PALEOZOIC STRUCTURE, METAMORPHISM, AND TECTONICS OF THE BLUE RIDGE OF WESTERN NORTH CAROLINA

EDITORS:

KEVIN G. STEWART
MARK G. ADAMS
CHARLES H. TRUPE

CAROLINA GEOLOGICAL SOCIETY
1997 FIELD TRIP AND ANNUAL MEETING

Trip Leaders: Kevin Stewart, Mark Adams,
Chuck Trupe, Rick Abbott, and Loren Raymond

Banner Elk, North Carolina
September 26-28, 1997

CAROLINA GEOLOGICAL SOCIETY
1997 FIELD TRIP GUIDEBOOK

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Edited by:

Kevin G. Stewart
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

Mark G. Adams
Department of Geology
Appalachian State University
Boone, NC 28608

Charles H. Trupe
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

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FOREWORD AND ACKNOWLEDGEMENTS

The Blue Ridge of western North Carolina has served as a classic field area for the study of the tectonics of crystalline rocks. Beginning with Arthur Keith at the turn of the century, the work of innumerable Blue Ridge field geologists has provided the sound base upon which we now build our research. Certainly one of the greatest contributors was J. Robert Butler from the University of North Carolina at Chapel Hill.

The papers in the guidebook cover various aspects of the structural and metamorphic history of the Blue Ridge thrust complex. In addition we have provided a detailed roadlog to accompany the field trip stop descriptions. We hope this additional information will provide participants with an understanding of the geology <u>between</u> field stops.

We thank the authors of the papers included in the guidebook. We should note that the first two papers (Stewart et al. and Adams and Trupe) are syntheses of previously published data and did not undergo peer review. The remaining papers were reviewed and we thank the reviewers for their careful work.

We are grateful to the sponsors of the 1997 CGS meeting. As of the time of this writing, we have received generous donations from Vulcan Materials, Olson Enterprises, Turner Environmental Consultants, and Appalachian Resources. The generosity of our sponsors allowed us to keep the registration costs down.

We also thank the student assistants who provided invaluable help in many phases of the meeting: Lauren Hewitt, Shelly Kitchens, Caleb Pollock, and Cheryl Waters. We are especially indebted to Jane Gue who handled all of the registration.

Dedication to the memory of

J. Robert Butler

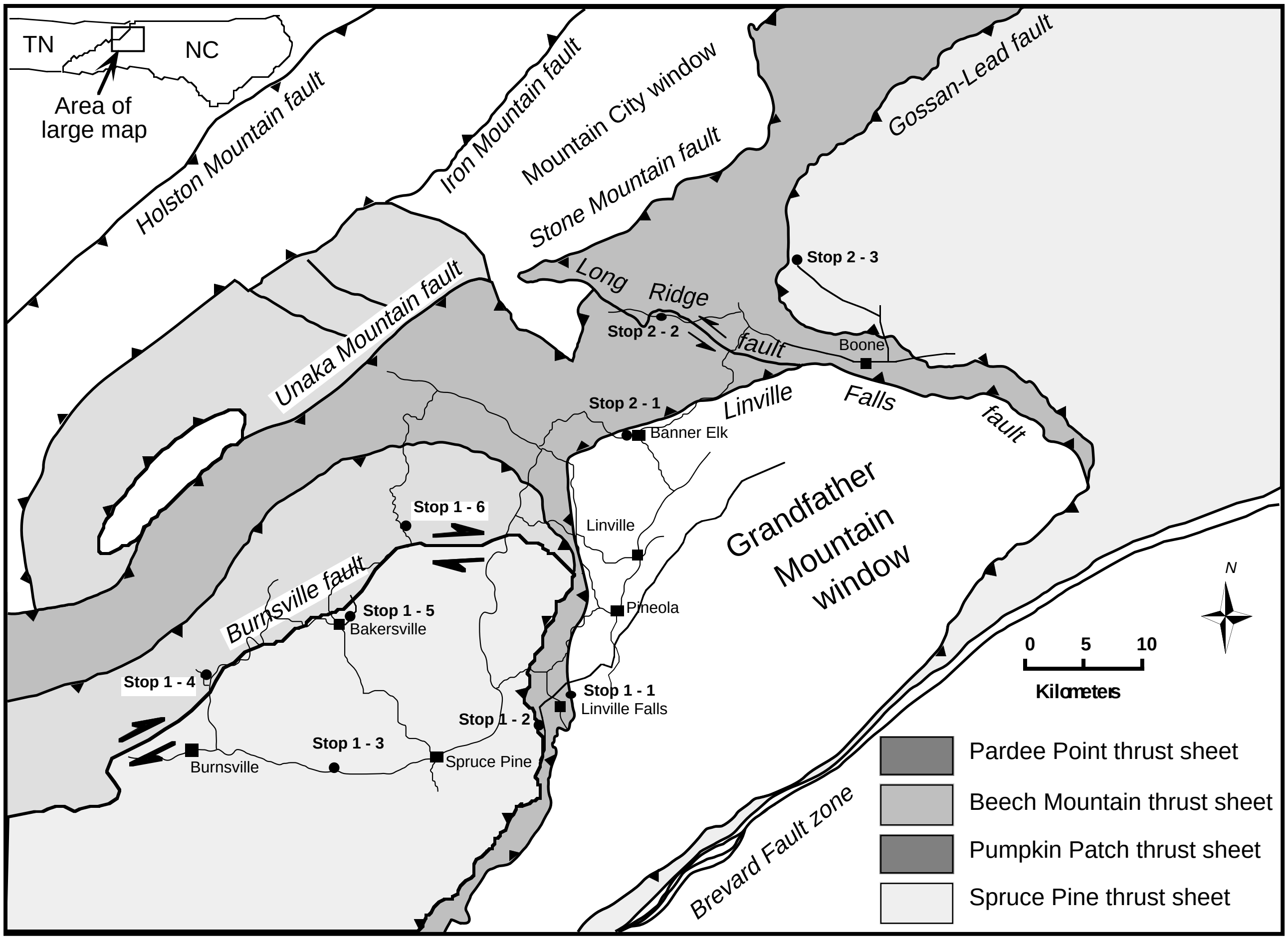
We dedicate the 1997 Carolina Geological Society Guidebook to the memory of J. Robert Butler. Bob Butler was a geology professor at the University of North Carolina at Chapel Hill for over thirty years and was well known for his work on the geology of the Carolinas. Bob’s passion for field geology was unmatched and he was a regular participant and trip leader at past Carolina Geological Society meetings. Our own interest in the geology of the Blue Ridge can be almost entirely attributed to Bob. His wealth of ideas, encyclopedic knowledge of Carolina geology, and readiness to head into the field made Bob a perfect colleague and mentor. Many of the ideas in this guidebook originated during conversations and field trips with Bob Butler. Bob’s influence is especially evident when one considers how many of his former students have continued to work in the Blue Ridge and on geologic problems throughout the Carolinas. We believe it is only fitting that we dedicate this book to his memory.

Kevin Stewart, Mark Adams, and Chuck Trupe

Bob Butler and his Blue Ridge "Bullys". Pictured from left to right: Mark Adams, Rod Willard, Chuck Trupe, Bob Butler. Not pictured: Kevin Stewart. Photo taken during SEGSA Field Trip, Banner Elk, NC, March 21, 1992.

CAROLINA GEOLOGICAL SOCIETY
1997 FIELD TRIP AND ANNUAL MEETING

ROAD LOG AND STOP DESCRIPTIONS



Generalized tectonic map of the Blue Ridge thrust complex showing locations and numbers of field trip stops.

INTRODUCTION

This field trip will focus on the structural and metamorphic history of the Blue Ridge thrust complex in the vicinity of the Grandfather Mountain window in northwestern North Carolina. The Blue Ridge thrust complex is defined as the sequence of thrust sheets overlying the Grandfather Mountain window west of the Brevard zone. At least four thrust sheets have been recognized in the complex. These thrust sheets include, from structurally lowest to highest, the Pardee Point, the Beech Mountain, the Pumpkin Patch, and the Spruce Pine thrust sheets.

The rocks of the Blue Ridge record a tectonometamorphic history that ranges from the Grenville orogeny (ca. 1 Ga) to the Late Paleozoic Alleghanian orogeny. The Grenville orogeny was a Mesoproterozoic collisional event associated with the assembly of a large Precambrian supercontinent, Rodinia. Intrusions of mafic rocks and the presence of large rift basins (such as the Grandfather Mountain window) provide evidence for the Neoproterozoic break-up of Rodinia which resulted in the formation of the North American paleocontinent, Laurentia. Following the break-up of Rodinia was the accumulation of sedimentary strata along the passive margin of Laurentia, and the formation of oceanic crust and marine sediments in the evolving basin of the Iapetus Ocean. Paleozoic orogenic events commenced with the destruction of the Laurentian margin during early stages of the Ordovician Taconic orogeny. Closure of the Iapetus Ocean basin was associated with various compressional or transpressional events resulting from arc-continent or continent-continent collision. Paleozoic orogenic events in the Appalachian belt culminated with the Alleghanian orogeny. During this time, the Blue Ridge thrust complex was transported from southeast to northwest (present geographic coordinates) over rocks now exposed in the Grandfather Mountain window. Duplex faulting at structurally lower levels created doming of the area and subsequent erosion exposed rocks below the thrust sheets, thus creating the Grandfather Mountain window.

Formation of the Grandfather Mountain window has provided a unique opportunity to examine the overriding thrust sheets and their exposed boundaries. Within a relatively small area, there are exposures of rocks that record evidence for the Grenville and subsequent Paleozoic orogenies. The objective of the field trip is to present the participants with a geologic cross section through the Blue Ridge thrust complex. The field stops will range from the Grandfather Mountain window and its bounding fault, the Linville Falls fault, to the uppermost thrust sheet of the complex, the Spruce Pine thrust sheet. The trip will emphasize results of recent research by the authors. Day One will begin with an examination of the shear zone and fault bounding the Grandfather Mountain window at the base of the complex, followed by stops in the structurally highest thrust sheet to examine ultramafic rocks, eclogite and other high grade metamorphic rocks. Day two will concentrate on the nature of deformation in the Beech Mountain thrust sheet, followed by a stop to recently discovered retrogressed eclogite northeast of the Grandfather Mountain window.

Mi. DESCRIPTION

DAY ONE SATURDAY, SEPTEMBER 27, 1997

0.0 Leave parking lot at Holiday Inn of Banner Elk. Turn left (south) on NC 194. The town of Banner Elk and the Holiday Inn are at the northwestern edge of the Grandfather Mountain window. The prominent mountain to the northwest is Beech Mountain, which lies outside the window. The prominent mountain to the southwest is Sugar Mountain.

1.1 Outcrop of Grandfather Mountain Formation sandstone on left side of road.

2.0 Escarpment at shopping center shows contact between Montezuma Member (metabasalt) with sandstone of the Grandfather Mountain Formation. Continuing to the south along 194 the prominent mountain due south is Grandfather Mountain.

3.0 Intersection of NC 194 and NC 105 at Linville Gap. Turn right on 105 South.

3.8 Outcrops of Linville Metadiabase on right side of road.

7.0 Intersection of NC 105 and US 221. Proceed straight through intersection.

8.7 Intersection with NC 181 and US 221. Turn left on US 221/ NC 181 South.

10.5 Bear to the right on US 221 South.

13.5 Cross the western boundary of the Grandfather Mountain window into the Linville Falls shear zone in the hanging wall of the Linville Falls fault. For about 2 miles, US 221 runs along the western boundary of the window.

18.2 Entrance to Blue Ridge Parkway. Turn left on Blue Ridge Parkway North.

19.3 Turn right on Blue Ridge Parkway spur to Linville Falls Visitor Center.

19.6 Cross Linville Falls fault back into the Grandfather Mountain window. Outcrops along road are Chilhowee Group sandstone within the Table Rock thrust sheet.

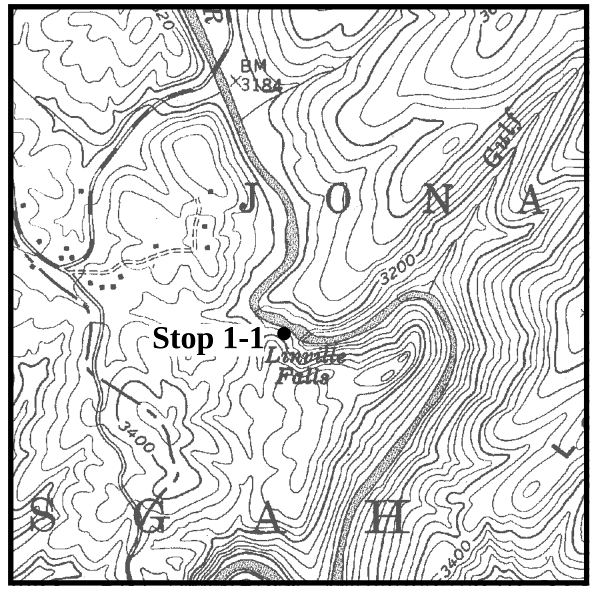
20.8 National Park Service Linville Falls Visitor Center parking area.

STOP 1-1 LINVILLE FALLS FAULT AT LINVILLE FALLS, LINVILLE FALLS, NC QUADRANGLE

Location: Blue Ridge Parkway National Park, Linville Falls Overlook, approximately 0.3 mi S of the National Park Service Linville Falls Visitors Center, Linville Falls, NC quadrangle. UTM coordinates: 416510mE, 3978520mN

Note: This stop is within the Blue Ridge Parkway National Park, and taking samples or breaking rock is prohibited except by special permit. Cross the wall on the upstream side of the overlook to exposure of mylonite at the base of the outcrop. Space at the outcrop is limited; we will lead groups of 25 people at a time to view this exposure.

Stop Leader: Charles H. Trupe



The Linville Falls fault frames the Grandfather Mountain window, and separates crystalline rocks of the Blue Ridge thrust complex from underlying rocks of the window. At Linville Falls, Neoproterozoic and Mesoproterozoic rocks of the Beech Mountain thrust sheet overlie Cambrian Chilhowee Group metasedimentary rocks of the Tablerock thrust sheet. The fault was named for this exposure by Bryant and Reed (1970), which they interpreted as a top-to-northwest thrust fault. Van Camp and Fullagar (1982) and Schedl et al. (1992) obtained a Rb-Sr whole-rock date of 302 Ma for mylonite from this location.

The Linville Falls fault dips gently west at this location. The overlook is on Chilhowee Group metaquartzite, which exhibits northwest-trending mineral stretching lineation, isoclinal folds with hinges parallel to this lineation, and open folds with northeast-trending hinges (Bryant and Reed, 1970; Hatcher and Butler, 1986). Crenulation cleavage is parallel to axial planes of the folds. Hatcher and Butler (1986) stated that this cleavage (F3 cleavage of Butler, 1973) is a penetrative feature that affects the mylonite zone, and rocks in both the hanging wall and footwall.

