. 16).

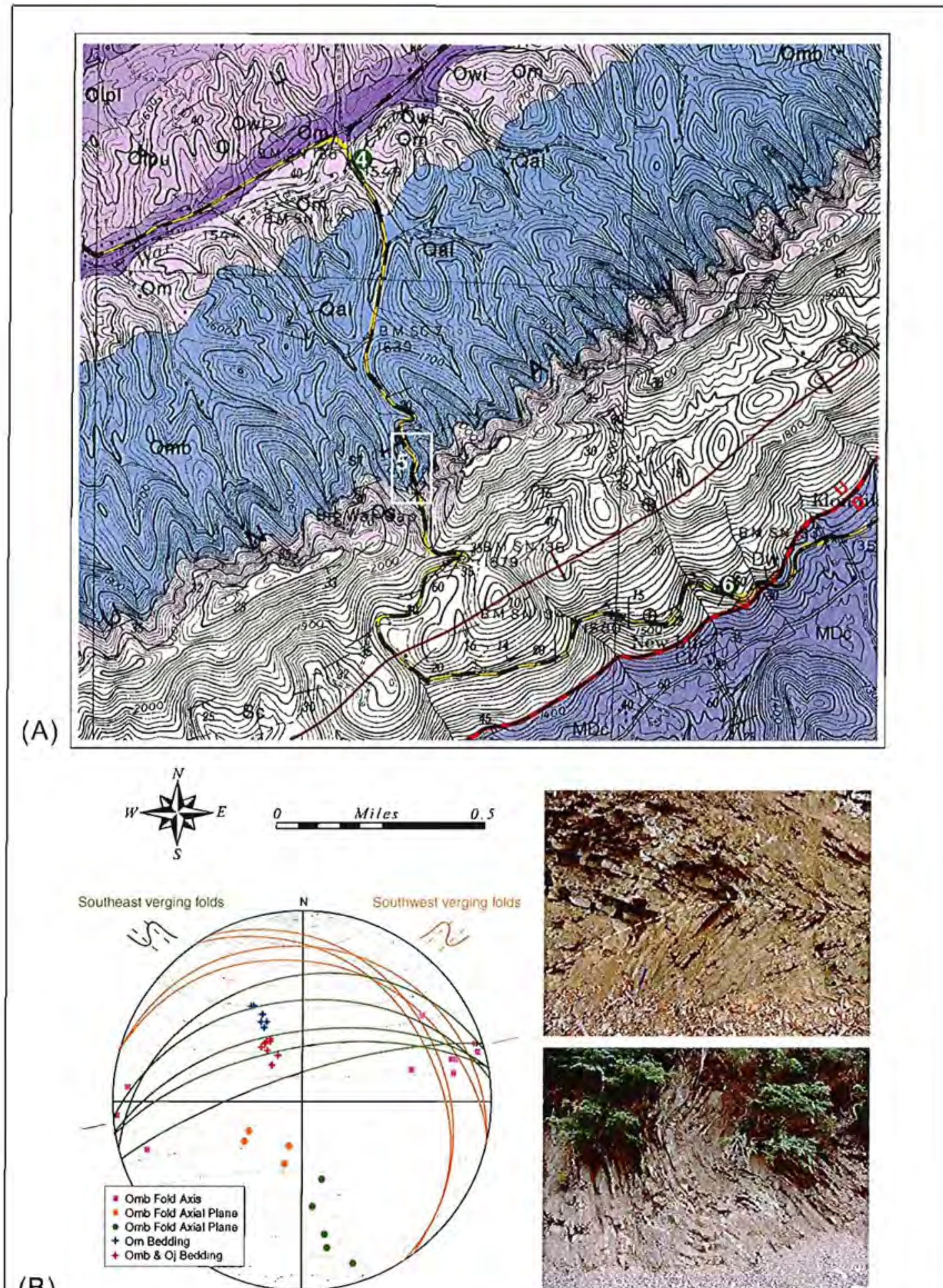

Figure 15. Mesoscopic folds in the Martinsburg Formation with a southeast and southwest vergence. (A) Leesburg quadrangle geologic map (Brent, 2000) with the location of Stops 4–6. Refer to other figures for an explanation of formation symbols except, Olp = Lonesome Pine Formation, Om = Moccasin Formation, Os = Oj, and Dw = Wildcat Valley Sandstone. Note absence of map scale structures in the vicinity of Stop 5. (B) Stereonet plot of bedding indicates a decrease in dip from the Moccasin Formation southeast to the Juniata Formation. Fold axes in the Martinsburg Formation plunge gently and trend east-northeast. Poles to axial planes and associated great circles indicate that fold vergence is to the southeast and southwest.

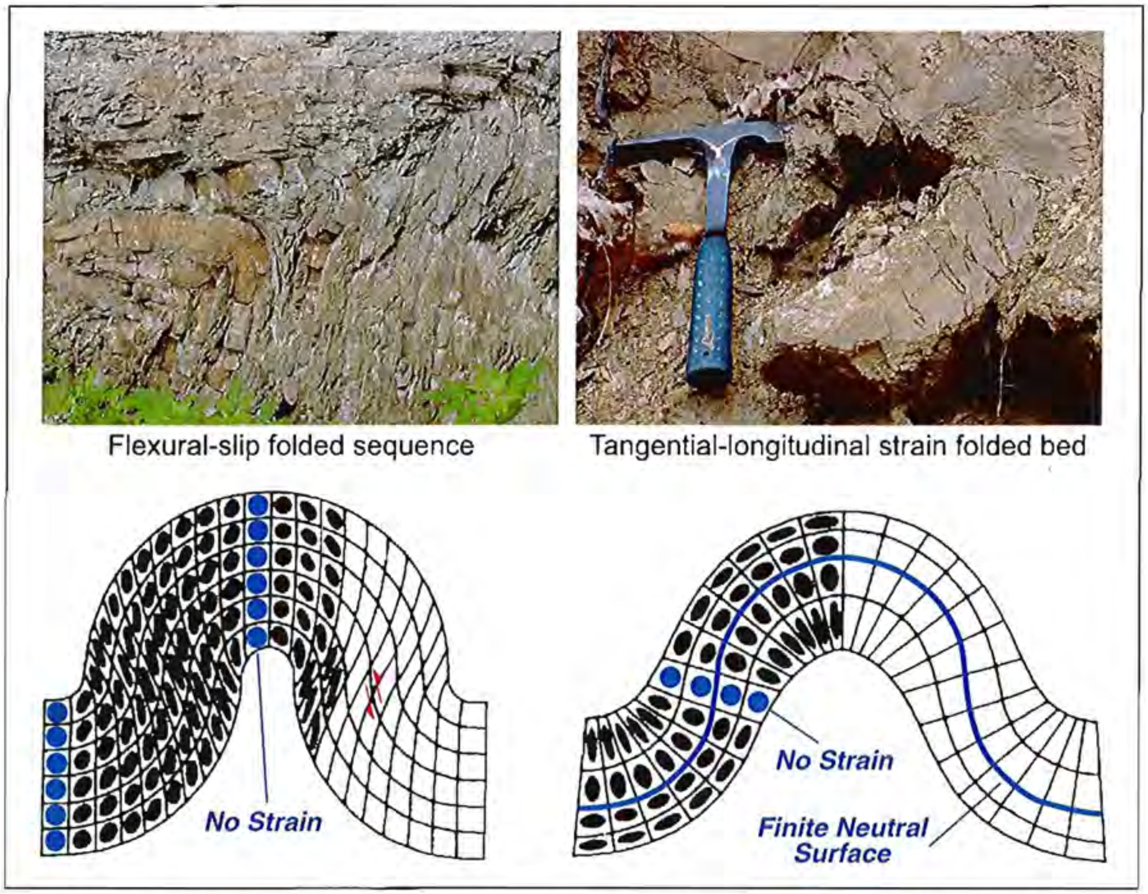

Figure 16. As shown by the deformed circles (strain ellipses), the strain pattern within a folded layer varies between a flexural slip–flow fold and tangential-longitudinal strain fold (from Ramsay and Huber, 1987). Calcite filled fractures formed in hinge of competent siltstone bed. Shale beds thicken around some of the fold hinges.

Flexural-flow folds develop in layers with a high mechanical anisotropy parallel to bedding. Such folds can be produced by compressing a stack of paper sheets parallel to the layering. As the pack buckles, the individual sheets slide past each other. The maximum amount of slip occurs on the limbs at the inflection points and decreases toward the hinges. The strain ellipses (Fig. 16) show that the maximum strain occurs at the inflection points and little to no strain occurs at the hinge. If these slip planes were very close together, then the layer-parallel shear would be uniformly distributed across the folded layer. If, however, the slip planes were more widely spaced, the layer parallel shearing would be concentrated along the bedding planes, and the structure would be referred to as a flexural-slip fold. One of the most common features associated with flexural-slip folding is slickensides that form on the surfaces of the layers. Slickensides have the opposite sense of slip on each fold limb and generally die out toward the fold hinge where the slip between beds is zero. Another structure that can develop within the folded layer is arrays of en-echelon tension gashes that become less sigmoidal toward the fold hinge.

The strain pattern associated with a tangential-longitudinal strain fold develops when a homogeneous, isotropic layer is buckled. In contrast to flexural-slip folds, the maximum strain occurs at the hinges, and no strain occurs at the inflection points (Fig. 16). As its name implies, one of the principal strains is always parallel (tangential) to the layer boundary. The outer arc of the hinge area is in extension, and the inner arc is compressed. The boundary between these two strain states is called the neutral surface. The layer-parallel extension generated in the outer arc commonly produces extension fractures and normal faults (Fig. 16). In the inner arc of the fold, the large layer-parallel compression may form cleavage, shear fractures, and reverse faults. In sedimentary rock folds, as seen in this outcrop, there is a combination of flexural-slip folding between layers, and tangential-longitudinal strain folding within layers.

Continue 1.4 mi. crossing over the crest of Clinch Mountain and pass numerous exposures of Clinch Sandstone to Stop 6. Drive past the stop and park on the right where the road curves to the left.

STOP 6. Lower Silurian Clinch Sandstone (Lee Valley quadrangle: 36.4359°N, 83.1397°W).
The youngest rock unit we will examine today is the Lower Silurian Clinch Sandstone, which conformably overlies the Upper Ordovician Juniata Formation. Age assignments for the Clinch Sandstone are inexact, because it lacks dateable body fossils (Driese, 1988). Pre-Middle Devonian uplift and erosion have resulted in little or no preservation of Middle or Upper Silurian deposits; the Devonian-Mississippian Chattanooga Shale unconformably overlies the Clinch Sandstone.

According to palinspastic restorations in this area, the Clinch Sandstone is part of a westward prograding wedge of sandstone. Studies by Driese (1988) have concluded that sediment transport was primarily in a west or northwest direction and that the sandstone represents deposition on a beach shore face with some marine shelf components. All this material is assumed to have a source in mountains formed during the Taconic orogeny. The mature composition of the Silurian sandstone sequence suggests that the sediments are recycled sedimentary rocks (Driese, 1988).

This exposure and most of the Clinch Sandstone belongs to Driese's (1988) cross-stratified sandstone facies. This facies consists of medium- to large-scale sets of trough cross strata developed in medium- to coarse-grained quartz sandstone. Trace fossils are dominated by *Skolithus*, *Planolites*, and *Arthrophycus*.

Besides an opportunity to examine the Clinch Sandstone, the main purpose of this stop is to point out the development of the *Arthrophycus* trace fossil. *Arthrophycus* typically occurs where sandstone is underlain by shale and therefore forms at the base of sandstone beds. They are simple or branched, straight-to-curved, annulated burrows that show well-defined and regularly spaced ridges within the burrow fill. *Arthrophycus* is interpreted to be a feeding burrow made by a worm-like organism.

Continue heading southeast on Hwy 66. Note colluvial boulder trains as we travel down into Poor Valley. Exposures on the other side of the valley, going up Stone Mountain, are brecciated and sheared Grainger Formation near the axis of the Greendale syncline. Thin zones of Chattanooga Shale mark horizontal slip surfaces. After a drive of 4.4 mi., Stop 7 is on the left. Park on the right just before intersection with Choptack Road.

STOP 7 (Optional). Lower Silurian Clinch Sandstone overturned at the base of Stone Mountain (Camelot quadrangle: 36.4111°N, 83.1138°W).
The purpose of this brief stop is to present outcrop evidence that the southeast limb of the Greendale syncline is overturned. We mapped the Camelot quadrangle as part of a 2003–2004 USGS STATEMAP cooperative mapping agreement. Most of the area was previously mapped as part of a Yale dissertation in the 1950s (Sanders, 1952). Sanders (1952) appears to be the first to subdivide the sedimentary sequence in this area into mappable units and to document the overturning of this limb of the Greendale syncline.

The southeast dip of the Clinch Sandstone along Stone Mountain is the first evidence that the rocks along this limb of the syncline are overturned. Why?—because the older Juniata Formation is toward the southeast and overlies the Clinch Sandstone, and the younger Chattanooga Shale underlies it to the northwest. In addition to the stratigraphic relationships, the Clinch Sandstone exposure here contains *Arthrophycus* on the top of bedding. Additional features used to indicate overturning in the Clinch Sandstone along Stone Mountain are inverted graded beds and cross beds.

Note that the geologic map of Tennessee indicates a syncline here but not that the southeast limb is overturned (Fig. 1; Hardeman, 1966). Many regional cross sections based on the state geologic map have been drawn through this area, but most have missed this. Recognizing that the limb is overturned does not greatly increase estimates of thrust belt shortening through the area, but it does influence how cross sections are drawn.

Turn right on Choptack Road. Choptack Road passes through overturned rocks of the Martinsburg Formation, Chickamauga Group, and Mascot Dolomite. Go 2.3 mi., cross the new alignment of US 11-W and turn left at the "T" intersection (Old Hwy 11-W). Proceed 0.4 mi. to Stop 8 in the pasture on the right. Parking is by barn on left.

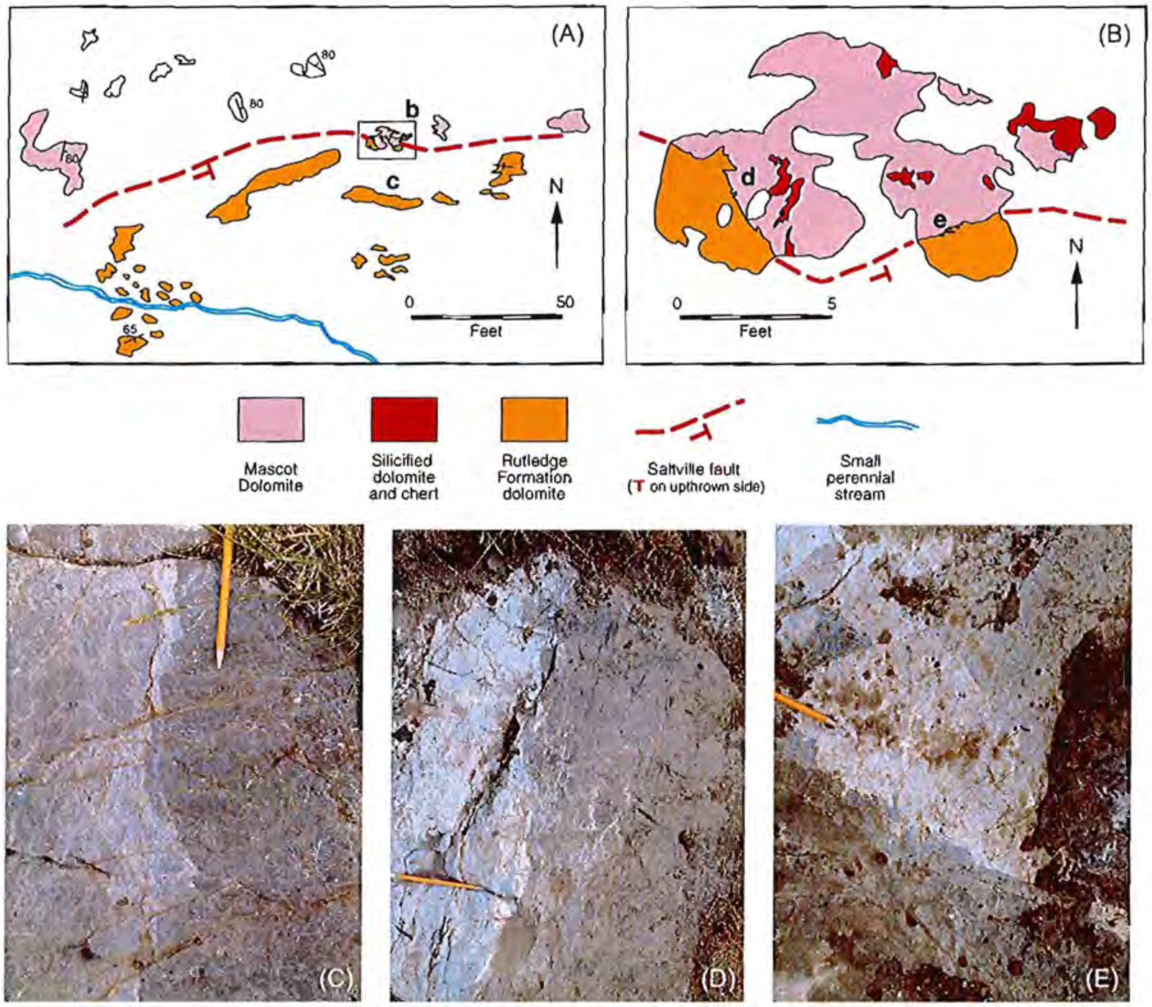

Figure 17. Bedrock exposures in the pasture at Stop 8. (a) Overview sketch map. (b) Detail of outcrop showing contact between brecciated Lower Ordovician Mascot Dolomite and brecciated Middle Cambrian Rutledge Formation dolomites. (c) Breccia zone within the dark Rutledge Formation dolomites. Pencil points southeast here and in the following views. (d) A portion of the irregular fault contact between brecciated dark dolomite and intensely brecciated Mascot Dolomite. Brown areas near center are soil. (e) Another part of the brecciated contact.

STOP 8 (Optional). Saltville Fault (Camelot quadrangle: 36.3847°N, 83.1090°W).

The Saltville fault is exposed in a series of low natural outcrops in the pasture south of the road (Fig. 17). It is the floor thrust of the Caney Valley duplex, of which the Town Knobs fault is the roof thrust. Here, the Saltville separates dark chert-free dolomite of the Conasauga Group (Rutledge Limestone) on the hanging wall, from lighter-colored generally overturned cherty dolomite of the Knox Group. The dark dolomite is exposed repeatedly in Caney Valley along with several repetitions of the Rogersville Shale. Attitudes of the Knox Group in the footwall are locally anomalous, with stringers of chert suggesting northwest-southeast strikes, steeply dipping, and possibly overturned. Although exposure is limited, one can see an extremely irregular and brecciated fault surface and a zone of microbreccia between the two kinds of dolomite, in sharp contrast to the planar surface at Stop 9 (Fig. 17).

Continue 1.1 mi. and turn right on new US 11-W. Stop 9 is 1.2 mi. to the east, on the left side of the highway. Pull to the right shoulder and use caution with fast traffic and noise.

STOP 9. Town Knobs Fault along Highway 11W southwest of Rogersville (Camelot quadrangle: 36.3788°N, 83.0686°W).

Here a large highway cut exposes the Town Knobs fault, which places the Middle Cambrian Pumpkin Valley Shale over Middle Cambrian Conasauga Group carbonate rocks. This area was previously mapped by Haney (1966). Prominent structural features include contractional and extensional faults in the hanging wall and deformed carbonates in the footwall truncated by the Town Knobs fault. The Town Knobs fault is the roof thrust of the duplex (antiformal stack?) of Conasauga carbonates and shales underlying Caney Valley (Fig. 18 and see the cross section in Figure 1). It is the base of a belt of much less deformed Conasauga and Knox Group rocks in the hanging wall, which underlie the city of Rogersville and the hills to the southeast.

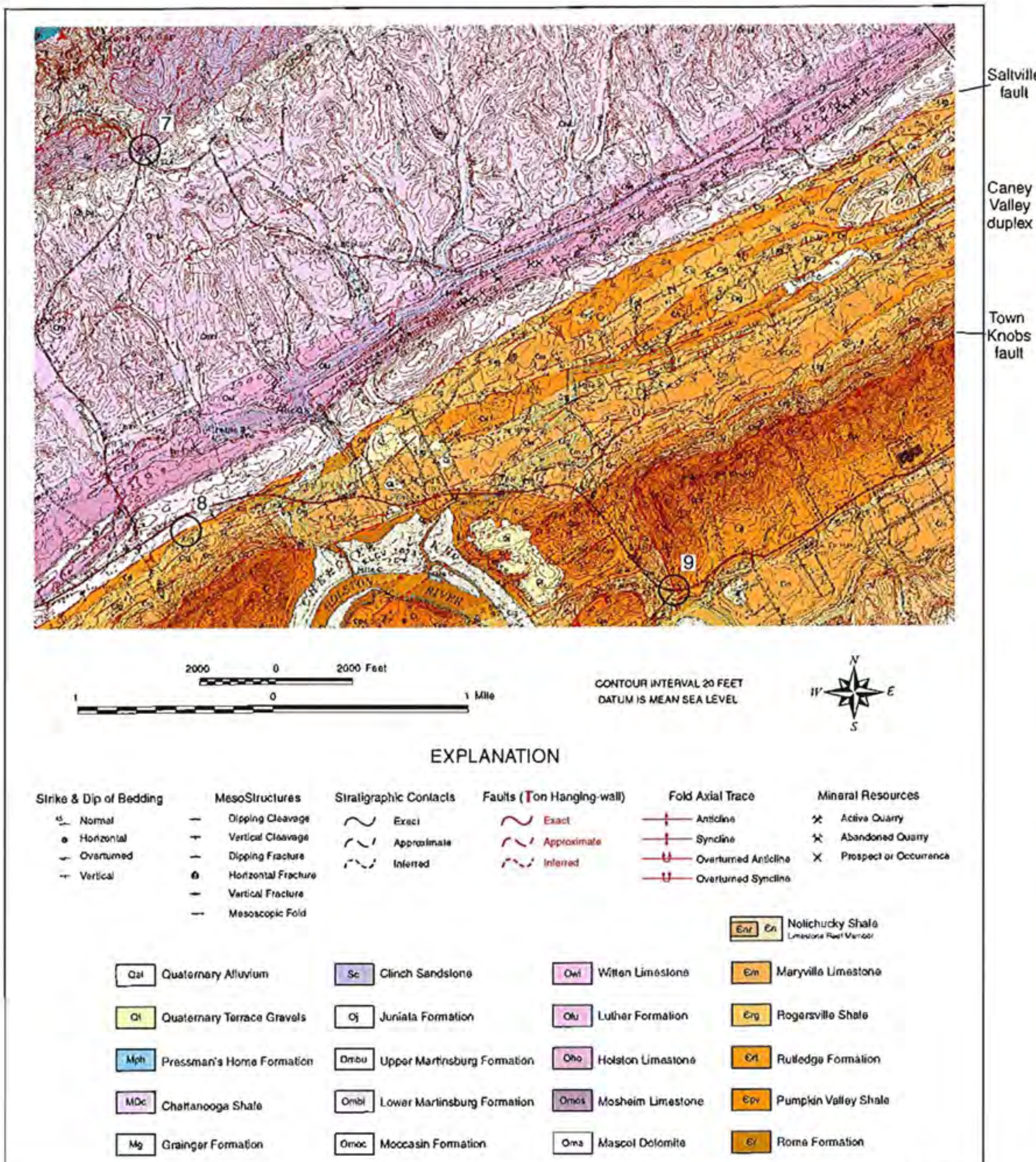

Figure 18. Geologic map of a portion of the Camelot quadrangle with the location of Stops 7 - 9 (Kohl and Lemiszki, 2004), based in part from geologic mapping by Sanders (1952) and Haney (1966). Note the complex faulting in Caney Valley, which is interpreted to be an antiformal stack duplex.

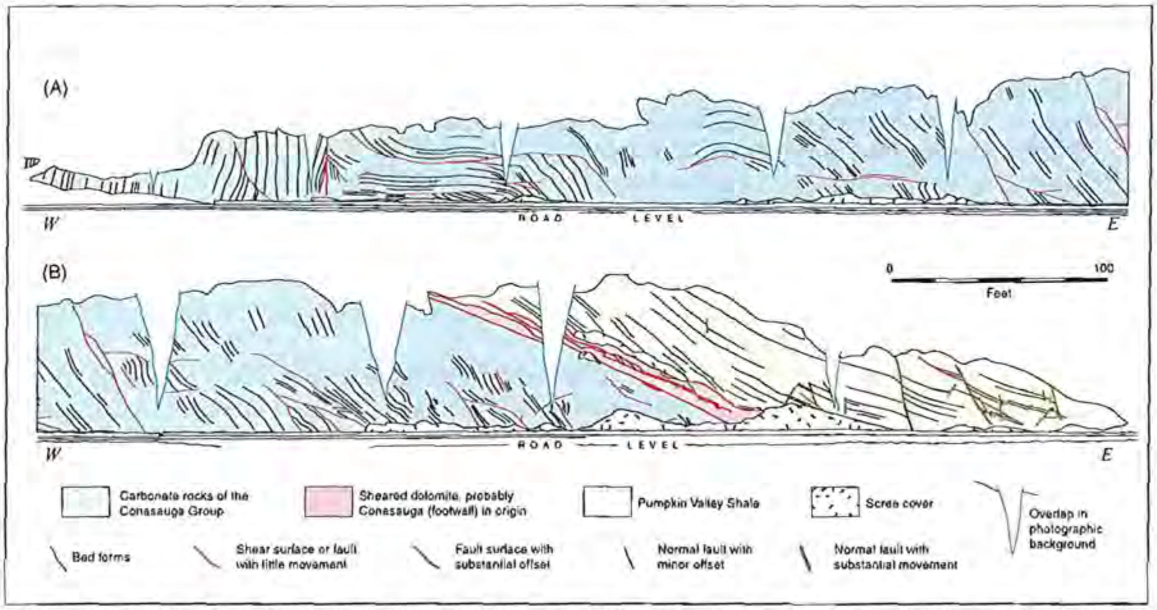

Figure 19. Exposure of the Town Knobs fault at Stop 9. (a) Western half of exposure showing structural features in footwall. (b) Eastern half of exposure showing Town Knobs fault zone and complex reverse and normal faulting in hanging wall. Scale approximate.

The hanging-wall rocks adjacent to the fault are the uppermost part of the Rome Formation or base of the Pumpkin Valley Shale. The presence of the Rome is a function of how we choose to define the formations. A light-colored quartzitic sandstone bed is commonly taken to mark the top of the Rome Formation. In this area the highest such bed occurs below the sequence of reddish siltstone and fine-grained sandstone exposed here. It was decided to use that unit for the top of the formation because it could be fairly easily located along the ridge spurs of Town Knobs. This places some of the ferruginous sandstone in the Pumpkin Valley Shale, thins the rocks mapped as "Rome" substantially, and leaves it entirely missing here. The greenish-gray, micaceous, and glauconitic rocks more characteristic of Pumpkin Valley Shale are not well exposed in this area but can be seen in places below the fine-grained ferruginous sandstone.

There are up to five repetitions (horses) of the Maryville and Rutledge Limestones (dark dolomites that are not always differentiable) and greenish Rogersville Shale in Caney Valley (Fig. 18). The Craig Limestone Member may also be present. Where well exposed, the Rogersville Shale above the Craig is just a few feet thick, so the Craig Member has probably been included with the Maryville here. The Rogersville Shale exposed in Caney Valley contains several distinctive beds of orange silty dolomite with dark flecks of glauconite.

Although at first glance this exposure appears to be another textbook example of an East Tennessee thrust fault, it differs from the Copper Creek fault at Stop 1 in several ways (Fig. 19). The first is the orientation of the fault, which is N20W/34NE. The fault bends at this location, rising in the footwall to cut out the Rome Formation entirely and most of the Pumpkin Valley Shale (Fig. 18). The absence of Rome Formation sandstones localized the gap in Town Knobs, the old and new highway alignments, and therefore the generation of this exposure. The second notable features are normal faults in the hanging wall, but not the footwall (Fig. 19). This is well expressed by the displacement of the massive silt-carbonate bed in this exposure. A missing interval resulting from normal faulting also explains how the Rutledge and overlying formations in the hanging wall are not deflected, but occur close by, under the lake to the southeast. Third, the planar color boundary is not concordant with the slightly irregular lithologic boundary a few feet above it. The intervening material appears to be pulverized dolomite probably derived from the footwall. Fourth, bedding in the immediate footwall is steeply dipping to the southeast but can be quite variable and difficult to identify. In contrast to the hanging wall, there are a few poorly defined blocks separated by shear planes in the footwall, and faults generally follow bedding.

Continue 2.6 mi. on US 11-W toward Rogersville and veer right onto West Main Street. Go 0.5 mi. and turn right on Hwy 66/70 (Trail of Lonesome Pine). We will detour for lunch somewhere along here. This log does not include that mileage. River Road, a potential detour for the lunch stop is at mile 2.3. Turn left after a total of 3.6 mi. to continue on TN Hwy 70 where it leaves TN Hwy 66. Travel 4.1 mi. on TN Hwy 70 to Stop 10.

Lunch Break in Rogersville or John Sevier Steam Plant Campground.

STOP 10. Middle Ordovician Bays Formation (McCloud quadrangle: 36.3426°N, 82.9499°W).
This quadrangle was recently mapped as part of a University of Tennessee Master's thesis by John Bultman (2005). The purpose of his mapping was primarily to subdivide the Sevier Shale around Bays Mountain. This exposure is part of the northwest limb of a map-scale syncline associated with the Bays Mountain synclinorium.

The Middle Ordovician Bays Formation is correlative with the Moccasin Formation seen at Stops 1 and 4. However, now that we are in the Saltville thrust sheet, the rocks below the Bays Formation are not the Chickamauga Group limestone and red bed formations, but rather the deep flysch basin deposits of the Sevier Shale (Fig. 5). The contact with the underlying Sevier Shale is gradational and covered, but there is Sevier Shale exposed along Old TN Highway 70, just past the northwest end of the outcrop.

Cummings (1962) made a detailed study of the Bays Formation and determined that: (1) it thins from 870 ft (265 m) in the east to 600 ft (183 m) in the west across the synclinorium; (2) the red beds and sedimentologic features formed in a deltaic environment; and (3) that the heavy minerals are consistent with the sediments having been derived from eroded Precambrian basement through Cambrian age rocks that now form the Blue Ridge Province. All suggest that the source rocks for the Bays Formation was toward the present-day southeast.

We are looking at the lowermost beds in the Bays Formation. Bedding in this exposure is oriented N55E/80-90SE and consists of predominantly medium- to thick-bedded sandstone, siltstone, and mudstone. Typically the siltstone and mudstone beds are maroon but are altered to a greenish color adjacent to overlying sandstone beds. The mudstone is calcareous, bioturbated, and contains calcite birdseyes and rare mud cracks. The red color is probably disseminated hematite. The repetition of maroon to tan color bedded sequences is an example of cyclical deposition.

Also, within this outcrop is an exposure of a thin K bentonite, which is an altered volcanic ash bed. The bentonite is in a thin zone that has weathered white and that overlies a silicified sandstone–chert bed. There have been several K bentonite beds found in the Middle Ordovician Chickamauga Group throughout the Valley and Ridge and Central Basin in Tennessee (Haynes, 1994). The two most widespread and mappable K bentonites are called the Deicke and Millbrig. These beds have been traced throughout the eastern United States and are considered excellent time stratigraphic markers.

Deformation features in this outcrop consist of a pervasive "fracture" cleavage in the mudstones that is nearly perpendicular to bedding, quartz veins, some of which are slickensided, open fractures, and fracture surfaces with plumose marks. Also within the maroon beds are thin, continuous surfaces that are nearly parallel to bedding. These surfaces may be a deformation fabric formed to accommodate interbed slip during folding. There are a few locations where slip along bedding formed bed-parallel slickensides with a left-lateral (sinistral) shear movement, which is consistent with the flexural-slip between beds expected on the northwest limb of a syncline.

Fracture plumes are features that form on extensional (Mode I) fractures. The morphology of the plume projects back to the fracture initiation point and records the direction of fracture propagation (Fig. 20). All of the out-

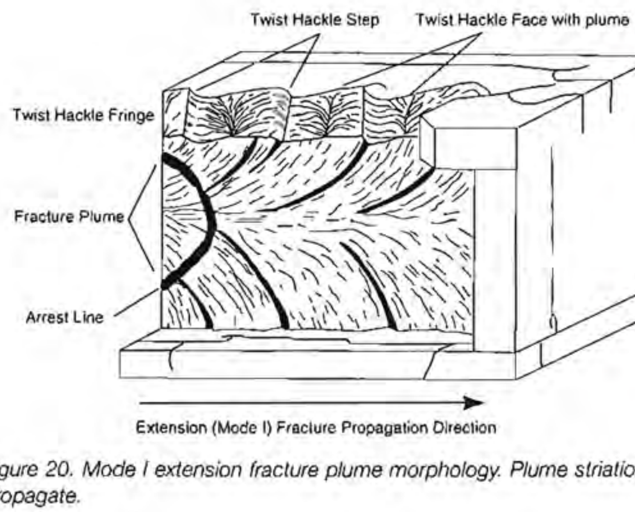

Figure 20. Mode I extension fracture plume morphology. Plume striations point back to the initiation point where the fracture started to propagate.

crops we have examined on this trip contain abundant extension fractures, but most do not develop or preserve fracture plumes. Rock type strongly controls the development of a plume; fine-grained sandstone and siltstone tend to form the best plumes.

Continue 1.3 mi. southeast on TN Hwy 70 and turn left onto Tarpine Valley Road. Travel 4.7 mi. to a T-intersection and turn right onto Goshen Valley Road (Hwy 347). Across the road at the intersection are crossbedded quartz sandstones of the Bays Formation. Proceed 0.8 mi. to Stop 11 and park on the right.

STOP 11. Middle Ordovician Bays Formation & Middle to Upper Ordovician Martinsburg Formation (Stony Point quadrangle: 36.4005°N, 82.8662°W).