Bryant and Reed (1970, p. 163) described the fault as "marked by 6 to 18 inches of white to green finely laminated blastomylonite which is parallel to bedding in the quartzite and to foliation in the gneiss". The "blastomylonite" separates "Cranberry Gneiss" in the hanging wall from Chilhowee Group quartzite of the Tablerock thrust sheet in the footwall. Bryant and Reed (1970) noted extensive shearing in basement rocks above the fault, and described slices of quartzite, amphibolite, and mica schist intercalated with mylonitic gneisses along the fault at several locations around the Grandfather Mountain window.

New mapping in the vicinity of Linville Falls shows that the hanging wall of the fault locally consists of tectonic blocks of alkali feldspar granite, informally referred to as the Linville Falls granite (Trupe, this volume). The "blastomylonite" of Bryant and Reed (1970) occurs between the granite and Chilhowee Group quartzites in the footwall. The Linville Falls granite is similar petrographically and chemically to the Beech Granite, and may represent tectonic slices of that unit. The granite is typically strongly sheared, and mylonitic fabric is locally overprinted by cataclastic fabric. Cataclastic fabric in the granite is well-exposed in outcrops on the north side of the Linville River across from the National Park Service Linville Falls Campground. Chilhowee Group metasedimentary rocks in the footwall are strongly sheared to quartz-sericite (± feldspar) mylonite.

The Linville Falls granite is structurally overlain by a thick ductile shear zone consisting of several hundred meters of basement-derived mylonite and ultramylonite, termed the Linville Falls shear zone by Trupe et al. (1990). The mylonitic rocks record top-to-northwest shear sense, and were deformed at greenschist facies conditions (Trupe, 1997, this volume). The shear zone contains tectonic blocks of various lithologies, including slices of magnetite-hornblendite, metagranite, and amphibolite. The Linville Falls shear zone extends to the contact with the Ashe Metamorphic Suite, ~ 3 kilometers southwest of the Linville Falls fault.

Some previous studies have assumed that the Linville Falls fault is a meter-scale feature at Linville Falls, and changes to a much thicker zone in exposures along the northern margin of the Grandfather Mountain window (e.g., Wojtal and Mitra, 1988; Newman and Mitra, 1993). These previous workers failed to recognize the significant thickness of mylonitic rocks present in the Linville Falls shear zone, the occurrence of cataclasites near Linville Falls, and the presence of slices of granite along the base of the shear zone. Models that attempt to explain thickening of the fault zone are not necessary, as there is no large variation in shear zone thickness between Linville Falls and Banner Elk. The mylonite exposed at the Linville Falls overlook did not accommodate all of the strain associated with emplacement of the Blue Ridge thrust complex. This strain is represented by hundreds of meters of mylonite of the Linville falls shear zone.

References

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

Butler, J.R., 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge thrust sheet, North Carolina: American Journal of Science, v. 273-A, p. 72-88.

Hatcher, R. D., Jr. and Butler, J. R., 1986, Linville Falls fault at Linville Falls, North Carolina: Geological Society of America Centennial Field Guide, Southeastern Section, p. 229-230.

Newman, J., and Mitra, G., 1993, Lateral variations in mylonite zone thickness as influenced by fluid-rock interactions, Linville Falls fault, North Carolina: Journal of Structural Geology, v. 15, p. 849-863.

Schedl, A., McCabe, C., Montanez, I., Fullagar, P. D., and Valley, J., 1992, Alleghanian regional diagenesis: A response to the migration of modified metamorphic fluids derived from beneath the Blue Ridge-Piedmont thrust sheet: Journal of Geology, v. 100, p. 339-352.

Trupe, C. H., 1997, Deformation and metamorphism in part of the Blue Ridge thrust complex, northwestern North Carolina: Ph.D. Dissertation, University of North Carolina at Chapel Hill, 176 p.

Trupe, C. H., Butler, J. R., Mies, J. W., Adams, M. G., and Goldberg, S. A., 1990, The Linville Falls fault and related shear zone: Geological Society of America Abstracts with Programs, v. 22, p. 66.

Van Camp, S. G., and Fullagar, P. D., 1982, Rb-Sr whole-rock ages of mylonites from the Blue Ridge and Brevard zone of North Carolina: Geological Society of America Abstracts with Programs, v. 14, p. 92-93.

Wojtal, S., and Mitra, G., 1988, Nature of deformation in some fault rocks from Appalachian thrusts, *in* Mitra, G., and Wojtal, S., editors, Geometries and Mechanisms of Thrusting, With Special Reference to the Appalachians: Geological Society of America Special Paper 222, p. 17-33.

COFFEE BREAK

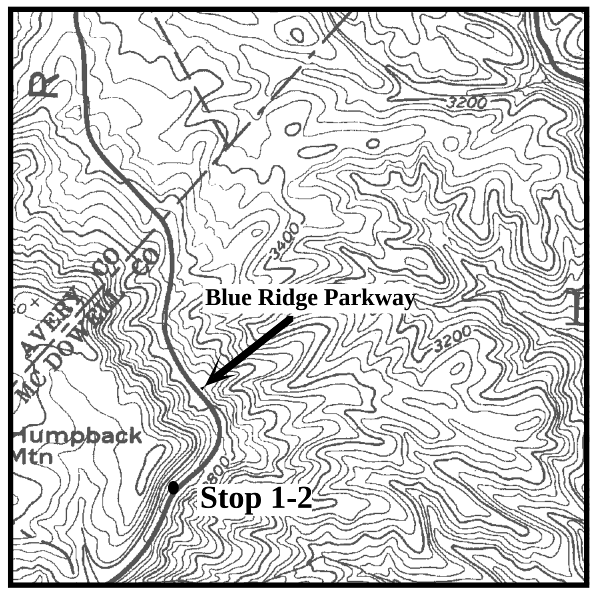
Return to Blue Ridge Parkway.

22.3 Turn left (south) on Blue Ridge Parkway. Parkway continues within the Linville Falls shear zone (hanging wall of Linville Falls fault). The shear zone is composed of blocks of sheared and unsheared rocks incorporated into mylonites predominantly derived from crystalline basement rocks.

26.0 Outcrops on the right (mile marker 320). Buses will unload here, then continue south to Gillespie Gap and turn around at the Museum of North Carolina Minerals.

STOP 1-2 CONTACT BETWEEN THE LINVILLE FALLS SHEAR ZONE AND THE ASHE METAMORPHIC SUITE, BLUE RIDGE PARKWAY, LINVILLE FALLS, NC QUADRANGLE

Location: Blue Ridge Parkway National Park, Blue Ridge Parkway, mile marker 320, Linville Falls, NC quadrangle. UTM coordinates: 413650 mE, 3977350 mN.



Note: This stop is within the Blue Ridge Parkway National Park, and taking samples or breaking rock is prohibited except by special permit. There is limited space along the shoulder of the Parkway. Participants must be extremely careful of traffic on the Parkway.

Stop Leader: Charles H. Trupe

The purpose of this stop is to examine the contact between Ashe Metamorphic Suite (AMS) rocks in the Spruce Pine thrust sheet and mylonitic rocks of the Linville Falls shear zone. Bryant and Reed (1970) and Abbott and Raymond (1984) postulated that the contact between the AMS and underlying basement rocks is a fault. The basal contact of the Spruce

Pine thrust sheet was defined as a northwest-directed, post-metamorphic thrust fault (Butler et al., 1987), and subsequent work has verified these relationships adjacent to and northeast of the Grandfather Mountain window (Mies, 1990). Along strike to the southwest, the contact between the AMS and basement is a dextral strike-slip fault (Burnsville fault, Stop 1-4) that predates the thrust fault adjacent to the window (Adams et al., 1995a). Field relations indicate that the strike slip faulting is overprinted in the vicinity of the Grandfather Mountain window by Alleghanian shearing and thrust faulting (Adams et al., 1995a). Farther to the southwest, other workers have stated that the presumably equivalent contact is a pre-metamorphic thrust fault, correlative with the Hayesville fault (Hatcher, 1987; Merschat and Wiener, 1988).

At this stop, garnet mica schist (± kyanite) and amphibolite of the AMS overlie Linville Falls shear zone mylonite derived from biotite gneiss and granitic gneiss of the Beech Mountain thrust sheet. The mylonites contain alkali feldspar and plagioclase porphyroclasts in a matrix of recrystallized quartz and fine-grained biotite, with minor epidote, sphene, and opaque minerals. Foliation and compositional layering in the hanging wall and footwall rocks dip southwest. Northwest-trending mineral stretching lineation is well-developed in the mylonitic footwall rocks. Pegmatites in the AMS are sheared and boundinaged; asymmetric boudins demonstrate top-to-northwest shear sense.

Amphibolite facies assemblages in the AMS rocks have been sheared and retrograded near the contact. Hornblende in the amphibolites is partially replaced by green biotite, and epidote is abundant. Garnet in the mica schists has been partially to totally replaced green by biotite (± chlorite). Plagioclase is sausseritic, and fine-grained white mica is abundant. The earlier regional metamorphic foliation is overprinted by shearing. Muscovite fish and shear bands show top-to-northwest shear sense. The retrogressive metamorphism and shearing are interpreted to represent late Paleozoic deformation during Alleghanian thrusting.

References

Abbott, R.N., Jr., and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic history. American Journal of Science, 284, 350-375.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995a, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, New Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

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

Butler, J.R., Goldberg, S.A., and Mies, J.W., 1987, Tectonics of the Blue Ridge west of the Grandfather Mountain window, North Carolina and Tennessee: Geological Society of America Abstracts with Programs, v. 19, p. 77.

Hatcher, R.D., Jr., 1987, Tectonics of the southern and central Appalachian internides: Annual Review of Earth and Planetary Sciences, v. 15, p. 337-362.

Merschat, C.E., and Wiener, L.S., 1988, Geology of the Sandymush and Canton quadrangles, North Carolina: North Carolina Geological Survey Bulletin 90, 66 p.

Mies, J.W., 1990, Structural and petrologic studies of mylonite at the Grenville basement - Ashe Formation boundary, Grayson County, Virginia to Mitchell County, North Carolina: Ph. D. Dissertation, University of North Carolina at Chapel Hill, 330 p.

Turn around. Head north on Blue Ridge Parkway.

29.7 Turn left into Linville Falls Picnic Area.

LUNCH

30.8 Exit for US 221. Turn right (north) on US 221.

32.0 Intersection with NC 194. Turn left (south) on NC 194.

33.0 In this vicinity, cross from the Linville Falls shear zone into the Ashe Metamorphic Suite of the Spruce Pine thrust sheet.

36.0 Turn left (south) on US 19E.

43.2 Intersection with NC 226. Continue south on US 19E through the Town of Spruce Pine, “The Mineral City”, the center of the Spruce Pine mineral district. This area is the leading producer of domestic feldspar and is also a major producer of scrap and sheet mica, quartz, and kaolin. The area is also known for museum-quality specimens of beryl, tourmaline, garnet, and other precious and semiprecious minerals. Abandoned and active mica and feldspar mines are visible on many of the mountainsides in this area.

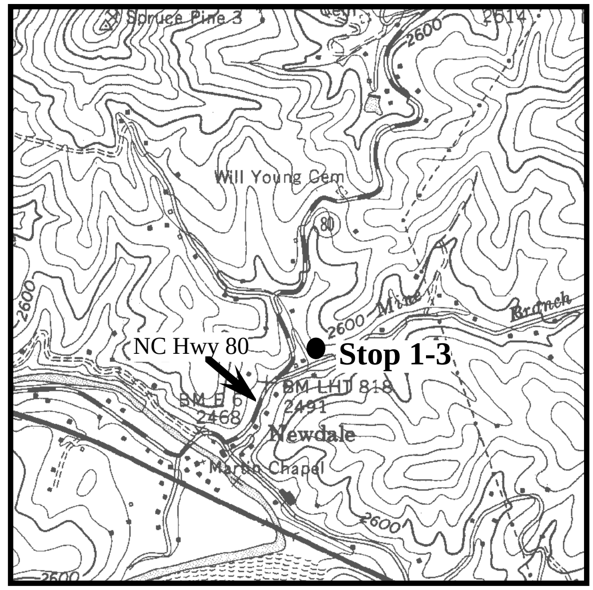
49.8 Turn right on NC 80 North. Park in parking area adjacent to buildings on right, or continue ~100 yards across Toe River Bridge and park on gravel pull-over on right.

STOP 1-3 NEWDALE DUNITE NEAR NEWDALE, NC, MICAVILLE, NC QUADRANGLE

Location: NC 80 ~400 meters north of South Toe River bridge, Micaville, NC quadrangle. UTM coordinates: 392830mE, 3974520mN.

Stop leader: Loren A. Raymond

The Newdale Dunite is one of the numerous ultramafic rock bodies present within the Ashe Metamorphic Suite of the Spruce Pine



Thrust Sheet (Toe Terrane). Immediately east of the Highway, a quarry was operated in the dunite during the 1970s, but termination of mining operations allowed the quarry to fill with water by the late 1980s. Dunite is exposed both along the highway and along an east trending, local road that intersects the highway near the south edge of the quarry.

The Newdale Dunite body, mapped as part of the Spruce Pine District mapping project of the USGS (Brobst, 1962), is an east-northeast trending, elliptical body. The body is about 440m long and 210m wide (Vrona, 1977). Brobst (1962) shows the body to be in contact primarily with hornblende schist and gneiss (amphibolite). Vrona (1977) made a more detailed map of the Newdale Dunite and found that the dunite is surrounded by hornblende schist and gneiss, but it seemingly cuts a body of anthophyllite-plagioclase gneiss enclosed within the hornblende-rich rocks.

In spite of the exposures of ultramafic rocks in mine workings and road cuts, Vrona (1977) was unable to locate any exposures of the contacts. He noted, however, no evidence of contact metamorphism, he observed apparent cross-cutting relations between structures in the ultramafic rocks and those in surrounding gneisses, and he recognized serpentine- and talc-bearing rocks near the contacts. From these data, Vrona (1977) concluded that the contact was tectonic and he figured it as a thrust fault.

The dominant rock of the Newdale ultramafic body is metadunite, but metaharzburgite and metachromitite are present locally (Vrona, 1977). The metadunite is typically somewhat serpentinized, but is characterized by LPO (Lattice preferred orientation) fabrics (Vrona, 1977). Metaharzburgite occurs where orthopyroxene forms layers, and chromite occurs both in layers and in one podiform mass (Vrona, 1977, p. 30). More commonly, however, sparse chromite and orthopyroxene are scattered among the dominant olivine grains within the metadunite. Tremolite is similarly distributed. Veins containing talc, anthophyllite, and magnesite, as well as locally extensive veins of serpentine minerals reflect local fluid-enhanced, retrograde metamorphism of the metadunite. Thin-section petrography reveals textures and mineral associations that suggest at least three successive metamorphic “events.” An early olivine + chromite + pyroxene assemblage is overprinted by an Amphibolite Facies olivine + chromite + tremolite + chlorite + pyroxene assemblage, which in turn is overprinted by one or more Greenschist Facies assemblages composed of serpentine + magnetite + chlorite + talc + tremolite. The vein assemblage composed of tremolite + anthophyllite + chlorite + talc + magnesite may represent an Amphibolite Facies, fluid-dominated, localized metasomatic event. Textural evidence suggests that the Greenschist Facies metamorphism followed earlier Amphibolite Facies metamorphism.