The purpose of this stop is to:

1. view the contact between the Bays Formation and Martinsburg Formation;
2. examine some of the apparent controls that bedding has on fracture and vein development;
3. discuss if the "fracture cleavage" in the red mudstones is an early layer-parallel shortening fabric that formed perpendicular to bedding prior to bed rotation;
4. discuss the implications of a subtle cleavage in the shales of the Martinsburg Formation; and
5. provide an opportunity to collect some fossils in float from the Martinsburg Formation.

The lithologic characteristics of the Bays Formation are similar to the previous stop, but we are now looking at the uppermost part of it. As previously mentioned, the Bays Formation correlates with the Moccasin Formation. The Bays Formation, however, contains sandstone and overlies the Sevier Shale, which differs from the limestone- and mudstone-rich Moccasin Formation overlying the more carbonate-rich facies of the Chickamauga Group (Fig. 5). Because the Saltville fault has offset these two formations, we never see them interfingering in Tennessee. The major change in basin setting signified by the difference between the underlying Sevier Shale and Chickamauga Group limestones is one piece of evidence to suggest that there is a large displacement along the Saltville fault. On the other hand, the lithologic characteristics of the Martinsburg Formation here is similar to that seen at Stop 5, where it overlies the Moccasin Formation. This suggests that the depositional environment for the Martinsburg Formation was the same across both thrust sheets. The contact here does not appear to be erosional, but gradational from the Bays into the overlying Martinsburg. Bedding is oriented N55E/46SE.

Continue southeast 0.9 mi. and turn right on Butcher Valley Road. Proceed 5.7 mi. back to TN Hwy 70 and turn left. After a total distance of 8.3 mi. on TN Hwy 70, crossing I-81, turn right on Brown Springs Road. Go 1.3 mi. to Albany Road at a tight bend to the right, turn left, and go 0.3 mi. to Stop 12. Parking is tight. Pull to right on narrow secondary road, or turn around.

STOP 12. Knox Unconformity–Middle Ordovician Mosheim and Lenoir Limestones (Mosheim quadrangle: 36.2323°N, 82.9185°W).

This outcrop is located on the southeast limb of the Mosheim anticline, which was mapped in detail by Brokaw et al. (1966) because there are some zinc prospects in the Knox Group. The Mosheim quadrangle was mapped by Lemiszki as part of a 2002–2003 USGS STATEMAP cooperative agreement (Fig. 21).

The Mosheim anticline is cored by the Knox Group and is interpreted to be a transported fault-bend fold with upright limbs. The location of the thrust fault responsible for lifting the Knox Group to this structural elevation is poorly defined, but is interpreted to outcrop in the Sevier Shale northwest of the anticline (see Figure 4).

The post-Knox unconformity at the top of the Mascot Dolomite is exposed here as are the overlying Mosheim and Lenoir Limestones. As previously discussed, the post-Knox unconformity is one of the first signals that the Cambro-Ordovician passive margin is encroaching a convergent plate margin (Shanmugam and Walker, 1980). The Mosheim and Lenoir Limestones have an average thickness of 50 ft (15 m) and are not mapped separately. These units represent the reestablishment of the carbonate platform after the development of the post-Knox unconformity, but prior to the influx of sediments associated with the development of the Sevier basin. Across the road to the southeast the Sevier Shale overlies the Mosheim and Lenoir Limestones.

The dolomite beds of the Mascot Dolomite are medium-bedded, light-gray, and fine-grained. These beds typically contain a crisscrossing fracture pattern. Where unexposed, the unconformity is identified based on the distinct change between the dolomite beds in the Mascot Dolomite and overlying limestone units. Where exposed, the unconformity is placed where eroded clasts of dolomite and chert are seen in limestone beds that directly overlie dolomite beds. The Mosheim Limestone facies is thick-bedded, medium-gray, fine-grained limestone with calcite birdseyes. Weathering typically produces a smooth and rounded outcrop appearance. The Lenoir Lime-

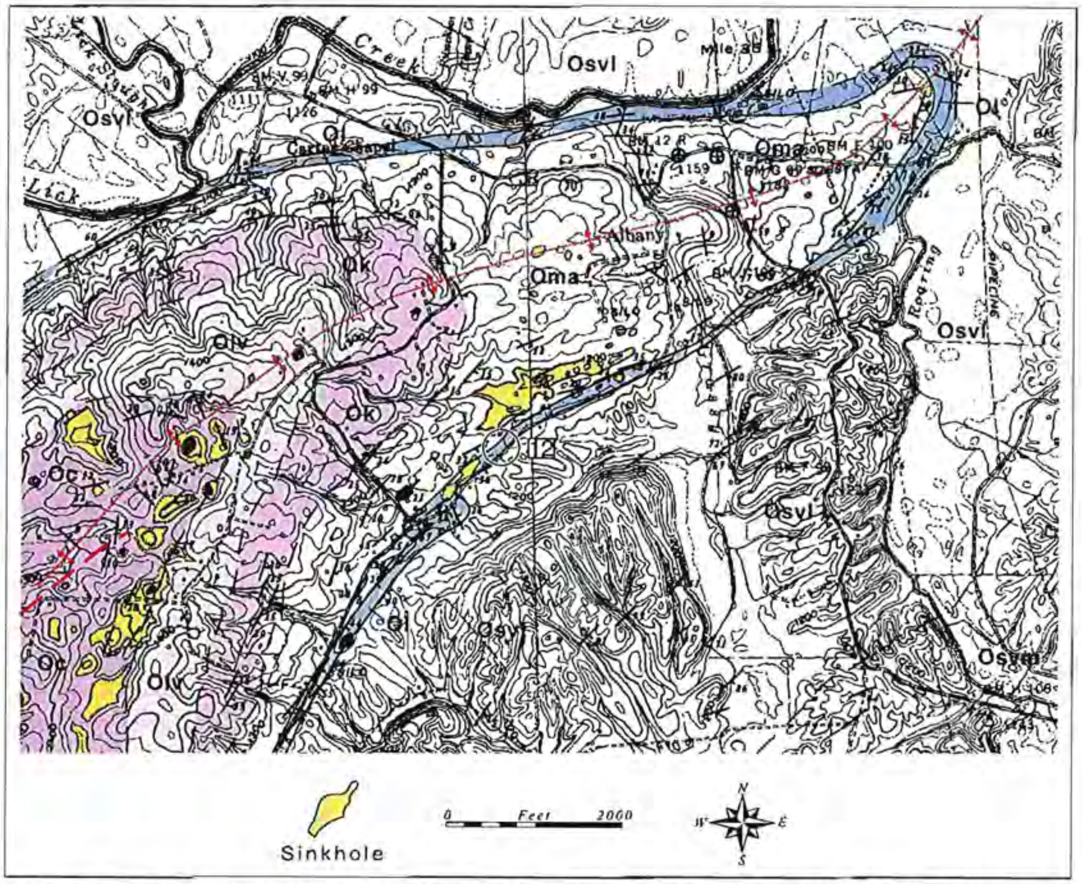

Figure 21. Geologic map of the northeastern portion of the Mosheim anticline and the location of Stop 12. Closed topographic depressions are karst sinkholes that typically form in the Knox Group, which are a major geologic hazard in Tennessee. See other figures for explanation of symbols.

stone facies is nodular bedded with thin clay seams bounding the limestone nodules. Both the Mosheim and Lenoir contain fossils or fossil hash zones. In particular, specimens of the gastropod *Maclurities* can be found in a few places here.

Also shown on the geologic map are sinkholes. There are many sinkholes and caves in the Knox Group on the Mosheim anticline. Some of the sinkholes are swallets that drain streams into the karst groundwater system.

Drive back to Brown Springs Road and continue 2.7 mi. toward Mosheim to Blue Springs Highway (crossing Main) and turn left. Proceed 0.8 mile, turn right on Emerald Road. Go 0.5 mi. and turn left (east) on new US 11-E. Go 0.3 mi. and left into Stop 13, a wide excavation with a new metal building. You will pass another large excavation into Sevier Shale immediately before this point.

STOP 13. Middle Ordovician Sevier Shale (Mosheim quadrangle: 36.1826°N, 82.9297°W).

This outcrop is located on the southeast side of the Mosheim anticline. The Middle Ordovician Sevier Shale in this quadrangle was divided into three members and may reach a total thickness of 9000 ft (2700 m). The lowest member is a graptolite rich, predominately black to dark-gray, laminated shale and interbedded siltstone. Near the top of this member the shale contains thin, dark-gray limestone beds and a mappable interval with septarian limestone concretions. The middle member is predominately graywacke sandstone turbidite deposits interbedded with shale. The upper member consists of shale and siltstone. The shale was deposited in well-laminated massive beds that are blue-gray (weathers tan-brown), calcareous, and contain rare pyrite crystals.

This outcrop is in the upper member of the Sevier Shale. The thickness of this member is unknown because the contact with the overlying Bays Sandstone is eroded. Deformation consists of poorly defined folds and faults, cleavage (intersection with laminations produces "pencils"), fractures, and calcite veins. Some of the veins are folded and others are slickensided. Bedding in this outcrop is defined by the northwest dipping laminations but

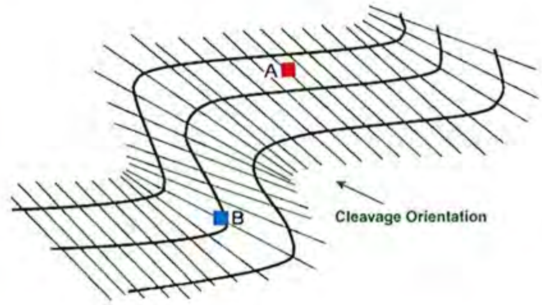

Figure 22. Bedding and cleavage relationships at individual outcrops are used to deduce the location of map-scale structures and the facing direction of bedding in the Sevier Shale. Photos (A) and (B) correspond to the locations shown in the sketch. Photo (A) is from Stop 13.

can be obscured by the well-developed southeast dipping pressure solution cleavage. The bedding–cleavage relationship is used to infer that the beds here are upright and a syncline fold hinge is to the southeast (Fig. 22).

In the course of scouting for this trip, several occurrences of quartz crystals were found here. They occur in vugs in the calcite veins and partially filled vugs within a deformed zone in the shale. Hopefully we will be able to see some crystals *in situ* at this location, where the crystal morphology, mode of occurrence, and host rock are substantially different from those at Stop 14.

Drive southwest directly across 11-E onto a short (unnamed?) road and turn left on Baughard Hill Road. At the stop sign turn right on Radar Sidetrack Road. Follow road across the railroad tracks and continue approximately 2.0 mi. staying on Dulaney Road. Turn right on Maple Road and go 0.6 mi. to Glenwood Drive (no sign). Turn right on Glenwood and go 1.1 mi. to Shackleford Road. Turn right and continue 0.2 mi. to Fincher Lane. Turn right and drive 0.3 mi. to end and park by gate in front of barn for Stop 14.

STOP 14. Lower Ordovician Knox Group Kingsport Formation Quartz Crystals (Mosheim quadrangle: 36.1413°N, 82.9476°W).

At this stop, we will have an opportunity to collect quartz crystals, commonly referred to as "field diamonds" when encountered in surface soils. Such crystals are often compared to those from Herkimer County, New York, and the term "Herkimer" is sometimes applied to them. There, quartz occurs in cavities in the Cambrian Little Falls Dolomite, a brown crystalline stromatolitic dolomite. There is little evidence of the brecciation and structural deformation we have in our region.

According to Robert Burruss (USGS personal communication, 2006) these crystals are similar to other occurrences of doubly terminated quartz crystals in other fold-thrust belts. Many crystals contain inclusions of carbonaceous material or hydrocarbons that could be used to determine P-T conditions and the composition of the fluids present when the crystals grew.

Here, they occur in scattered locations in the East Tennessee Valley and Ridge Province, most commonly in residual soils overlying dolomites of the Knox Group and siltstones of the Sevier Shale (Fig. 23). They are only rarely seen within bedrock. Nevertheless all originally grew in vugs or veins within bedrock. The presence of water-worn crystals also indicates that some have been subsequently transported and redeposited.

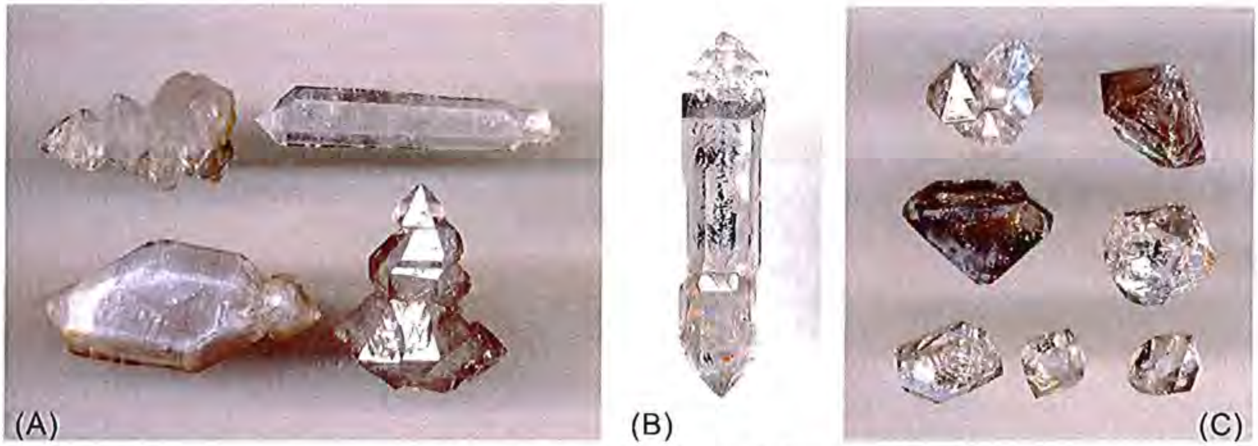

Figure 23. (A) Crystals from regolith above Knox Group bedrock, Greene County. (B) Crystal from Knox Group bedrock at Douglas Dam. (C) Bipyramidal crystal morphology from the Sevier Shale Muddy Creek locality.

Crystals in the Sevier Shale occur in partly filled calcite veins associated with faults and folds. The best-developed veining is localized where the more massive silty or sandy facies are deformed. Once open, fractures provided sites for growth of quartz crystals. So far, occurrences in shale bedrock seem to be limited to the Sevier Shale. In spite of grossly similar rock type and structure in other shale formations, such as the Cambrian Nolichucky Shale or the Mississippian Grainger Formation, no other rock unit in this region contains such an abundance and variety of calcite veins. As we have already seen, veins within the Moccasin and Martinsburg appear to be barren of quartz crystals, but it is uncertain at this time whether this is a function of their suitability as a host rock, or their location relative to a regional zonation.

Those crystals that may have the most significance to the history of the Appalachian region occur in carbonate units of the Knox Group, specifically the Mascot, Kingsport, and the partially equivalent Longview Formations. All these are thick-bedded silicic limestone and dolomite. There are several occurrences in these units, associated with paleokarst-related breccia zones in the bedrock. However, in most areas underlain by these formations, field diamonds are absent, even where brecciation is present.

One such occurrence, at the Douglas Dam boat launch and campground, is in Mascot Dolomite. There, most quartz crystals are found in the residuum, together with cherty gravels, rounded terrace cobbles, and other debris. The most conspicuous stratigraphic feature is the unconformable upper contact of the Mascot, only a few tens of stratigraphic feet above the crystal-bearing area. This can be seen at low water, where approximately two feet of limestone separates the Mascot Dolomite from the overlying Sevier Shale. Nearby, there was an unusual paleokarst sinkhole uncovered during the construction of Douglas Dam (Laurence, 1944). It contained dolomite conglomerate, occasional erratic dolomite boulders, and volcanic ash that may have acted as a local source of silica. Unfortunately, this feature is no longer visible, but similar ones could be present elsewhere.

In the Mascot Dolomite at Douglas Dam, quartz crystals occur in vugs within a brecciated zone, often partly filled with a distinctive gray crystalline dolomite. Much of the breccia is of the "crackle" type, where the bedrock is broken into fragments separated by cracks and mineralized open space, but the fragments are not substantially moved or rotated. All *in-situ* crystals observed so far have been in that breccia. In addition sedimentary breccia is present, with angular fragments incorporated within a matrix of dark impure dolomite. These features suggest that considerable open space may have existed at one time within the system.

The area we will visit has some similar features, but is not located on or kept exposed by a lake shore. Here quartz crystals can be found within residuum overlying the Kingsport Formation, at least 300 ft (91 m) below the post-Knox unconformity. There are also several outcrops of bedrock to examine, one of which shows conspicuous paleokarst brecciation. The challenge here is to find barren soil, where crystals become exposed by rain and other causes.

While all these occurrences are of low temperature alpha quartz, few field diamonds resemble the prismatic rock crystal quartz characteristic of Arkansas, or the stubby inward-growing pyramids of geodes. Smaller crystals may be perfectly clear, while larger ones commonly contain inclusions and may be have an irregular form. Doubly terminated crystals are common in all locations and often show little or no evidence for a surface of attachment on which the crystal grew. Compound crystals composed of several units aligned and in contact with each other are also found area-wide.

In occurrences underlain by Sevier Shale, a bi-pyramidal or stubby prismatic habit is the most commonly encountered. Prismatic faces are usually small and may be missing entirely. Distortions are common, most often producing tabular crystals through enlargement of opposite pyramidal faces.

In contrast, those developed in the Knox carbonates, have a variety of habits and show evidence of morphologic change during growth. Prismatic forms are common. Distortions include semi-parallel "bowtie" clusters, and conspicuous "scepter" growth forms (Fig. 23).

In scepter crystals, growth habit changes between a more equant bi-pyramidal habit and a more prismatic form, elongated along the *c* axis. Within this category are relatively normal looking crystals thickened at one end, crystals with rib-like thickenings along the prismatic length, and strange "pagoda" or "Christmas tree" forms. Most scepters appear to have resulted from bipyramidal growth on top of earlier prismatic habit crystals, but some appear to be the opposite. Phantoms are evident within some of the crystals, indicating discontinuous growth, or episodes when other materials were precipitating. Future investigations could include the mineralogy and chemistry of inclusions, and the physical and chemical controls of crystal morphology. This information helps to interpret conditions of their formation and fits them into regional events such as the formation of East Tennessee's zinc deposits or the timing and conditions of the Alleghanian orogeny.

End of Field Trip

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GEOTRAVERSE: Geology of northeastern Tennessee and the Grandfather Mountain region

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Introduction

The purpose of this field trip is to examine the rocks, macroscopic geology, and topography of parts of northeastern Tennessee and northwestern North Carolina to illustrate the tectonic history of this region (Figs. 1, 2, and 3). The area contains some of the most interesting and critical relationships that exist in the Blue Ridge, between the Blue Ridge and Valley and Ridge, and some of the largest and best-known structures in the Appalachian orogen, particularly the Mountain City and Grandfather Mountain windows (Hardeman, 1966; King and Ferguson, 1960; Bryant and Reed, 1970). The trip will begin in basement rocks along the newly opened section of I-26 between Asheville, North Carolina, and Johnson City, Tennessee. Spectacular exposures include Grenville basement containing intrusions of Bakersville Gabbro (-diabase) dikes, Middle Proterozoic to late Paleozoic shear zones (Stop 1-1 and 1-2), and the basement cover contact at the northernmost exposure of the basement and Walden Creek or Snowbird Group (Ocoee Supergroup) cover (Stop 1-3). We will next proceed into the Holston-Iron Mountain thrust sheet (Stop 1-4) to examine some of the Lower Cambrian Chilhowee Group clastic rocks that rest on small basement remnants. Next we will cross the Mountain City window into Middle Proterozoic basement rocks intruded by the Neoproterozoic Beech Granite of the Stone (Beech) Mountain thrust sheet (Stops 1-5 and 1-6). We then cross into a higher thrust sheet (Fork Ridge or Fries) near Roan Mountain (elev. 6,285 ft) to examine an exposure of 1.8 Ga Carvers Gap granulite gneiss (Stop 1-7)—the oldest rock unit identified to date in the orogen (Gulley, 1985; Carrigan et al., 2003). These and related rocks, the Pumpkin Patch Metamorphic Suite (Trupe et al., 1993), comprise the Mars Hill terrane (Bartholomew and Lewis, 1988; Raymond and Johnson. 1994). We also will be able to see Bakersville Gabbro dikes that intrude Mars Hill terrane rocks and those of the Fries thrust sheet.

We will continue southeastward through Carvers Gap (elev. 5,512 ft) into the Spruce Pine–Gossan Lead thrust sheet (Trupe et al., 2003, 2004) and Spruce Pine synclinorium to examine one of the few accessible exposures of eclogite in the southern Appalachians (Stop 1-8; Willard and Adams, 1994; Abbott and Raymond, 1997; Stewart et al., 1997a). The Burnsville fault has been interpreted as an Acadian SW-directed (dextral) strike-slip fault and suture that separates Grenvillian basement and rifted-margin cover to the NW and rocks of Laurentian provenance deposited on Neoproterozoic oceanic crust (Trupe et al., 2003), and very small fragments of Grenvillian basement located to the SW (e.g., Hatcher et al., 2004). The eclogite occurs immediately SE of the Burnsville fault and is structurally "imbedded" in Ashe (-Tallulah Falls) Formation rocks (Ashe Metamorphic Suite; Abbott and Raymond, 1984). We then will move farther into the thrust sheet to examine some Ashe Formation rocks (Stop 1-9) and an ultramafic body that occurs in this thrust sheet (Stop 1-10). Toward the end of Day 1 we will descend through several thrust sheets into the Grandfather Mountain window to examine some amygdaloidal basalt in the Montezuma Member of the Grandfather Mountain Formation (Stop 1-11). We then overnight in Boone, NC.

Day 2 begins with a stop in the Pumpkin Patch Metamorphic suite between the Gossan Lead and Fries thrust faults in Boone, NC (Stop 2-1). Here, we will examine structures in these rocks closely bounded by and deformed between two of the major thrust faults of the Blue Ridge. Next, we visit an exposure of conglomerate and siltstone of the Grandfather Mountain Formation arkose member (Bryant and Reed, 1970) inside the Grandfather Mountain window where we examine lithologic, bedding, and cleavage relationships (Stop 2-2). We will then descend into the underlying Blowing Rock Gneiss to examine the complex intrusive relationships in the basement (Stop 2-3), a 1.15 Ga old basement unit inside the Grandfather Mountain window with multiple intrusions and ductile deformation (Bryant and Reed, 1970; Raymond et al., 1992; Carrigan et al.,

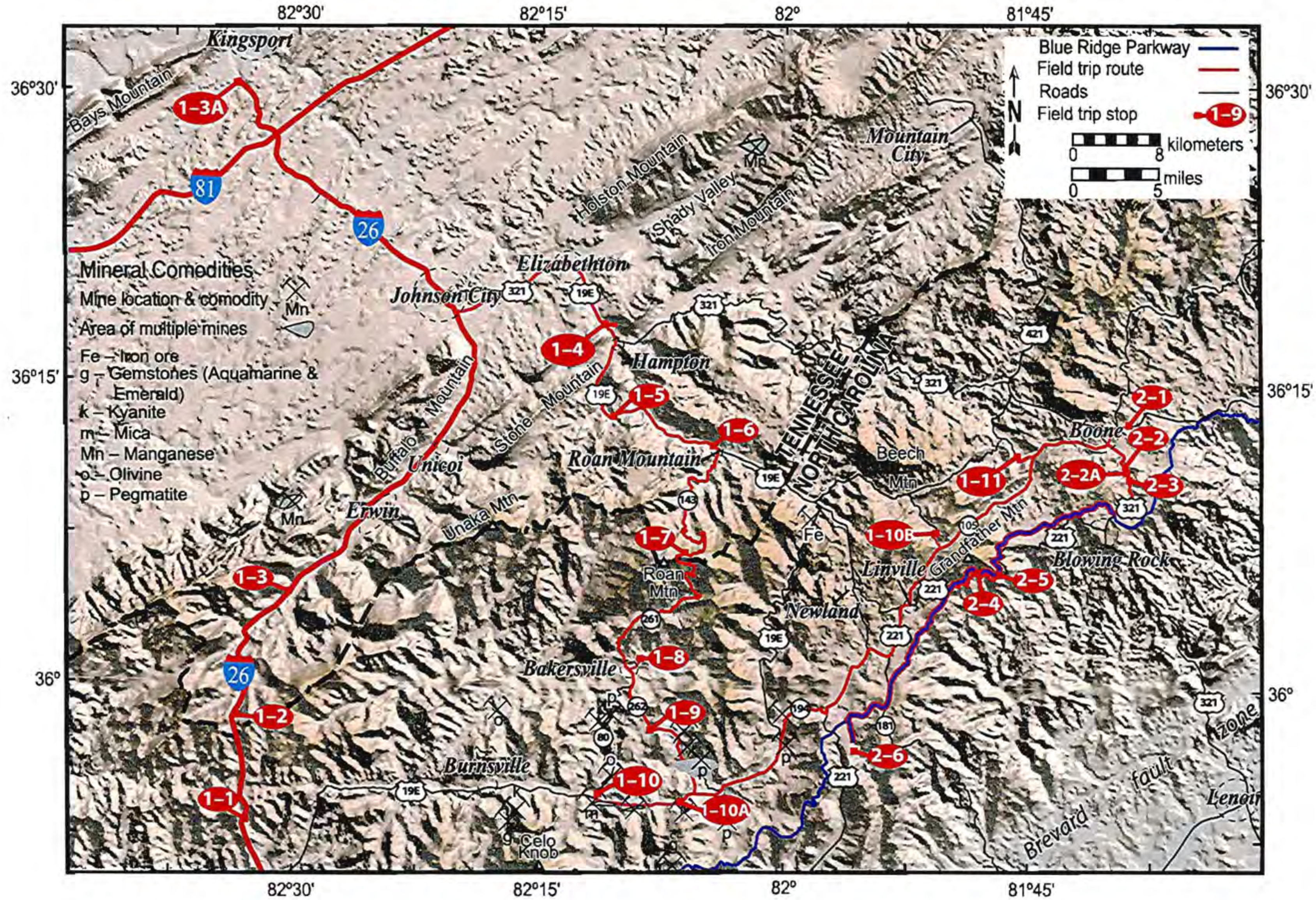


Figure 1. Road map and digital elevation model showing the location of major geographic features and the locations of stops for the March 25-26 field trip.

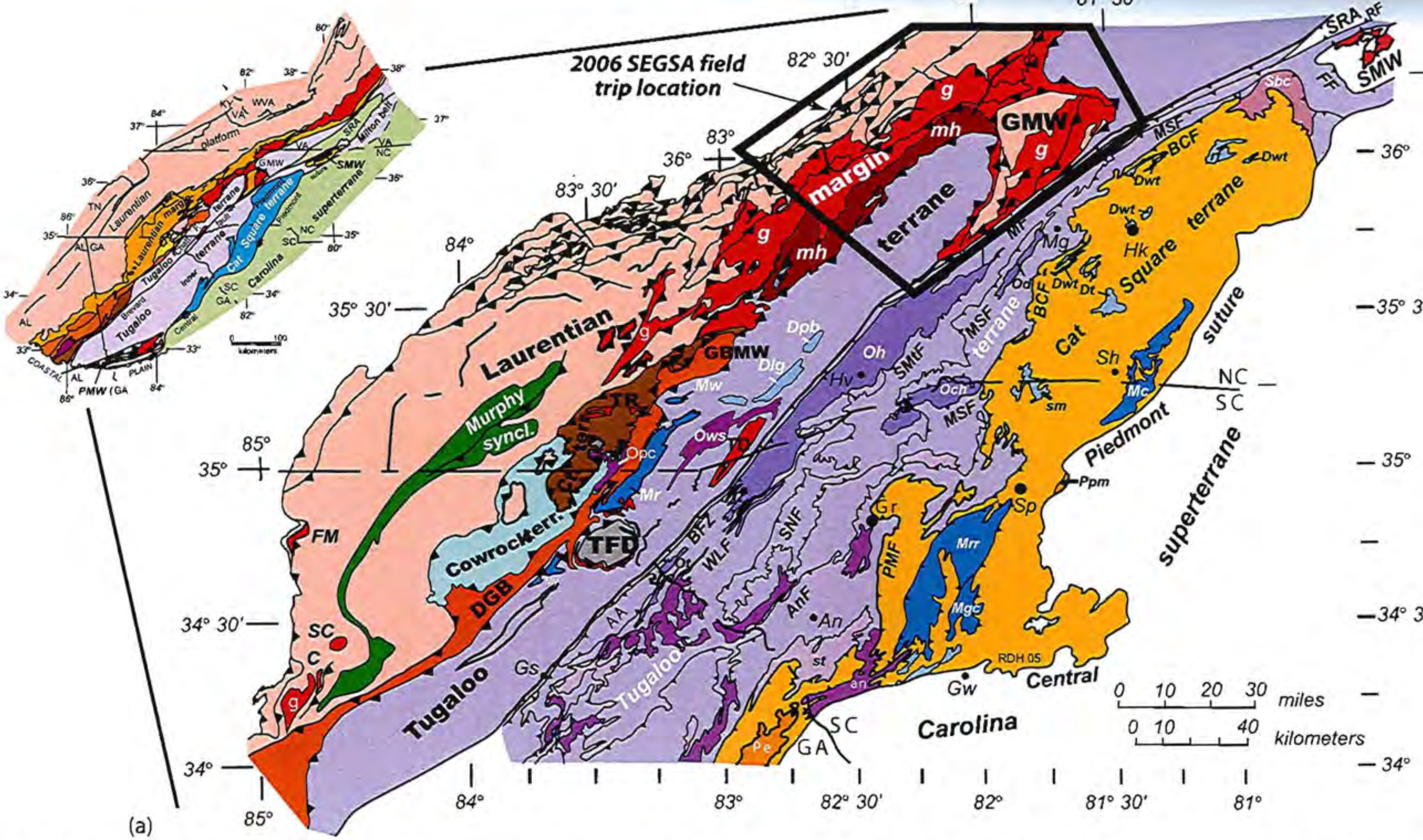


Figure 2. (a) Upper left map: major tectonic elements of the southern Appalachians. SMW–Sauratown Mountains window. GMW–Grandfather Mountain window. PMW–Pine Mountain window. SRA–Smith River allochthon. Larger map: tectonic elements of the southern Appalachian Blue Ridge and Inner Piedmont from northern Georgia to northwestern North Carolina showing the location of the field trip (heavy line box). G–mostly Grenvillian orthogneisses. Mh–Mars Hill terrane. DGB–Dahlonega gold belt. GMW–Grandfather Mountain window. FM–Fort Mountain massif. SC–Salem Church massif. C–Corbin massif. TR–Trimont Ridge massif. TFD–Tallulah Falls dome. TD–Toxaway dome. Ct. terr.–Cartoogechaye terrane. AA–Alto allochthon. AnF–Anderson. BCF–Brindle Creek. BFZ–Brevard. FF–Forbush. MF–Marion. MSF–Mill Spring. PMF–Paris Mountain. RF–Ridgeway. SNF–Six Mile. WLF–Walhalla. Named Ordovician (purple) and Ordovician(?) (lighter purple) granitoids: Och–Caesars Crossroads. Devonian and Devonian(?) plutons (light blue): Drf–Rocky Face. Dt–Toluca. Dwt–Walker Top. sm–Sandy Mush. Mississippian granitoids: Mc–Cherryville. Mgc–Gray Court. Mr–Rabun. Mrr–Reedy River (Stahr et al., 2005; Miller et al., 2006). Mw–Walnut Creek. My–Yonah (Mapes, 2002) Pennsylvanian granitoids: Pe–Elberton. Ppm–Pacolet Mills. (Carolina terrane). Towns: Gr–Greenville. Gs–Gainesville. Gw–Greenwood. Hk–Hickory. Hv–Hendersonville. Mg–Morganton. Sh–Shelby.

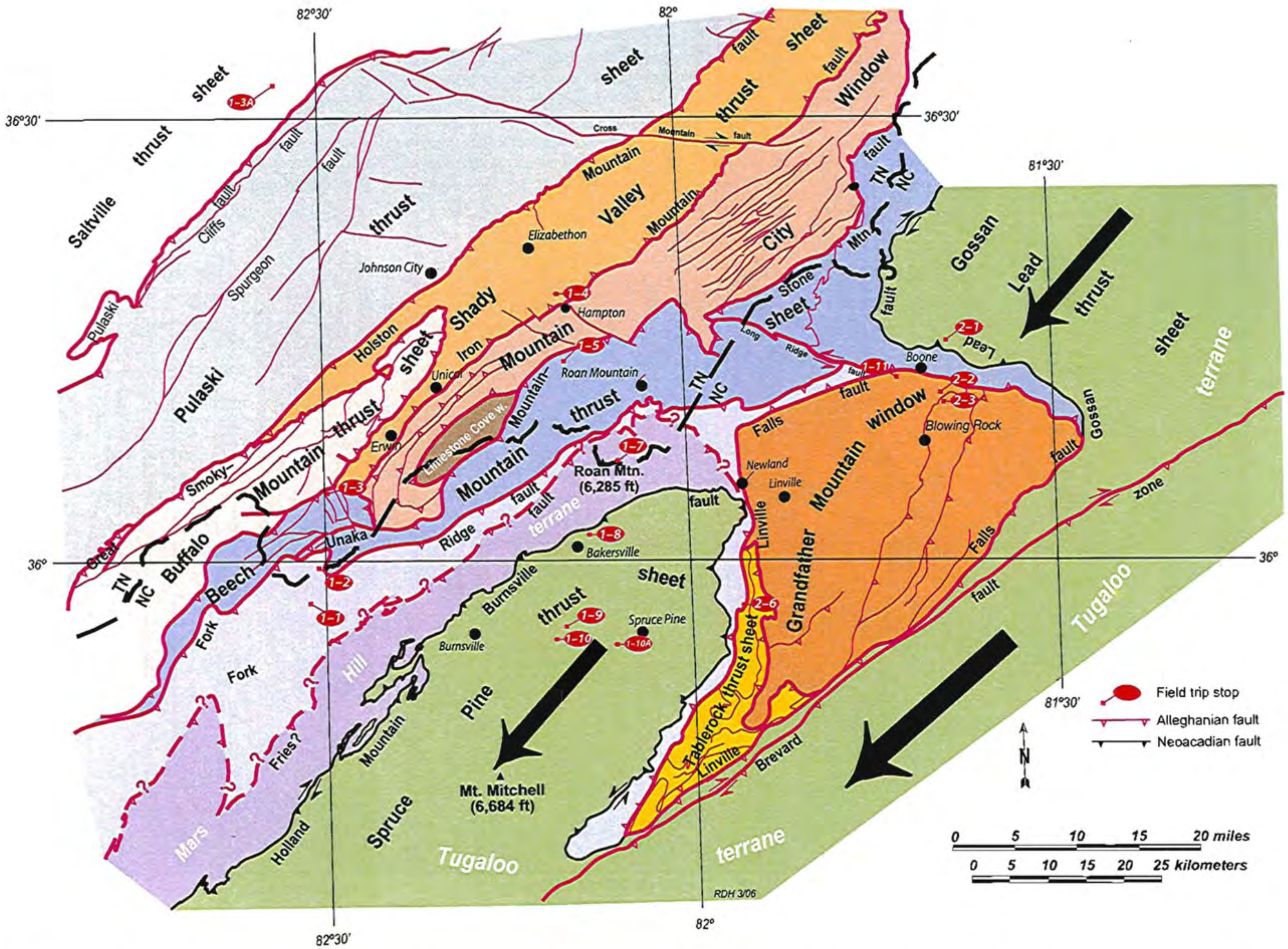


Figure 2, continued. (c) Tectonic map showing major tectonic units in the area of the geotraverse, and the locations of field trip stops. A–A' is the location of the cross section in Figure 8.

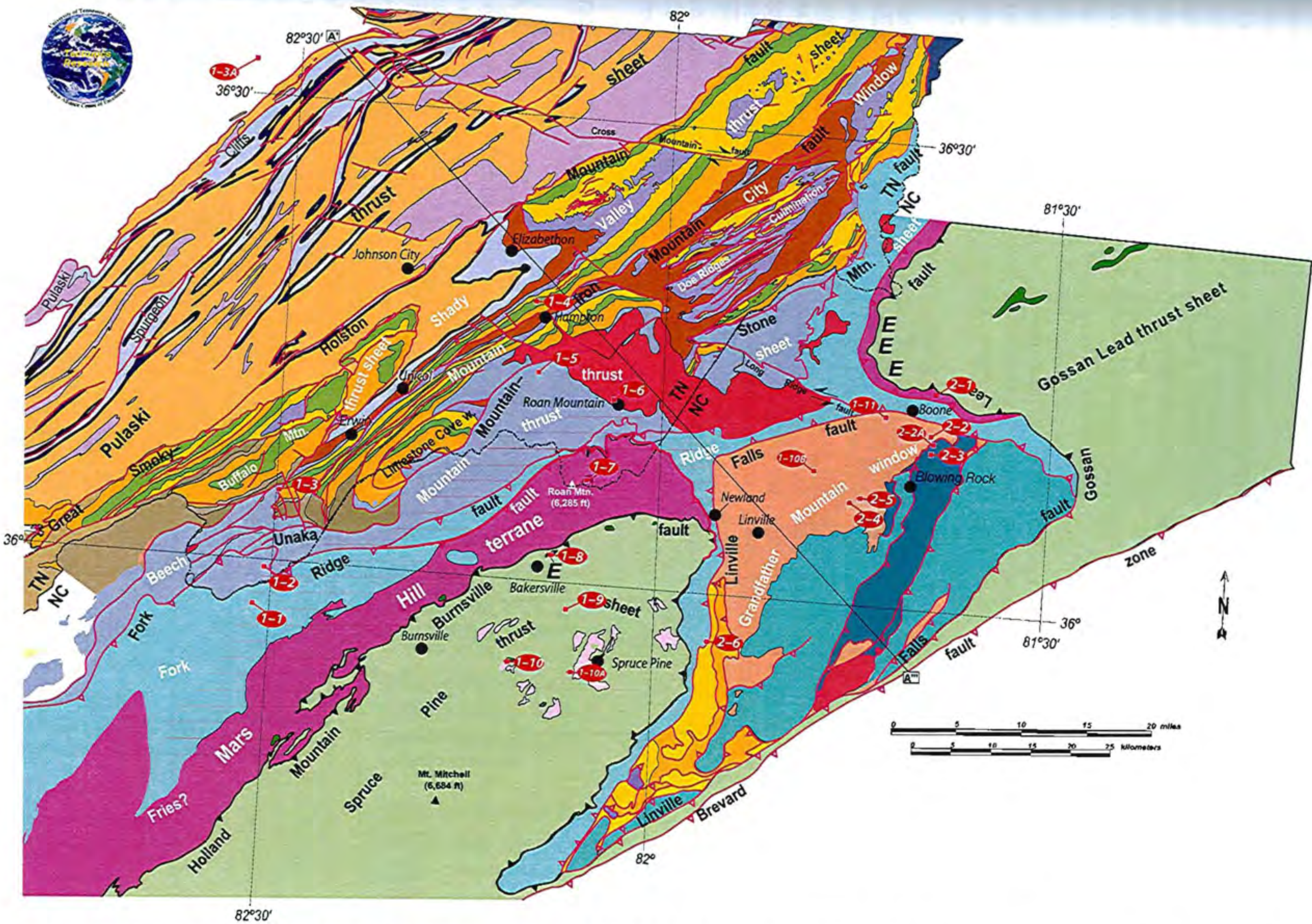


Figure 3. Geologic map of part of NE Tennessee and NW North Carolina in the area of the field trip. Compiled from King and Ferguson (1960), Hardeman (1966), Bryant and Reed (1970), Brown (1985), and M. W. Carter (North Carolina Geological Survey unpublished map).

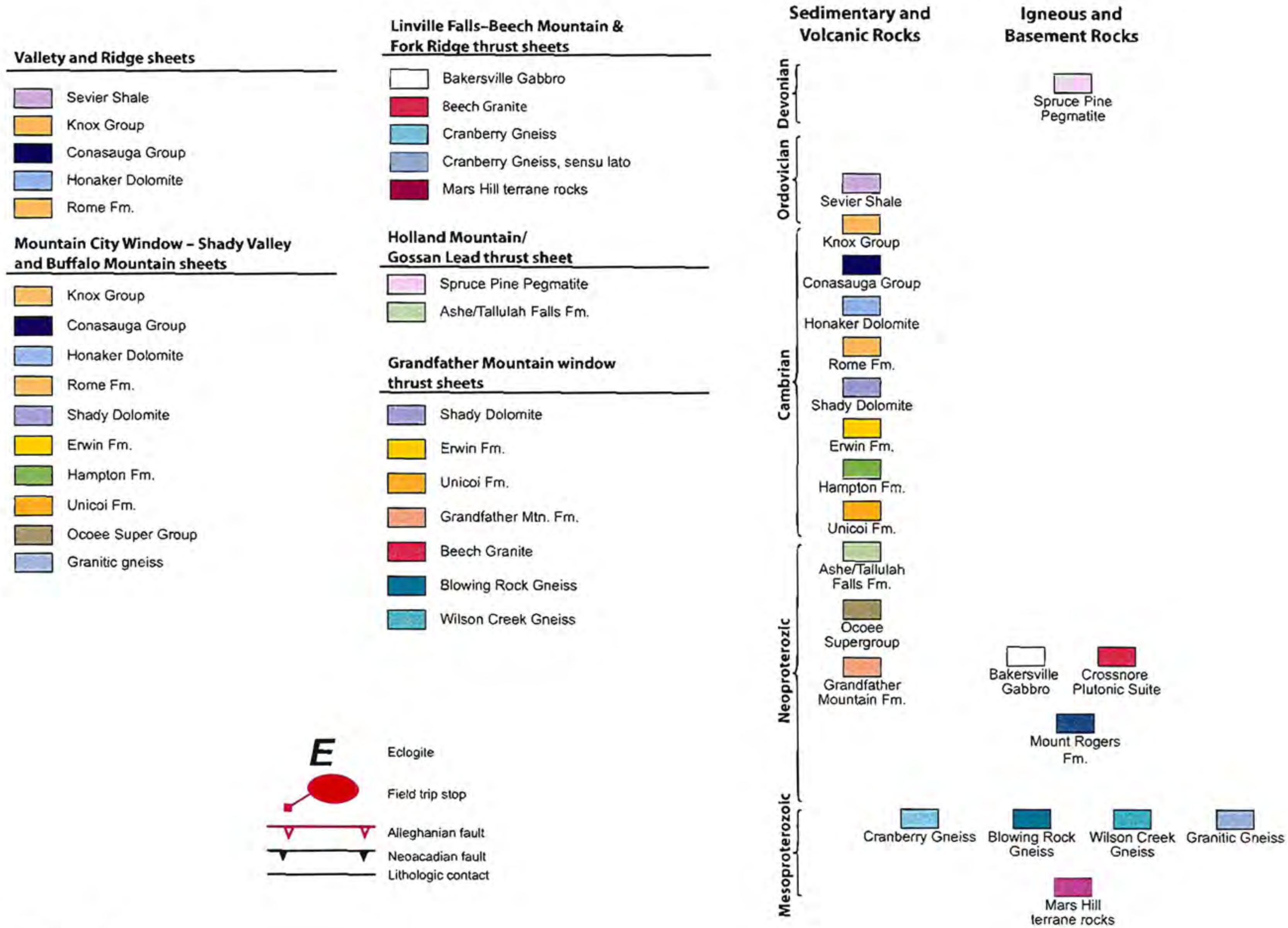


Figure 3, continued.

2003). We then head southwestward from Blowing Rock, NC, examine pseudo-cross bedding and ductile shear zones in the Grandfather Mountain Formation along the Blue Ridge Parkway near Ship Rock (Stop 2-4) and on U.S. 221 (Stop 2-5). Here, diffuse to discrete deformation is reflected in a series of structures ranging from a weak, but pervasive foliation, to discrete ultramylonite zones that cut older structures (Raymond and Love, in press 2006). From there we will follow the Parkway SW to Linville Falls, where we will observe the relationships between the Crossnore plutonic-volcanic suite (Rankin, 1970; Trupe, 1997) in the hanging wall of the Linville Falls fault juxtaposed againstChilhowee quartzite of the Table Rock thrust sheet below, and examine the fault zone (Stop 2-6). The field trip will conclude here, and return to Knoxville.

Differences of interpretation among the authors have not been resolved in all cases (e.g., with regard to whether the Ashe is a formation or a metamorphic suite), but the conventions chosen in this paper are generally those of the first author. In the case of the Ashe Formation/Metamorphic Suite problem, both terms are frequently used to credit both throughout the field guide. In many cases, however, differences were resolved during preparation of the guidebook to the enlightenment of all of the writers. Hopefully, the participants will benefit from these differences and solutions.

Geologic Setting

P. B. King (1970) doubtlessly had the southern Appalachians in mind when he characterized the Appalachians as "the most elegant on Earth." Northeastern Tennessee is very fulfilling of that statement, because the frontal thrust sheets comprise a transition from Valley and Ridge structure, with its very linear structural trends and topography, into Blue Ridge structure and thrust sheets more representative of continental margin sedimentation, basement, and cover. The tectonic assemblage farther into the Blue Ridge consists of higher thrust sheets of basement rocks, then the Spruce Pine thrust sheet (above the Burnsville-Gossan Lead fault) consisting of Neoproterozoic ocean crust overlain by metamorphosed distal Laurentian-derived sedimentary and volcanic rocks. Central Blue Ridge thrusts are breached by erosion to expose basement and rifted margin sedimentary rocks inside the Grandfather Mountain window (Figs. 2 and 3).

Basement rocks consist predominantly of Grenvillian granitic orthogneisses, with minor metasedimentary components (Bryant and Reed, 1970; Bartholomew and Lewis, 1984; Carrigan et al., 2003). The 1.8-Ga Mars Hill terrane (Fries thrust sheet) (Gulley, 1985; Raymond and Johnson, 1994; Ownby et al., 2004) is a block of pre-Grenville basement that was incorporated into the Grenville orogen. It contains metasedimentary and metaplutonic rocks that were metamorphosed and intruded during the Grenville orogeny (Gulley, 1985; Carrigan et al., 2001; Ownby et al., 2004). The Grenvillian (Ottawan) orogeny was the culminating event in the formation of supercontinent Rodinia (Tollo et al., 2004a).

The breakup of Rodinia from 750-565 Ma (Aleinikoff et al., 1995) was marked by initial rifting with bimodal volcanism and formation of the 747–735 Ma Crossnore plutonic-volcanic suite (Goldberg et al., 1986; Su et al., 1994), and eruption and deposition of the 765-740 Ma Mt. Rogers, Konnarock, and Grandfather Mountain Formations (Rankin, 1993; Aleinikoff et al., 1995; Fetter and Goldberg, 1995) exposed in the region of our geotraverse (Fig. 2). Crossnore plutonic rocks consist of the ~734 Ma Bakersville Gabbro (and diabase) (Goldberg et al., 1986; Ownby et al., 2004), the Crossnore pluton, and the 745 Ma Beech Granite (Su et al., 1994), and other plutons (e.g., Laskowski, 1978; Bartholomew and Gryta, 1980). The Crossnore plutonic-volcanic suite is nonconformably overlain by the Chilhowee Group (King and Ferguson, 1960, their Plate 1).

The Ashe Formation (Ashe Metamorphic Suite of Abbott and Raymond, 1984) and structurally overlying Alligator Back Formation (Metamorphic Suite) of the Spruce Pine–Gossan Lead thrust sheet (Tugaloo terrane) likely formed subsequent to initial rifting in a small ocean basin or back-arc basin oceanward of the edge of the rifted Laurentian margin. The basin floor consisted of newly formed MORBs and continental tholeiites that now appear as amphibolites in the Ashe Formation (Metamorphic Suite) (Misra and Conte, 1991) (Stop 1-9). These were overlain by turbidites and mudrocks (plus rare conglomerates and basin margin carbonate rocks [perhaps olistoliths]) that constitute the dominant metasedimentary lithologic units in the Ashe and Alligator Back units. Scattered metaultramafic rocks represent either ophiolitic fragments of oceanic crust or subcrustal mantle (e.g., Misra and Keller, 1978; Abbott and Raymond, 1984; Raymond and Abbott, 1997; Raymond et al., 2003).

The rifted-margin Ocoee basin to the southwest, containing perhaps 15 km of sedimentary rocks (largely without volcanic components; King et al., 1958), thins to a few 10s of m at Stop 1-3 in the Buffalo Mountain thrust sheet (Stop 1-3), and is absent in the Shady Valley thrust sheet beneath (Fig. 4). Neoproterozoic rifted-margin sedimentary and volcanic rocks reappear to the northeast in the Beech Mountain-Linville Falls thrust sheet (Mt. Rogers and Konnarock Formations; Rankin,

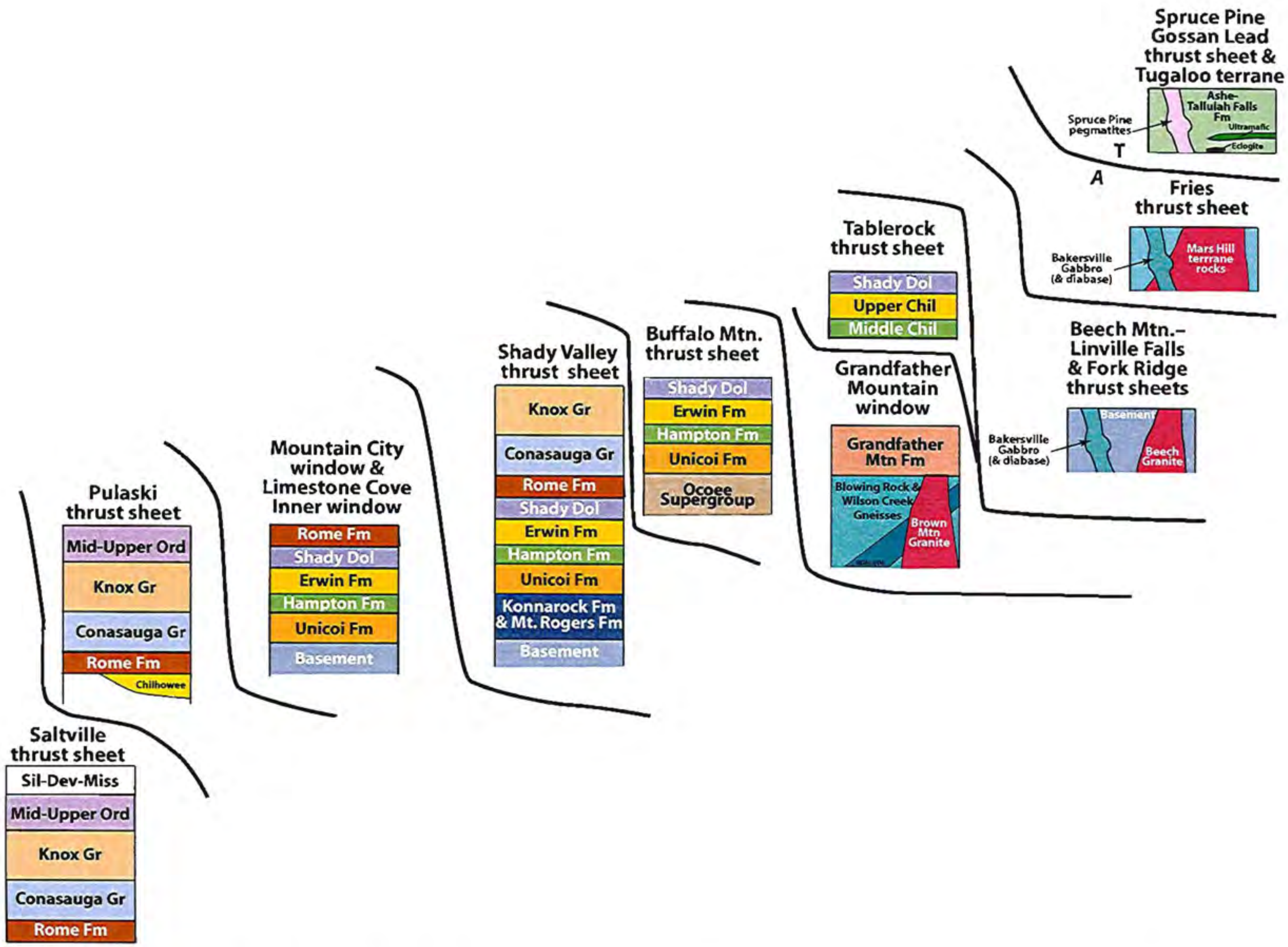


Figure 4. Stratigraphic columns in the different tectonic units in the field trip area, arranged in their present stacking order. Note that all thrust sheets except the Buffalo Mountain, Spruce Pine-Gossan Lead, and the Valley and Ridge sheets involve basement.

1970; 1993) and inside the Grandfather Mountain window (Grandfather Mountain Formation; Bryant and Reed, 1970). The Konnarock and Grandfather Mountain Formations are lithologically similar and include or are associated with bimodal volcanic rocks (Rankin, 1970; 1993). Volcanic rocks form layers and members in the Grandfather Mountain Formation (Bryant and Reed, 1970), whereas the bimodal volcanic rocks of the Mt. Rogers Formation underlie the glaciogenic Neoproterozoic (Vendian) Konnarock Formation (Rankin, 1993).

Thrust Sheets

The one attribute that could be considered characteristic of this part of the Appalachians is the dominance of large thrust sheets (Figs. 2 and 5). A transition from classic thin-skinned foreland fold-thrust belt-style thrusts sheets to those involving basement occur here. The basal detachment passes eastward and downward from the Rome Formation into the Chilhowee Group, and then into basement rocks along the brittle-ductile

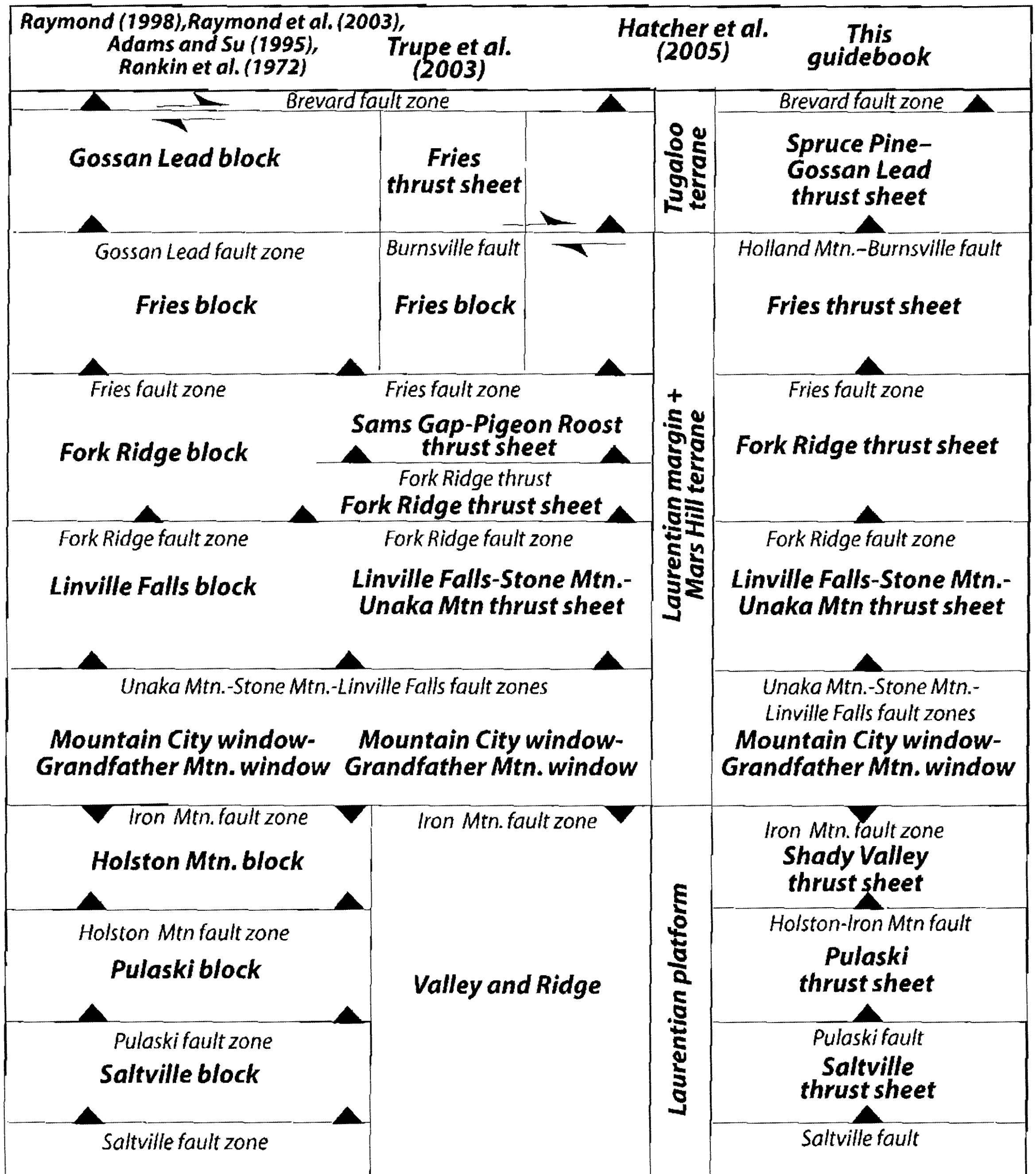


Figure 5. Comparison of thrust sheet nomenclature in the region of the field trip employed in several past syntheses and the present guidebook.

transition. The basement thrusts are considered Type C composite crystalline thrust sheets (Hatcher and Hooper, 1992; Hatcher, 2004). All thrusts originated as low-angle thrusts, so none should be considered thick-skinned in the classic sense of Rodgers (1949). Some of the earliest systematic geologic investigations of this area were made by Keith (1903, 1905, 1907) in the mapping of the Cranberry, Mt. Mitchell, and Roan Mountain 1:125,000 quadrangles, where he recognized several of the large thrust sheets and had a suggestion of the existence of the Grandfather Mountain window in the Cranberry map, where mapped a fault along the NW flank of what we now know is the window.

Valley and Ridge Sheets. Valley and Ridge thrust sheets from Alabama to Pennsylvania characteristically consist of a weak basal unit, commonly the Lower Cambrian Rome (Waynesboro) Formation, overlain by weak to strong Middle to Upper Cambrian Conasauga Group shale (W and SW) and carbonate rocks (Elbrook Dolomite) (E and NE), and then the strong Cambro-Ordovician Knox Group (Conococheague Dolomite and Beekmantown Group to the NE) (Rodgers, 1970). These units are unconformably overlain by several Middle Ordovician carbonate units to the NW that grade to the SE into thicker shale and some coarser clastic rocks (e.g., Walker et al., 1983). There are some Upper Ordovician and Lower Silurian rocks preserved in the larger thrust sheets in Tennessee and SW Virginia. These rocks are unconformably overlain by the Devonian-Mississippian Chattanooga Shale and equivalents, then by younger Mississippian units. It is likely that Pennsylvanian rocks were also present across the Valley and Ridge, but they have mostly been removed by erosion, e.g., in a small area in the Whiteoak Mountain fault footwall west of Cleveland, Tennessee (Hardeman, 1966).

Three major thrust sheets, Whiteoak Mountain, Saltville, and Pulaski, account for ~250 km of the ~350 km maximum displacement in the Valley and Ridge, whereas a number of smaller thrusts account for another 100 km in the NW Georgia-Tennessee-SW Virginia Valley and Ridge (Hatcher et al., in review). Aside from their large displacements, most of their other characteristics are similar to the features of the smaller thrusts. The Pulaski thrust sheet is an exception. It exposes Chilhowee Group sandstone in the Glade Mountain and Lick Mountain anticlines in SW Virginia, suggesting that the basal detachment is in the Chilhowee Group (Rodgers, 1970), and that the Pulaski is not a "usual" Valley and Ridge thrust sheet. The Pulaski thrust sheet may contain the initial transition from the Rome Formation Valley and Ridge master décollement southeastward into the Chilhowee Group, and the overlying Holston-Iron Mountain thrust sheet (see below) represents the transition downward from detachment in the Chilhowee Group to detachment in the basement.

Shady Valley Thrust Sheet. One of the most intriguing components of the geology of this region is the Holston-Iron Mountain fault system and Shady Valley thrust sheet, which occurs above the Pulaski sheet. Within this structure are Grenvillian basement rocks overlain continuously by the Chilhowee Group, then the Shady Dolomite-Rome Formation-Conasauga Group, and much of the Knox Group (King and Ferguson, 1960) (Figs. 2, 3, and 4). This thrust sheet is overridden to the southwest by the Buffalo Mountain thrust sheet, which carries the thin remaining components of the Ocoee Supergroup (Hardeman, 1966). The Holston-Iron Mountain thrust sheet thus could be considered a Valley and Ridge thrust sheet, because it contains all of the pre-Middle Ordovician platform units of the Valley and Ridge. Yet others might contend that it belongs to the Blue Ridge, because it contains basement rocks and the overlying rifted continental margin sedimentary rocks that occur from northeastern Tennessee into southwestern Virginia.

The Lower Cambrian Chilhowee Group in the Shady Valley thrust sheet consists of three formations, each of which marks upward compositional and textural maturity of the sandstones (Figs. 1 and 2). Sandstones of the basal Unicoi Formation comprise a coarse arkose to graywacke assemblage interlayered with dark shale, conglomerate, and local basalt flows (King and Ferguson, 1960). The Unicoi is overlain by the dark gray to black mudrock-rich Hampton Formation, and the Hampton is succeeded by the Erwin Formation, which contains quartz arenite and a calcareous shale unit near its top (Helenmode Member). The Chilhowee Group is overlain by the Lower Cambrian Shady Dolomite, which marks the first time the southeastern Laurentian margin faced open ocean. The rift-to-drift transition, however, probably resides below in the Erwin Formation. The Rome Formation, which gradationally overlies the Shady Dolomite in the Mountain City window is more carbonate-rich than the Rome exposed farther west (Rodgers, 1953), and locally contains peculiar deformed zones that Diegel and Wojtal (1985) interpreted to be areas in which appreciable quantities of evaporates occur in the section.

Buffalo Mountain Thrust Sheet. The Buffalo Mountain sheet lies structurally above the Shady Valley thrust sheet, and truncates the Holston Mountain fault. It is a composite sheet that contains the northeasternmost remnants of the Ocoee Supergroup, and the overlying Chilhowee Group and Shady Dolomite (Hardeman, 1966). Cross sections through this thrust complex reflect the composite nature of the thrust sheet (e.g., Bearce, 1969). The common element that ties together the composite Buffalo Mountain thrust sheet is the occurrence of most of the same stratigraphic units in each thrust sheet, with the exception of the Ocoee Supergroup units. These latter units occur in the SE and SW parts of the composite thrust sheet.

Mountain City Window and Limestone Cove Inner Window. Southeast of the Shady Valley thrust sheet is the Mountain City window, consisting of a series of imbricate faults that form the internal parts of a duplex (Figs. 2 and 3). The roof is the Holston-Iron Mountain thrust and the floor is not exposed (Diegel, 1986) (Fig. 6). King and Ferguson (1960) did not recognize the duplex, but their maps and cross sections thoroughly illustrate the duplex imbricates and roof structure. The Mountain City window closes to the NE as the Iron Mountain fault is traced around the NE end of the window (King and Ferguson, 1960, their Plates 1 and 15). Toward the SW, the Iron Mountain fault merges with the Stone (Unaka) Mountain fault, suggesting the Mountain City window is not a simple window like those in the frontal Blue Ridge in the Great Smoky Mountains (King et al., 1958), but an "eyelid" window (Oriel, 1950). SW of the Long Ridge fault the Unaka Mountain fault bounds the SE flank of the Mountain City window and closes the window to the SW by truncating the Iron Mountain fault (Figs. 2 and 3). The Mountain City window exhibits additional internal complexity with the Limestone Cove inner window and the Doe Ridges culmination. The Limestone Cove inner window exposes basement rocks, Chilhowee Group, Shady Dolomite, and Rome Formation. Additionally, Diegel interpreted the Limestone Cove structure as a "foreland-dipping" duplex, because the entire structure is overturned to the NW (Diegel, 1986) (Fig. 6). More recent mapping of the Limestone Cove window suggests it has a more classic antiformal structure (Merschat et al., 2001).

Linville Falls-Stone (Beech) Mountain-Unaka Mountain Thrust Sheet. The Linville Falls-Stone Mountain-Unaka Mountain thrust sheet forms the SE boundary of the Mountain City window. This thrust sheet contains Grenvillian Cranberry Gneiss (Bryant and Reed, 1970; Carrigan et al., 2003) (Stop 1-5) and Neoproterozoic Crossnore Suite Beech Granite and Mt. Rogers Formation (Stop 1-6). The Cranberry Gneiss is a complex unit that has been subdivided locally into sev-

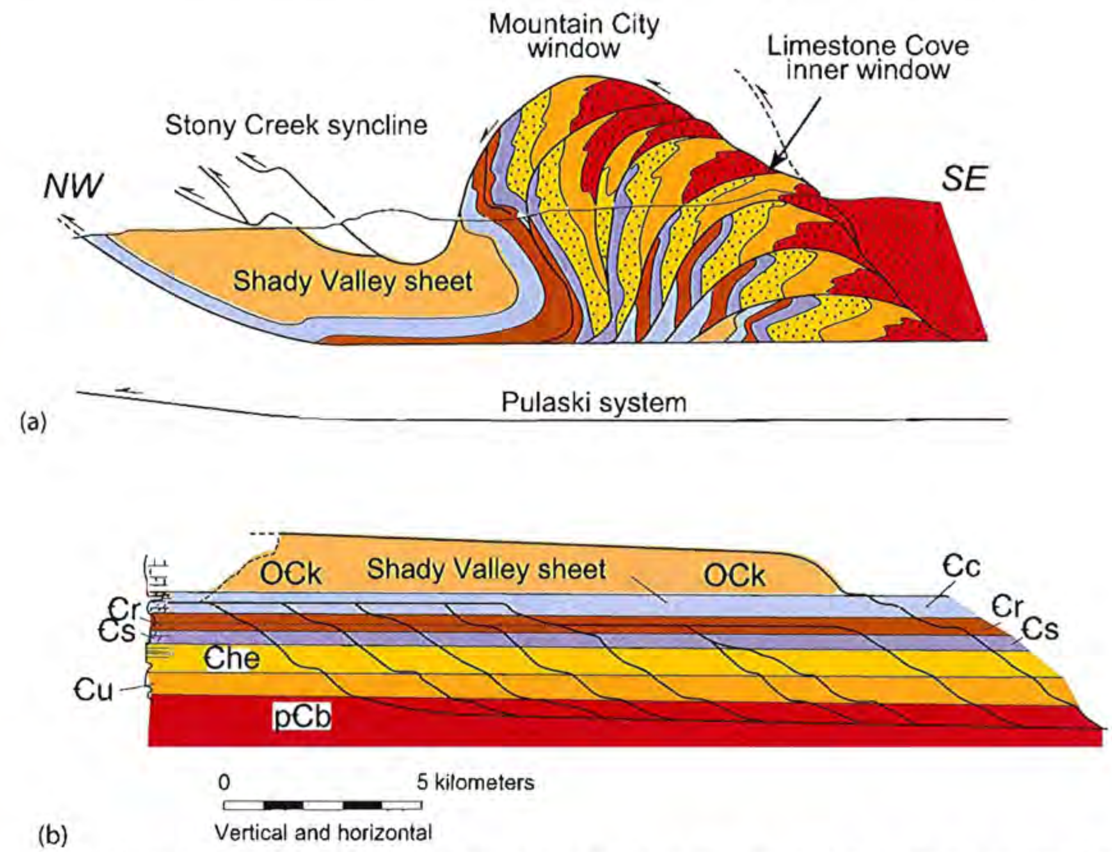


Figure 6. Cross section (a) and restored (b) section through the Shady Valley thrust sheet, part of the Mountain City window, and the Limestone Cove inner window (after Diegel, 1986).

eral units (Bartholomew and Lewis, 1984; Adams and Su, 1996). Its complexity derives from a variety of features, including the presence of multiple lithologic units, later deformation, intrusion of younger mafic rocks, mylonitization, migmatization, and at least two Paleozoic (Taconian? and Alleghanian) metamorphic overprints. The Cranberry Gneiss sensu lato includes: (1) the Cranberry Mine layered gneiss—gray, layered felsic micaceous-quartz-feldspar orthogneiss, exposed at numerous localities, including along U.S. 19E; (2) the Watauga River Gneiss, greenish-gray to pinkish-green, massive to ultramylonitic, locally porphyroclastic, biotite orthogneiss, exposed north and south of Beech Mountain; (3) the Whaley Gneiss, pink to yellowish-gray biotite orthogneiss exposed south of Beech Mountain; (4) the Potts Cemetery Gneiss, a dark gray garnet-biotite-tonalitic gneiss exposed on the south flank of Beech Mountain; (5) the Valle Crucis Gneiss, a complex unit containing a variety of layered to massive, mylonitic to migmatitic, biotite orthogneisses; and (6) some granitoid plutons that appear to intrude older gneisses (Bartholomew and Lewis, 1984; Adams, 1990; Adams and Su, 1996). Farther south the Cranberry Gneiss sensu lato has been subdivided into additional units by Merschat and Wiener (1988) and Cattanach and Merschat (2005).