References:

Brobst, D.A., 1962, Geology of the Spruce Pine district, Avery, Mitchell, and Yancey Counties, North Carolina: United States Geological Survey Bulletin 1122-A, 26 p.

Vrona, J.P., 1997, Structure of the Newdale ultramafite, Yancey County, North Carolina: M.S. Thesis, Southern Illinois University, 115p.

Return to intersection of NC 80 and US 19E. Turn right (south) on US 19E.

55.0 Turn right (north) on NC 197.

59.0 Turn left on Clearmont School Road (NCSR 1416). Day Book ultramafic body is on the right. Clearmont School Road traverses the Burnsville fault which separates the Spruce Pine thrust sheet from the Pumpkin Patch thrust sheet.

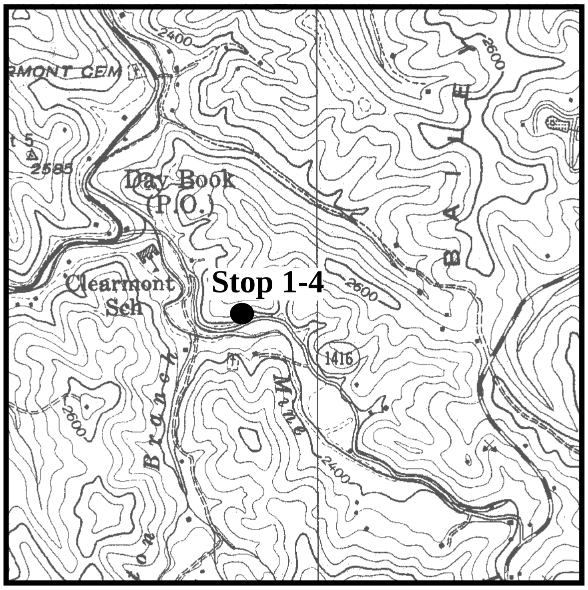
60.0 Park at gravel area adjacent to Clearmont School Road. Walk back east along road for 0.2 miles to Stop 1-4.

STOP 1-4 SHEARED BAKERSVILLE GABBRO ALONG THE BURNSVILLE FAULT ZONE, CLEARMONT SCHOOL ROAD, BURNSVILLE, NC QUADRANGLE

Location: Clearmont School Road (NCSR 1416) approximately 0.3 miles east of intersection with Jacks Creek Road (1336), Burnsville, NC quadrangle. UTM coordinates: 383390mE, 3981720mN.

Stop Leaders: Kevin G. Stewart, Mark Adams

This outcrop contains strongly sheared Bakersville Gabbro associated with the Burnsville fault zone. The rock is strongly foliated and lineated. Foliation strikes northeast and dips moderately to the southeast. The well-developed mineral-stretching lineation trends northeast and is subhorizontal. Northeast trending, mineral-stretching lineations have been recognized along the Burnsville fault from the Carvers Gap quadrangle to at least the Mars Hill quadrangle to the southwest for a distance at least 50 kilometers. Kinematic indicators from rocks along the Burnsville fault are consistent



with dextral strike-slip movement (Mallard et al., 1994; Adams et al., 1995; Burton, 1996).

Petrographic observations and P-T estimates based on mineral chemistry indicate that deformation along the Burnsville fault zone occurred under amphibolite facies conditions. Ribbons of dynamically recrystallized hornblende indicate crystal-plastic deformation of amphibole, which is thought to occur at 600-650° C (*cf*., Burton, this volume; Adams et al., 1995). Additionally, equilibrium grain boundary textures in dynamically recrystallized quartz and plagioclase are consistent with deformation under high temperature conditions. Adams and Stewart (1993) reported P-T estimates of 6 - 8 kbar and 580 - 640° C for sheared pelitic schist associated with the Burnsville fault. These authors interpreted these conditions to represent final equilibration during shearing. Burton (1996) estimated temperatures of 640 - 730° C at assumed pressures of 6 - 8 kbar for dynamically recrystallized hornblende and plagioclase from sheared amphibolite along the Burnsville fault zone.

Amphibolites facies conditions of deformation along the Burnsville fault contrast with greenschist facies conditions reported for deformation along other major shear zones in the Blue Ridge thrust complex (e.g., Linville Falls fault, Long Ridge fault, Fries-Gossan Lead fault, Stone Mountain fault).

The Burnsville fault juxtaposes rocks of the Ashe Metamorphic Suite with crystalline rocks of the Laurentian margin. This contact has been interpreted by many workers to be the Taconic suture in this part of the Blue Ridge. Most tectonic syntheses of this area correlate the Burnsville fault with the Hayesville fault to the south (for details of fault correlations see Adams et al., 1995). If the Burnsville fault corresponds to the Taconic suture then it was originally an Ordovician thrust. Recent geochronology of mylonites within the Burnsville shear zone, however, suggest strike-slip faulting occurred during the Siluro-Devonian (Goldberg and Dallmeyer, 1997). The Bakersville gabbro in this outcrop is intruded by a Spruce Pine-type pegmatite (Siluro-Devonian; Kish, 1983). Spruce Pine pegmatites are generally restricted to the Spruce Pine thrust sheet while Bakersville intrusive rocks are found only in the Laurentian basement rocks. The presence of the pegmatite in the gabbro indicates that the Spruce Pine and Pumpkin Patch thrust sheets were initially juxtaposed prior to the intrusion of the pegmatite, possibly during the Ordovician. Shearing of the pegmatite indicates that strike-slip faulting followed intrusion. These field relations combined with the geochronology are consistent with the interpretation that the strike-slip motion on the Burnsville fault is a Siluro-Devonian reactivation of an original Taconic thrust.

To the southwest, in the Barnardsville quadrangle, the Burnsville fault zone widens to several miles and consists of large blocks of relatively unsheared basement and Ashe Metamorphic Suite bounded by thick mylonite zones with consistent dextral strike-slip kinematic indicators.

To the northeast, approaching the Grandfather Mountain window, the nature of the fault changes. The lineations become more northwesterly and the conditions of shearing are upper greenschist. We believe this is an overprinting of later Alleghanian thrusting along the Linville Falls shear zone, as seen at Stop 1-2. North of the window, the base of the Spruce Pine thrust sheet (the Fries/Gossan-Lead fault) is a greenschist facies, northwest-directed thrust. This fault has also been interpreted as an Alleghanian feature and in our model would represent late transport of rocks which were originally east of the Taconic suture.

References

Adams, M.G., and Stewart, K.G., 1993, Tectonic implications of the occurrence of eclogite in the Blue Ridge, northwestern North Carolina, Geological Society of America Abstracts with Programs, v.25, p. 424.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, Current Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

Burton, F.H., 1996, Kinematic study of the Taconic suture, west-central North Carolina: M.S. thesis, University of North Carolina at Chapel Hill, 114 p.

Goldberg, S.A., and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge thrust complex, North Carolina and Tennessee: American Journal of Science, v. 297, p. 488-526.

Kish, S.A., 1983, A geochronological study of deformation and metamorphism in the Blue Ridge and Piedmont of the Carolinas: Ph. D dissertation, University of North Carolina at Chapel Hill, 220 p.

Mallard, L.D., Adams, M.G., and Stewart, K.G., 1994, Kinematic analysis of a possible suture in the southern Appalachians, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 26, n. 4, p. 25-26.

Return east along Clearmont School Road to NC 197.

61.0 Turn left (north) on NC 197.

62.6 Cross the Burnsville fault into the Pumpkin Patch thrust sheet.

67.7 On north side of Toe River Bridge, beside railroad tracks. Outcrop of mylonitic Bakersville gabbro exhibiting well-developed, sub-horizontal, northeast-trending mineral stretching lineations.

68.3 Turn right (south) on NC 226.

69.6 Outcrops of Bakersville Gabbro along left side of road.

72.5 Outcrops of Mesoproterozoic biotite-hornblende gneiss typical of basement rocks of the Pumpkin Patch thrust sheet.

73.1 Cross the Burnsville fault back into the Spruce Pine thrust sheet.

73.8 Enter Bakersville, NC. Turn right following NC 226. Then turn left at stop light onto North Mitchell Avenue (NCSR 1211).

74.1 Turn left on Redwood Road (NCSR 1217).

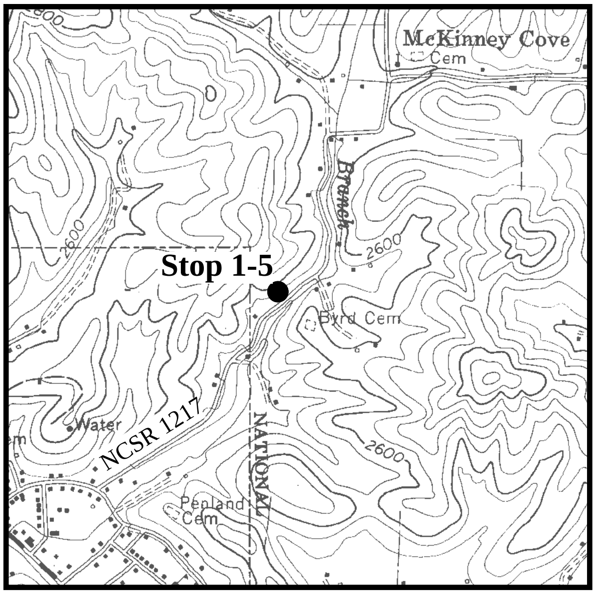
74.6 Unload from buses for Stop 1-5.

STOP 1-5 ECLOGITE AND RETROGRESSED ECLOGITE ALONG HONEYCUTT BRANCH, BAKERSVILLE, NC-TN QUADRANGLE

Location: NCSR 1217 ~ 3000 feet NE of intersection with NCSR 1211, northeast of Bakersville, NC, Bakersville, NC-TN quadrangle. UTM coordinates: 396550mE, 3986740mN

Stop Leader: Mark G. Adams

Eclogite and retrogressed eclogite are exposed in the road cut along the northwest side of the road. The exposure is continuous for



approximately 300 feet and discontinuous for approximately 1000 feet. This occurrence is the original outcrop of eclogite discovered by Rod Willard and described by Willard and Adams (1994). This exposure is one of several large blocks of eclogite that occur in the area. The majority and the largest of the blocks occur along Lick Ridge (8000 feet, N24E from here) and are described in Adams et al. (1995).

The outcrop shows a complete progression from relatively pristine eclogite to thoroughly retrogressed eclogite (amphibolite). The primary assemblage in the eclogite is garnet + omphacite + quartz + rutile. Variably the rocks contain retrograde minerals that include one or more of the following: diopside, plagioclase, hornblende, sphene, ilmenite, and epidote. In the most thoroughly retrogressed samples, the resulting mineralogy is dominated by hornblende + plagioclase + quartz ± sphene ± ilmenite ± epidote. The most thoroughly retrogress eclogite is petrographically indistinguishable from other amphibolite in the Ashe, which led Adams et al. (1995) and Abbott and Raymond (this guidebook) to speculate that much of the Ashe Metamorphic Suite was metamorphosed to eclogite facies conditions, but retrogressive metamorphism has obscured most evidence for earlier, high pressure conditions.

The eclogite shows a characteristic compositional layering defined by alternating concentrations of garnet-rich and pyroxene-rich material. This layering is generally oblique to the regional metamorphic foliation. Locally, as retrogression becomes more pervasive, the layering is transposed into concordance with the regional foliation (a feature more prevalent in exposures on Lick Ridge; see photograph on cover of guidebook).

The blocks of eclogite are incorporated into sheared pelitic schist, gneiss, and amphibolite of the Ashe Metamorphic Suite. An exposure of the contact between this block and the pelitic schist is located in the bed of Honeycutt Branch off of the road bank to the east. The exposure in the creek bed also shows several small (~ 30 cm in diameter) pods of eclogite incorporated into the pelitic schist matrix. In addition to these blocks of eclogite, small bodies of ultramafic rock are also incorporated into the pelitic schist and amphibolite. One small body of altered ultramafic rock (predominantly actinolite schist) occurs approximately 2000 feet to the southwest, but is not easily accessible.

Adams et al. (1995) reported P-T estimates from geothermobarometry based on mineral chemistry for eclogite and adjacent rocks in the area. Garnet-omphacite pairs from eclogite yield temperatures ranging from 626° to 790° C. Omphacite-plagioclase pairs yield pressure estimates ranging from 13 to 17 kbar. As plagioclase is a retrograde product, these pressure estimates are considered to be minimum pressures.

The structural base of the Ashe Metamorphic Suite is represented by the Burnsville fault. This fault occurs approximately 2000 feet to the northwest. Locally, sheared rocks associated with the Burnsville fault show mesoscopic and microscopic kinematic indicators (such as, shear bands, porphyroclasts with asymmetric tails, and composite planar fabric) indicating a major component of dextral shear sense along the fault.

References:

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, New Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

Willard, R.A., and Adams, M.G., 1994 Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61-70.

Walk 0.6 miles northeast to McKinney Cove Church. Very large, well-exposed outcrops of eclogite occur on Lick Ridge, which is the prominent ridge observable to the northeast during this walk.

COFFEE BREAK

Return to North Mitchell Avenue, turn right. At stop light turn right onto NC 226. Go ~ 100 feet to flashing light and proceed straight (north) on NC 261.

76.9 Cross Burnsville fault from Spruce Pine thrust sheet into Pumpkin Patch thrust sheet.

79.5 Outcrop of two-pyroxene granulite on left side of road. Granulite facies rocks have been reported from a few scattered locations in basement rocks of the Pumpkin Patch thrust sheet. Pumpkin Patch Mountain is the prominent mountain on the left. Meadlock Mountain is the prominent mountain on the right.

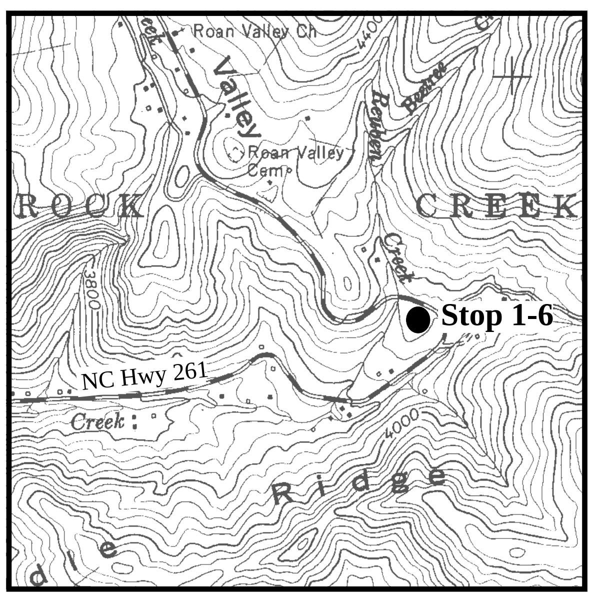
81.5 In this vicinity, enter back into the Burnsville fault zone. NC 261 continues within the fault zone for approximately 3.5 miles, then turns north out of the fault zone into the Pumpkin Patch thrust sheet.