The Beech Granite is one of the components of the alkalic Crossnore Plutonic-Volcanic Suite (Rankin (1970). It consists of coarse megacrystic, locally protomylonitic alkali granite containing perthitic microcline megacrysts in a matrix of K-spar, plagioclase, quartz, biotite, and minor sphene, zircon, and purple fluorite (Bryant and Reed, 1970). The Beech Granite has a U-Pb age of 745 Ma (Su et al., 1994), and was intruded synchronously with rifting of Rodinia during formation of the Neoproterozoic Laurentian margin.

Dikes and larger bodies of Bakersville Gabbro (and diabase), also part of Rankin's Crossnore suite, intruded this thrust sheet. The Bakersville Gabbro consists of fine- to coarse-grained gabbro, typically composed of plagioclase, augite, and magnetite. The rock is commonly metamorphosed, in which case it ranges from fine- to medium-grained, is foliated and locally lineated, and is most commonly hornblende metagabbro that locally contains garnet (Goldberg et al., 1986; Stewart et al., 1997). Interestingly, it locally consists of coarse-grained gabbro containing all components of the discontinuous part of Bowen's reaction series and labradorite (Stop 1-7); fine-grained diabase; and megacrystic diabase, with plagioclase megacrysts (Stop 1-5).

Fork Ridge (-Pigeon Roost-Sams Gap-Devils Fork) Thrust Sheet. The Fork Ridge thrust sheet is a higher basement sheet that contains, again, Cranberry Gneiss sensu lato and its subdivisions, notably the Cranberry Mine Layered Gneiss and the Valle Crucis Gneiss (Bartholomew and Gryta, 1980; Bartholomew and Lewis, 1984; Adams, 1990; Cattanach and Merschat, 2005). Rocks in and around Boone, NC, in exposures behind Arbys™ and Pizza Hut™ restaurants and various other excavated hillsides contain exposures of the Cranberry Mine Layered Gneiss within this thrust sheet. West of the Grandfather Mountain window, rocks of the Fork Ridge thrust sheet crop out south and southwest of Beech Mountain.

Fries Thrust Sheet. The Fries thrust sheet, also known as the Mars Hill terrane of 1.8 Ga old rocks, contains the heterolithic Pumpkin Patch Metamorphic Suite (Gulley, 1985; Raymond and Johnson, 1994; Carrigan et al., 2003; Ownby et al., 2004; Trupe et al., 2003). The lithologically diverse Mars Hill terrane contains pyroxene granulite paragneiss (Carvers Gap gneiss) cut by younger Grenvillian orthogneisses, Neoproterozoic granitoid rocks and mafic rocks, and Paleozoic veins and dikes (Gulley, 1985; Ownby et al., 2004). The high metamorphic grade is likely a product of the Grenvillian orogeny. Questions exist about the nature of the Mars Hill terrane and whether or not it was a separate crustal block "floating" in an ocean that was accreted during the Grenville orogeny, or whether it was a piece of old crust that was caught up during the collision process after having had a different origin. The shear zone along the western contact of the Mars Hill terrane is essentially the Alleghanian Fries fault (e.g., Raymond, 2000; Trupe et al., 2003; Ownby et al., 2004). This fault has to terminate, however, along the western edge of the Mars Hill terrane, or track westward to join the Fork Ridge fault system to the SW, because North Carolina Geological Survey geologists have been unable to map a fault along this boundary farther SW (Cattanach and Merschat, 2005; C. E. Merschat pers. comm.., 2003) (also, see discussion below). Bakersville Gabbro dikes intrude the Mars Hill terrane in many areas.

Burnsville – Holland Mountain – Gossan Lead thrust and Spruce Pine Thrust Sheet. North of the Grandfather Mountain window, the mylonitic Gossan Lead fault zone extends south from Virginia along the western margin of the structurally highest major thrust sheet west of the Brevard fault zone (Stose and Stose, 1957; Abbott and Raymond, 1984; Mies, 1990). The Holland Mountain fault was mapped as a premetamorphic fault along the western edge of the equivalent terrane southwest of the Grandfather Mountain window by Merschat and Wiener (1988), but more recently obtained data from the southwest clearly indicate that the Chattahoochee (Holland Mountain?) fault is an Alleghanian fault from southern North Carolina into Georgia (Hatcher et al., 2005; Miller et al., 2006). This boundary is considered by some to mark the location of the Taconic suture between an accretionary wedge and the Laurentian continental basement rocks (Abbott and Raymond, 1984; Horton et al., 1989; Adams et al., 1995; Miller et al., 2006). Yet, south and SW of the Grandfather Mountain window, between Bakersville and Asheville, NC, the boundary between the underlying Mars Hill terrane and Laurentian rocks is defined by the Burnsville fault, a dextral strike-slip fault (Adams et al., 1995; Trupe et al., 2003). All of the aforementioned faults form the west boundary of the Spruce Pine–Gossan Lead thrust sheet.

The Spruce Pine–Gossan lead thrust sheet, the highest thrust sheet in the eastern Blue Ridge (Hatcher, 1978), contains the Ashe Formation, a sequence of metasandstones, pelitic schists, metabasalts, metagabbros, rare eclogite, and metaultramafic rocks; and the overlying Alligator Back Formation, a unit dominated by pelitic schists (Rankin et al., 1973; Abbott and Raymond, 1984). Eclogite is preserved near Bakersvillle NC (Stop 1-7), and retrogressively metamorphosed relict eclogite crops out northeast of the Grandfather Mountain window where it is enclosed in Ashe Formation rocks of the Spruce Pine–Gossan Lead thrust sheet (Abbott and Raymond, 1997) (Fig. 3). The Spruce Pine–Gossan Lead thrust sheet contains very few bodies of Grenville basement. These are preserved in NE Georgia, NW South Carolina, and southwestern North Carolina, in the Tallulah Falls and Toxaway domes (Hatcher et al., 2004).

Trupe et al. (2003) recognized that the Burnsville thrust was emplaced after Taconic suturing. Miller et al. (2006) depicted the Burnsville fault cutting previously accreted Ashe rocks and subsequently being transported westward with those and other rocks during the Alleghanian orogeny (Trupe et al., 2003; Stahr et al., 2005; Miller et al., 2006). Trupe et al. (2003) recognized that the Chattahoochee fault to the south is an Alleghanian fault, and correlated it (in one of two models) with the Alleghanian Fries fault, speculating that the Fries truncated the older Burnsville fault NW of Asheville. If that is the case, the Fries fault should be traceable southwestward into the area mapped in detail by the North Carolina Geological Survey in the west half of the Asheville 100,000-scale sheet (Cattanach and Merschat, 2005; Merschat et al., this guidebook). It appears, however, that the Fries fault tracks more toward the west and joins (or truncates) the Unaka Mountain fault. Cattenach and Merschat (2005, C. E. Merschat personal commun., 2003) have found no evidence of faulting along the NW boundary of the Mars Hill terrane, but its SE boundary is clearly faulted (Holland Mountain fault). The Spruce Pine–Gossan Lead thrust sheet is truncated to the SE by the Alleghanian Brevard fault zone (Reed and Bryant, 1964; Hatcher, 2001). Truncation of the Rabun pluton (335 Ma; Miller et al., 2006; Stahr et al., 2005) by the Chattahoochee-Holland Mountain fault in the NE Georgia and SW North Carolina Blue Ridge indicates the fault is Alleghanian (Stahr et al., 2005). As such, the Gossan Lead predecessor of the Burnsville fault in the area of this field trip emplaced middle to upper amphibolite and eclogite facies assemblages onto Grenville and pre-Grenville basement rocks of the central Blue Ridge thrust sheets. Trupe et al. (2003) dated (U-Pb TIMS) a deformed pegmatite in the Burnsville fault zone, and interpreted the 377 + 6 Ma age as a maximum age for the time of faulting. While they may only have obtained another age date on a Devonian Spruce Pine pegmatite, they have established a maximum age of faulting, and correctly interpreted the timing of the Burnsville fault as Devonian or younger.

As noted above, the Spruce Pine–Gossan Lead thrust sheet is the highest in the thrust stack in this area, and it contains Ashe Formation rocks that are quite different from rocks of thrust sheets below, because those below clearly have a North American origin. Detrital zircons from this thrust sheet, however, indicate that this thrust sheet had a predominantly Grenvillian and older granite–rhyolite province zircon source from the North American craton (Bream, 2003; Bream et al., 2004). These rocks were likely deposited on ocean crust and as such were thrust back onto the stack of basement and rifted margin metasedimentary rocks during the Neoacadian or Alleghanian orogenies. Thus the Spruce Pine–Gossan Lead thrust sheet contains metamorphic rocks derived from a predominantly deep-ocean assemblage of sedimentary and volcanic rocks including pieces of ocean crust and mantle. Most agree that the Burnsville–Gossan Lead fault is a suture. Several (e.g., Horton et al., 1989; Rankin et al., 1993) have also suggested that the crust of the Spruce Pine thrust sheet originated far from North America and is exotic, but the new detrital zircon data indicate that this is not the case (Bream, 2003; Bream et al., 2004). Another argument in favor of a proximal North American origin for these rocks is that the similarity of chemical characteristics and ages of Beech Mountain thrust sheet basement rocks, and those inside the Grandfather Mountain window, with those in the Spruce Pine thrust sheet suggests a common origin (Carrigan et al., 2001; Hatcher et al., 2004). The eclogite in the Spruce Pine thrust sheet is the product of high temperature and very high-pressure recrystallization of basaltic rocks. Adams et al. (1996) estimated a temperature range of 626–790°C and 13-17 kbars.

Grandfather Mountain Window. Our geotraverse will cross the Holland Mountain-Gossan Lead and Fries thrust sheets into the Fork Ridge thrust sheet, then cross the Linville Falls fault that frames the Grandfather Mountain window. An intermediate thrust sheet—the Table Rock sheet—occurs along the Linville Falls fault. It contains Chilhowee Group sandstone and shale, and Shady Dolomite (Stop 2-6). Inside the window rocks of the Grandfather Mountain Formation are underlain by 1.15 Ga Blowing Rock Gneiss and Wilson Creek Gneiss basement (Bryant and Reed, 1970; Carrigan et al., 2003). The Grandfather Mountain Formation consists of Neoproterozoic greenschist facies conglomerate, metasandstone, metapelite, and minor metacarbonate rocks, plus both felsic and mafic volcanic rocks that first formed along the rifted margin of North America. As noted above, parts of this sequence are very similar to the Konnarock Formation (Rankin, 1993) in northeastern Tennessee, northwesternmost North Carolina, and SW Virginia. The Mount Rogers Formation occurs in the Beech Mountain and Shady Valley thrust sheets, and consists predominantly of bimodal volcanic rocks and lesser amounts of sedimentary rocks (King and Ferguson, 1960; Rankin, 1970). Thus, whereas the rocks of the Konnarock and Mount Rogers Formations represent a succession from dominantly sedimentary protoliths to dominantly volcanic protoliths, these equivalent rocks are interbedded in the Grandfather Mountain Formation.

The Grandfather Mountain window is neither a simple window in the sense of being a single thrust sheet that has been eroded into its footwall, nor is it an eyelid window like Mountain City and Hot Springs windows. The window, however, developed by erosion through three higher thrust sheets, contains an intermediate thrust sheet along its west-SW border, and contains several thrusts inside the window that repeat basement rocks and pieces of Grandfather Mountain Formation (Boyer, 1984; Boyer and Mitra, 1988; Raymond and Love, 2006). Boyer and Elliott (1982) suggested that the structure inside the Grandfather Mountain window is a major duplex. Recent fission track dating by Naeser et al. (2005) suggests there also may be uplift along a large younger normal fault or recent renewed doming of the Grandfather Mountain area. In addition to the thrust faults, diffuse deformation zones are common in the lower part of the Grandfather Mountain Formation (Boyer, 1992; Raymond and Love, 2006 in press).

The exposure of the Linville Falls fault at Linville Falls (Stop 2-6) is one of the most important exposures in the southern Appalachians, and has been described in numerous other field trip guides (e.g., Hatcher and Butler, 1979, 1986; Stewart et al., 1997b). Layered quartz-chlorite-muscovite mylonite in the 1–2 m-thick fault contact zones underlies a km-scale deformation zone and overlies the multiply deformed Chilhowee Group rocks of the Table Rock footwall (Trupe, 1997), indicating the fault moved under greenschist facies conditions, but the quartz fabric is annealed. Linville Falls fault mylonite yielded a Rb-Sr age of 302 Ma (Van Camp and Fulagar, 1982), which places the timing of movement into the Alleghanian event. Crenulation cleavage overprinted the fault zone, and mica-rich layers in the underlying Chilhowee rocks. The Table Rock thrust sheet beneath the Linville Falls fault is also overturned (Bryant and Reed, 1970, their Plate 1) (Fig. 3).

Metamorphism

At least four phases of metamorphism affected the rocks of this region: Middle Proterozoic Grenvillian (1050-970 Ma) upper amphibolite to granulite facies metamorphism (Gulley, 1985; Carrigan et al., 2003; Ownby et al., 2004); Ordovician (470-455 Ma) Taconian greenschist to granulite facies metamorphism (e.g., Willard and Adams, 1994; Moecher et al., 2004; Ownby et al., 2004); Devonian-Mississippian (360-355 Ma) "Neoacadian" middle to upper amphibolite facies metamorphism (Carrigan et al., 2003); and a late Paleozoic event that produced chlorite to biotite grade, greenschist facies metamorphic rocks inside the Grandfather Mountain window. Late Alleghanian(?) retrograde metamorphism also affected the rocks of the thrust sheets outside the Grandfather Mountain window.

Frontal Blue Ridge thrust sheets and windows contain rocks that are either unmetamorphosed or are at anchizone to chlorite grade, increasing to biotite grade, of Paleozoic metamorphism (Weaver, 1984; Hatcher and Goldberg, 1991; Raymond, 2002, p. 561-568). The intermediate Fork Ridge and Fries thrust sheets attained at least garnet zone amphibolite facies conditions locally, although it is difficult to separate older from Paleozoic garnet grade metamorphism, because garnets formed at higher grade during the Grenvillian event. Many of the Fork Ridge and Linville Falls–Stone Mountain–Unaka Mountain thrust sheet rocks have retrograde greenschist facies overprints. Likewise, local areas in the Gossan Lead thrust sheet, for example along the Blue Ridge Escarpment east of Boone, NC, exhibit a retrograde greenschist facies overprint on older kyanite grade amphibolite facies assemblages (D. West, pers. comm., 1985). The Spruce Pine–Gossan Lead thrust sheet, however, contains widespread middle to upper amphibolite facies mineral assemblages (Abbott and Raymond, 1984; Hatcher and Goldberg, 1991; Adams et al., 1997), easily documented in the aluminous schist member of the Ashe (Tallulah Falls) Formation that is traceable throughout this thrust sheet in most areas covered by detailed geologic mapping where this unit occurs. Eclogite facies rocks in this unit occur as localized pods of

Ordovician eclogite (459 Ma; Miller et al., 2000) within amphibolite units re-metamorphosed during the Devonian–Mississippian Neoacadian orogeny (Willard and Adams, 1994; Abbott and Raymond, 1997). Rocks inside the Grandfather Mountain window reach a maximum Paleozoic metamorphic grade of greenschist facies biotite zone, but chlorite grade rocks are widely distributed in the window (Bryant and Reed, 1970).

Palinspastic Implications

An interesting and useful exercise is to think about the thrust stack along our geotraverse, take it apart, and place the components of the stack end to end based on position, stratigraphic assemblage, Paleozoic metamorphic grade (and timing of metamorphism), and tectonic heredity of each component. Other factors to be considered include presence or absence of Paleozoic plutons, and presence or absence of pre-Paleozoic basement rocks. Additional difficulty arises because: (1) the rocks of the Blue Ridge record events related to the Grenville orogeny, with the likelihood of southern Appalachians Grenville rocks having a South American, not Laurentian, origin, based on Pb isotopic data (Loewy et al., 2003; Tohver, et al., 2004) (Fig. 7); (2) breakup of Rodinia formed a Neoproterozoic to Early Cambrian rift-to-drift sequence with the opening of various Paleozoic oceans; (3) several Paleozoic deformational and metamorphic events related to arc accretion (Taconian), zippered closing of the Theic ocean by subduction of early Paleozoic crust and accretion of the Carolina superterrane (Neoacadian; Hatcher and Merschat, in press); and (4) zippered closing of the Rheic ocean and initially oblique, then head-on collision of Gondwana with Laurentia (Alleghanian; Hatcher, 2002). The Alleghanian event resulted in at least 50 percent across-strike shortening with emplacement of the Blue Ridge thrust sheet (Hatcher et al., 1989, in review), whereas the Neoacadian event was dominantly strike slip, resulting in SW transport of the entire Tugaloo terrane (including the Spruce Pine–Gossan Lead thrust sheet and Inner Piedmont) from a source some 400 km or more to the NE (Merschat et al., 2005; Hatcher and Merschat, in press). The Spruce Pine–Gossan Lead thrust sheet is the highest in the region, and it must be noted that it is a strike-slip sheet (Trupe et al., 2003) likely related to the oblique collision of Carolina terrane with Laurentian elements to the west (Merschat et al., 2005; Hatcher and

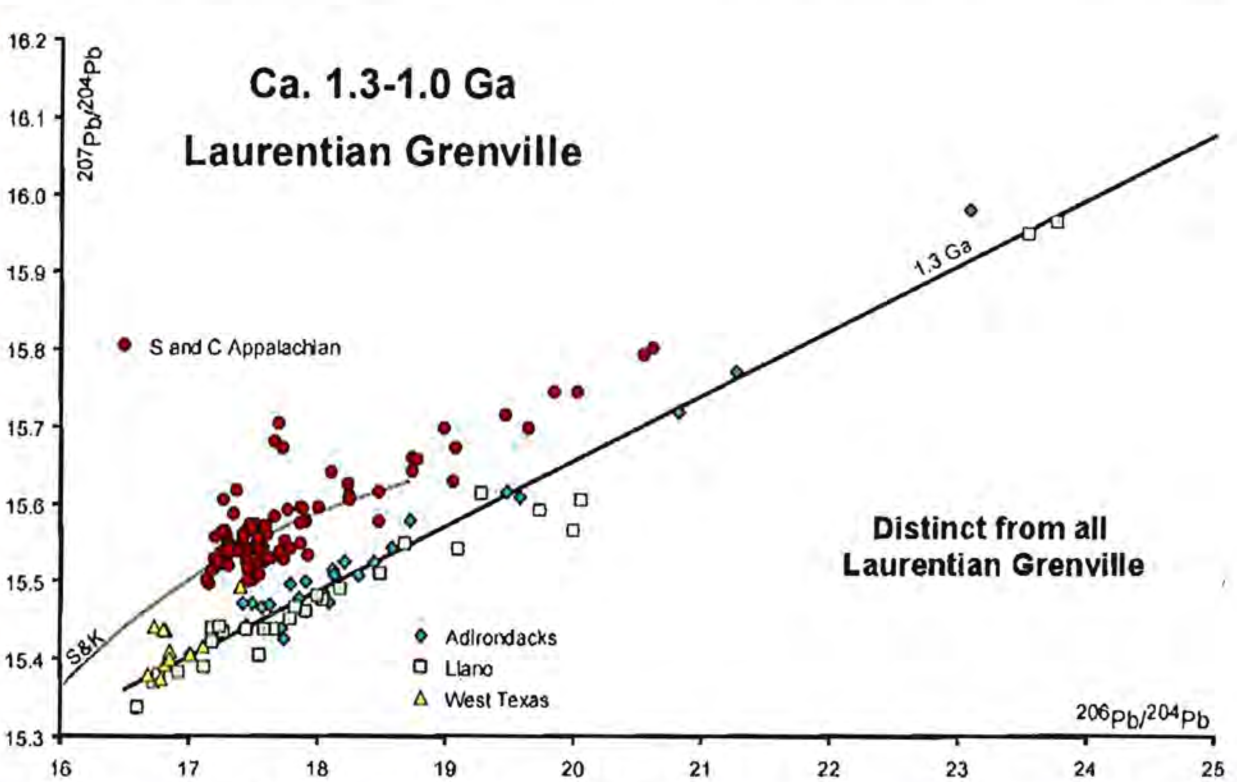


Figure 7. Comparison of Pb isotopic data from the southern and central Appalachians with similar data from known Laurentian sources (from Loewy et al., 2003). Southern and central Appalachians data plot on the same line with data from the Amazonian craton, suggesting that all of the Blue Ridge basement rocks are Gondwanan (Loewy et al., 2003; Tohver et al.,2004), so there is likely to be a suture in the basement beneath the Blue Ridge-Piedmont megathrust sheet (New York-Alabama lineament?).

Merschat, in press). With these factors in mind, we will attempt to retrodeform the Alleghanian thrust stack in the Tennessee-Carolina-NE Georgia Blue Ridge.

The westernmost sheets would be the lowest in the stack if they could be stacked vertically, so the Pulaski and Saltville sheets would be the lowest in the thrust stack, and thus most westerly then the stack is retrodeformed (Figs. 2, 4, 5, and 8). The Shady Valley thrust sheet rests atop the Pulaski sheet, and the Buffalo Mountain on top of the Shady Valley. These thrust sheets are truncated by the Beech Mountain-Linville Falls thrust sheet, then the Fork Mountain sheet, Fries sheet, and the Spruce Pine-Gossan Lead sheet. The rocks inside the Grandfather Mountain window comprise a lower thrust sheet of relatively low-grade rocks, Grenvillian basement, and a cover sequence that closely resembles the Konnarock Formation, so this thrust sheet probably belongs west of both the Beech Mountain and Shady Valley thrust sheets. Placement of the Grandfather Mountain window rocks west of these thrust sheets makes the stacking order work, but the rocks inside the window are unlike most of the rocks in the higher thrust sheets, except those containing Mt. Rodgers and Konnarock Formations. Thus there are two alternative retrodeformed configurations of the Grandfather Mountain window, Tablerock Shady Valley, and Buffalo Mountain thrust sheets suggested in Figure 8.

Conclusions

1. The geology of NE Tennessee and NW North Carolina Blue Ridge consists of Neoproterozoic to Cambrian rifted margin sedimentary and volcanic rocks, overlain by Cambrian to Ordovician platform sedimentary rocks, underlain by Gondwanan 1.0-1.2 Ga Grenvillian basement that contains a block of 1.8 Ga crust. In addition, the suspect (now acquitted?) Tugaloo terrane of distal Laurentian sedimentary and ocean floor to continental tholeiitic volcanic rocks occurs to the east.
2. Tugaloo terrane rocks were thrust from at least 400 km from the NE during the Late Devonan-early Mississippian Neoacadian orogeny onto Laurentian margin rocks.
3. The Laurentian rifted margin and platform rocks were deformed into a complex stack of NW-directed. thrusts during the late Mississippian-Permian Alleghanian orogeny carrying with them the earlier accreted Tugaloo terrane and other components from the SE.

Acknowledgments

The geologic database for this field trip is provided largely by the mapping of other geologists, principally Philip King, Herman Ferguson, Bruce Bryant, and Jack Reed. Although there has been additional geologic mapping in this area, particularly that of Bob Butler and his students west of the Grandfather Mountain window, the configurations of major tectonic and geologic units have changed very little in the last 35 years, except for the important recognition of the eclogite bodies to the west and northeast of the window, recognition of Devonian dextral strike slip on the Burnsville fault, and the greater subdivision of the basement rocks by the North Carolina Geological Survey and others to the west and southwest. The success of this field trip thus largely depends on their work, but also on the large amount of modern geochronologic and petrologic data that now exist here.

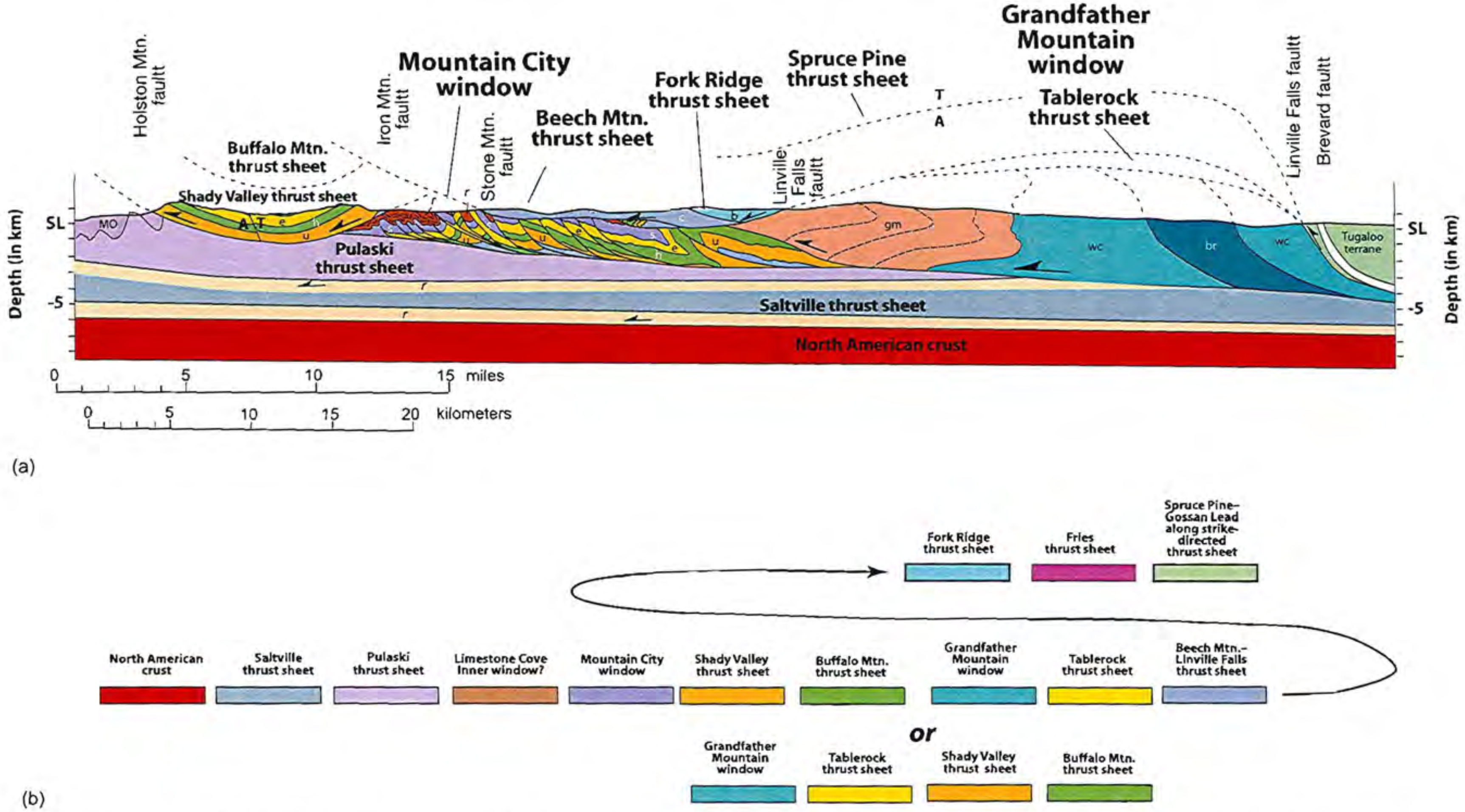


Figure 8. (a) Cross section through the field trip region showing the major tectonic units and some details of important rock units. c–Cranberry and related basement gneisses. wc–Wilson Creek Gneiss. br–Blowing Rock Gneiss. b–Beech Granite. gm–Grandfather Mountain Formation. u–Unicoi Formation. h–Hampton Formation. e–Erwin Formation. s–Shady Dolomite. r–Rome Formation. MO–Middle Ordovician rocks. Modified from cross sections by King & Ferguson (1960), Bryant and Reed (1970), Boyer & Elliott (1982), and Diegel (1985). See figure 2(c) for section location. (b) Retrodeformed thrust sheets without regard to geometry or magnitude of displacement. Note the two options for the relative positions of the Shady Valley, Buffalo Mountain, Grandfather Mountain window, and Tablerock thrust sheets.

Field Guide

Day 1

Saturday, March 25, 2006. 8 am. Depart Howard Johnsons Biltmore, Exit 50 on I-40, Asheville, NC. Turn right out of the motel onto U.S. 25 (Hendersonville Road, and then left onto I-40 W. Exit onto I-240-I-26 W (actually north) toward Asheville, follow ~3 mi to split of I-240-I-26, and follow I-26 W. Continue on I-26 for ~20 mi past the U.S. 19-E exit to Mars Hill, and pull off at ~ milepost 5 at large cut on right (and left) side of the highway.

STOP 1–1

Polydeformed Middle Proterozoic Grenville gneiss near Whittaker Gap at mile 5, I-26W: Deciphering ~1 billion years of southern Appalachian geology (Arthur J. Merschat and John G Bultman). 35° 53.270′ N, 82° 32.790′ W.

Purpose. To examine lithologic and structural complexites Middle Proterozoic Grenville gneisses in a pristine exposure and unravel its structural evolution.

Description. Interstate 26 was recently finished from Mars Hill, NC to the Tennessee-North Carolina border (opened fall, 2003) creating pristine exposures of wBR Grenville rocks and structures. The outcrop is a ~240 m long by ~50 m high west-facing roadcut approximately 5 mi south of the North Carolina-Tennessee border on I-26. It is located 0.5 km south of Whittaker Gap in the southeastern quarter of the Sams Gap 7.5 minute quadrangle, NC-TN. The outcrop is a complexly folded and varied assemblage of interleaved migmatite, metagranitoid, biotite-granitoid gneiss, and massive to weakly foliated metagabbro (Fig. 1-1-1). The main lithologies are biotite granitoid gneiss to metagranitoid and migmatitic amphibolite. Migmatitic inequigranular hornblende-biotite gneiss, metagabbro, and other minor lithologies constitute the rest of the outcrop. Similar units have been described by Merschat et al. (2002) in the Sam Gap 7.5 minute quadrangle, North Carolina-Tennessee. The following lithologic descriptions are based on outcrop and thin section observations and compared to other studies in the area (e.g. Merschat et al., 2002, Ownby et al., 2004).

Lithologies

Biotite granitoid gneiss and metagranitoid. Light pinkish gray to very light gray medium- to coarse-grained, equigranular to inequigranular biotite granitoid gneiss composes more than half of the outcrop. Granitoid gneiss bodies are strongly foliated near the edges and layering ranges from 2 to 50 cm. The cores of larger bodies (greater than 5-m wide) are weakly foliated to massive, and locally pegmatitic. Folded and dismembered white, medium-grained, quartz-feldspar layers occur in some bodies. Multiple sugary, quartz veins, ranging from a 1 cm to 50 cm thick, cut the larger granitoid gneiss bodies, and have a consistent NNW orientation. This unit correlates with biotite granitoid gneiss of Merschat et al., (2002), which is part of the layered gneisses of the Elk River-French Broad massifs of Bartholomew and Lewis (1984) and Rankin et al., (1989). U-Pb ion microprobe ages of gneisses from the Elk River-French Broad massifs yielded magmatic ages of 1.165-1.15 Ga (Carrigan et al., 2003), and these biotite granitoids and granitoids gneisses are assumed to be of similar age.

Migmatitic amphibolite. The southern third of the outcrop is composed of dark gray, medium- to coarse-grained migmatitic amphibolite, dominated by stromatic migmatite. Alternating layers of amphibolite (melanosome), and medium- to coarse-grained, equigranular quartz-feldspar layers (leucosome) vary from 1 cm to 1 m thick. Thin diatexite layers of coarse-grained, granoblastic hornblende-quartz-feldspar occur parallel to layering and around elliptical amphibolite pods. Amphibolite layers often contain significant amounts of biotite, generally aligned parallel to the migmatite layering. Boudins of biotite granitoid and granitoid gneiss, between 10 cm to greater than 10 m long occur frequently in the migmatitic amphibolite.

Migmatitic inequigranular hornblende-biotite gneiss. The most unique lithology observed is a medium- to coarse-grained, migmatitic inequigranular gneiss (Fig. 1-1-2a). Equigranular, polymineralic augen are in a medium- to coarse-grained matrix of plagioclase, quartz, biotite, and hornblende. Augen are strongly aligned to the dominant foliation and range in size from 1cm to 15 cm long. Minor quartz-feldspar layers occur locally and are parallel to the dominant foliation. This lithology has not been described by other workers in the area, likely because it is not mappable at 1:24,000 scale.

Bakersville metagabbro. Two dark greenish gray to black, medium- to coarse-grained, massive to foliated gabbro intrudes the migmatitic amphibolite and inequigranular hornblende-biotite gneiss. The dikes may be connected at depth and represent a single irregular pluton. Locally, subophitic to ophitic textures are preserved, but the majority of the gabbro has been altered to medium- to coarse-grained amphibolite, with thin black layers of chlorite, biotite, and epidote (~0.25 - 1 cm thick). Coarse-grained amphibolite, and lenticular quartz veins define a narrow contact aureole, 1-20 cm wide, around the each dike (Fig. 1-1-3). A weak foliation parallel to the contact is developed in the gabbros within one meter from the contact. Various other studies in the wBR of northwestern North Carolina (e.g. Merschat, 1977; Brown, 1985; Goldberg et al., 1986, and Merschat et al., 2002) have mapped similar metagabbros as Bakersville metagabbro. Based on similarity of texture and composition these metagabbros dikes are correlated with 734 ± 26 Ma Bakersville metagabbro of the Crossnore Plutonic suite (Goldberg et al., 1986).

Minor lithologies. Other, less extensive lithologies occur in the outcrop including: 1) very light gray, medium-grained, strongly layered protomylonite granitoid gneiss; 2) white, fine-grained sugary quartz veins; 3) medium-grained biotite schist; and 4) migmatitic biotite gneiss. Often these minor lithologies are interlayered with and subsequently grouped with the major units in the outcrop.

Mesoscopic Structure

Copious structural and tectonic elements are exhibited within the outcrop (Fig. 1-1-2). The outcrop is defined by a large anvil-shaped body of biotite granitoid gneiss that roughly corresponds to the symmetry axis for the outcrop (Fig. 1-1-1). Folds verge oppositely around the anvil-shaped core, and many layers appear continuous around the core. Foliation, defined by stromatic migmatite and metamorphic layering dips steeply west and is folded by inclined to reclined, isoclinal to open, gently plunging folds trending N-S. Cuspate-lobate folds (mullions) occur along the contacts of biotite granitoid gneiss and migmatitic inequigranular gneiss with the sharp hinge crests protruding into the biotite granitioid gneiss. These folds parallel the larger fold controlling the outcrop pattern (Fig. 1-1-1). Axial surfaces of these folds are generally parallel to quartz veins (Fig. 1-1-1). Boudins of biotite granitoid gneiss and amphibolite are common, with long axes oriented parallel to the dip of the dominant foliation.

The dominant foliation in the gneisses and migmatites is deflected and truncated by Bakersville metagabbro dikes. A weak, steeply dipping foliation parallel to the contact occurs in the metagabbro, and in the narrow contact aureole. Upright to inclined folds, with axial surfaces parallel to the country rock-metagabbro contact occur within the aureole. These structures are overprinted by a NE-trending, moderately SE-dipping foliation. This foliation is well developed in the largest metagabbro body where it is defined by coarse-grained hornblende and dark, ~0.5 cm thick, layers of chlorite, biotite, and epidote. This later foliation is likely well developed in the gneisses and migmatites, but the similar orientation to earlier foliations makes it difficult to recognize.

The youngest structures observed are low-grade to brittle structures. A weakly developed mylonitic foliation, characterized by grain-size reduction of feldspars and mineral stretching lineation in the layered biotite granitoid gneiss in the northern part of the outcrop. Brittle faults and joints are the youngest structures. Minor brittle faults are recognized by down-dip and oblique slickenlines on the fault surfaces. Displacement is minimal and difficult to estimate with scarce marker units. Filled and unfilled joints were observed, and the major joints sets trend N 70° W and N 20° W. Filled joints commonly contain chlorite, quartz, and epidote. Alteration zones observed around some joints are up to 2 cm thick, and contain pink potassium feldspar, epidote, and minor fluorite (Fig. 1-1-2).

Deformation History

Nearly 1 billion years of evolution of the Appalachian orogen are recorded in the outcrop on I-26. Crosscutting relationships permit the development of a detailed deformational history, although, absolute timing of deformation is based on correlation of outcrop lithologies with described lithologies for which published ages exist.

Three Middle to Late Proterozoic deformations are recognized in the outcrop. The earliest deformation, D_1, occurred after ~1.15 Ma corresponding to the magmatic ages of biotite-granitoid and granitoid gneisses throughout the western Blue Ridge (Carrigan et al., 2003). D_2 is interpreted to be a progressive, upper amphibolite facies event.

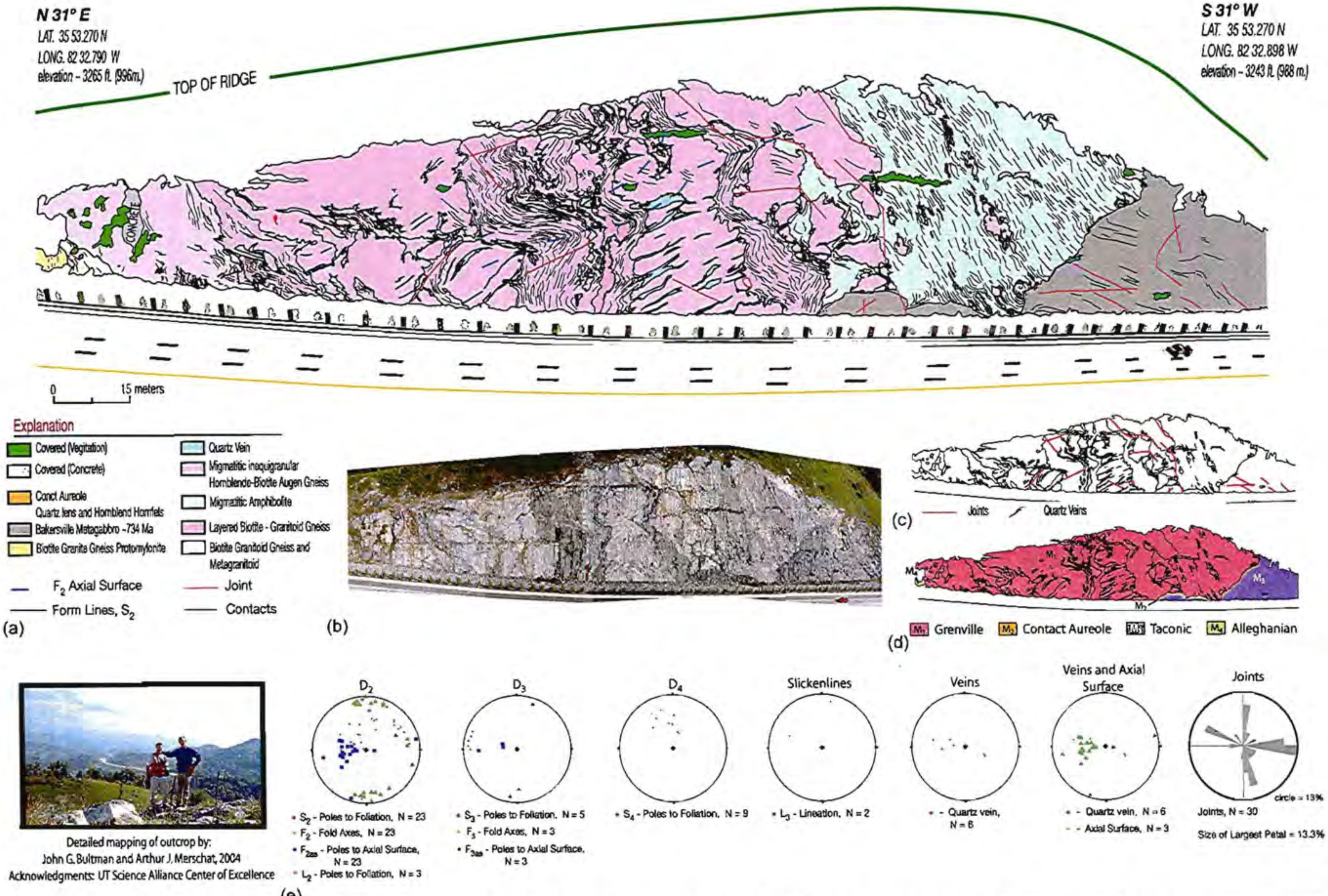


Figure 1-1-1. (a) Detailed drawing from photographs of exposure at Stop 1-1. (b) Photograph of exposure. (c) Sketcvh from photographs of the distribution of quartz veins at Stop 1-1. (d) Distribution likely timing of metamorphism at Stop 1-1. (d) Lower hemispheres equal-area plots of several fabric elements, and one rose diagram with joint orientations at Stop 1-1. Fabric diagrams are lower hemisphere, equal-area projections.

Early D_1 structures include S1 foliations preserved in amphibolite and biotite granitoid gneiss boudins, and intrafolial folds, F_1. The dominant foliation, S_2, is defined by alignment of biotite, hornblende, metamorphic, and stromatic migmatite layering. F_2 folds are reclined to recumbent, gently plunging, N-S trending disharmonic folds. The majority of folds in the outcrop are F_{2b}. Quartz veins truncate S_2 in the granitoid and formed cuspate-lobate structures in the inequigranulat hornblende-biotite gneiss (Fig. 1-1-2b). Exact timing is difficult to constrain, but, the axial planar relationship of quartz veins and F_{2b} indicate intrusion during folding. Intrusion of the ~734 Ma Bakersville metagabbro, D_3, produced a narrow contact aureole with F_3 folds and an axial planar foliation S_3. Heat from the Bakersville metagabbro produced M_2, hornblende hornfels facies contact metamorphism.

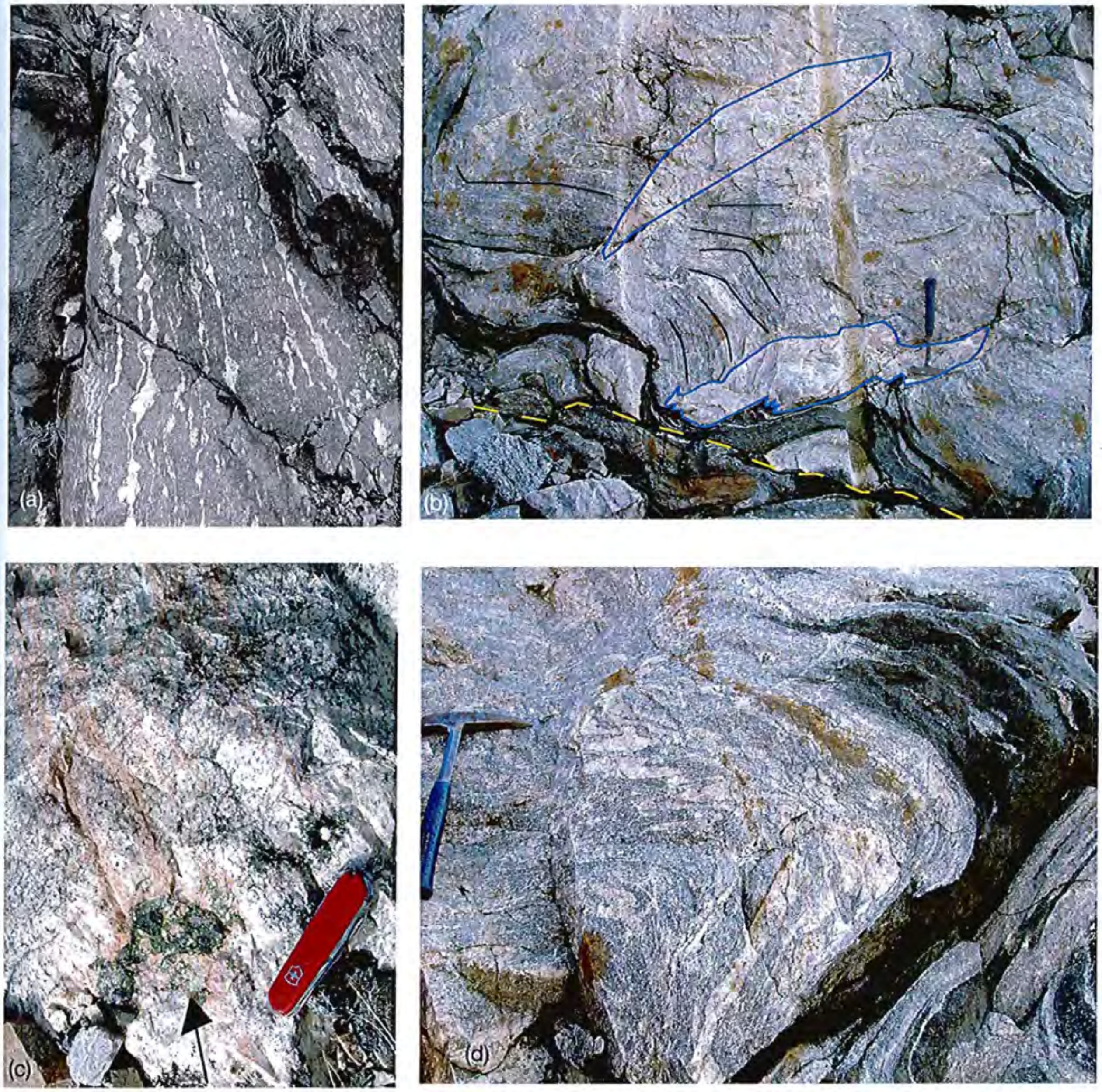


Figure 1-1-2. (a) Sheared migmatitic inequigranular hornblende-biotite gneiss with dextral, down-to-the-SW shear sense. Polymineralic augen are composed of equigranular quartz, plagioclase, and minor hornblende. (b) Fault-bounded block with lower shear zone (yellow line) at the bottom. Quartz veins (blue outline) truncate S_2 foliation in biotite granitoid gneiss and interferes with S_{2b} in migmatitic biotite schist. (c) Alteration zone around joints contain pink potassium feldspar, epidote, and minor fluorite. Joint trends N 81° W, and dips 78° SW. (d) Intrafolial folds in biotite-granitoid gneiss, folded by a later inclined closed fold, F_2.

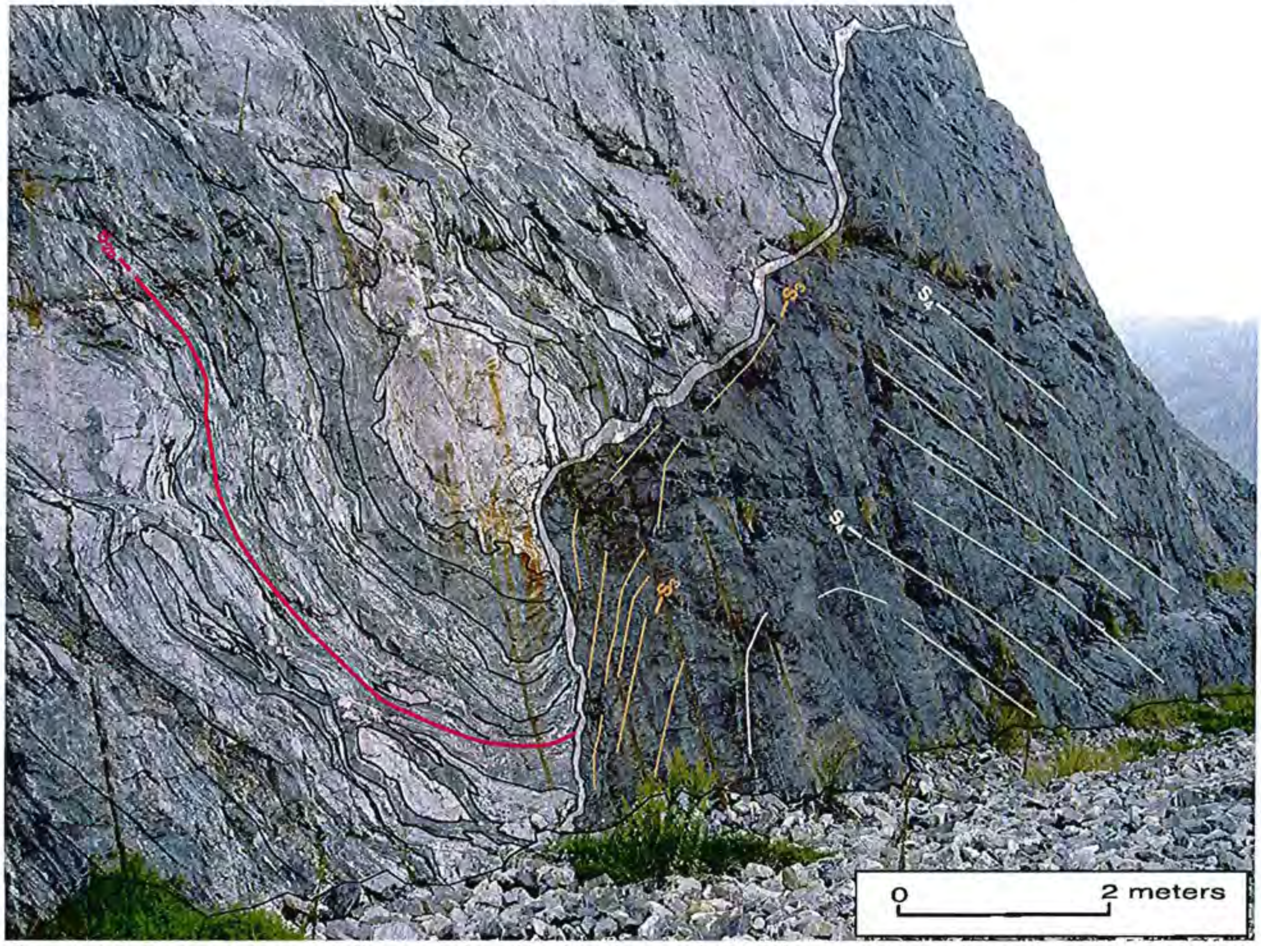


Figure 1-1-3. Contact of the Bakersville metagabbro with migmatitic amphibolite. White quartz lens and medium gray massive hornfels adjacent to the metagabbro mark the contact aureole. Three different foliations are sketched on the photograph. Intrusion of the Bakersville metagabbro truncated and produced drag folds of the S_{2b} foliation.

The remaining deformations record a complete Wilson cycle during the Paleozoic, followed by Mesozoic rifting and development of a passive margin. Medium- to coarse-grained hornblende and 0.25-1 cm thick layers of chlorite, biotite, and epidote define a foliation, S_4, that trends NE and dips moderately SE. S_4 is not restricted to the Bakersville metagabbro, but is parallel to S_{2b} in the migmatites and gneiss making it difficult to recognize. S_4 is the result of an early to mid-Paleozoic, lower amphibolite facies metamorphism, M_3, that correlates with either the Taconic or Acadian orogeny, D_4. Long et al. (1959) reported ~457 and ~433 Ma K-Ar biotite ages from the Bakersville metagabbro. Recent U-Pb ion microprobe zircon rim ages from western Blue Ridge orthogneisses yield ~470 Ma overgrowths (Ownby et al., 2004), therefore we interpret D_4 as the result of Taconic metamorphism. Protomylonites in the northern part of the outcrop and minor oblique and dip slip faults are interpreted to be Alleghanian structures related to Pigeonroost-Sams Gap shear zone (Carter et al., 1998). Joints with alteration zones are also interpreted to be Alleghanian structures that were acting as conduits for hot fluids expelled from deeper within the orogen (Schedl et al., 1992). Alleghanian retrogression and shearing culminated in multiple kilometer scale shear zones through the biotite granitic gneiss on the Sams Gap quadrangle and continue to the northeast and southwest. The final deformation, D6, includes the Mesozoic to Cenozoic(?) development of joints.

Discussion: Ductile Flow and Diapirism

The structures observed in this outcrop support N-directed Middle Proterozoic ductile flow. Anvil-shaped fold geometries, like those cored by biotite granitoid gneiss in this outcrop are typical of sheath folds (e.g., Cobbold and Quinquis, 1981; Mies, 1993; Alsop and Holdsworth, 1999). Further, F_2 folds are coaxial to the large anvil-shaped structures, and the few mineral lineations measured. Unfortunately, the steep face of the roadcut and its intersection with S_2 hinders recognition of shear sense indicators and mineral lineations. Normals to boudins are also sub-parallel to F_{2b} and indicate vertical extension. Viscosity contrasts between layers produce lobate-cuspate folds referred to as fold mullions (Ramsay and Huber, 1987). The sharper crests protrude into the lithology with a higher viscosity, indicating that the anvil-shaped biotite granitoid gneiss have a higher viscosity than the surrounding inequigranular gneiss. Truncations of structures along the edges of biotite granitoid gneiss bodies are related to the more viscous inequigranular gneiss flowing around the less viscous granitoid gneiss (Fig. 1-1-2b). Marques and Cobbold (1995) demonstrated that sheath folds would develop in a bulk simple shear regime as material flows around prolate and oblate rigid objects. Similarly, the less viscous granitoid gneisses acted as semi-rigid clasts, forming the sheath fold cores, which the inequigranular biotite gneisses flowed around.

The quartz veins are axial planar to F_2 and thin towards the south or core of fold. Figure 1-1-2b shows quartz veins axial planar to F_{2b} truncating S_2. We suggest that as the fold began to form the less viscous biotite granitoid did not deform as rapidly as the inequigranular gneiss and the veins open from north to south. Upon opening only quartz vein material intrudes from north to south.

This outcrop may be one of the best exposures to examine the Bakersville metagabbro. It preserves evidence for emplacement mechanism and a narrow contact aureole. Around both Bakersville metagabbro bodies the S2b foliation is deflected into closed to recumbent, upright to inclined rim synforms with pluton up shear sense. S3 in the Bakersville metagabbro and country rock are parallel to the metagabbro-country rock contact. These observations are consistent with emplacement of the Bakersville metagabbro bodies in this outcrop as diapirs. Diapiric emplacement of a gabbroic magma is not common, but it is possible (Raymond, 1995). This is the first reported contact aureole associated with the Bakersville metagabbro. Goldberg et al. (1986) observed only chilled margins and concluded that the Bakersville metagabbro intruded at shallow levels in the crust. These differences may simply be related to size of the intrusion. The maximum width examined by Goldberg et al. (1986) was only a couple of meters wide, compared to the 5 and 60 m wide dikes observed here. Larger gabbro bodies would have the heat required to produce a contact aureole in the surrounding country rocks.

Conclusions

1. Rocks of the western Blue Ridge record 1 billion years of southern Appalachian evolution, including the formation and rifting to two supercontinents.
2. Six distinct deformational events are recognized.
3. Middle Proterozoic, upper amphibolite grade deformation, D_2, is responsible for the majority of outcrop structures.
4. Viscosity contrast between the units resulted in an outcrop-scale fold mullions, and synkinematic intrusion of quartz veins axial planar to F_2.
5. Anvil-shaped folds cored by biotite granitoid gneiss may represent outcrop-scale sheath folds resulting from ductile flow during the Grenville orogeny, D_2.
6. Intrusion of the ~734 Ma Bakersville metagabbro caused local contact metamorphism in a narrow 1-20 cm-thick aureole adjacent to the intrusions. Shape, existence of rim synclines, and S_3 parallel to the metagabbro-country rock contact suggest emplacement of these Bakersville metagabbros as diapirs.
7. Early to middle Paleozoic orogenies do not completely destroy or transpose D_2 Grenville structures and fabrics as previously thought. Foliation defined by coarse-grained hornblende in Bakersville metagabbro is interpreted as a Taconic overprint.
8. Alleghanian retrogression and brittle structures were observed locally in the outcrop.

STOP 1–2

Separating Grenvillian and Alleghanian mylonitic fabrics. (Donald W. Stahr and J. Ryan Thigpen). 35° 57.51′N, 82° 33.56′ W.

Purpose. To examine structural relationships and mineral assemblages to differentiate Grenvillian vs. Alleghanian deformation (Fig. 1-2-1).

Description. Mesoproterozoic (~1.1 Ga?) Grenville basement gneisses and amphibolite intruded by foliated mafic dikes of the Bakersville suite (~735 Ma) exposed in a new roadcut on I-26 approximately 5 km north of the TN-NC border reveal evidence of a polydeformational history (Fig. 1-2-1). A dominant foliation (S1) defined by gneissic layering and alignment of biotite and quartz-feldspar aggregates is overprinted by a later weak to moderately developed foliation (S_2). Relative timing of S_1 and S_2 is constrained by crosscutting relationships, mineral assemblages defining the foliations, and relationship to mesoscale structures. Approximate metamorphic conditions were estimated from observed mineral parageneses and microstructures associated with active deformation mechanisms.

The earliest recognized deformational event, D_1, involved development of S_1 axial planar to isoclinal (F_1) folds. Continued deformation sheared common limbs between antiform-synform pairs. Rare shealth folds indicate local perturbations in the flow paths, caused by inhomogeneous shear. Mesoscopic kinematic indicators and microscopic mantled quartz and plagioclase porphyroclasts reveal consistent top-to-the-northwest sense of shear. Early folds and mineral elongation lineations parallel the transport direction inferred from kinematic indicators (Fig. 1-2-1). Pervasive core-and-mantle microstructure suggests subgrain rotation or grain boundary migration recrystallization were the dominant deformation mechanisms (regimes 2 and 3 of Hirth and Tullis, 1992). Absence of this high temperature fabric in the mafic intrusives indicates D_1 is Grenvillian. Presence of back-rotated σ-type porphyroclasts (Fig. 1-2-2) suggests noncoaxial deformation in the sub-simple shear realm (i.e., transpressional; Tikoff and Fossen, 1995). Ubiquitous σ-type and absence of δ-type porphyroclasts also suggests a high recrystallization rate to shear strain rate ratio during Grenvillian deformation (Hatcher, 1978; Passchier and Trouw, 1996).

D_2 involved closed to tight, northwest-vergent folding (F_2) of S_1 and development of a local axial-planar foliation (S_2) in the biotite gneiss and mafic intrusives defined by biotite and chlorite aggregates. Pervasive epidote and chlorite alteration of feldspar in pegmatite veins, and pyroxene altered to green amphibole + biotite + epidote ± chlorite in the Bakersville Gabbro indicates greenschist to lower amphibolite facies retrograde metamorphism associated with Paleozoic (Alleghanian?) deformation. Overprinting foliations observed in the gabbros are defined by the same mineral assemblages (Ep + Hbl + Bt ± Chl) suggesting progressive late Paleozoic deformation.

STOP 1–3

Anticline cored by 1.1 GA Cranberry Gneiss overlain by Ocoee Supergroup (Walden Creek Group?) black slate. 35° 04.837′ N, 82° 29.794′W.

Purpose. To examine the basement–cover contact between 1.1 Ga basement rocks of the Buffalo Mountain thrust sheet and Ocoee Supergroup rocks.

Description. Brittlely deformed black graphitic slate overlies equally deformed 1.15 Ga rocks correlative with the Watauga River Gneiss(?) (Fig. 1–3–1). The slate is the northernmost occurrence of Ocoee Supergroup (Wilhite and Sandsuck Formations) rocks exposed in the lower thrust sheets of the Buffalo Mountain composite thrust sheet, which increases SW along strike from the few hundred m-thick veneer exposed here to >15 km thick in the Great Smoky Mountains. These rocks are overlain by Chilhowee Group rocks (Lowry, 1958; Hardeman, 1966). Lowry (1958) and Hardeman (1966) correlated these rocks with the Snowbird group, although a better correlation based stratigraphic position and lithologic character is with Walden Creek Group rocks.

The pyritic black slate produces acid runoff as it oxidizes. Harry Moore, Tennessee Department of Transportation engineering geologist, recognized the potential environmental impact of excavating large amounts of this material and leaving it exposed to weathering processes. To avoid acid runoff, material removed from this cut was encapsulated in heavy rubberized plastic bags and buried beneath the highway along the last section of gentle grade of I–26 to the north as the highway enters the Nolichucky River flood plain south of Erwin, Tennessee.

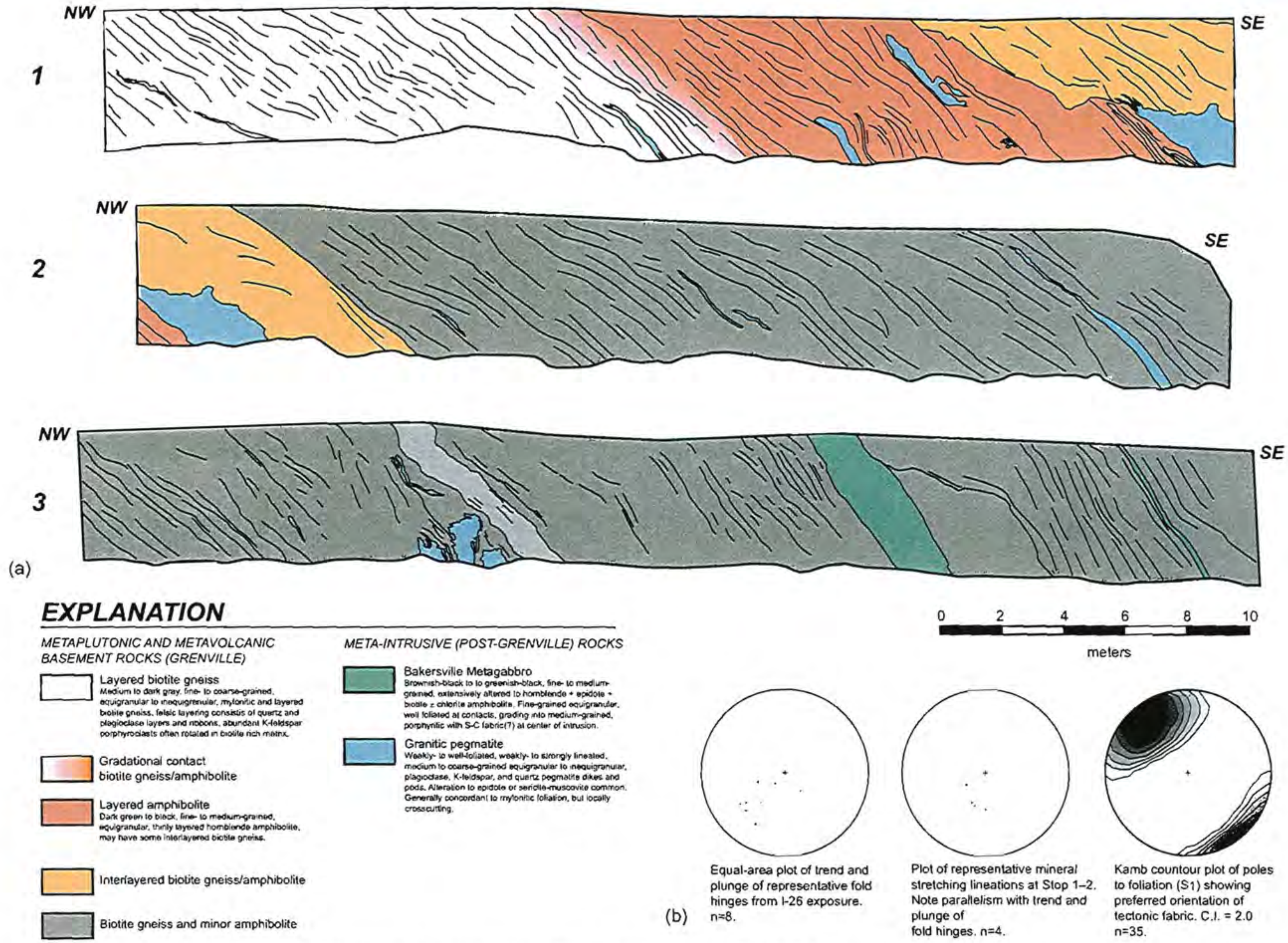
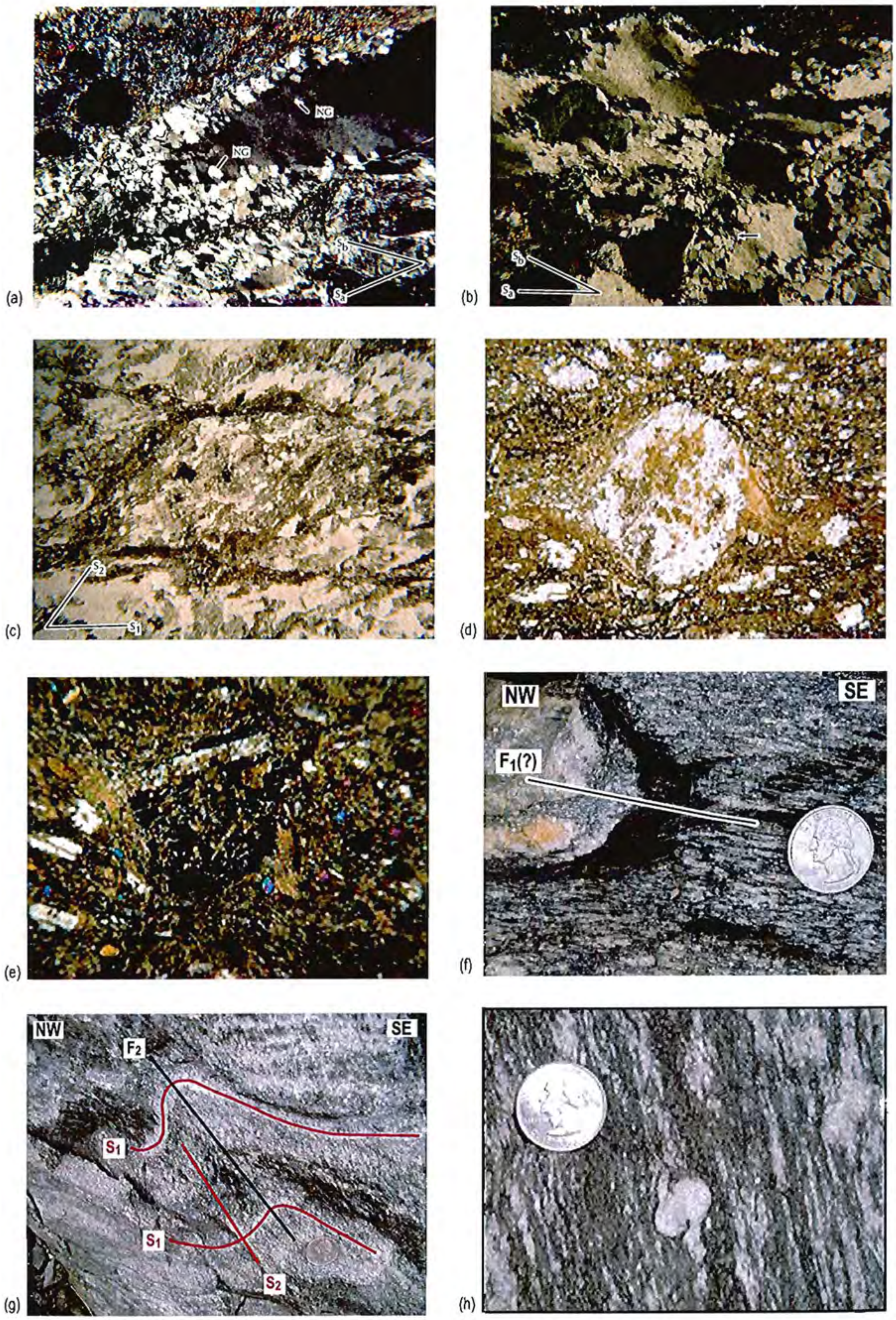


Figure 1–2–1. (a) Sketch from photographs of the geology exposed at Stop 1–2. (b) Mesoscopic fabric data.