85.2 Outcrop of Meadlock Mountain gneiss on left side of road. Continue 0.2 miles and park on wide shoulder on left side of road. Walk back to outcrop of Meadlock Mountain gneiss.

STOP 1-6 MEADLOCK MOUNTAIN GNEISS ALONG NC HWY 226 NEAR ROAN VALLEY, CARVERS GAP, NC-TN QUADRANGLE

Location: Along NC - 261 ~ 1.2 mi NE of Glen Ayre, Carvers Gap, NC-TN quadrangle. UTM coordinates: 402150mE, 3993830mN

Stop Leader: Mark G. Adams



This stop highlights the Meadlock Mountain gneiss, a mafic basement gneiss in the Pumpkin Patch thrust sheet. The Meadlock

Mountain gneiss is juxtaposed with the Ashe Metamorphic Suite along the Burnsville fault in the eastern part of the Bakersville quadrangle and the western part of the Carvers Gap quadrangle. The fault is located approximately 1000 feet to the south. East of this area, the nature of the Ashe-basement contact changes from a relatively high grade (amphibolite facies), dextral strike-slip shear zone to a lower grade (greenschist facies), northwest directed thrust fault (Adams et al., 1995a). Adams et al. (1995a) suggested that the original juxtaposition of the Pumpkin Patch and Spruce Pine thrust sheets was a result of collision during the Taconic orogeny, the dextral movement resulted from reactivation of the fault during the Acadian orogeny, and the thrust fault overprinted the earlier strike-slip fault during the Alleghanian orogeny.

The stable metamorphic assemblage in this rock includes garnet + hornblende + diopside + biotite + plagioclase + quartz + rutile + ilmenite. Adams et al. (1995b) estimated “peak” P-T conditions of ~13 kbar at 725° C and final equilibration conditions of ~9 kbar at 660° C. Thin sections from this locality show deformation of primary metamorphic phases, but do not show significant retrograde phases. Deformation is manifested by grain-size reduction by dynamic recrystallization and the formation of ribbons of quartz, hornblende, and pyroxene. Equilibrium textures of dynamically recrystallized grains in pyroxene ribbons indicate deformation occurred under relatively high grade conditions.

Gulley (1985) and Monrad and Gulley (1983) documented granulite facies conditions (6.5 - 8 kbar at 750° - 847° C) for the Cloudland and Carvers Gap gneisses on Roan Mountain. These authors interpreted these granulite facies conditions to represent metamorphism during the Precambrian. They also estimated upper amphibole facies conditions (10 - 12 kbar at 680 - 760° C) interpreted to record Paleozoic (Taconic orogeny) metamorphism. The latter P-T estimates are consistent with those from the Meadlock Mountain gneiss reported by Adams et al. (1995).

The Meadlock Mountain gneiss may be correlative with parts of the Carvers Gap gneiss as described by Gulley (1985) and Monrad and Gulley (1983). However, these authors stated that mafic components of the Carvers Gap gneiss constitute a minor volume of the gneiss. Geologic mapping (Adams, 1995) indicates that the Meadlock Mountain gneiss covers a significant area in map view. Although felsic zones locally occur (exposed ~ 500 feet east of this stop) within the Meadlock Mountain gneiss, the mafic component is the dominant lithology along the Burnsville fault from Bakersville, NC to the community of Valley in the Carvers Gap quadrangle (Adams, 1995).

References:

Adams, M.G., 1995, The tectonothermal evolution of part of the Blue Ridge thrust complex, northwestern North Carolina: Ph.D. dissertation, University of North Carolina, 193 p.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995a, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, New Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

Adams, M.G., Trupe, C.H., Goldberg, S.A., Stewart, K.G., and Butler, J.R., 1995b, Pressure-temperature history of high-grade metamorphic rock along the eastern-western Blue Ridge boundary, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 27, p. 33.

Gulley, G. L., Jr., 1985, A Proterozoic granulite-facies terrane on Roan Mountain, western Blue Ridge belt, North Carolina - Tennessee: Geological Society of America Bulletin, v. 96, p. 1428-1439.

Monrad, J.R., and Gulley, G.R., Jr., 1983, Age and P-T conditions during metamorphism of granulite-facies gneisses, Roan Mountain, North Carolina-Tennessee, in Lewis, S.E., editor, Geologic investigations in the Blue Ridge of northwestern North Carolina: Carolina Geological Society Guidebook, North Carolina Geological Survey, Article IV, 29 p.

Walk back to buses.

Continue north on NC 261.

89.3 NC-TN state line at Carvers Gap. Optional stop: turn left at Carvers Gap to Roan Mountain overlook. The overlook provides a panoramic view of the Blue Ridge and Valley and Ridge Provinces. For detailed description of the geology at this stop, refer to 1983 Carolina Geological Society Field Trip Guidebook.

At the TN-NC state line, NC 261 becomes TN 143. Continue north on TN 143 to US 19E. Turn right (south) on US 19E. Continue for approximately 7 miles to NC 194 in the town of Elk Park. Turn left (north) on NC 194 toward Banner Elk. Continue to NC 184 in Banner Elk. Turn right at stop light and continue 1.3 miles to Holiday Inn.

DAY TWO SUNDAY, SEPTEMBER 28, 1997

0.0 Leave Holiday Inn parking lot. Turn right (north) on NC 184.

1.0 Low outcrop on left is stretched pebble metaconglomerate of the Grandfather Mountain Formation.

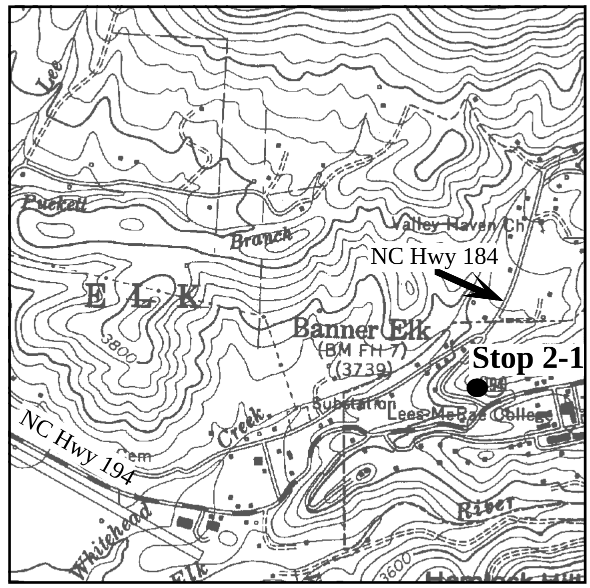
1.3 Turn left at traffic light onto NC 184/ NC 194.

1.6 Park in Sunrise Shopping Center lot on right.

STOP 2-1. LINVILLE FALLS FAULT AT BANNER ELK

Location: Intersection of NC highways 184 and 194, Elk Park 7.5' quadrangle. UTM coordinates: 420990mE, 4002050mN.

Stop Leader: Charles H. Trupe



The Linville Falls fault (Bryant and Reed, 1970) is exposed on the west side of Banner Elk, North Carolina, approximately 30 meters northwest of the intersection of Beech Mountain Parkway (NC 184) and NC 194 (Figure 4). The fault juxtaposes Precambrian crystalline rocks of the Beech Mountain thrust sheet and underlying rocks of the Grandfather Mountain window. Approximately 50 meters of hanging wall and footwall rocks are exposed in a recent excavation. Metaquartzite and sericitic quartz mylonite and ultramylonite in the hanging wall dip moderately northwest, concordant with the orientation of the fault surface. The footwall consists of low-grade metasedimentary rocks of the Grandfather Mountain Formation in which sedimentary layering dips moderately northeast and cleavage dips moderately east. Although the major Blue Ridge thrusts are generally recognized as hinterland dipping structures, the northwest dip of the fault at Banner Elk is due to large amplitude folding of the thrust surface during formation of the Grandfather Mountain window (Bryant and Reed, 1970), possibly due to the presence of an underlying thrust duplex (Boyer and Elliott, 1982).

Recent work in the area has shown that the Linville Falls fault lies at the base of a thick shear zone, appropriately termed the Linville Falls shear zone (Trupe et al., 1990; Trupe, this volume). Adams and Su (1996) showed the shear zone to be approximately 1 kilometer thick in the Banner Elk area. Kinematic indicators in the mylonites of the shear zone yield top-to-northwest sense of shear (Trupe, 1989; Adams, 1990; Adams and Su, 1996). The shear zone contains tectonic slices of metaquartzite and exotic crystalline rocks (granoblastic layered gneisses and metagranite) surrounded by greenschist-grade mylonite and ultramylonite. Contrary to assumptions by Newman and Mitra (1993), the relatively small, exotic slice of quartz diorite gneiss (Potts Cemetery gneiss of Adams and Su, 1996) that crops out 500 meters above the fault zone is not a likely protolith of the hanging wall mylonites.

Cataclastic deformation overprints mylonitic fabric several meters into the hanging wall rocks at Banner Elk. A progression from ultracataclasite (2-3 cm) to cataclasite (1-2 m) to protocataclasite may be observed immediately above the fault. Cataclastic rocks also occur at an exposure of the fault at Bowers Gap, 4 km east of the Banner Elk exposure, and at the type locality of the fault at Linville Falls, NC (Trupe, this volume). The Long Ridge fault (Adams and Su, 1996) to the northeast, and the Stone Mountain fault farther to the northwest also exhibit cataclastic deformation overprinting mylonitic fabrics, and are related to the Linville Falls shear zone .

References

Adams, M.G., 1990, The geology of the Valle Crucis area, northwestern North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 95 p.

Adams, M. G., and Su, Q., 1996, The nature and timing of deformation in the Beech Mountain thrust sheet between the Grandfather Mountain and Mountain City windows in the Blue Ridge of northwestern North Carolina: Journal of Geology, p. 197-213.

Boyer, S.E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196-1230.

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

Newman, J., and Mitra, G., 1993, Lateral variations in mylonite zone thickness as influenced by fluid-rock interactions, Linville Falls fault, North Carolina: Journal of Structural Geology, v. 15, p. 849-863.

Trupe, C.H., 1989, Kinematic analysis and deformation mechanisms in mylonites from the Blue Ridge thrust complex, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 21, p. 62.

Trupe, C.H., Butler, J.R., Mies, J.W., Adams, M.G., and Goldberg, S.A., 1990, The Linville Falls fault and related shear zone: Geological Society of America Abstracts with Programs, v. 22, p. 66.

Leave Sunrise Shopping Center. Turn left on NC 184 South/ NC 194 North.

1.9 Turn right at traffic light on NC 184 South.

6.2 Turn left on NC 105 North.

14.4 Turn left on NC 105 North Truck Route. Felsic metavolcanic rocks of the Grandfather Mountain Formation are expose on the left side of road.

15.4 Outcrops of Montezuma Member (metabasalt) and metaconglomerate of the Grandfather Mountain Formation.

15.7 Cross the Linville Falls fault along the northern border of the Grandfather Mountain window into the Beech Mountain thrust sheet. The first well-exposed rock on the left, north of the fault, is part of a slice of Broadstone Camp granite incorporated into the Linville Falls shear zone.

17.3 Intersection of NC194 Truck Route with NC 194 in the town of Valle Crucis. Continue north on NC 194.

18.0 Cross Watauga River. In this area the flood plain of the Watauga River coincides with the location of the Long Ridge fault zone.

18.7 Turn left on Mast Gap Road (NCSR 1117). Outcrop on right is Valle Crucis gneiss (Adams, 1990) Cranberry Mine-layered gneiss of Bartholomew and Lewis (1984); Cranberry Gneiss of Bryant and Reed (1970).

20.9 Turn left on US 321 North.

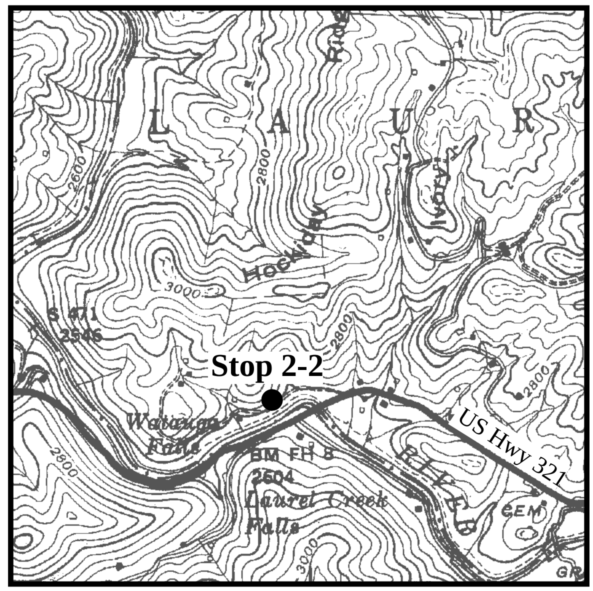
23.4 Cross Fork Ridge fault of Bartholomew and Lewis (1984). The Fork Ridge fault is a thrust within the Beech Mountain thrust sheet and separates Valle Crucis gneiss in the hanging wall from Watauga River Gneiss in the foot wall.

25.0 Park in store parking lot on right. Walk 0.1 miles and turn right on Bull Harmon Road. Walk about 700 feet to Stop 2-2.

STOP 2-2 LONG RIDGE FAULT

Location: Along Bull Harmon Road ~700 feet NW of intersection with US 321, Sherwood, NC-TN quadrangle. UTM coordinates: 423500mE, 4012390mN

Stop Leader: Mark G. Adams



This exposure was designated as the "type locality" of the Long Ridge fault by Adams and Su (1996). Part of the fault was mapped as the "upper branch of the Stone Mountain fault" by Bryant and Reed (1970). Bryant and Reed (1970) mapped this fault from the Stone Mountain fault along the southeastern boundary of the Mountain City window to the southeast where it "dies out in the vicinity of Long Ridge." Adams (1990) traced the fault farther to the southeast where it merges with the Linville Falls fault in the vicinity of Valle Crucis. Adams and Su (1996) interpreted the Long Ridge fault to be a low angle tear fault within the Beech Mountain thrust sheet, resulting from differential movement of the thrust sheet during the Alleghanian orogeny. Mineral-stretching lineations and kinematic indicators are consistent with top-to northwest, dextral strike-slip movement along the Long Ridge fault (Adams and Su, 1996)

The Long Ridge fault is similar to the border faults (Linville Falls and Stone Mountain faults) of the Beech Mountain thrust sheet in several respects. Associated with the Long Ridge fault is a thick (up to 400 meters), mixed-rock mylonite zone termed the Long Ridge shear zone. This shear zone contains blocks of sheared and unsheared rock and discontinuous slices of metasedimentary rocks (predominantly metaquartzite, meta-arkose, and metaconglomerate of the Chilhowee Group and/or the Grandfather Mountain Formation) incorporated into mylonite, ultramylonite, and phyllonite derived predominantly from basement rocks. In addition to ductile deformation, manifested by mylonite and ultramylonite; the Long Ridge shear zone shows evidence of brittle deformation evidenced by cataclasite, ultracataclasite, and pseudotachylyte (?) (O'Hara, 1992; Adams, 1994; Adams and Su, 1996). The deformed rocks show evidence of alternating episodes of brittle and ductile deformation. Adams and Su (1996) documented evidence for overprinting episodes including a sequence of ductile-brittle-ductile-brittle deformation. Adams and Su (1996) stated that both styles of deformation (brittle and ductile) occurred essentially synchronous under the same regional P-T conditions.