(a)
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S_2
(h)

Fig. 1-2-2 (left). (a) Mylonitic biotite gneiss showing subgrain rotation recrystallization microstructure and resulting SPO of new grains at ~25° to mylonitic foliation. Recrystallized grains of quartz porphyroclast are larger than subgrains in quartz porphyroclast. New grains (NG) with significantly different lattice orientations formed by subgrain rotation recrystallization are also observed in interior of clast. Crossed polars. Base of photo 2 mm. (b) Mylonitic biotite gneiss showing dominant subgrain rotation recrystallization microstructure. Recrystallized quartz grains are approximately the same size as subgrains in porphyroclasts, and define an oblique SPO (Sb) at ~25° to mylonitic foliation (Sa). Grain boundary bulging is also observed in recrystallized grains (arrowed). Crossed polars. Base of photo 2 mm. (c) Biotite gneiss showing development of two foliations defined by aligned biotite. Plane polarized light. Base of photo 2 mm. (d) Photomicrograph of rounded plagioclase porphyroclast in Bakersville gabbro. Recrystallized quartz and biotite occupy pressure shadows by long axis of grain. Foliation is parallel to bottom of photo, defined by alignment of biotite, epidote, and euhedral to subhedral plagiocalse laths. Plane polarized light. Base of photo approximately 2 mm. (e) Same field of view as adjacent photomicrograph (rotated ~20° CW). Lamellar growth twin in plagioclase and lack of recrystallized grains indicate lower-temperature deformation (greenschist to lower amphibolite facies). Cross-polarized light. Base of photo approximately 2 mm. (f) Folded medium-grained porphyroclastic amphibolite. Plagioclase porphyroclasts define strong lineation parallel to fold hinge. Fold Axis plunging 30° toward 210°. quarter for scale, diameter 24 mm. (g) Gneissic foliation (compositional layering; S1) refolded during a later event (F_2) that produced a local foliation (S2) oblique to S1. Penny for scale, diameter 19 mm. (h) Back-rotated plagioclase □-type porphyroclast in mylonitic biotite gneiss. quarter for scale, diameter 24 mm.

Figure 1–3–1. Altered Cranberry Mine(?) Gneiss (greenish) unconformably overlain by black, graphitic Walden Creek Group(?) slate at Stop 1–3 on southbound I–26 near Erwin, Tennessee. The basement here occupies the core of a broad anticline wrapped by the black slate.

NOTE: *the following optional stop is included here because there is another excellent exposure of rocks on the S-bound side of I-181 ~3 mi nw of I-81 (toward Kingsport), but will not be visited on this trip in the interests of time.*

STOP 1–3A (Optional Stop)

Cleavage development and folding in part of the Appalachian foreland fold-thrust belt: A case study of Sevier Shale (Middle Ordovician) exposed in part of the Bays Mountain synclinorium (Crystal G. Wilson and Shawna R. Cyphers). 36° 31.47′ N, 82° 34.76′ W.

Purpose. To examine folds and slaty cleavage development in an exposure of Sevier Shale on I-181.

Description.

Introduction. Slaty cleavage is an important structure in deformed, low-grade metamorphic rocks. This planar fabric is usually penetrative and defines a new S-surface along which rocks have a tendency to break (Hatcher, 1995). Cleavage is considered to be an end-member component of continuous metamorphic differentiation opposing the coarser end of the spectrum, which would include schistose and gneissose textures (Wood, 1974). Cleavage is also directly linked to folding, as cleavage and axial planar surfaces of folds often parallel (or near-parallel) the XY plane of the strain ellipsoid (Wood, 1974; Williams, 1975). An understanding of cleavage geometry and its origin on meso- and microscales can be used to elucidate the nature of regional metamorphism, as well as deformation.

The study area is a roadcut on the west shoulder of I-181 near Kingsport, TN which exposes folded, faulted and jointed beds of massive, gray, calcareous shale of the Middle Ordovician Sevier basin (Fig. 1–3A–1). These rocks were deformed and transported to their present position as part of the foreland fold-thrust belt during the Allegheanian orogeny in the southern Appalachians. Although polyphase deformation is rare in the southeastern Valley and Ridge, it has been noted (Roeder et al., 1978; Kohles, 1985). Ohlmacher and Aydin (1995) observed at least seven stages of progressive Alleghanian deformation at the Bays Mountain synclinorium: (1) early thrust faulting, (2) folding, (3) intermediate thrust faulting, (4) intermediate folding, (5) normal faulting, (6) strike-slip faulting, and (7) jointing (Fig. 1–3A–2). The purpose of this study is to examine geometric attributes and cleavage-folding relationships to discriminate the number of fold events and deformation mechanisms associated with formation of the Bays Mountain synclinorium.

Geologic Setting. The Sevier Shale and associated terrigenous clastic and carbonate rocks were deposited during the Blountian phase of the Taconic orogeny in a 2500+ m deep foreland basin, the Sevier basin (Finney, et al., 1996). Due to the absence of clasts of Blountian-age arc volcanics, it has been proposed that the Sevier basin was in fact a back-bulge basin cut off from younger age sediment deposition by the fore-bulge (Hatcher et al., 2004b). This idea has been disregarded as modeling illustrates the inability of crust to deform and warp producing a basin deep enough to accommodate the observed thickness of the Sevier sediments (Whisner, 2004). These rocks are now part of the foreland fold-thrust belt of the southern Appalachians that formed during the Alleghanian orogeny during the final collision of Gondwana with Laurentia.

Two different fold geometries are present in the outcrop; at the southernmost end inclined-tight folds with an interlimb angle of 30°-40° occur separated by ~264m (866 ft,) of inclined beds from upright-open folds at the northernmost end of the outcrop that have an interlimb angle of 120°-130° (Fig. 1–3A–1). Tight folds strongly fan the cleavage throughout the limbs and are axial planar only within the hinge. Cleavage is inclined to bedding with little variation in orientation throughout the open folds and distal limbs. Cleavage-bedding intersection lineations have a shallow plunge toward 070 or 250 (Fig. 1–3A–1). Slickenlines found on folded bedding surfaces indicate folding was accommodated by flexural slip. Tension fractures filled with calcite pervade the outcrop.

Structural Analysis. Dip isogon analysis (Fig. 1–3A–3) of both fold types discriminates tight, class 1C folds from open, parallel folds. Dip isogons strongly converge in the core of the tight folds. Inclined to recumbent, tight and upright, open folds have β-axes of 071, 1, and 249, 2, respectively, in equal-area stereonet analyses of fold hinges and cleavage-bedding relationships (Fig. 1–3A–1). This correlates well with fold axes and cleavage-bedding intersection lineations measured. Poles to cleavage surfaces in distal limbs and in open folds plot in a clustered pattern, whereas poles to cleavage in tight folds are more scattered. This corresponds with field observation of weakly fanned cleavage in open folds and more intensive fanning in tight folds with axial planar cleavage in hinges.

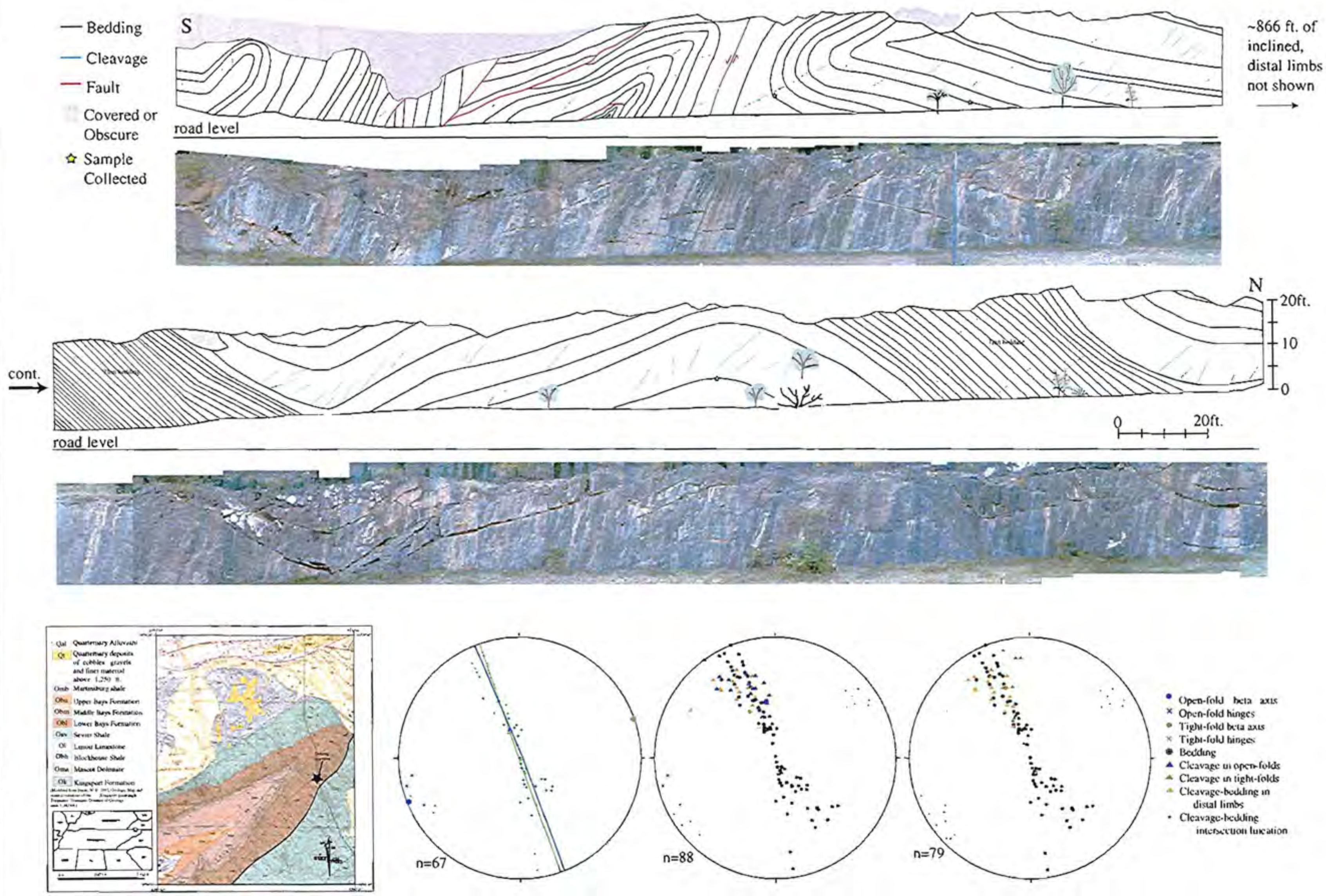


Figure 1–3A–1. Fold-bedding-cleavage relationships at the I–181 (southbound) exposure SE of Kingsport, Tennessee. (a) Sketch from photographs of the exposure. (b) Geologic index map from Brent (1993). (c) Lower-hemisphere equal-area plots of mesoscopic fabric data at Stop 1–3A.

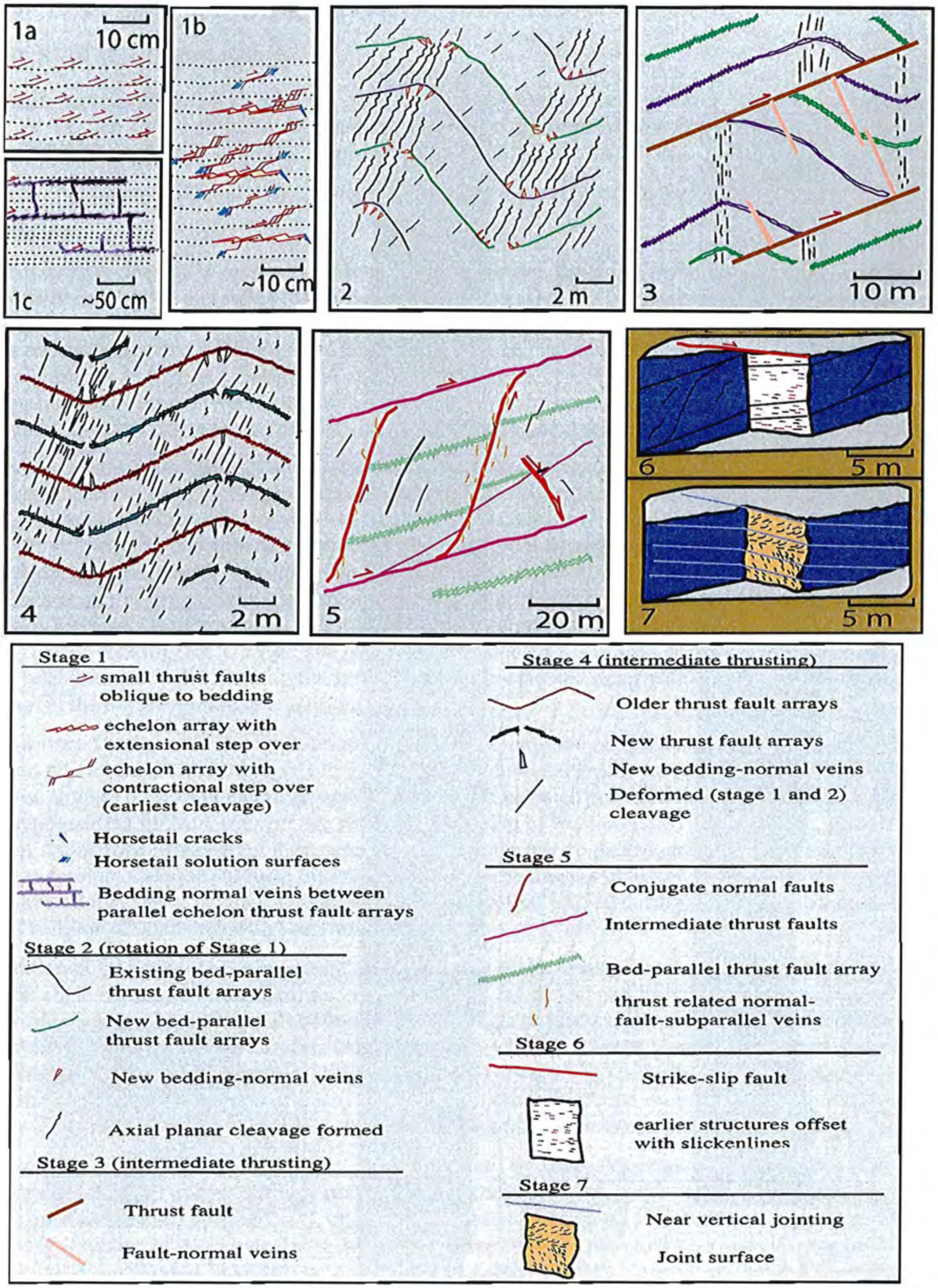


Figure 1–3A–2. Seven stages of progressive deformation at the Bays Mountain synclinorium during the Alleghanian orogeny. Two separate stages of folding occur. The first stage produces axial planar cleavage in the hinge of tight folds, which is later deformed about stage 4 folds. (from Bultman, 2005; modified from Ohlmacher and Aydin, 1995).

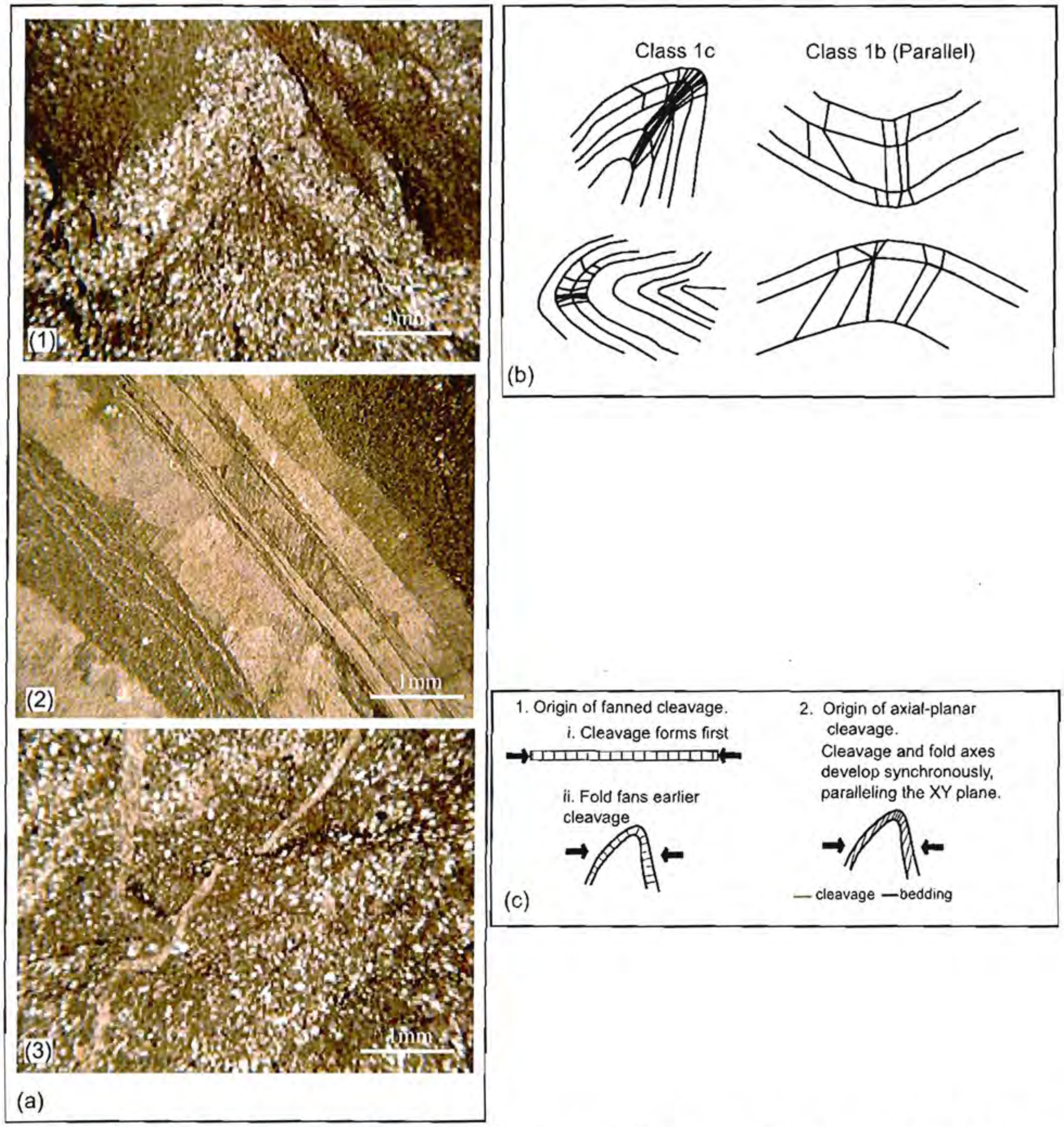


Figure 1–3A–3. (a) Cleavage-bedding relationships. (1) Micro-scale tight parasitic fold in limb section with axial planar cleavage in hinge. (2) Fibrous calcite viens. (3) Calcite vein truncated by pressure solution cleavage. (b) Dip isogon analysis of tight and open folds. Tight folds are class 2 similar folds, and open folds are class 1b, parallel folds according to Ramsay's (1967) fold classes. (c) Cleavage-folding relationships. 1) Cleavage develops before folding and fans upon deformation. 2) Cleavage and folding form synchronously.

Microscopic Fabrics. Microscopic analysis of thin sections from a tight fold hinge, an open fold hinge, and a distal limb was carried out to distinguish possible cleavage-forming mechanisms and determine whether these mechanisms vary with position in the outcrop. Our observations indicate pressure solution is the dominant mechanism forming the rough, disjunctive cleavage in all samples. An XRD analysis of a sample from a tight fold hinge (Fig. 1–3A–1) was conducted to determine the degree of illite recrystallization to muscovite. Analysis was performed using a Siemens XRD using a Cu source. The abundance of illite and absence of muscovite reconfirms recrystallization was not a cleavage-forming mechanism.

Bedding at the microscale is often obscured by sedimentary load structures, bioturbation, or lack of layering between the coarser-grained micrite and intermittent clay-rich clays. Nevertheless, the same angular cleavage-bedding relationship can be observed in thin section as in outcrop. The cleavage is inclined ~45° to bedding in the open-fold, hinge-perpendicular section and parallel to bedding in the hinge-parallel section. The ~45° inclined relationship is also perpendicular to strike in the distal limb section. Cleavage is perpendicular to bedding in the tight fold hinge. This relationship is well illustrated in a microscopic, tight parasitic fold in the distal limb section (Fig. 1–3A–3a1).

Syntaxial fibrous calcite veins (Durney and Ramsay, 1973) parallel bedding in the distal limb (Fig. 1–3A–3a2). The dominant orientation of the fibers is perpendicular to the wall rock, indicating $\sigma 3$ was aligned parallel to bedding at some incremental strain interval. This orientation must change during a later increment, as some fibers change orientation in a 45° counterclockwise direction.

A calcite vein is present that is inclined to bedding and near perpendicular to cleavage that has undergone apparent displacement due to pressure solution (Fig. 1–3A–3a3). This precludes a pre- or synchronous origin of extension veins with respect to cleavage formation.

Discussion. Analysis of cleavage-bedding relationships suggests a two-stage folding event is responsible for producing the different fold-cleavage geometries observed in the outcrop. The presence of axial planar cleavage in tight folds indicate cleavage may have formed prior to this early stage of progressive deformation which rotated the cleavage into an axial planar orientation only within the hinge of these folds and fanned the cleavage throughout the limbs (Figs. 1–3A–1 and 1–3A–3c). We interpret the open folds at the northern end of the outcrop to represent both a change in stress location and a later stage of folding in progressive deformation of the Bays Mountain synclinorium. These later-stage open folds fan the earlier-formed cleavage and produced no axial planar cleavage orientations. This interpretation is consistent with the work of Ohlmacher and Aydin (1995) who recognized a stage 2 formation of axial-planar cleavage, followed by deformation of this cleavage during stage 4 of a 7-part deformation scheme. The occurrence of stage 2 structures at the SW-end of the outcrop may be associated with a local stress state resulting from proximal map-scale bedding-parallel thrusts to the SW (Fig. 1–3A–1). The lack of refolded folds may be related to a shift in the local state of stress indicated by spatial relationships between stage 1, 3, and 5 structures, and pressure solution surfaces (Ohlmacher and Aydin, 1995). A single multistage progressive deformation event is supported by similar orientations of β-axes, measured fold hinges, and intersection cleavage-bedding lineation, which all plot as shallow-plunging features with a general trend of 070 or 250.

Microscopic analysis of cleavage-bedding fabrics clearly shows pressure solution was the dominant cleavage-forming mechanism in the hinges of both fold types and in inclined distal limbs. Recrystallization is discounted as a possible mechanism because of the absence of muscovite. Cleavage in all samples has a rough, disjunctive form and has the same orientation in thin section as in outcrop. At least one generation of calcite veins formed earlier or synchronous with cleavage formation, as illustrated by a truncation of vein calcite by pressure solution cleavage. The crosscutting relationship of this truncated vein to bedding indicates $\sigma 3$ was inclined to bedding. Change in the orientation of principal strain axes during progressive incremental deformation can be noted due to at least two different orientations of fibrous calcite growth.

(If this stop is made, continue SE on I-181, crossing I-81, and continuing SE on I-26. Exit at U.S. 321 and turn E toward Elizabethton.)

Continue S on I-26 and turn around at the next exit (Flag Pond). Continue N on I-26 to U.S. 321 exit and turn E toward Elizabethton.

Things to observe between stops

As we drive northeast on I-26, and then exit onto U.S. 321, several prominent ridges appear to the NE of I-26, and even higher ridges to the SE (straight in front of the vehicles). Two ridges, Holston and Iron Mountains, end just NE and SE of Elizabethton. The terminations of these ridges are related to the SW plunge of the Shady Valley syncline bringing younger carbonate rocks to the present level of erosion and forming the valley where Johnson City and Elizabethton reside today. The higher ridges to the SE are underlain by Chilhowee Group rocks in frontal thrusts and 1.1 Ga basement rocks of the Beech Mountain thrust sheet. After we pass through Elizabethton and turn SE again, we will see several large ridges in front of us. These are the ridges of Iron Mountain.

Continue through Elizabethton and turn right at the intersection of U.S. 321 and 19-E. Drive ~3 mi and park on the roadside opposite a large cut in light-colored sandstone and shale. We will get out here for a few minutes, and then continue slowly down section through the Chilhowee Group toward Hampton, TN.

STOP 1–4

Upper Chilhowee Group (Erwin Fm.) sandstone and shale, Doe River Gorge. 36° 18.055' N, 82° 11.230' W.

Purpose. To observe the nearly complete section of Lower Cambrian Chilhowee Group on SE limb of Shady Valley syncline.

Description. The Lower Cambrian Chilhowee Group is a clastic sequence that can be recognized from Alabama to Newfoundland and represents the rift-to-drift transition (e.g., Hatcher, 1989). We will briefly examine the Doe River Gorge section along 19-E between Valley Forge and Hampton, Tennessee. King and Ferguson (1960) described this section in detail—as have others (e.g. Safford, 1869)—and suggested it is "the most accessible and best exposed section of the Chilhowee Group in northeastern Tennessee". Unfortunately, recent widening of 19-E resulted in poorly to unexposed parts of the section. The NW-dipping strata of the Chilhowee Group are part on the SE limb of the Shady Valley syncline, a SW plunging syncline that extends from SW Virginia, to SW of Johnson City, Tennessee (Figs. 2 and 3). The syncline is preserved in the hanging wall of the Iron Mountain–Holston Mountain fault, and is part of the roof of the Mountain City window (Boyer and Elliot, 1982; Diegel, 1986). The Shady Valley thrust sheet contrasts markedly with other southern Appalachian thrust sheets, because it contains a complete stratigraphic section from Precambrian basement to the Cambrian-Ordovician Knox Group. Exposures along the next ~1 mile of U.S. 19-E comprise the Lower Cambrian Chilhowee Group. In NE Tennessee the Chilhowee Group (4000–7000 feet thick) consists of the lowest Unicoi Formation (2000-5000 ft thick), overlain by the Hampton Formation (500 – 2000 ft thick), and the uppermost Erwin Formation (1200–1500 ft thick) (King and Ferguson, 1960). This stratigraphy is different from that originally defined by Safford (1856, 1869) on Chilhowee Mountain west of Sevierville, Tennessee, so King and Ferguson (1960) suggested the correlations listed in Table 1-4-1. We will begin at the western entrance of the Doe River Gorge, near Valley Forge, Tennessee, and stop to examine the top of the Erwin Formation. Then we will continue E through the gorge to Hampton, Tennessee, moving down

Table 1-4-1. Stratigraphic correlation of Neoproterozoic and Cambrian rift and rift-to-drift facies modified from King and Ferguson (1970).
[1](Aleinikoff et al., 1995)

Age	Group		East-central Tennessee, Chilhowee Mountain	Northeasternmost Tennessee, southwestern Virginia	Northern Virginia
			Shady dolomite	Shady dolomite	Tomstown dolomite
Lower Cambrian	Chilhowee Group		Hesse sandstone Murray shale Nebo sandstone	Erwin Formation	Antietam quartzite
			Nichols Shale	Hampton Formation	Harpers shale
			Cochran formation	Unicoi Formation	Weverton quartzite Loudoun Formation ~565 Ma Catoctin greenstone[1]
Neoproterozoic	Ocoee Supergroup	Walden Creek Group	Walden Creek Group	Sandsuck *Snowbird Fm. Grandfather Mountain Formation	
		Great Smoky Group	Great Smoky Group		
		Snowbird Group	Snowbird Group		

Figure 1–4–1. Erwin Formation exposure on U.S. 19E N of Hampton, Tennessee.

section through the Chilhowee Group, and eventually crossing the Iron Mountain fault and entering the Mountain City window.

The Erwin Formation consists of white to pale fleshy white fine- to medium-grained quartz arenite, siltstone, and some greenish-gray clay shale. Quartz arenite beds may contain Scolithos tubes and reach 25 ft thick (King and Feguson, 1960). The roadcut begins at the contact of the overlying Shady Dolomite (reddish brown laminated residual clays deformed by recent slumping) and the top of the Erwin Formation, marked by the pyrite- and limonite-bearing calcareous shale and sandstone of the Helenmode Member (Fig. 1–4–1). The measured thickness of the Helemode member reported by King and Ferguson (1960) in the original roadcut is 67 ft, and the thick-bedded sandstone layer marks the top of the quartz arenite-dominated Hesse Member. As we continue through the gorge the Erwin Formation is dominated by siltstone and greenish gray shale of the Murray Gap member, which is poorly exposed. Approximately 1000 feet before the highway crosses the Doe River for the first time, the contact of the Erwin and Hampton Formation is placed at the lowest white sandstone bed (Nebo Member) and the beginning of gray to dark gray shale. After crossing the first bridge to the south, Hampton Formation arkose occurs briefly followed by poorly exposed black fissile shale of the basal Carden Bluff Member and continues on the north side after crossing the Doe River for a second time. The bend in the Doe River is likely the result of the river following NW-trending joints in the resistant sandstones of the Erwin and Unicoi Formations, but follows strike in the less resistant shale of the Hampton Formation. The top of the Unicoi is marked by the first very light yellowish-brown sandstone beds, which, thanks to TDOT, we can recognize by the light yellowish brown blocks of arkose and wacke rip-rap blocks left in the roadcut. The Unicoi is dominated by occasionally conglomeratic, medium- to coarse-grained feldspathic wackes, and lesser conglomerates, siltstones and dark gray shales. Areas dominated by dark gray to black rocks are likely amygdaloidal basalts near the base of the Unicoi. King and Ferguson (1960; their Plate 1 and 12) traced several amygdaloidal basalts near the base of the Unicoi, including one basalt for ~1 mi along the lower SE slopes of Iron Mountain south of the Doe River Gorge. The base of the Unicoi rests nonconformably on Middle Proterozoic basement rocks locally preserved along the SE base of Iron Mountain (King and Ferguson, 1960; their Plate 1 and 12). We remain in the Unicoi until we cross the bedding-parallel, NW-dipping Iron Mountain fault (not exposed) just before arriving in the open valley at Hampton, TN.

Continue driving SE on U.S. 19-321. Look for Tiger Creek Road (turns right) and a cut of relatively fresh rock. Continue driving to top of hill beyond cut and park on right.

Things to observe between stops

The valley around Hampton is part of the Mountain City window, and small ridges on the SE side of the valley are underlain by Chilhowee Group sandstone brought up on imbricate thrusts in the interior of the window. As we drive farther SE, we will cross the Stone Mountain fault and see low roadcuts in light-colored 1.1 Ga Cranberry Gneiss of the Beech Mountain thrust sheet.

STOP 1–5

Middle Proterozoic (~1.1 Ga old) Cranberry Mine Gneiss and ~735 Ma-old Porphyritic Diabase 36° 13.366′ N, 82° 10.697′ W.

Purpose. To examine characteristic rocks of the Beech Mountain thrust sheet intruded by Late Proterozoic Bakersville Gabbro dikes.

Description. The Beech Mountain thrust sheet consists of Middle Proterozoic orthogneisses intruded by the bimodal assemblage of the Neoproterozoic Crossnore Plutonic Suite (CPS). At this exposure we will examine Middle Proterozoic Cranberry Mine Gneiss intruded by several Bakersville Gabbro (porphyrotic diabase) dikes of the CPS. Carrigan et al. (2003) reported an ion microprobe U–Pb age of 1192 ±11 Ma for the Cranberry Mines Gneiss from near Newland, NC. Medium to light gray, fine- to coarse-grained biotite granitic gneiss is the dominant lithology in this exposure with interlayers, lenses, and pods of even-grained biotite granitoid, weakly foliated megacrystic biotite granitoid, and fine- to medium-grained layered amphibolite. Quartz in coarse- to medium-grained layers of biotite granitic gneiss often appears to have a bluish color. This bluish color (actually interstitial Ti lattice defects) is characteristic of many of the basement gneisses in North Carolina and Virginia that have not been overprinted by medium grade Paleozoic metamorphism. Amphibolite occurs as lenses and layers that range from 10–50 cm thick. Layering dips gently to the east, and truncates earlier foliations in amphibolite lenses. Late coarse-grained to pegmatitic biotite granitoid dikes truncate metamorphic layering. Multiple generations of folds are present including intrafolial folds, reclined isoclinal folds, and later open folds. At least 8 dark gray to black mafic dikes trending approximately N40°W, dipping steeply (70-90°) SW truncate all structures in the Cranberry Gneiss. These mafic dikes are correlated with the ~735 Ma Bakersville Gabbro (Goldberg et al., 1986) based on their distinctive fine-grained ophititc to sub-ophibitic texture. Dikes range from 10 cm to over 3 m wide. The largest and most interesting is a porphyritic dike that contains randomly oriented plagioclase phenocrysts up 10 cm long. Chilled margins are recognized by a decrease in size and abundance of phenocrysts from the center of the dike to the contact where they are almost absent. Correlation of the mafic dikes with the Bakersville Gabbro suggests that the structures observed in the Cranberry Mine Gneiss at this exposure formed during the Grenville orogeny.

Continue to drive S on U.S. 19-321. Note that the character of weathered rocks in roadcut exposures changes from orange-weathering layered (Cranberry) gneiss to massive, crumbly saprolite as we approach Roan Mountain, TN. Pull off onto Old Rock Quarry Road at entrance to recycling center and park.

STOP 1–6

Beech Granite (~741 Ma) at Roan Mountain, Tennessee, Recycling Center. 36° 12.188′ N, 82° 04.888′ W.

Purpose. Examine the characteristics of the ~741 Ma Beech Granite, the largest pluton of the Crossnore Plutonic Suite.

Description. The Beech Granite is areally the largest pluton of peralkaline granitoids of the Neoproterozoic Crossnore Plutonic Suite (CPS). The Beech Granite is interpreted to have intruded the Watauga River and Cranberry Mines Gneisses, despite the contact frequently being sheared (Bryant and Reed, 1970; Adams and Su, 1996). Su et al. (1994) reported a TIMS U–Pb age of 745 ± 3 Ma for the Beech Granite, and a weighted average of 741 ± 3 Ma for all granitoids of the CPS. This abandoned quarry is located near the southern contact of the Beech Granite. Mylonitic greenish gray Watauga River Gneiss is exposed in roadcuts along U.S. 19-E immediately to the west, and a fresh cut exists on the other side of the valley on Crabtree Road. Light pink, coarse-grained, weakly foliated biotite metagranite is exposed in the quarry. Pink potassium feldspars range from ½ to 3 cm long and may be perthitic. Biotite clots define a SE plunging lineation (orientation ~160) that is pervasive throughout the Beech Granite. Other accessory minerals that occur in the Beech Granite include aegerine–augite, hastingnite/riebeckite, and fluorite (McSween et al., 1991). Adams and Su (1996) suggested that the present shape of the Beech Granite pluton is the result of differential slip on parts of the Beech Mountain thrust sheet, although it equally could be the product of arching of the thrust sheet NW of the Grandfather Mountain window (Fig. 2).

Continue on U.S. 19-321 ~0.7 mi and turn right onto TN 143 toward Roan Mountain.

LUNCH at Roan Mountain State Park or at Stop 1–7, depending on weather.

Continue toward Carvers Gap on TN 143.

STOP 1–7

Carvers Gap Granulite Gneiss (~1.8 Ga) Intruded by Bakersville Gabbro, Near Carvers Gap, NC–TN. 36° 06.772′ N, 82° 06.2270′ W.

Purpose. Oldest rocks in the Appalachian orogen (from Alabama to Newfoundland) intruded by coarse-grained Bakersville Gabbro.

Description. Medium gray, even-grained poorly foliated to Carvers Gap Granulite Gneiss that contains plagioclase, quartz, garnet, and one or two pyroxenes. The absence of hydrous minerals and presence of pyroxene(s) indicate these rocks reached peak granulite facies metamorphim during the Grenville (Gulley, 1985; Ownby et al., 2004). This metamorphic assemblage is present throughout this area (where there is no gabbro), indicating the metamorphism is not related to the intrusions. These rocks contain 1.3, 1.8, 1.9, and 2.7 Ga detrital zircons and have yielded eNd model ages ranging from 1.7–2.0 Ga, suggesting these are the oldest rocks in the Appalachians (Carrigan et al., 2003; Ownby et al., 2004). Gulley (1985) defined the Carvers Gap Granulite Gneiss as including layered granulite gneiss, massive granulite gneiss, layered amphibolite, non-layered amphibolite, and granitoid segregations. These rocks are part of the Mars Hill terrane (Raymond and Johnson, 1994) (Fig. 2), a piece of pre-Grenville crust that was caught up in the collisional event that formed the Grenville mountain chain ~1.1 Ga, and were subsequently incorporated into the Appalachians. The Bakersville Gabbro is a coarse-grained, even-grained, dark gray massive, unfoliated rock. It is composed of bladed tan to gray plagioclase and dark brown to black clinopyroxene.

Continue along TN 143 to Carvers Gap then on NC 262 into North Carolina and to Bakersville (~13 mi). Turn left onto North Mitchell Avenue (County 1211) at stop light in Bakersville, drive ~0.2 mi and turn left onto Redwood Road. Drive ~0.5 mi and pull off onto the right shoulder.

STOP 1–8

Eclogite on Redwood Road. 36° 01.612′ N, 82° 08.871′ W.

Purpose. To examine ~460 Ma Bakersville eclogite, and retrograded eclogite.

Description. Dark greenish gray rocks exposed in the roadcut are eclogite and partially retrograde eclogite. The eclogite is generally massive and contains the assemblage garnet + ophacite + quartz + rutile (Willard and Adams, 1994). Retrograded eclogite marked by presence of coarse-grained hornblende and a weak to well-developed foliation contains the assemblage hornblende + plagioclase (Willard and Adams, 1994). Minimum estimates of peak eclogite facies yielded conditions 625–790 °C, 13–17 kbar, and retrograde conditions of 650-740°C, 8.5–12 kbar (Willard and Adams, 1994; Adams et al., 1995). The surrounding Ashe Formation (Ashe Metamorphic Suite) preserves only amphibolite facies assemblages with peak conditions of 640–700 °C, 7–9 kbar (Willard and Adams, 1994; Adams et al., 1995; Adams and Trupe, 1997). Miller et al. (2000) reported a zircon U–Pb age of ~460 Ma as the time of peak eclogite metamorphism, corresponding to the collision of Laurentia with an island arc that existed in the Iapetus ocean prior to the Taconic orogeny (480–460 Ma). The eclogite was exhumed by the Devonian dextral strike-slip Burnsville fault, post-377 Ma (Trupe et al., 2003). Recognition of the eclogite further constrains the P-T-t path of the Ashe Metamorphic Suite. The rocks were subjected to eclogite facies metamorphism during the Taconic and were retrograded to amphibolite facies during the Acadian (Willard and Adams, 1994; Abbott and Raymond 1997; Adams and Trupe, 1997).

Backtrack to Bakersville and turn left onto North Mitchell Avenue (State Road 1211). Drive 0.1 mi and turn right on Maple Street. Drive another 0.2 mi and turn left on NC 226. Drive 3.7 mi on NC 226 and park on right shoulder.

STOP 1–9

Ashe Formation (Ashe Metamorphic Suite) on Snow Hill, NC 226. 36° 55.738′ N, 82° 10.429′ W.

Purpose. To examine the typical assemblage of metagraywacke, schist, and amphibolite of eastern Blue Ridge Ashe (–Tallulah Falls) Formation (Ashe Metamorphic Suite) of the Spruce Pine–Gossan Lead thrust sheet (Fig. 1-9-1).

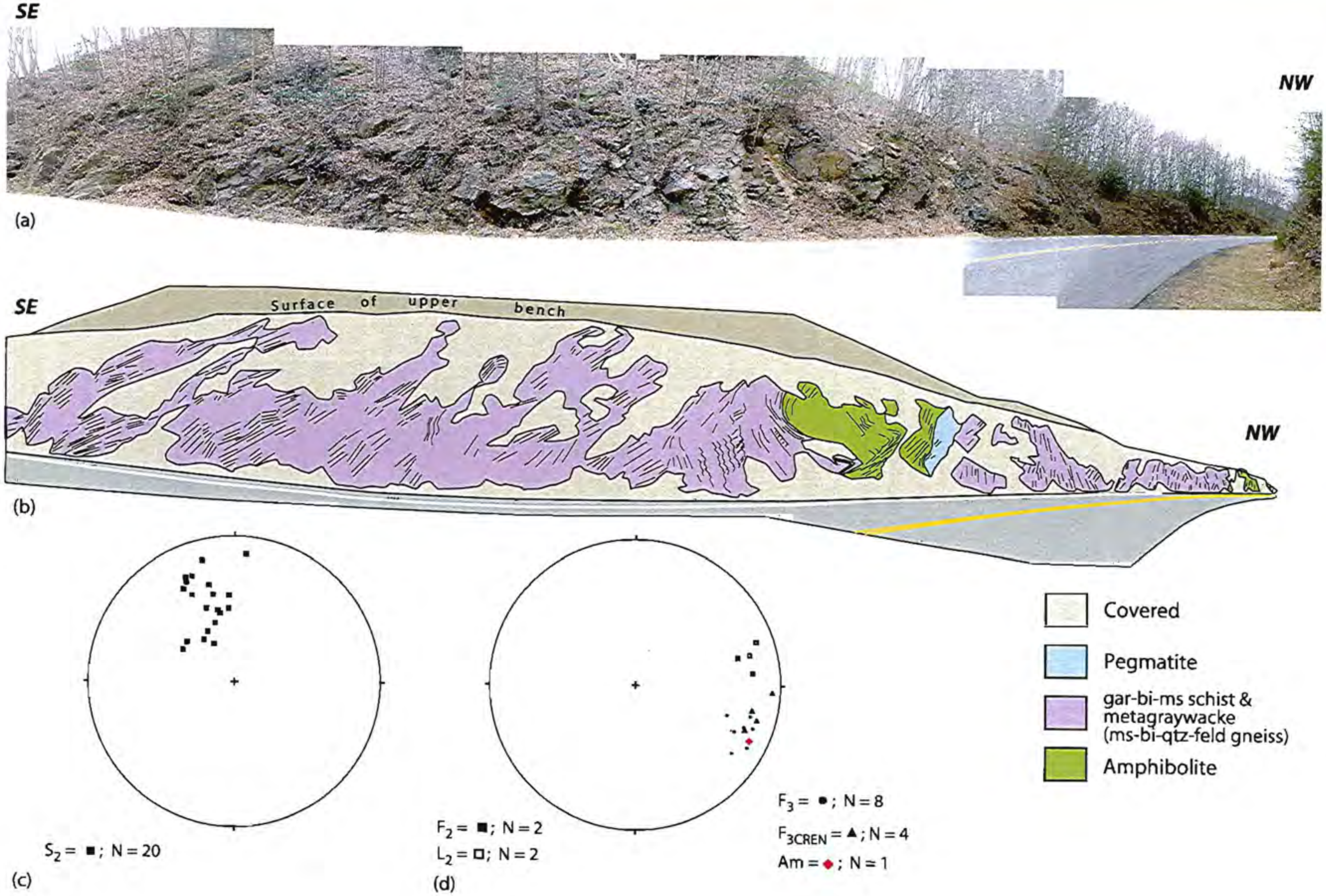


Figure 1-9-1. (a) Outcrop photograph of Stop 1-9 near Snow Hill looking obliquely to the WNW. (b) Simple outcrop sketch from photograph. (c) Equal area stereonet of poles to the dominant S_2 foliation. (c) Equal area stereo net of L_2, F_2 and F_3 fold axes, F_3 crenulation axes, and axis of large amphibolite pod.

Description. This representative exposure of Ashe Formation (Ashe Metamorphic Suite) rocks contains interlayered garnet, two-mica schist, metagraywacke (quartz-feldspar gneiss), amphibolite, and muscovite-bearing pegmatite (Fig. 1–9–1). Schist and metagraywacke dominate the exposure, but are often interlayered at cm-scale making separation of lithologies difficult. Metagraywacke consists of medium- to coarse-grained garnet, muscovite, biotite, feldspar, quartz paragneiss with transposed layering ranging from –10 cm. Schist layers are medium- to coarse-grained, porphyroblastic garnet, muscovite, biotite schist, and are commonly crenulated (Fig. 1–9–2a). Regional studies indicate these rocks are amphibolite facies, kyanite grade (Bulter, 1991; Hatcher and Goldberg, 1991), but aluminum silicate minerals are difficult to find in this roadcut. Both schist and metagraywacke are variably sulfidic and stained a light yellow to reddish brown to black. Amphibolite is very dark gray to black medium-grained ± epidote, plagioclase, hornblende gneiss to ± biotite, hornblende schist. Layering is commonly defined by to 1 cm thick, white to light pistachio green layers of plagioclase, or plagioclase ± epidote, which may be the result of later retrogression, although epidote is stable under middle amphibolite facies conditions (Fig. 1–9–2b). Locally, layers of dark gray to black, epidote-plagioclase-biotite schist that resemble amphibolite occur here, and are probably completely altered amphibolite layers. A ~1 m-thick N75°W-striking, 60°SW-dipping pegmatite sill can be observed in cuts on both sides of the road. The pegmatite is weakly foliated, defined by coarse-grained muscovite, and folded. Accessory minerals in the pegmatite include biotite and sugary garnets. This pegmatite dike is probably one of the Devonian Spruce Pine pegmatites (392 ±2, 361 ±2 Ma; Mapes, 2002; 377.7 ±2.5 Ma; Miller et al., 2006) intruded into the Ashe Formation. Larger pegmatite bodies in the Spruce Pine area are actively mined for high purity quartz, feldspar, muscovite, and other commodities. We will pass several mines en-route to STOP 1–10.

Evidence from this outcrop supports the polydeformed history of the eastern Blue Ridge as recognized by other workers (Hatcher et al., 1979; Abbott and Raymond, 1984; Hopson et al., 1989; Hatcher and Goldberg, 1991). Sulfide and manganese staining make recognition of earlier structures difficult. The dominant foliation defined by transposed compositional layering, and minor stromatic migmatite layers strikes N60-85°E and dips 25-75° SE, generally decreasing from W to E across the exposure (Figs. 1–9–2c and 1–9–2d). Earlier foliations are rare to absent in this roadcut, and comparison with other studies in the eastern Blue Ridge suggests that the dominant foliation is

Figure 1-9-2. (a) Intrafolial isoclinal folds, F_2, in amphibolite at the NW end of the roadcut. (b) Amphibolite with light pistachio green layers of epidote + plagioclase defining S_2. Epidote also fills the nearly E-W joint exposed in the lower left of the picture. (c) S_2 foliation with L_2 defined quartz rods are superposed by later reclined, tight to open F_3 folds. Photograph from outcrop located on south side of Snow Hill. (d) F_3 crenulations in a muscovite schist layer. (e) Contact between amphibolite and muscovite pegmatite. The pegmatite is weakly foliated and F_3 folds in the amphibolite and pegmatite are parallel.

probably S_2. Very steeply inclined to upright isoclinal folds in amphibolite in the western end of the south side of the exposure plunge ~25°, and trend N80°E. Axial surfaces of the folds are parallel to S_2 and interpreted to be F_2 formed during the same event, D_2. Quartz rods define a mineral lineation, L_2 parallel to F_2 folds axes, in protomylonitic rocks along the east end of the outcrop and on the ridge to the south of the roadcut (Figs. 1–9–2c and 1–9–2d). The dominant S_2 foliation is superposed by crenulations in schist and tight-to-open folds occur in metagraywacke and amphibolite. Crenulations and inclined to reclined tight folds plunge 15-25°, and trend S65°E, and are interpreted to be F_3. Rare F_3 folds in the muscovite pegmatite dike suggest D_3 is post intrusion of the pegmatite, 390-360 Ma (Fig. 1–9–2e). The large anvil-shaped structure cored by amphibolite near the center of the south side of the outcrop is possibly a fold, boudin, or a sheath fold. The axis of this structure is parallel to F_3 fold axes and is interpreted to be related to and coeval with coeval with F_3.

Continue on NC 226 past rubbly outcrops of fresh AMS rocks on the right and left sides of the highway at 5.2 mi that include Spruce Pine intrusive rocks. Continue 0.2 mi and turn right (west) on Hwy 19E. Drive 6.3 mi and turn right (north) on NC 80. Continue another 0.45 mi and park on either side of the highway.

STOP 1–10

Newdale Dunite. 35° 54.689′ N, 82° 11.277′ W.

Purpose. To examine a representative of numerous dunite bodies in the eastern Blue Ridge.

Description. The Newdale Dunite is one of the many ultramafic rock masses within the Ashe Formation (Ashe Metamorphic Suite) of the Spruce Pine–Gossan Lead thrust sheet (Tugaloo terrane). These quarries were operated in the dunite during the 1970s and 1980s, but termination of mining operations allowed the main quarry north of the road to fill with water by the late 1980s.

The Newdale Dunite was mapped by Brobst (1962) and Vrona (1979) and discussed by Raymond and Abbott (1997). The body forms an east-northeast-trending, elliptical body surrounded by hornblende schist and gneiss, but it seemingly cuts a body of anthophyllite-plagioclase gneiss enclosed within the hornblende-rich rocks. Although the contact between the dunite and the country rocks is not exposed, there is no evidence of contact metamorphism or intrusion of the body, and Vrona (1979) concluded that the contact was tectonic. He suggested it as a thrust fault. The metadunite does not represent an intrusion. The structural and metamorphic evidence from both the metadunite here and metaultramafic rocks in the surrounding region (Swanson, 2001; Raymond et al., 2003) clearly show these rocks to be structural units tectonically emplaced into and metamorphosed with enclosing Ashe Metamorphic Suite rocks.

The small quarry on the south side of the road contains relatively fresh exposures of the dominant rock of the body, upper amphibolite facies metadunite, as well as related rocks of at least two other metamorphic grades. In the quarry here, the main mass of rock is chromite- and tremolite-bearing metadunite (an upper amphibolite facies assemblage). Metaharzburgite and metachromitite are present in the body (Vrona, 1979), but are not present in this quarry. The metadunite is typically somewhat serpentinized, and is characterized by LPO (Lattice preferred orientation) fabrics. Sparse orthopyroxene is scattered among the dominant olivine grains within the metadunite, just as are the chromite and tremolite. Silvery purple Cr-clinochlore (kammererite) occurs along the margins of some chromite grains.

Near the left roadside entrance to the quarry is a block of rock containing large veins of magnesite-talc-amphibole schist and diablastite (the minerals constitute lower amphibolite facies asssemblages). Typical amphiboles in the dunites of the area are tremolite, anthophyllite, magnesiocummingtonite, and actinolite. Only the latter is distinct in hand specimen, on the basis of its medium green color.

Thin-section analysis reveals mineral associations and textures that suggest at least four successive metamorphic "events" (Table 1–10–1). The oldest olivine + chromite + pyroxene assemblage representing the granulite or eclogite facies is overprinted by an upper amphibolite facies olivine + chromite + tremolite + chlorite + pyroxene assemblage, which in turn is overprinted locally by the lower amphibolite facies, talc + amphibole + magnesite assemblage. These are locally replaced, primarily along veins and grain boundaries, by one or more greenschist facies assemblages composed of serpentine + magnetite + chlorite + talc + tremolite. Along the right and left rear sides of the quarry are veins of serpentinite (representing the greenschist facies assemblages).

Table 1-10-1. Metamorphic Mineral Associations in Newdale Metaultramafic Rocks

Association A-1	Olivine + Chromite + Orthopyroxene
Association A-2	Olivine + Orthopyroxene + Tremolite ± Magnesiocummingtonite + Chlorite + Chromite
Association A-3	Talc ± Anthophyllite ± Magnesiocummingtonite ± Tremolite ± Chlorite ± Phlogopite ± Magnetite + Magnesite
Association A-4	± Serpentine (Antigorite) ± Magnetite ± Chlorite ± Talc

(Modified from Raymond, 1995, Table 31.3; Raymond et al., 2003).

The metadunite does into represent an intrusion. The structural and metamorphic evidence from both the metadunite here and metaultramafic rocks in the surrounding region (Swanson, 2001; Raymond et al., 2003) clearly show these rocks to be structural units tectonically emplaced into and metamorphosed with enclosing Ashe Metamorphic Suite rocks.

Return to Hwy 19E, by driving 0.45 mi south on NC 80. Turn left (east) onto Hwy 19E. Drive 5.3 mi and pull off on right shoulder.

Stop 1–10A (Optional Stop)

Spruce Pine Pegmatite Exposure on U.S. 19E. 35° 54.415□N, 82° 06.033□W.

Purpose. To examine a representative exposure of 390-360 Ma pegmatite of the Spruce Pine Intrusive Suite.

Description. The exposure consists of light tan to white, very coarse-grained biotite-muscovite-quartz-feldspar pegmatite. Feldspar crystals (tan to white) up to 30 cm long and occasionally perthitic occur here. This pegmatite is part of the Chalk Mountain pluton, which is actively being mined (entrance to mine on Chalk Mountain just beyond roadcut) for feldspar, mica, and other commodities. Miller et al. (2006) reported a TIMS U-Pb zircon age of ~377.7 ±2.5 Ma from a granitoid sample from the Chalk Mountain mine. The Spruce Pine Intrusive Suite intrudes rocks of the Ashe Formation. Brobst (1962) mapped numerous small to large plutons, like Chalk Mountain, throughout the Spruce Pine area, and reported coarser-grained schists in the Ashe Formation near the contact of the intrusions. As we continue north on 19-E, several large pegmatite mines will be visible to the north (Fig. 1-10A–1).

Continue east on Hwy 19E. Note the Unimin Schoolhouse Mine and processing plant on the right at 6.8 mi. Pegmatitic granitoid rock is processed here for high purity quartz and other minerals. Continue 1.1 mi and turn

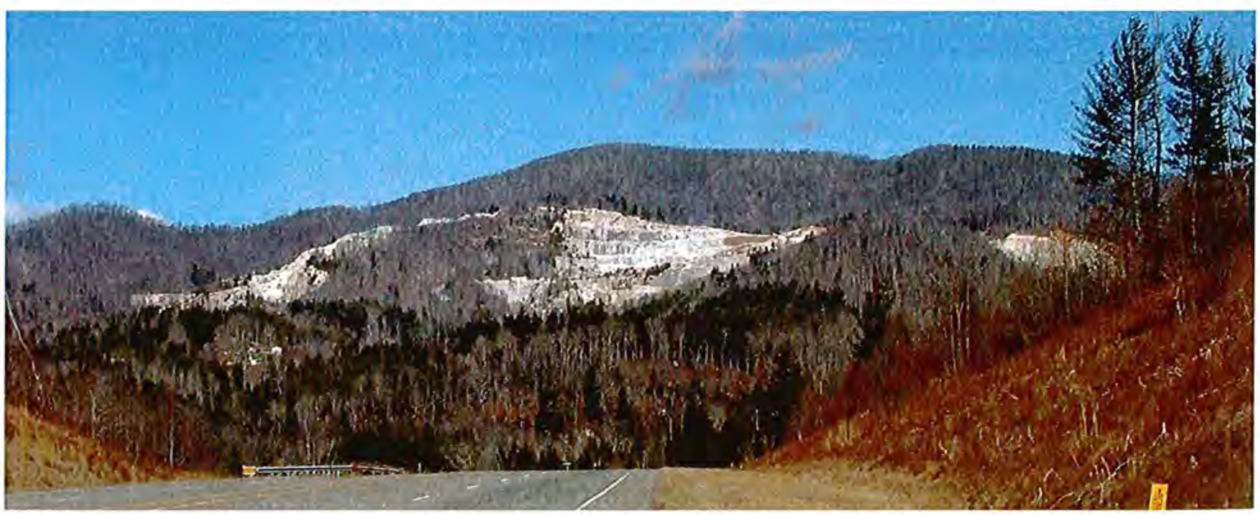


Figure 1-10A-1. Active pegmatite mines visible from the intersection of NC 226 and US 19-E looking N.

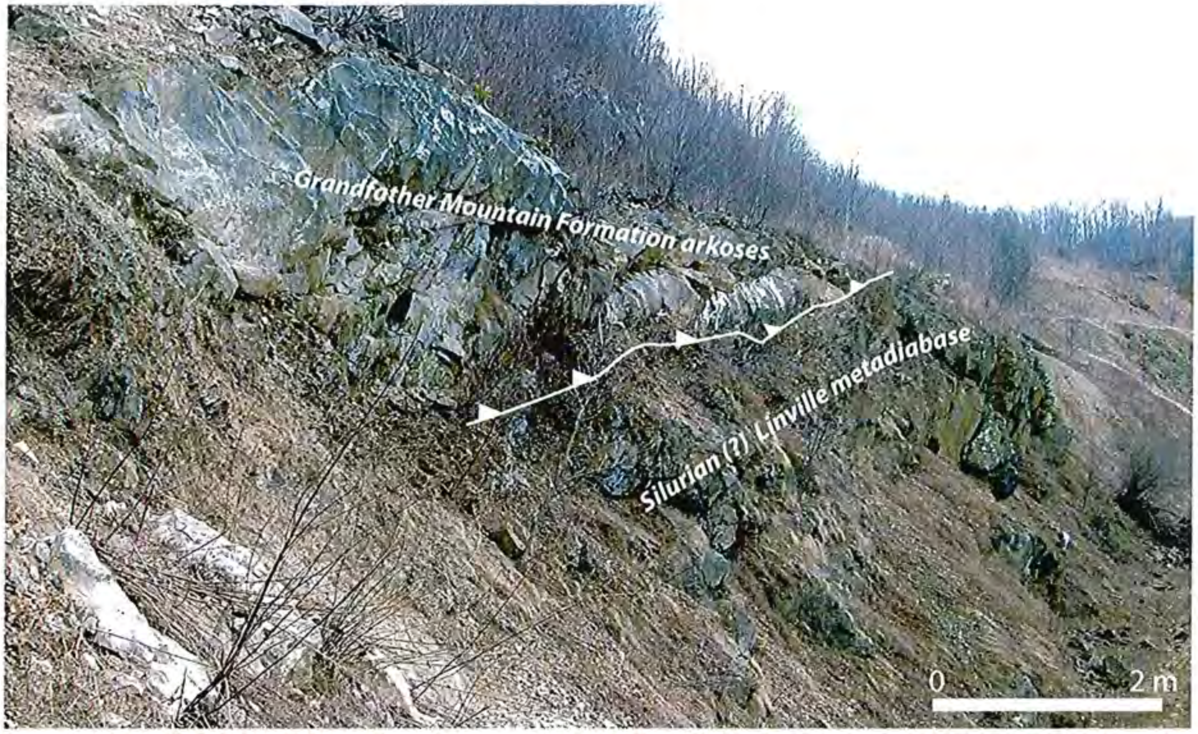


Figure 1-10B-1. Grandfather Mountain Formation arkose and the Silurian(?) Linville Metadiabase. Brittle deformation along the contact suggests it maybe faulted at this outcrop, and interpreted as a gently dipping thrust.

right at Howell's Store on Stater Road 1106, Mullin Hill Road. Drive 0.9 mi and turn right on NC 194 (Three Mile Highway). Drive 3.2 mi and turn left on US 221/NC 194. Continue north on US 221 (NC 194 turns left toward Newland at 4.9 mi) some 4.4 mi to a T intersection. Continue north on US 221 by turning right on US 221/ NC 181after another 0.6 mi. Turn left at stop light in Linville onto NC 105 (leaving US 221). Continue 4.0 mi and turn right at the stop light onto NC 184. Drive 1.0 mi and turn right into the parking lot of the shopping center. Park behind Food Lion.

Stop 1–10B (Optional Stop)

Linville metadiabase behind Food Lion™ in Banner Elk. 36° 7.816′N; 81° 50.815′W.

Purpose. To examine the Linville Metadiabase in contact with Grandfather Mountain Formation Arkose.

Description. The Linville Metadiabase is a Silurian(?) gabbro unit (Fetter and Goldberg, 1993) that intrudes the Grandfather Mountain Formation. Here on the northwest side of Grandfather Mountain, the rock generally retains its original diabasic texture, though some of the minerals are partially to entirely replaced (plagioclase by epidote; augite by Ca-amphibole). To the southeast, the rock is highly deformed into amphibole schists and mylonites.

Two parts of the large exposure at the rear of the parking lot are of interest. On the right rear, high on the outcrop, weathered gabbro includes a faulted slice of flow-banded Grandfather Mountain metarhyolite(?). Grain sizes vary in the metagabbro.

At the far left end of the exposure, medium to coarse-grained metasandstone (meta-quartz arenite and meta-feldspathic arenite) and metagranule conglomerate of the Grandfather Mountain Formation are faulted along a brittle fault—trending horizontally across the middle of the exposure—against the Linville Metadiabase (Fig. 1-10B–1).

Drive 0.3 mi turn left out of parking lot onto NC 184. Continue 1.0 mi and turn left at light onto NC 105.

Figure 1-11-1. Weakly to moderately foliated, S_1 (near vertical), amygdaloidal metabasalt of the Montezuma Member at Camp Broadstone.

Drive 8.0 mi to a traffic light and bridge. Turn left onto NC 194/Broadstone Rd. (State Rd. 1112) towards Valle Crucis. Continue another 1.15 mi and park in the large dirt area to the right (above the Appalachian State University Camp Broadstone playing fields). Across the road is an outcrop (beware of traffic, which travels fast, and note that the shoulder is narrow).

Stop 1–11

Amygdalodial metabasalt of Montezuma Member (Grandfather Mountain Formation) and metasediments of the Grandfather Mountain Formation, near Camp Broadstone. 36° 11.57′N, 81° 45.55′W

Purpose. Examine amygdaloidal metabasalt of the Montezuma Member and its relationship to metasediments of the Grandfather Mountain Formation.

Description. Camp Broadstone locality in the Grandfather Mountain Formation. The exposures here consist of a thick pile of metabasalt (the Montezuma Member, Grandfather Mountain Formation) exposed in the prominent cuts along the road at this stop was approached and a thin section of metasedimentary rocks. The metasedimentary rocks belong to the "upper siltstone" unit (Grandfather Mountain Formation) of Bryant and Reed (1970).

Facing the exposure from the parking area across State Rd. 1112, the rocks on the right are the metasedimentary rocks. A nearly flat-lying, anticlinal section on the right is folded into an overturned, northwest-vergent syncline on the left Fig. 1-11-1). About 4.5 m of metasedimentary section, dominated by green metasiltstone and very fine-grained metasandstone at the top (right), contains cobble to boulder conglomerate/diamictite at its base, designated here the Broadstone Lodge diamictite by Neton and Raymond (1995; also see Raymond et al., 1992). The metaconglomerates contain a variety of clasts, the protoliths of which were rhyolite, granite, basalt, quartz, quartz arenite sandstone, and siltstone. Greenschist facies assemblages of quartz + alkali feldspar + chlorite + white mica + epidote characterize the metasedimentary rocks. Rare copper mineralization (e.g., bornite, malachite) is present at this locality.

At the left end of the exposure facing the parking area, but slightly around the turn, is an overturned contact between metasandstone and metabasalt (PLEASE DO NOT sample the contact area). The overlying sandstone is lithic sandstone with grains apparently derived from the underlying basalt. Basalt pebbles do occur in the overlying metasedimentary rocks.

The Montezuma basalt is locally blasto-amygdaloidal, with locally zoned amygdule fillings of calcite, epidote, quartz, and minor hematite. The metabasalt is characterized by greenschist facies assemblages of plagioclase, actinolite, chlorite, epidote, titanite (sphene), quartz, and opaque minerals (Raymond et al., 1992). Chemically, the metabasalts are alkali olivine, within plate rift basalts (T. Cook, pers. comm., 1992).

In additon to the folds present in the metasedimentary section, a dominant cleavage (S_1) pevades both metasedimentary and metabasaltic rocks. This continuous cleavage has an attitude of N16°E 65°SE.

Return to NC 105 via Broadstone Road, drive 1.15 mi and turn left onto NC 105. Continue straight past the US 421 North/US 321 Truck bypass intersection (on the left). Continue 4.0 mi to High Country Inn, and turn right into High Country Inn parking lot.

End of Day 1.

Day 2

Depart High Country Inn at 8 am.

Exit the parking lot by turning right onto Hwy 105, and drive 0.8 mi. Continue straight through the intersection on 105 that extends up the hill ahead, and drive another 0.8 mi. Turn right on US 421/221/NC 194. Drive 0.6 mi and pass straight through the intersection, where Hwy 194 turns north (left). Folded Mars Hill terrane rocks (Pumpkin Patch Metamorphic Suite) are exposed at 0.3 mi beyond this point. Turn right into Three Forks Baptist Church parking lot in another 0.6 mi, turn across the highway, and park on the grassy shoulder and enter Boone Industrial Park.

STOP 2–1

Pumpkin Patch Metamorphic Suite with metamorphosed Bakersville Dikes and overturned northwest-verging folds. 36° 13.23′N, 81° 38.63′W.

Purpose. To examine some representative rocks of the Pumpkin Patch Metamorphic Suite (Mars Hill terrane), and to observe structures formed in the thin thrust sheet between the Gossan Lead and Fries faults.

Description. Industrial Park outcrop on U.S. 421. Pumpkin Patch Metamorphic Suite, Fries thrust sheet (Mars Hill terrane). The rocks exposed here have been tentatively assigned to the Pumpkin Patch Metamorphic Suite on the basis of their structural position and heterogeneity. No dating of any type, to our knowledge, has been done on the rocks northeast of the Grandfather Mountain window. The rocks were initially mapped as a mixed rock zone by Bryant and Reed (1970). The Fries (thrust) fault, however, recognized by Stose and Stose (1957) in SW Virginia, is thought to underlie this block of rock and separates the Pumpkin Patch Metamorphic Suite from the structurally underlying Cranberry Mines Gneiss, present in exposures near New Market Center, about a km west of this locality. The Gossan Lead fault lies less than a km to the north and east, and separates the rocks exposed here from those of the Ashe Formation (Rankin, 1969).

The rocks at this locality consist of a variety of felsic, mylonitic and migmatitic gneisses, granitoid lenses, and mafic rocks. Some of the felsic rocks are porphyroclastic schists similar to rocks in the Mars Hill terrane exposed southwest of the Grandfather Mountain window. Like the rocks of the Mars Hill terrane west of the window, the rocks in this exposure are invaded by mafic dikes that appear as highly folded amphibolite with a strong greenschist facies metamorphic overprint. These dikes are likely metamorphosed Bakersville Gabbro dikes.

Figure 2-1-1. Rocks of the Pumpkin Patch Metamorphic Suite exposed at the Boone Industrial Park on U.S. 421.

Structurally, the rocks are dominated by a NW-striking, moderately (~35°) NE-dipping foliation that is asymmetrically folded about NW- and NE-plunging fold axes. Asymmetry indicates movement is top-to-the-northwest, consistent with thrusting towards the northwest along the overlying Gossan Lead fault. The fold styles of mesoscopic folds are lithologically controlled, with chevron folds occurring in phyllosilicate-dominated rocks in the axial regions of larger folds and tight flexural-slip folds occurring in more rigid quartzo-feldspathic rock types. A sparsely distributed, northwest-plunging, mineral elongation lineation lies within the foliation.

Return toward the center of Boone on US 421. Move to left lane, and drive 1.6 mi, turn left follow US 221. Move to left lane and continue 0.8 mi. Turn left onto US 321/221 toward Blowing Rock, NC, and drive 1.9 mi, then pull off and park near intersection of US 321 and Payne Branch Road on the right of the highway. Carefully cross the highway--beware of high-speed traffic!

STOP 2–2

Grandfather Mountain Formation across from Payne Branch Road. 36° 11.173′N, 81° 39.160′W.

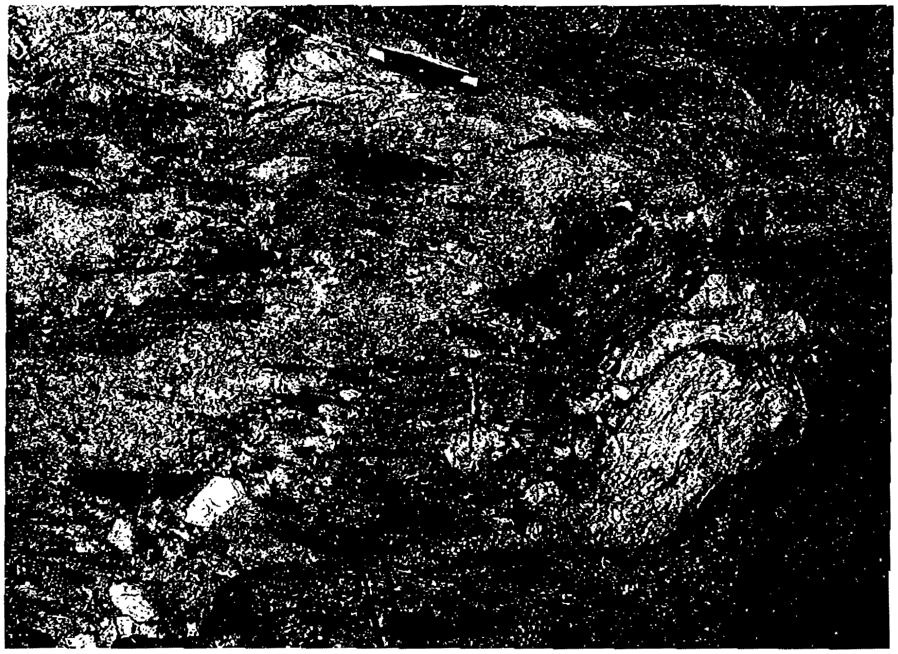
Purpose. To examine primary and tectonic structures in a representative exposure of arkose member of Grandfather Mountain Formation that forms all of the high ridges, including Grandfather Mountain, inside the window.