At this stop, the outcrop shows a slice of metasedimentary rock incorporated into the Long Ridge shear zone. Also exposed are veinlets of pseudotachylyte (or ultracataclasite) cross cutting the basement rocks. The outcrop also locally shows ductilely deformed pseudotachylyte (?), indicating alternating episodes of brittle-ductile deformation. Isotopic evidence indicates that both the ultramylonite and pseudotachylyte from this locality were formed around 300 Ma. (Adams and Su, 1996).

References:

Adams, M.G., 1994, Major- and trace-element constraints on the petrogenesis of a fault-related pseudotachylyte, western Blue Ridge province, North Carolina - Comment: Tectonophysics, v. 233, p. 145-147.

Adams, M.G., and Su, Q., 1996, The nature and timing of deformation in the Beech Mountain thrust sheet between the Grandfather Mountain and Mountain City windows in the Blue Ridge of northwestern North Carolina: Journal of Geology, p. 197-213.

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

O'Hara, K., 1992, Major- and trace-element constraints on the petrogenesis of a fault-related pseudotachylyte, western Blue Ridge province, North Carolina. Tectonophysics, 204: 279-288.

Trupe, C.H., and Adams, M.G., 1991, Cataclastic deformation in the Linville Falls shear zone, western North Carolina Blue Ridge: Geological Society of America Abstracts with Programs, v. 23, p.141.

COFFEE BREAK

Return to Buses.

Turn around and head south on US 321.

30.0 Intersection with US 421. The top of the prominent ridge directly in front (to the east) is Ashe Metamorphic Suite of the Spruce Pine thrust sheet. The thrust fault (Fries/Gossan Lead fault) separating the Spruce Pine thrust sheet from the underlying Beech Mountain thrust sheet is about half way up the mountain. Turn right and head south on US 321/421. The highway parallels a relatively narrow strip of the Beech Mountain thrust sheet bounded above by Fries/Gossan Lead fault and below by the Linville Falls fault.

33.5 Intersection with US 321/421 Truck Route. Continue straight on US 321/421 South.

34.9 Enter Boone, North Carolina city limits.

37.1 Turn left (north) on NC 194. In this area NC 194 crosses the Fries/Gossan Lead fault into the Spruce Pine thrust sheet.

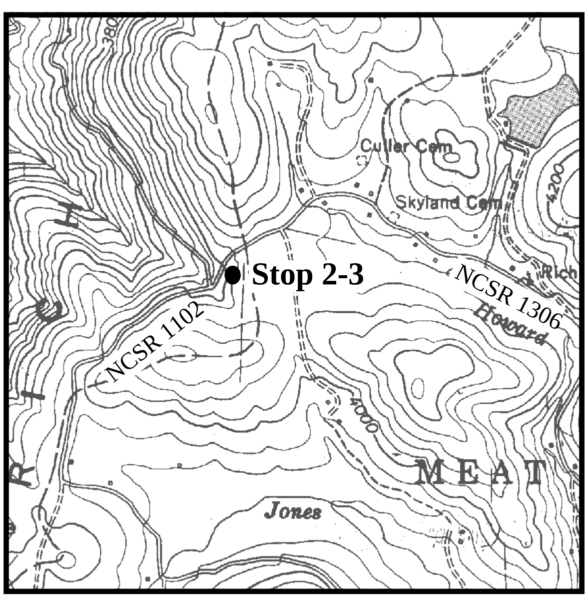
38.7 Turn left on Howards Creek Road (NCSR 1306).

44.8 Unload from buses at open field on left (southeast). Walk 0.1 miles further to Stop 2-3.

STOP 2-3 RETROGRESSED ECLOGITE ON TATER HILL, ZIONVILLE, NC-TN QUADRANGLE

Location: NCSR 1306 ~ 300 feet E of intersection with NCSR 1102, Southeast of Silverstone, NC, Zionville, NC-TN quadrangle. UTM coordinates: 434620mE, 4014890mN.

Stop Leader: Richard N. Abbott



The purpose of this stop is to examine recently discovered retrograded eclogite in the Ashe Metamorphic Suite (AMS) north of the Grandfather Mountain window. The only other area of bona fide eclogite occurs in a similar structural setting in the AMS, but southwest of the Grandfather Mountain window (Willard and Adams, 1994; Adams et al., 1995). The best exposures of retrograded eclogite north of the Grandfather Mountain window (this stop) are along the east side Howard Creek Rd, 50 to 100 meters north of the junction with Tater Hill Rd. and the north end of Junaluska Rd (lat. N 36° 16' 44.2", long. W 81° 43' 41"). While the outcrop is clearly on a state right-of-way, please respect the owners of adjacent properties. Permission to examine the outcrop should be obtained from Mr. Donald Price of Zionville.

The local distribution of retrograded eclogite has not been mapped in detail. Boulders of retrograded eclogite, on the south slope of the hill, immediately north of the roadside exposures, suggest that retrograded eclogite extends at least 200 meters to the northeast. One other location of retrograded eclogite has been discovered in a small outcrop approximately 2 km to the south (lat. N 36° 15' 34", long. W 81° 43' 22", along Junaluska Rd.).

The retrograded eclogites are close to the base of the AMS, near the western edge of the Spruce Pine thrust sheet. The actual base of the thrust sheet, which is down hill to the west, is concealed by colluvium. The location of the retrograded eclogites is consistent with the area of highest metamorphic pressures in the AMS, as inferred from the general direction of increasing P (Abbott and Raymond, this volume). The retrograded eclogites occur as thin (cm-scale), gray-green granoblastic layers in otherwise typical garnet-hornblende schist. The essential mineralogy consists of symplectic intergrowths of diopside and plagioclase (representing former omphacite), generally euhedral to subhedral garnet (< 1mm), polygonal epidote, and quartz. Boundaries between layers of retrograded eclogite and hornblende schist are gradational, showing a progressive replacement of the eclogite by hornblende schist. Plagioclase occurs only in the symplectite and with quartz in coronas around garnet. Adams et al. (1995) have suggested that such coronas formed in response to a retrograde reaction between garnet and surrounding symplectite. Hence, at it's highest-grade the rock was bona fide eclogite. The distinctive coronas are common in the symplectite-free hornblende schist, especially near the base of the AMS. Interpreted as relict features inherited from an earlier, high-grade condition of the rock, the coronas suggest that a significant volume of the hornblende schist in the AMS is retrograded (amphibolitized) eclogite (Adams et al., 1995). The presence of epidote distinguishes these eclogites from those described by Willard and Adams (1994), and probably reflects a higher fugacity of O_2. Additional details of the petrography are given in Abbott and Raymond (this volume).

The presence of eclogite, or retrograded equivalents, in the AMS is significant for at least three reasons. (1) The eclogites record the earliest recognizable and highest grade metamorphism affecting mafic rocks during the Taconic Orogeny. (Evidence for even earlier, and higher grades of metamorphism may be preserved in ultramafic rocks of the AMS.) (2) The eclogites strongly support an ensimatic origin for the AMS, as part of a subduction-related accretionary melange. (3) Much of the Amphibolite Facies metamorphism in the western part of the AMS is retrograde.

References:

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, Current Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p 21-42.

Willard, R.A., and Adams, M.G., 1994, Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61-70.

Return to buses.

Turn around and follow Howards Creek Road back to NC 194. Return to Banner Elk via US 421 - NC 105 - NC 184.

PALEOZOIC STRUCTURAL EVOLUTION OF THE BLUE RIDGE THRUST COMPLEX, WESTERN NORTH CAROLINA

Kevin G. Stewart, Mark G. Adams[1] , and Charles H.Trupe[2]

Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

ABSTRACT

The Blue Ridge thrust complex in the region surrounding the Grandfather Mountain window consists of four major thrust sheets. Structurally lowest to highest these are the Pardee Point, the Beech Mountain, the Pumpkin Patch, and the Spruce Pine thrust sheets. The Spruce Pine thrust sheet is especially noteworthy because it contains large bodies of eclogite near its base.

All the thrust sheets were transported to the northwest during the Alleghanian orogeny at the end of the Paleozoic. The Pumpkin Patch and the Spruce Pine thrust sheets, however, were juxtaposed prior to the Alleghanian and were affected by the Taconic and possibly Acadian orogenies. Published metamorphic mineral ages from amphibolite facies rocks in the Pumpkin Patch and Spruce Pine thrust sheets and eclogite from the Spruce Pine thrust sheet are Ordovician, indicating that they were initially juxtaposed during the Taconic orogeny. The eclogite bodies within the Spruce Pine thrust sheet were probably generated in a Taconic subduction zone and thrust onto the Laurentian margin as relatively coherent bodies. The contact between the Pumpkin Patch and Spruce Pine thrust sheets is now an amphibolite facies dextral strike-slip shear zone. Preliminary mineral ages from rocks in this shear zone are Devonian, suggesting that the original Taconic thrust in this area was reactivated during the Acadian orogeny as a strike-slip fault.

The faults bounding the Beech Mountain and Pardee Point thrust sheets are Alleghanian northwest-directed thrusts. The fault separating the Pumpkin Patch and Spruce Pine thrust sheets is cut by one of these Alleghanian faults in the vicinity of the Grandfather Mountain window, indicating that this fault was transported to the northwest along with the composite Blue Ridge thrust complex at the end of the Paleozoic.

INTRODUCTION

The Blue Ridge thrust complex refers to the stack of crystalline thrust sheets west of the Brevard fault zone which structurally overlie the Linville Falls fault (Figure 1; Goldberg et al., 1989). Individual thrust sheets are distinguished by changes in rock type, metamorphic history, and the presence of thick mylonitic or cataclastic fault zones. The thrust sheets, from structurally lowest to highest, are the Pardee Point thrust sheet, the Beech Mountain thrust sheet, the Pumpkin Patch thrust sheet, and the Spruce Pine thrust sheet.

Other authors have subdivided the rocks of the North Carolina Blue Ridge into

Present addresses:
1. Dept of Geology, Appalachian State Univ., Boone, NC 28608 and Appalachian Resources, 205 Providence Rd., Chapel Hill, NC 27515.
2. 2619 Mt. Gilead Church Rd., Pittsboro, NC 27312.

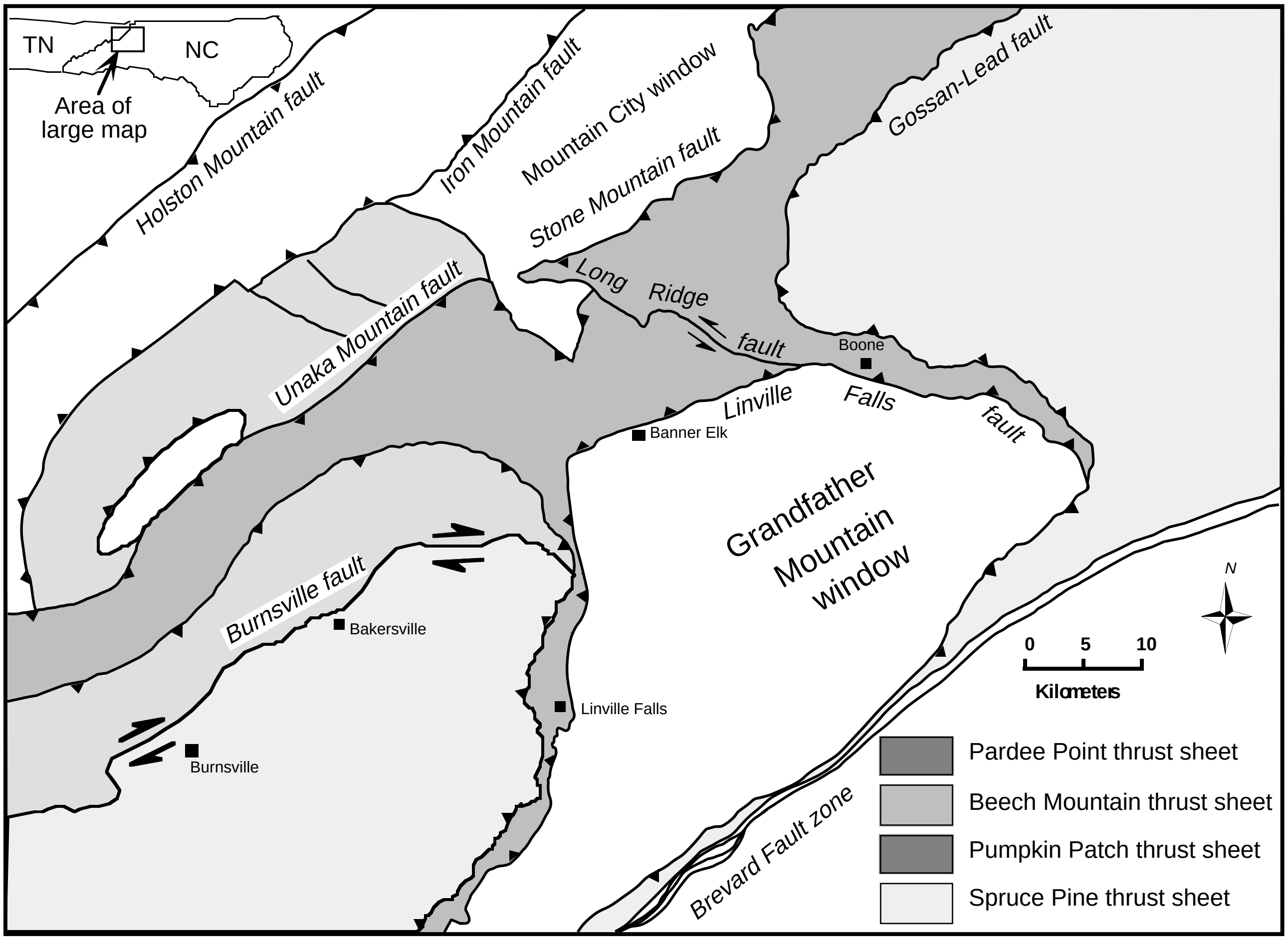


Figure 1. Generalized geologic map of the Blue Ridge of western North Carolina. Four thrust sheets of the Blue Ridge thrust complex are shown. All faults are Alleghanian thrusts and strike-slip faults except for the Burnsville fault, which is Ordovician - Devonian. Modified from Adams et al. (1995).

different terranes or thrust sheets, using similar criteria. Figure 1 in Raymond and Abbott (this volume) summarizes the classification schemes used by other authors. We have used the classification of Goldberg et al. (1989) in our past work and will continue this practice in this paper.