Description. The excellent exposure of Grandfather Mountain Formation rocks here contains metamorphosed conglomerate, feldspathic arenite, wacke, and siltstone, folded into a broad, gentle outcrop scale (mesoscopic) anticline (Fig. 2-2-1a). Excellent bedding is present forming an S0 fabric element. The rocks are lower greenschist facies grade and contain a diffuse foliation (S_1) imparted by phyllosilicate minerals (white mica and chlorite) (Fig. 2-2-2).

The sedimentology of these rocks was described by Raymond et al. (1992). Michael Neton measured the section (Fig. 2-2-3), and Raymond et al. (1992) described several coarsening-up sequences characteristic of fluvial deposition on prograding alluvial fans.

The section is right-side-up as indicated by a number of sedimentological features including graded bedding, cryptic trough cross strata, and load structures. Four metaconglomerates of the Poplar Grove type are interbedded

Figure 2-2-1. Payne Branch outcrop looking towards the WNW. Bedding, S_0 dips moderately NW, steeper than the subhorizontal S_1 foliation indicating the section is overturned. This is consistent with primary sedimentary structures (see description) that indicate the section here is overturned.



(a)

(b)

Figure 2–2–2. (a) Deformed polymictic conglomerate in the arkose member of the Grandfather Mountain Formation. Pebbles are composed of quartz, rhyolite, shale (now slate), granitoid, and other rock types. Knife is 8.5 cm long. (b) Contact between conglomerate and green siltstone that contains a few pebbles (not in field of view). Quartz veins may be the result of pressure dissolution of quartz in the siltstone and redeposition at sites of decreased pressure.

here with metasandstones (Fig. 2–2–1b). Both clast- and matrix-supported conglomerates are present and grading is both normal and reversed. A bimodal (basalt-rhyolite) suite of volcanic clasts dominates the lower conglomerates, whereas a suite of quartz + granite + gneiss clasts dominates the upper conglomerates. Within the Grandfather Mountain Formation, metaconglomerate beds are typically 2 to 7 m thick, but thinner and thicker beds occur locally. At the Payne Branch locality, some conglomerate layers are less than a m thick. Metasandstones tend to be fine- to coarse-grained and pebbly. Metawackes are decidedly less abundant than meta-arenites and occur primarily in the upper part of the section. Metasandstone beds typically are 5 cm to 80 cm thick. The metamudrock beds stand out from the other beds, because of their dark green color. Close examination reveals that the protoliths were predominantly siltstones rather than finer-grained rocks. The metasiltstones commonly are finely laminated and are locally pebbly.

One of the most striking features of the Payne Branch outcrop is the occurrence of white, en echelon, foliation-parallel quartz veins in the metasiltstone beds. Crosscutting quartz veins also cut the rocks. The data suggest that quartz veins formed over a period of time and are sytectonic to post-tectonic. En echelon veins are syntectonic. One of us (Raymond), hypothesizes that fluid flow during metamorphism was relatively uninhibited in the metasandstones and metaconglomerates, but was blocked by the metasiltstones. Fluid pressures may have increased to the point that the metasiltstones were hydrofractured at the same time that folding or bedding parallel shear was occurring, which then allowed fluids to pass into the fractured metasiltstone beds, where quartz was deposited in the relatively lower pressure fractures, forming the veins.

Of note here, for comparison with the structures in rocks at later stops, are structures that indicate primary bedding. These include interbedded lithologic units and the sedimentary structures mentioned above. Note that there is a significant angle between the bedding (S_0) and the foliation (S_1) at this locality.

Continue S 0.6 mi toward Blowing Rock on U.S. 321 and pull off at roadcut on right.

STOP 2–2A (Optional)

Blowing Rock Gneiss (~1.1 Ga) inside the Grandfather Mountain Window. 36° 10.80′ N, 81° 38.85′ W.

Purpose. To examine a representative exposure of one of two 1.1 Ga old units inside the Grandfather Mountain window.

Description. The Blowing Rock Gneiss is one of the two Mesoproterozoic basement units within the Grandfather Mountain Window (Bryant and Reed, 1970). Outcrops of this unit are characterized by a distinctive spotted appearance created by large white porphyroclasts of alkali feldspar in a dark greenish-black matrix of green biotite and chlorite. In some exposures, thin leucocratic dikes of trondhjemite appear as light gray bands that are subparallel to the dominant foliation. Locally, these and the gneiss are cut at high angles by mafic (gabbbroic to basaltic) and locally pegmatitic granitoid dikes. This is the locality from which Carrigan et al. (2003) reported an ion microprobe U-Pb zircon age of 1081 ± 14 Ma for the Blowing Rock Gneiss.

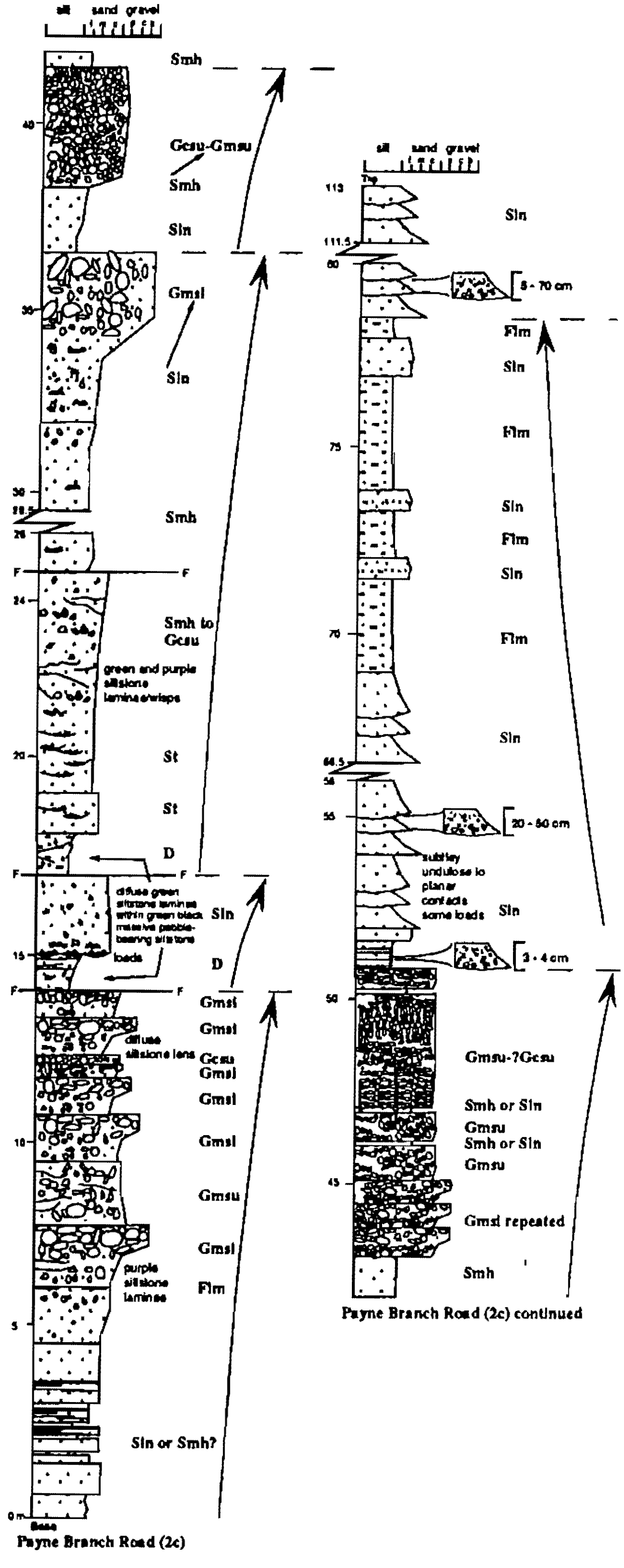


Figure 2-2-3. Measured stratigraphic section of the Payne Branch outcrop from Neton (1992). Several coarsening-upward sequences were recognized by Neton (1992).

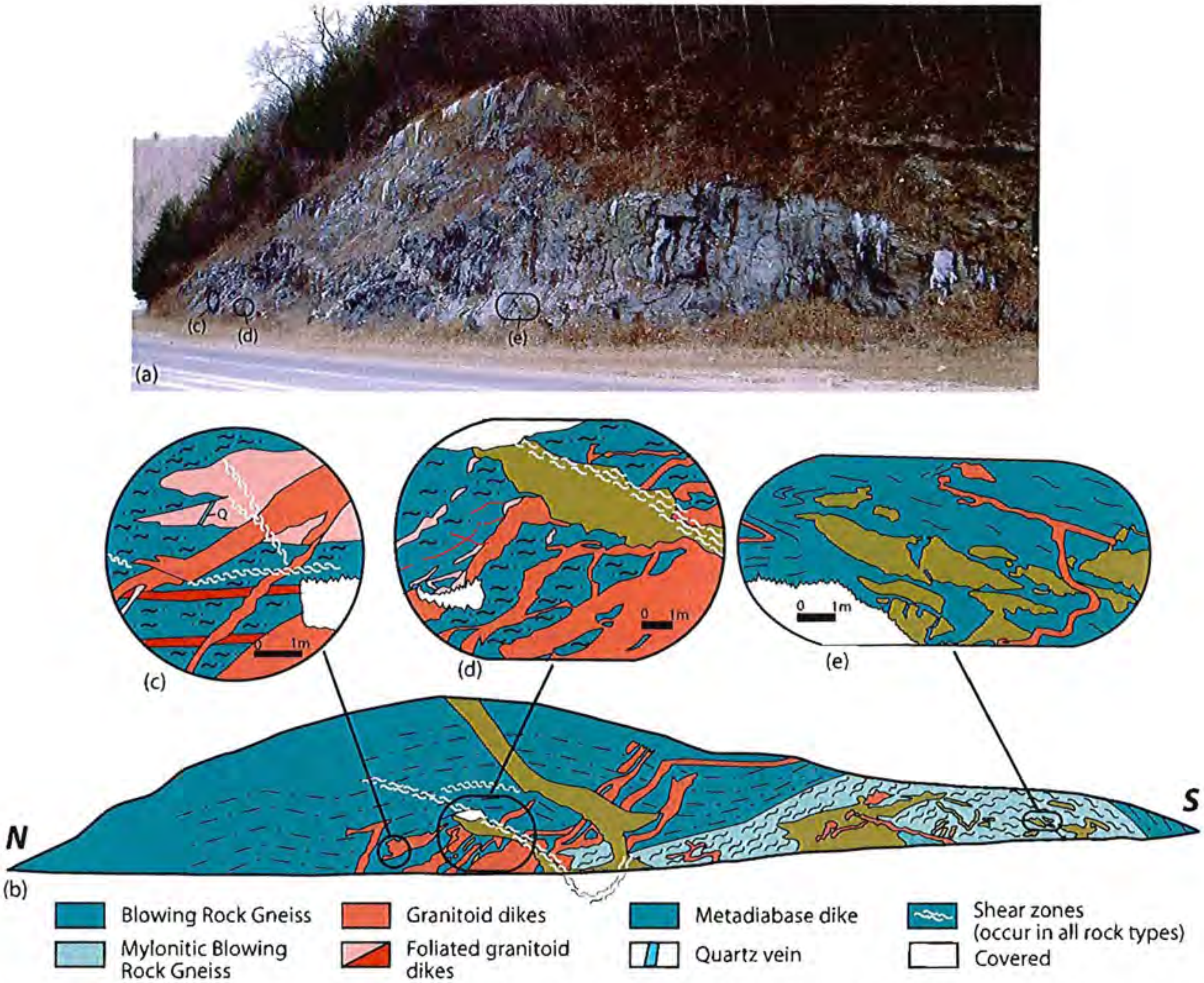


Figure 2-3-1. (a) Photograph of the "Tweetsie Outcrop" looking obliquely to the NW. approximate locations of detailed drawings(c,d,e) are indicated (b) Outcrop sketch of the exposure drawn from a different perspective than shown in (a). The scale is variable because of the curvature of the outcrop along the road. The Blowing Rock Gneiss is intruded by multiple granitoid and metabasite dikes, and cut by several shear zones. (c) Detailed sketch showing Blowing Rock Gneiss cut by older foliated dikes, which are then cut by younger granitoid dikes. Late ductile shear zone cross all rocks. (d) Detailed sketch showing metabasite dike cutting granitoid dikes. (e) Sketch showing fragmentation and ductile deformation, including folding of metabasite dike.

Continue S of U.S. 321 1.0 mi toward Blowing Rock. Turn left into gravel parking lot at intersection of U.S. 321 and entrance to Tweetsie Railroad.

STOP 2–3

"Tweetsie Outcrop" Complexly deformed ~1.1 Ga Blowing Rock Gneiss intruded by felsic and mafic dikes. 36° 10.072′N, 81° 38.802′W.

Purpose. To examine a complex exposure of one of two 1.1 Ga-old units inside the Grandfather Mountain window.

Description. Blowing Rock Gneiss, dikes, and ductile shear zone. This outcrop contains a wide range of features common to exposures of Blowing Rock Gneiss (Fig. 2-3-1). Typical gneiss provides a screen for trondhjemite dikes and younger mafic and felsic (granitoid) dikes (Fig. 2-3-2). These, in turn, are cut or deformed in the lower, central part of the exposure by a ductile shear zone that extends to the base of the outcrop. Some dikes are fragmented, whereas others are boudinaged parallel to the new mylonitic foliation. At several places in the outcrop, it is possible to observe a 15-cm zone over which the (spotted) porphyroclastic Blowing Rock Gneiss is transformed to gray, thinly banded ultramylonite. The mylonite displays tight to isoclinal folds, the axial surfaces of which generally are parallel to subparallel to the mylonitic foliation. Late granitoid dikes cut, but are locally deformed, along mylonitic foliation surfaces. The rocks of this outcrop, including the folded mylonites, are refolded by broad, gentle folds with wavelengths of tens of m.

Continue south 2.2 mi on Hwy 321. Turn right onto the access road to the Blue Ridge Parkway (BRP) and drive 0.2 mi (do not turn left off of this road at the first intersection [with Flat Top Road], but continue to the T intersection with the BRP). Turn left onto the BRP and stop at Price Park for restroom facilities. Pull back onto the BRP and continue S 4.7 mi crossing a dam and passing Price Lake. Drive 6.6 mi and turn right into the Rough Ridge parking area and park.

Figure 2–3–2. Zoned pegmatite in coarse Blowing Rock Gneiss at Stop 2–3.

Fig. 2-4-1. Rough Ridge outcrop of the Grandfather Mountain Formation along the Blue Ridge Parkway. Layers dipping down to the right are DDDZ pseudobeds (S_2), cut by DMFZ (S_3) fault zones, also dipping down to the right and marked by vegetation. Anthony Love (1.3 m) provides scale.

STOP 2-4

Pseudo-cross bedding in the Grandfather Mtn. Formation at Rough Ridge. 36°5.875□ N; 81°41.812□W (Rough Ridge parking area); 36° 05.076□N, 81° 48.127□W (exposure).

Purpose. To observe Grandfather Mountain Formation diffuse deformation zones, pseudobedding, pseudo-cross bedding, and mylonitic fault zones. No Hammers! This is a national park. Walk south along the Parkway to the large layered outcrop at the base of Rough Ridge (Shiprock) (Fig. 2-4-1).

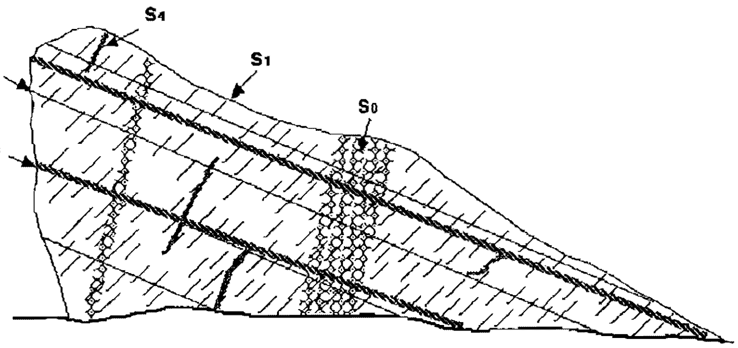


Fig. 2-4-2. Schematic representation of S-surfaces in the Grandfather Mountain Formation. Note that angular relationships are not necessarily drawn accurately: Rather the figure is stylized to clearly depict S_0 to S_4 as cross-cutting features (modified from Raymond and Love, 2006, in press).

Description. The Grandfather Mountain Formation at this locality displays diffuse ductile deformation zones (DDDZs) that have the appearance of metamorposed sedimentary beds of quartz-rich metasandstone (Raymond and Love, 2006). Internally, the foliated layers (pseudobeds with layers = S_2) are deformed by crystal-plastic deformation and the - to -m layers are bounded by surfaces of ductile shear that create pseudo-cross bedding. S_0 has apparently been transposed to some degree and S_1 is largely replaced by the more strongly defined S_2 foliation. Careful examination of the exposures will reveal opposing false facing directions (pointing up and down) within less than a meter of one another (Fig. 2-4-2).

S_2 (DDDZs) occur in three forms that may be mixed within a single exposure. Type 1 DDDZs are - to -m thick, foliated layers well developed at this locality. Type 2 DDDZs are thinly pseudolaminated packets of layers that have the appearance of laminated sandstone-mudrock couplets. Some poorly developed Type 2 DDDZs are present in this exposure. Type 3 DDDZs are thicker zones dominated by light green to green epidosite or epidote metaquartzite layers and boudins within a dark green phyllosilicate-rich, mylonitic, matrix. Local zones of type 2 DDDZs typically occur within the areas dominated by Type 3 DDDZs. Folds are common within the layers and boudins of the Type 3 DDDZs.

The pseudobeds are cut, in turn, by S_3 discrete mylonitic fault zones (DMFZs) (mylonitic thrust faults) that look superficially like metashale interbeds. Vegetation grows preferentially along these S_3 zones, five of which are present in the Parkway exposure. On the nearby, south-facing cliffs of Shiprock, truncated partial folds and isoclinal folds are associated with these and two additional DMFZ thrust faults. All indicators in these zones (folds, sigmoidal porphyroclasts; simoidal shear zones) indicate movement was top to the NW (toward the crest of Grandfather Mountain).

Continue S 2.6 mi on the BRP and turn right on the BRP exit ramp, then drive 0.2 mi and turn left onto US 221 (north). Drive 5.0 mi and pull into the gravel area on the right. This exposure is a favorite rock climbing locality well known to local climbers. Cross the road and climb the steep trail with crude rock steps and follow the trail to the base of the cliff.

Figure 2-5-1. (a) Epidote metaquartzite boudins cut by both deformed and undeformed quartz veins. (b) S_2 DDDZ cut by S_3 DMFZ with deformed quartz veins (Q). Note the irregular weather pattern in the metasandstone layers, and the occasional lithic clasts (c). Just above the S_3 DMFZ is an elliptical shaped quartz vein (possible sheath fold ?).

STOP 2-5

Grandfather Mountain Formation at “”Morphin-Endorphin” rock. 36°5.805′ N; 81°46.631′ W.

Purpose. To examine additional ductile deformation zones in Grandfather Mountain Formation sandstone.

The Grandfather Mountain Formation here displays a Type 3 DDDZ that is cut by DMFZs. Epidote metaquartzite boudins, local folding, and zones of Type 2 DDDZs attest to the deformation of the metasedimentary rocks at this locality (Fig. 2–5–1). DMFZs are best displayed in the exposure around the “corner” of the outcrop first encountered. Here, these thin (<10 cm-wide) mylonitic fault zones cut the S_2 fabric of Type 2 and Type 3 of the DDDZ. Sheath fold-like deformed quartz veins are present locally, as are zones of Type 2 layering.

Quartz veins reveal an S_4 fabric—a widely spaced cleavage typically filled with quartz. Quartz veins cutting boudins are locally truncated at the margins of the boudins or have sigmoidal bends where the veins pass from boudins into the adjoining phyllosilicate-rich matrix, indicating syntectonic vein formation. Some veins, however, cut all earlier structures, suggesting a history of diachronous vein formation spanning the times of S_2, S_3, and late-stage, brittle deformation.

The evidence provided by these and other nearby outcrops suggests a defomational history that began with the development of the diffuse S_1 foliation that cuts bedding, S_0. Apparently, over time, deformation was partitioned into increasingly discrete zones, from S_2 to S_3 deformation zones. Work hardening may have led to local brittle failure and the resulting quartz veins (Fig. 2–5–2).

Return to the vehicles, turn around, and backtrack 5.0 mi S on US 221 to the BRP, drive 0.2 mi and Turn right onto Blue Ridge Parkway (south). Continue ~6.0 mi, cross NC 181 and continue another 4.0 mi and turn left toward the Linville Falls parking area. Chilhowee sandstone is exposed in cuts along the 1.4 mi to the Linville Falls parking area.

STOP 2–6

Linville Falls Fault at Linville Falls. 35° 57.290′ N, 81° 55.679′ W.

NOTE: *This stop lies within the Blue Ridge Parkway National Park. Consequently, collecting of samples and breaking of rocks is prohibited. The actual fault exposure is about 100 yd (90 m) above the falls at the end of the trail from the parking lot and is in the area indicated by a sign to stay back of the sign (upstream). We should follow their instructions by staying behind the sign, but, seriously, please walk very carefully on the rocks and flood debris, because the rocks can be very slippery and the flood debris provides unstable footing.*

Purpose. To examine the best exposure of Linville Falls fault that frames the Grandfather Mountain window.

Description. The Grandfather Mountain window is the largest window in the Blue Ridge (Fig. 2). It is framed by the Linville Falls fault that separates medium-grade metamorphic basement and younger rocks of the Blue Ridge thrust sheet(s) from the lower grade (chlorite–biotite) metamorphic rocks of the window. An intermediate thrust sheet, the Table Rock sheet, occurs in the southwest side of the window (Fig. 3). It contains rocks of the Erwin Quartzite (Chilhowee Group) overlain by the Shady Dolomite (Bryant and Reed, 1970). Rocks of the Table Rock thrust sheet were isoclinally folded prior to being emplaced and the sequence is locally overturned near Woodlawn, a few miles south of Linville Falls. The Linville Falls fault lies immediately above the Table Rock thrust sheet and crenulation folds with NE–SW orientations overprint both the schistose layers in the Chilhowee Group rocks that we walk on here, and the fault zone inside the window, and the hanging-wall rocks, indicating post-thrusting development of the crenulations (Fig. 2–6–1).

The rocks beneath the trail until the short steeper descent to the area above the falls belong to the Crossnore plutonic suite of the Linville Falls–Beech Mountain thrust sheet (Trupe, 1997). Upper Chilhowee (Erwin Formation) sandstone appears just above the riverbed so the fault is crossed just above the river. Enjoy the scenery for a couple of minutes, then walk past the warning sign about dangerous rapids, etc., climb over the low wall, and carefully walk upstream to the overhang to the left of the smaller upper falls. The Linville Falls fault is exposed here, and consists of a 60 cm-thick fault zone with highly deformed Crossnore plutonic suite above (literally the hanging wall) and Chilhowee sandstone (literally the footwall) below. On cursory examination, the sandstones appear to be only slightly deformed. Further examination, however, reveals they were polyphase-deformed and isoclinally folded prior to faulting and emplacement of later structures. An intersecting set (at 90°) of linear struc-

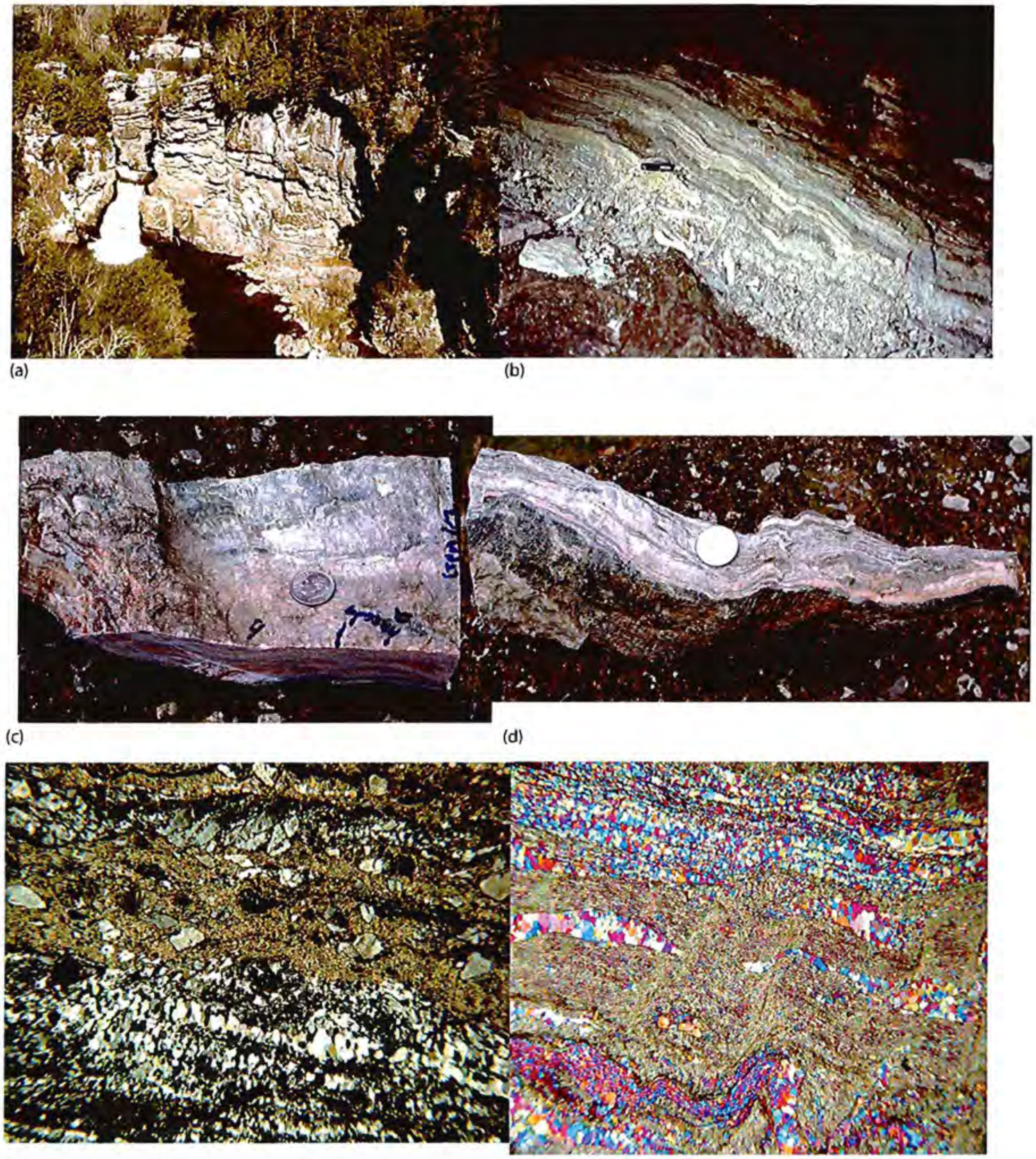


Figure 2–6–1. (a) Linville Falls. Note the convergence of layering toward the falls in the Chilhowee Group sandstone. The convergence and smaller parasitic folds define a recumbent antiform with its hinge at the main falls. This antiform trends NW, suggesting it could be the W limb of a NW-vergent sheath fold developed parallel to transport on the Linville Falls and Tablerock thrust sheets. The Linville Falls fault is located to the left of the small falls in the upper left part of the photo. (b) Linville Falls fault exposed above the main falls and immediately below the smaller upper falls. A ~40 cm-thick mylonite zone separates the upper Chilhowee Group (Erwin) sandstone in the footwall (Table Rock thrust sheet) from the orthogneiss mylonite of the hanging wall. Note the crenulations that overprint the fault zone. (c) Hand specimen of mylonite from just above the fault zone shown in (b). Note the mineral stretching lineation oriented left-right in the photo overprinted at a right angle by crenulation cleavage. (d) Same hand specimen as in (c) tilted to show the lithology and structure of the specimen along the surface cut parallel to the mineral stretching lineation and the orientation of the two photomicrographs in (e) and (f). Crenulations are prominently displayed on the bottom of the specimen. Pink layers are feldspar rich (both K-spar and plagioclase are present); white layers are dominantly quartz rich, but contain some feldspar. Darker layers are chlorite and sericite rich. (e) Photomicrograph of mylonite sample cut parallel to mineral stretching lineation. Grains in annealed quartz ribbons are flattened parallel to the axial surfaces of crenulations, suggesting the crenulations formed shortly after the quartz ribbons while the rocks were still hot enough to not record additional unrecovered strain. Feldspar porphyroclasts exhibit brittle deformation, and that together with the prograde mineral assemblage (sericite + chlorite + magnetite), suggest the temperature during both deformational events recorded here remained above 300° C. Width of field is ~4 mm; X-nicols. (e) Another field in the same thin section showing more strongly crenulated micas and quartz ribbons, along with a possible pressure-solution selvage at the boundary between the mica-rich area and the composite quartz ribbon layer in the lower left-hand part of the photo. Width of field is ~10 mm; X-nicols. Gypsum plate again reveals the lack of unrecovered strain in the otherwise annealed quartz grains.

tures is present at the overlook area above Linville Falls. The mineral lineation is parallel to the fold hinges observed in the walls of the gorge; the other is a crenulation cleavage.

Return to the main trail intersection, turn left, and walk another 0.25 mi to an overlook and view upstream of Linville Falls. Can you see the large folds in the sandstone that occur in the walls of the cliff to the right of the falls? Both the large fold and the parasitic folds trend N45°W, suggesting that these folds could be part of the W limb of a NW-vergent sheath fold in the Tablerock thrust sheet. Bryant and Reed (1969) interpreted the northwest trending lineation mentioned above as a cataclastic lineation parallel to the transport direction of the major thrust sheets, and they recognized that many of the small fold axes also parallel the lineation. They interpreted this lineation as a result of rotation of fold axes into a direction of transport during thrusting. We recognize that this rotation process generally accompanies the formation of sheath folds.

LUNCH at Linville Falls

End of field trip. Go to next exit (Temple Road), turn around, and backtrack to Knoxville.

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Lower Pennsylvanian siliciclastics of the northern Cumberland Plateau: Depositional environments and biogenic structures of the Fentress Formation and Rockcastle Conglomerate

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Introduction

The Cumberland Plateau is underlain by resistant Pennsylvanian sandstones that are separated from underlying Mississippian limestones by the transitional Pennington Formation. On the northern Cumberland Plateau (e.g., north of I-40), shale, siltstone, and fine-grained sandstone of the Fentress Formation crop out sparsely just under the plateau rim; quartz-rich sandstones with subordinate shale and coal comprise the sheet-like Rockcastle Conglomerate that holds up the western part of the northern Cumberland Plateau.

On this trip we will examine rocks at two outcrops on the western edge of the northern Cumberland Plateau (Fig. 1).

Stop A. Small flagstone quarry 10 miles NW of Jamestown, Tennessee operated by Thomas Broyles. Rock here is primarily thin-bedded, fine-grained sandstone that is rich in trace fossils and makes up one facies of the Fentress Formation in the region; the transition to the overlying Rockcastle Conglomerate also is exposed. The quarry is located about 110 miles northwest of Knoxville.

Stop B. Rockcastle Conglomerate on the edge of the plateau exposed in the Twin Arches in the Big South Fork National Recreation area. Twin Arches are about 15 miles ENE of the Broyles Quarry, 39 miles by road.

Why these outcrops? The change from fossiliferous Mississippian marine limestones to coal-bearing siliciclastics clearly records a change from marine-dominated to terrestrial-dominated depositional environments and processes. How did this change occur, what environments were extant along the marine margin, and what was the nature of the transitions between facies? Stop A allows examination of an unusual facies composed of laterally continuous beds of upward-fining sandstone capped by clay drapes. A remarkable diversity of bedding-plane trace fossils allows reconstruction of salinity conditions in spite of the total absence of body fossils.

Sheet sandstones of the Rockcastle Conglomerate were, by analogy with correlative sandstones of the southern Cumberland Plateau, inferred to be marine in origin (e.g., Milici et al., 1974) but were subsequently interpreted as braided stream deposits (e.g., Jackson, 1984; Miller, 1984). Outcrops of the Rockcastle Conglomerate at these two stops afford an excellent oppor-

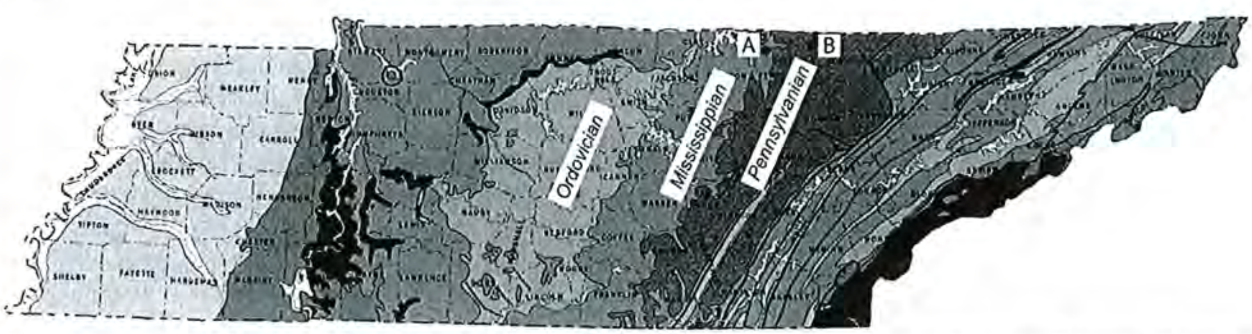

Figure 1. Locations of outcrops (A and B) to be visited on this trip superimposed on geologic map of Tennessee (Tennessee Division of Geology, http://www.state.tn.us/environment/tdg/smmap.php)