The structural history of the area outlined in this paper is primarily based on kinematic studies of the fault zones bounding the thrust sheets, structural geology of the rocks within the thrust sheets, and the grade and age of metamorphism. Although some of the thrust sheets record Precambrian deformation, metamorphism, and igneous activity, we are restricting our analysis to Paleozoic events. Not surprisingly, the record of early Paleozoic events has been obscured by later Paleozoic events and therefore our model becomes more generalized for early events. Our current model should be considered one in a series of successive approximations which are refined when new data become available. Nevertheless, we feel that we can provide a reasonable interpretation of the structural evolution of the Blue Ridge of western North Carolina from the Ordovician through the Pennsylvanian.

PALEOZOIC METAMORPHISM WITHIN THE BLUE RIDGE THRUST COMPLEX

Detailed descriptions of the metamorphic grade of the four thrust sheets in the Blue Ridge thrust complex can be found in Butler (1991) and Adams and Trupe (this volume). Ages of metamorphism of the thrust sheets can be found in Goldberg and Dallmeyer (1997) and are summarized by Adams and Trupe (this volume). The following summary is based on these studies.

ORDOVICIAN (TACONIC) AMPHIBOLITE AND ECLOGITE FACIES METAMORPHISM

Evidence for Ordovician amphibolite facies metamorphism is restricted to the Spruce Pine and Pumpkin Patch thrust sheets. Although Goldberg and Dallmeyer (1997) report a metamorphic mineral age of 451 Ma for a sample within the Beech Mountain thrust sheet, this sample actually belongs to the Pumpkin Patch thrust sheet (Adams and Trupe, this volume).

Eclogite facies metamorphism has been recognized in two places within the Spruce Pine thrust sheet: near Bakersville, North Carolina (Willard and Adams, 1994; Adams et al., 1995), and northwest of Boone, North Carolina (Abbott and Raymond, this volume). Sm-Nd mineral-whole rock isochrons from eclogite near Bakersville give a range of ages from about 410-450 Ma (Adams et al., 1995).

SILURO-DEVONIAN (ACADIAN) AMPHIBOLITE FACIES METAMORPHISM AND STRIKE-SLIP FAULTING

Goldberg and Dallmeyer (1997) report Silurian and Devonian amphibolite facies metamorphism in the Pumpkin Patch and Spruce Pine thrust sheets (see also Trupe and Adams, this volume). There is no evidence of Siluro-Devonian metamorphism in the Beech Mountain or Pardee Point thrust sheet.

The Burnsville fault (Figure 1), which separates the Spruce Pine thrust sheet from the Pumpkin Patch thrust sheet, is an amphibolite facies dextral strike-slip shear zone (Adams et al., 1995; Burton, 1996). Goldberg and Dallmeyer report a Devonian cooling age for rocks within the Burnsville fault zone.

MISSISSIPPIAN-PENNSYLVANIAN (ALLEGHANIAN) GREENSCHIST FACIES METAMORPHISM AND THRUSTING

Evidence of significant Alleghanian metamorphism is restricted to the Beech Mountain and Pardee Point thrust sheets (Butler 1991, Adams and Trupe, this volume). The Beech Mountain thrust sheet experienced pervasive greenschist facies metamorphism and the Pardee Point experienced greenschist to sub-greenschist facies metamorphism.

The Alleghanian thrusts throughout the Blue Ridge thrust complex were active under greenschist facies, or lower, conditions (Abbott and Raymond, 1984; Mies, 1990; Trupe, 1989; Adams, 1990; Schedl et al., 1992).

STRUCTURAL MODELS

ORDOVICIAN CONVERGENCE AND COLLISION

According to Hatcher (1989), the Taconic orogeny in the southern Appalachians was the result of the collision between the Piedmont terrane and Laurentia. Convergence began in the Early Ordovician as the Piedmont advanced over an east-dipping subduction zone (Figure 2). Raymond et al. (1989) and Adams et al. (1995) interpret the Ashe Metamorphic Suite (AMS) to be the metamorphosed accretionary wedge formed at the leading edge of the Piedmont terrane. The AMS contains pelitic schist, amphibolite, and ultramafic rocks

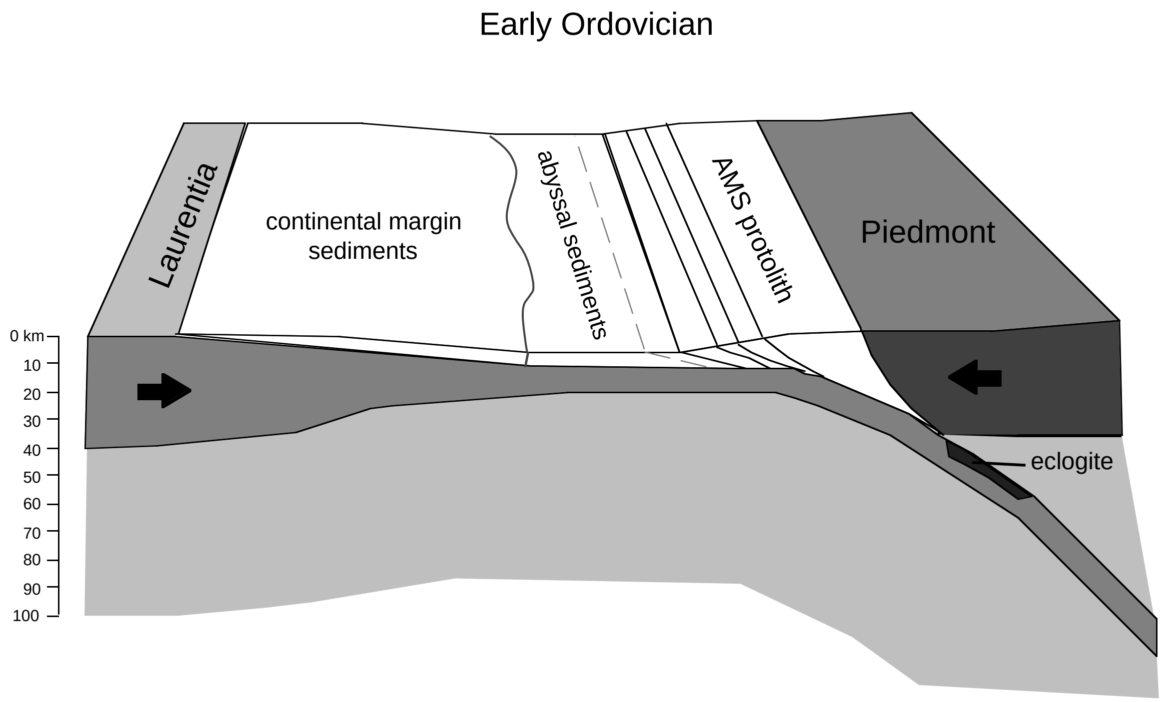


Figure 2. Ordovician convergence between Laurentia and Piedmont terrane. Subducted oceanic crust undergoes eclogite facies metamorphism. Accretionary wedge is protolith for Ashe Metamorphic Suite (AMS).

and commonly has a block-in-matrix texture, which is typical of accretionary melanges (Raymond et al., 1989).

Deeply subducted basaltic crust was metamorphosed to eclogite, which was eventually detached and incorporated into the accretionary wedge. The uplift mechanism of high-pressure metamorphic rocks is an enduring problem in structural geology. Cloos (1982) proposed that eclogite blocks in the Franciscan Complex of California were entrained in an upward-flowing mud melange. In his model, only blocks which are less than about 25 meters in diameter can be uplifted. The eclogite blocks in the Blue Ridge range in size from centimeter-scale blocks to continuous layers up to 200 meters thick and a kilometer long (Adams et al., 1995). The size of the largest blocks seems to prohibit uplift by Cloos' mechanism. Mechanisms which involve paired thrust and normal faults (e.g. Platt, 1986) have been proposed to explain uplift of large eclogite facies terranes, but as of this writing we have no evidence for large-displacement normal faults in the AMS. We do not know the extent of eclogite facies metamorphism within the AMS although Adams et al. (1995) suggested that high pressure metamorphism may have been widespread (see also Abbott and Raymond, this volume).

Collision of the Piedmont terrane with Laurentia occurred by the Middle Ordovician (Figure 3; Hatcher, 1989; Raymond and Johnson, 1994). The collision induced amphibolite facies metamorphism in the underthrust Laurentian margin and in the overlying AMS. The amphibolite facies metamorphic front propagated to the west as the collision progressed and affected rocks which were ultimately incorporated into the Pumpkin Patch thrust sheet. The eclogite bodies are locally retrograded to amphibolite which probably occurred sometime during the Ordovician and

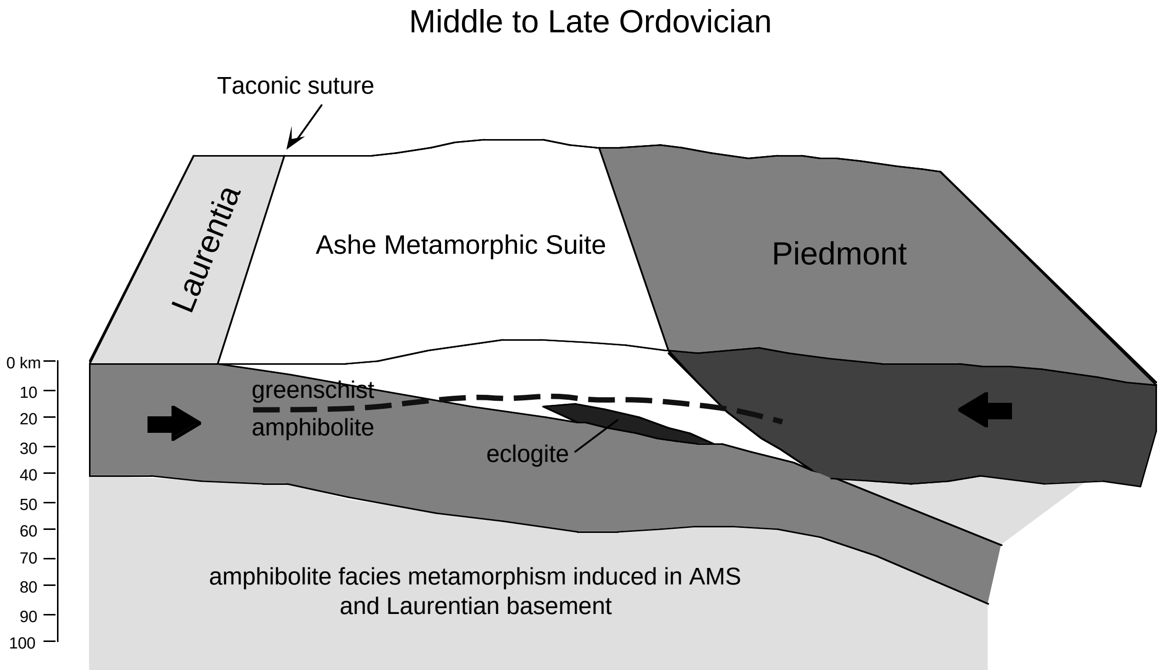


Figure 3. Taconic orogeny resulting from Middle to Late Ordovician collision between Piedmont and Laurentia. Underthrust Laurentian margin undergoes amphibolite facies metamorphism. Eclogite body is incorporated into Ashe Metamorphic Suite.

Silurian as the eclogite was brought to shallower levels.

SILURO-DEVONIAN STRIKE-SLIP FAULTING

Following the collision of the Piedmont terrane with Laurentia, the Taconic suture evolved into a dextral strike slip fault called the Burnsville fault (Adams et al., 1995; Figure 4). The presence of post-Taconic, dextral motion on the suture has been recognized at localities from Alabama to Newfoundland (Adams et al., 1995). This may have been a discrete event (Acadian orogeny?) which occurred tens of millions of years after the end of the Taconic collision or it could have been the final phase of a protracted event which began in the Ordovician and ended in the Devonian. Existing geochronologic data cannot discriminate between these two models (Goldberg and Dallmeyer, 1997).

The Spruce Pine Plutonic Suite was emplaced between 390 and 410 Ma (Kish, 1983). Spruce Pine pegmatites intrude mylonites within the Burnsville fault zone and are also sheared, indicating that shearing occurred sometime during the Siluro-Devonian. The part of the Burnsville fault zone currently exposed was active under amphibolite facies conditions (Adams et al., 1995; Burton, 1996).

The rocks of the Spruce Pine thrust sheet were initially juxtaposed against the rocks of the Pumpkin Patch thrust sheet during the Ordovician. Movement between these two terranes stopped by the end of the Devonian.

DEVONIAN-MISSISSIPPIAN UPLIFT AND COOLING

Goldberg and Dallmeyer (1997) report 40Ar/39Ar muscovite ages which indicate regional cooling of the Blue Ridge thrust

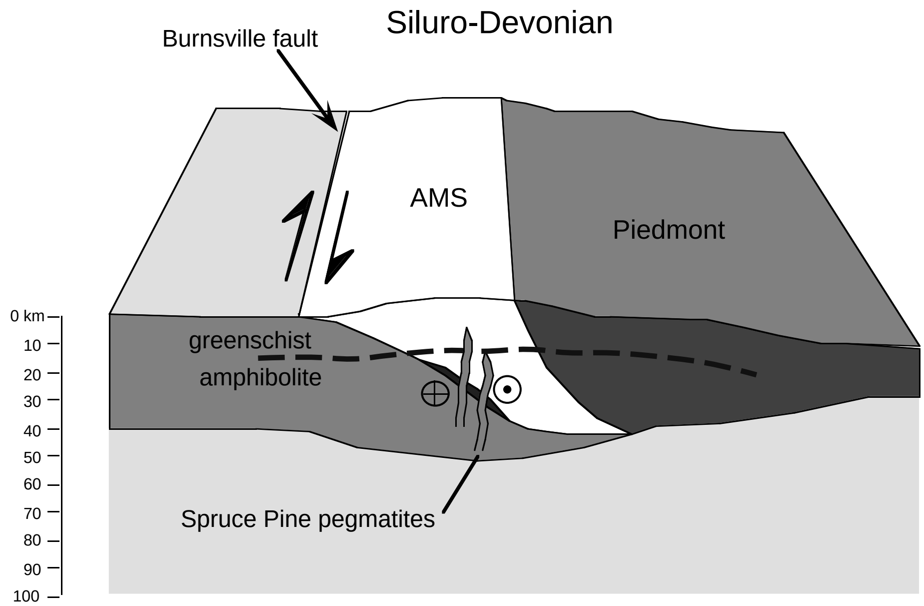


Figure 4. Taconic collision evolves into Siluro-Devonian dextral strike-slip shear zone (Burnsville fault). Spruce Pine pegmatites intrude fault zone, eclogite, AMS, and Laurentian basement rocks.

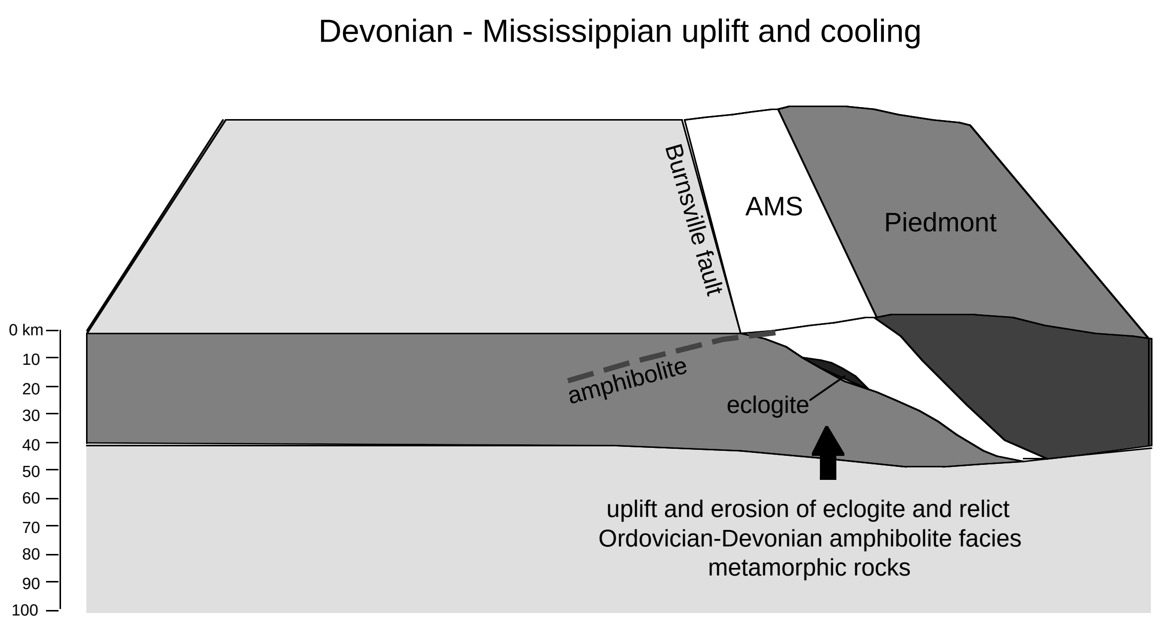


Figure 5. Uplift and cooling during Devonian - Mississippian time.

complex during the Devonian and Mississippian (Figure 5). Rocks metamorphosed under amphibolite and eclogite facies during the Ordovician through Devonian were uplifted and the amphibolite metamorphic front may have rotated to a steeper orientation.

MISSISSIPPIAN-PENNSYLVANIAN (ALLEGHANIAN) THRUSTING

Thrusting during the Alleghanian progressed from the southeast towards the northwest. The thrust below the composite Spruce Pine/Pumpkin Patch thrust sheet cuts through the part of the Laurentian crust that had experienced Ordovician - Devonian amphibolite facies metamorphism (Figure 6). If the thrust sheet had originally included lower grade Laurentian rocks, they have since been removed by erosion.

Northwest transport of the composite Spruce Pine/Pumpkin Patch thrust sheets was probably accompanied by movement of the Piedmont thrust sheet (Figure 7). This out-of-sequence thrust would have decapitated the Taconic suture and transported it to the northwest (see Rankin et al., 1991, for a similar interpretation). In addition, the relict Ordovician - Devonian amphibolite front would have been overridden such that later thrusts would cut Laurentian crust which had not experienced high grade Paleozoic metamorphism (Figure 8).

In our model, the pervasive Alleghanian greenschist metamorphism in the Beech Mountain thrust sheet was induced by emplacement of the composite Spruce Pine/Pumpkin Patch thrust sheet. The weak Alleghanian metamorphism present in the Pardee Point thrust sheet was induced by emplacement of the Beech Mountain thrust sheet along the Linville Falls fault. All of the thrust sheets were folded by duplexing of basement rocks beneath the Grandfather Mountain window (Figure 9; Rankin et al., 1991; Schedl et al., 1997).

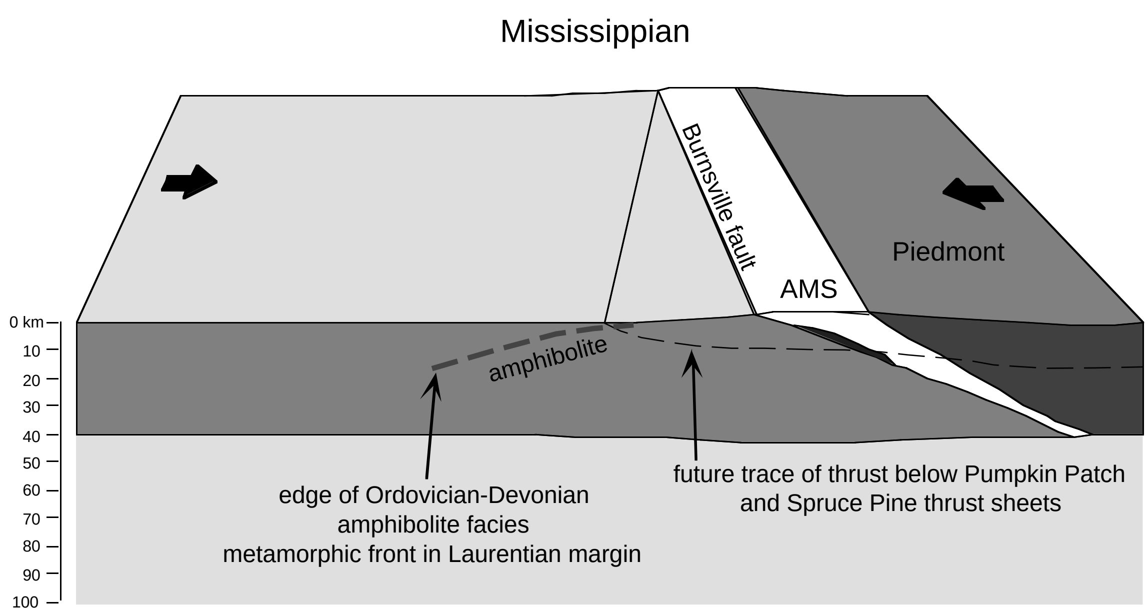


Figure 6. First Alleghanian thrust cuts through Taconic suture and into Ordovician - Devonian amphibolite grade rocks in the Laurentian basement.

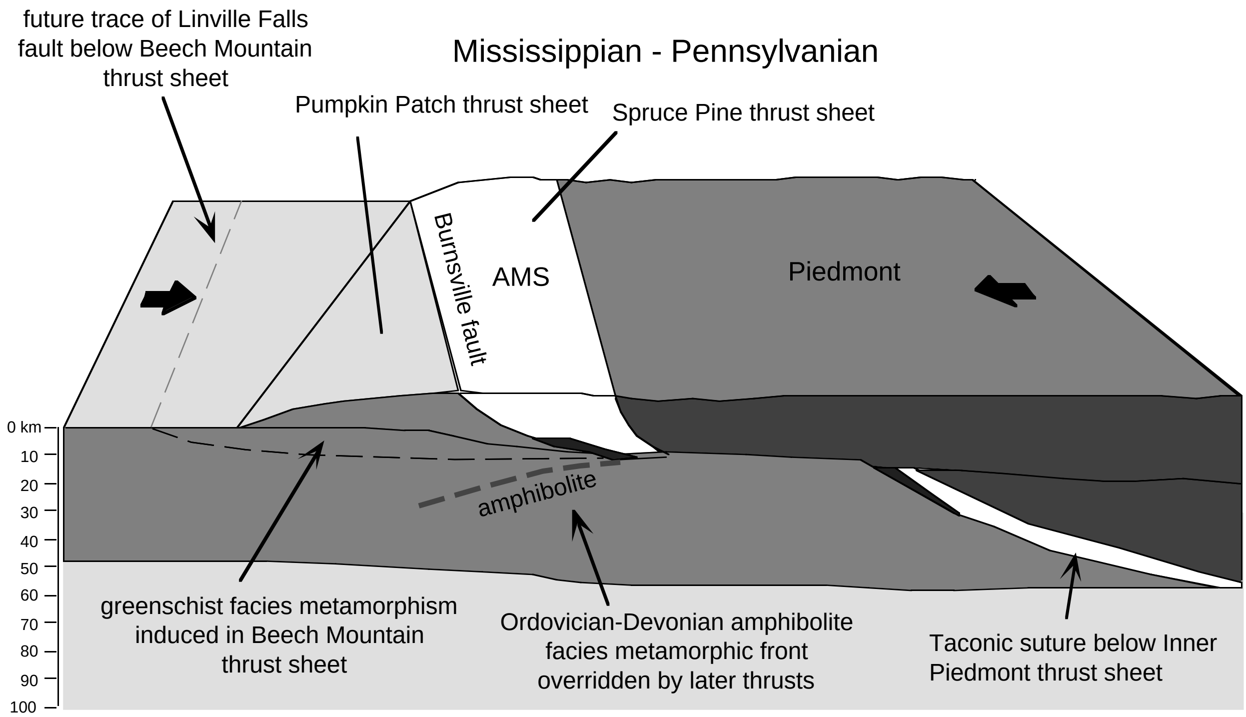


Figure 7. Composite Spruce Pine/Pumpkin Patch thrust sheet induces greenschist facies metamorphism in adjacent Beech Mount thrust sheet rocks. Decapitated Taconic suture in footwall is beneath Piedmont thrust sheet.

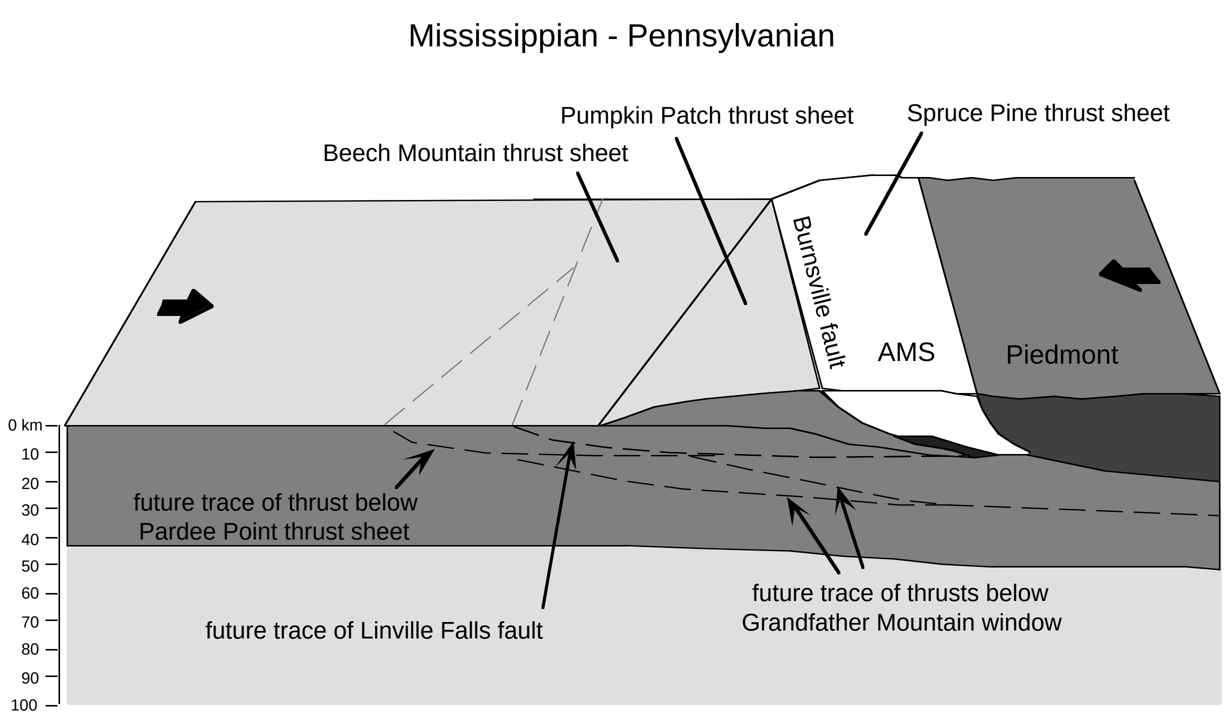


Figure 8. Later Alleghanian thrusts propagate into Laurentian basement which has not been affected by Ordovician - Devonian events.

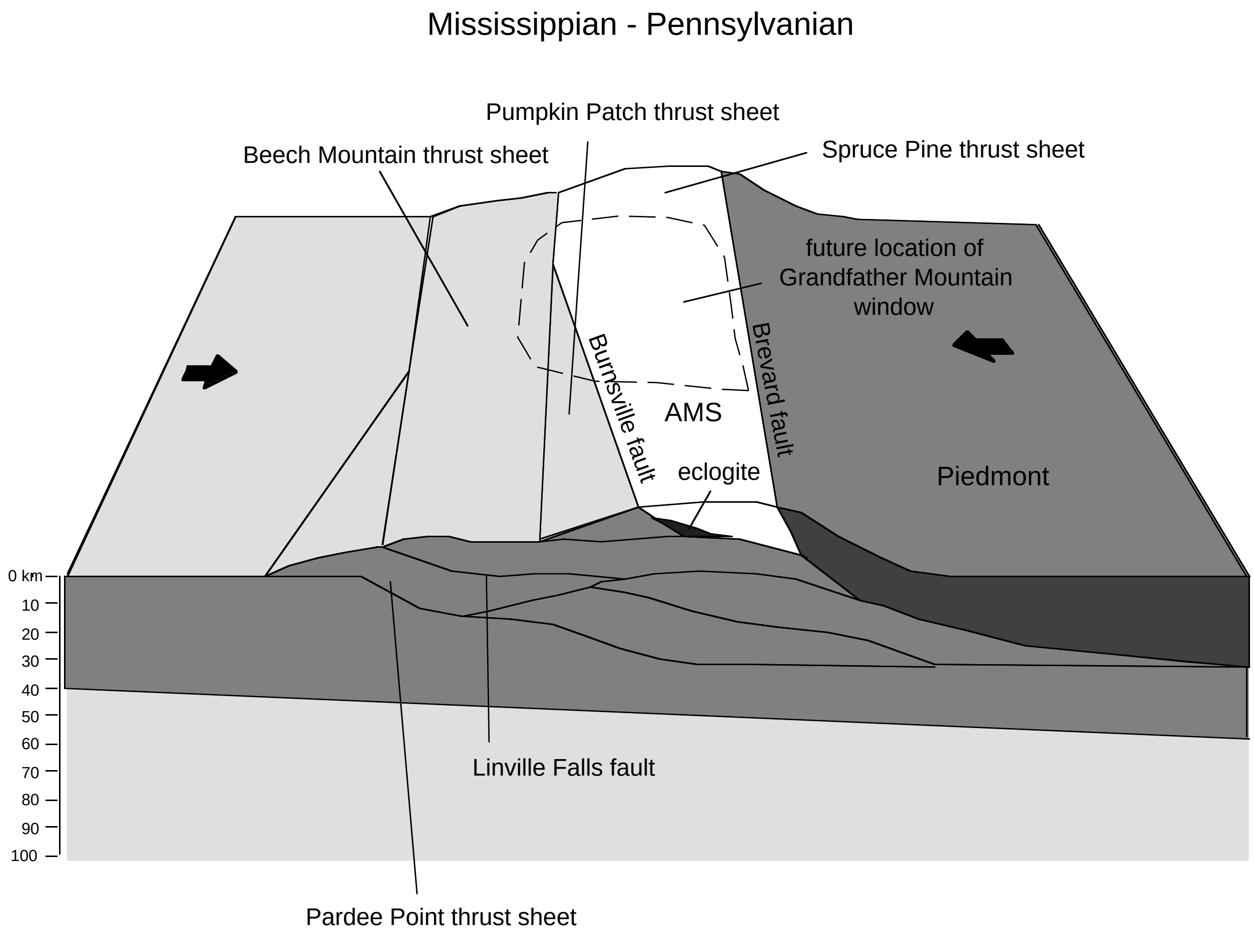


Figure 9. Duplexing beneath Grandfather Mountain window domes thrust sheets. Later erosion creates Grandfather Mountain window.

SUMMARY

The four thrust sheets of the Blue Ridge thrust complex contain a fairly complete record of at least two and possibly three distinct orogenic episodes. The structurally highest Spruce Pine thrust sheet contains eclogite and amphibolite facies metamorphic rocks associated with the Ordovician Taconic orogeny. This event sutured the Spruce Pine thrust sheet to the Laurentian rocks of the Pumpkin Patch thrust sheet and induced amphibolite facies metamorphism within the Pumpkin Patch sheet. Siluro-Devonian transpression, due either to a separate event (Acadian orogeny?), or a prolonged transpressional collision initiated during the Taconic orogeny, is recorded by the dextral strike-slip Burnsville fault. Devonian amphibolite facies rocks in the Spruce Pine and Pumpkin Patch sheets are a record of this event.

Northwest thrusting during the Alleghanian orogeny transported the composite Spruce Pine/Pumpkin Patch thrust sheet over the Laurentian rocks of the Beech Mountain thrust sheet. This induced pervasive greenschist facies metamorphism within the Beech Mountain sheet, which in turn was thrust over the adjacent Pardee Point thrust sheet along the Linville Falls fault. The lack of significant Paleozoic metamorphism in the Pardee Point thrust sheet suggests that the thickness of the thrust stack above the Pardee Point sheet was significantly less than above the Beech Mountain sheet.

ACKNOWLEDGMENTS

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REFERENCES

Abbott, R.N., Jr., and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: metamorphism and observations on geologic history: American Journal of Science, v. 284, p. 350-375.

Adams, M.G., 1990, The geology of the Valle Crucis area, northwestern North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 95 p.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, Current Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

Burton, F.H., 1996, Kinematic study of the Taconic suture, west-central North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 114 p.

Butler, J.R., 1991, Metamorphism, *in* Horton, J.W.,Jr., and Zullo, V.A., editors, The geology of the Carolinas: Carolina Geological Society Fiftieth Anniversary Volume: Knoxville, The University of Tennessee Press, Carolina Geological Society, p. 127-141.

Cloos, M., 1982, Flow melangés: Numerical modelling and geologic constraints on their origin in the Franciscan subduction complex: Geological Society of America Bulletin, v. 93, p. 330-345.

Goldberg, S.A., Butler, J.R., Mies, J.W., and Trupe, C.H., 1989, The southern Appalachian orogen in northwestern North Carolina and adjacent states: International Geological Congress Field Trip T365 Guidebook, American Geophysical Union, Washington, D.C., 55 p.

Goldberg, S.A., and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge thrust complex, North Carolina and Tennessee: American Journal of Science, v. 297, p. 488-526.

Hatcher, R. D., Jr., 1989, Tectonic synthesis of the U. S. Appalachians, p. 511-535, in Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, the geology of North America, v. F-2, 767 p.

Kish, S.A., 1983, A geochronological study of deformation and metamorphism in the Blue Ridge and Piedmont of the Carolinas: Ph. D dissertation, University of North Carolina at Chapel Hill, 220 p.

Mies, J.W., 1990, Structural and petrologic studies of mylonite at the Grenville basement - Ashe Formation boundary, Grayson County, Virginia to Mitchell County, North Carolina, Ph.D. dissertation, University of North Carolina at Chapel Hill, 330 p.

Platt, J.P., 1986, Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks: Geological Society of America Bulletin, v. 97, p. 1037-1053.

Rankin, D.W., Dillon, W.P., Black, D.F.B., Boyer, S.E., Daniels, D.L., Goldsmith, R., Grow, J.A., Horton, J.W.,Jr., Hutchinson, D.R., Klitgord, K.D., McKowell, R.C., Miltop, D.J., Owens, J.P., Phillips, J.D., with contributions by Bayer, K.C., Butler, J.R., Elliott, D.W., and Milici, R.C., 1991, Centennial Continent/Ocean Transect #16, E-4, Central Kentucky to the Carolina Trough, The Geological Society of America, 41 p.

Raymond, L.A., and Johnson, P.A., 1994, The Mars Hill Terrane: An enigmatic southern Appalachian terrane: Geological Society of America Abstracts with Programs, v. 26, n. 4, p. 59.

Raymond, L.A., Yurkovich, S.P., and McKinney, M., 1989, Block-in-matrix structures in the North Carolina Blue Ridge belt and their significance for the tectonic history of the southern Appalachian orogen, in Horton, J.W., Jr., and Rast, N., editors, Melangés and Olistostromes of the U.S. Appalachians: Geological Society of America Special Paper 228, p. 195-215.

Schedl, A., Fullagar, P.D., and Valley, J.W., 1997, Implications of geochemical and gravity data for the nature of strata beneath the Blue Ridge - Piedmont thrust sheet, USA: Earth and Planetary Science Letters, v. 146, p. 165-179.

Schedl, A., McCabe, C., Montanez, I., Fullagar, P.D., and Valley, J., 1992, Alleghenian regional diagenesis: A response to the migration of modified metamorphic fluids derived from beneath the Blue Ridge-Piedmont thrust sheet: Journal of Geology, v. 100, p. 339-352.

Trupe, C.H., 1989, Microstructural analysis of mylonites from the Blue Ridge thrust complex, northwestern North Carolina: M.S. Thesis, University of North Carolina at Chapel Hill, 101 p.

Willard, R.A., and Adams, M.G., 1994, Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61-70.

CONDITIONS AND TIMING OF METAMORPHISM IN THE BLUE RIDGE THRUST COMPLEX, NORTHWESTERN NORTH CAROLINA AND EASTERN TENNESSEE

Mark G. Adams[1] and Charles H. Trupe[2]
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

ABSTRACT

The Blue Ridge thrust complex in the vicinity of the Grandfather Mountain window consists of at least four thrust sheets with different metamorphic and deformational histories. The lower three thrust sheets contain Grenville-age amphibolite to granulite grade metamorphic rocks that were variably affected by subsequent Paleozoic tectonothermal events. In the lowest sheet, the Pardee Point thrust sheet, Paleozoic metamorphism was no higher than chlorite grade, and Grenville metamorphic assemblages are not significantly retrograded. Grenville basement and Neoproterozoic intrusive rocks of the Beech Mountain thrust sheet were pervasively deformed during greenschist grade Alleghanian faulting, but evidence for earlier Paleozoic metamorphism is equivocal. The Pumpkin Patch thrust sheet contains Grenville basement gneisses and Neoproterozoic Bakersville intrusive rocks that were affected by amphibolite facies Paleozoic metamorphism. The uppermost tectonic unit, the Spruce Pine thrust sheet, consists of metasedimentary and metavolcanic rocks of the Ashe and Alligator Back Metamorphic Suites. The occurrence of eclogite at the base of the Spruce Pine thrust sheet documents early high-pressure metamorphism. Pelitic schists and amphibolites of the Ashe Metamorphic Suite record kyanite grade peak regional metamorphism followed by cooling and decompression along a clockwise retrograde P-T path. Both Ordovician and Siluro-Devonian radiometric ages are recorded in metamorphic rocks from the Spruce Pine and Pumpkin Patch thrust sheets. Dextral strike-slip faulting along the Spruce Pine-Pumpkin Patch contact occurred under amphibolite-grade conditions, and was broadly contemporaneous with intrusion of the Spruce Pine pegmatites (~390-400 Ma). Late Paleozoic greenschist-grade deformation records assembly and emplacement of the Blue Ridge thrust complex along top-to-northwest thrust faults.

INTRODUCTION

The Blue Ridge thrust complex west and northwest of the Grandfather Mountain window (Figure 1) consists of a series of crystalline thrust sheets bounded by shear zones up to a kilometer thick (Goldberg et al., 1986a, 1989; Butler et al., 1987). The complex forms the hanging wall of the Linville Falls fault, which frames the Grandfather Mountain window, and is bounded on the west by the Stone Mountain-Iron Mountain-Holston Mountain fault system and on the east by the Brevard fault zone. Component thrust sheets display differences in P-T and deformation histories, and generally show a decrease in Paleozoic regional metamorphic grade with increasing structural depth within the complex (Goldberg et al., 1989). The Blue Ridge thrust complex thus preserves an inverted metamorphic gradient due to combined structural and metamorphic processes.

Present addresses:
[1] Appalachian Resources, 205 Providence Rd., Chapel Hill, NC, 28605 and Dept. of Geology, Appalachian State Univ., Boone, NC 28608
[2] 2619 Mt. Gilead Church Rd., Pittsboro, NC, 27312

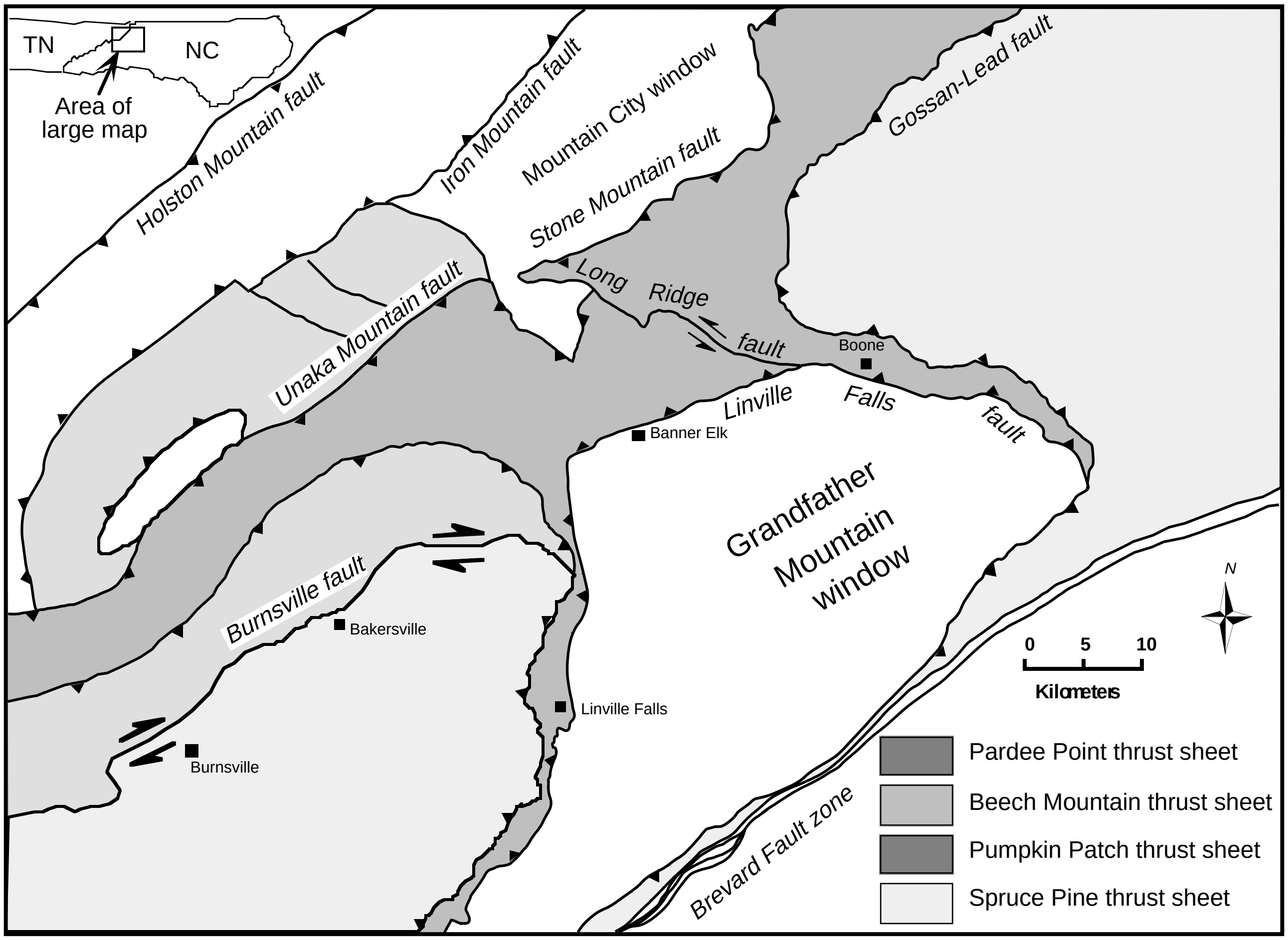

Figure 1. Generalized tectonic map of the Blue Ridge thrust complex of northwestern North Carolina and eastern Tennessee. Modified after Adams et al. (1995a).

The structurally highest sheet, the Spruce Pine thrust sheet (Toe terrane of Raymond et al., 1989; Jefferson terrane of Horton et al., 1989) contains high-grade metavolcanic and metasedimentary rocks (Ashe and Alligator Back Metamorphic Suites; Rankin, 1970; Abbott and Raymond, 1984; Raymond et al., 1989), Paleozoic granitic intrusive rocks, and ultramafic bodies, and lacks recognizable Grenville-age basement rocks. The three thrust sheets structurally below the Spruce Pine thrust sheet are characterized by the presence of Grenville basement rocks, Bakersville Suite mafic dikes and gabbro bodies, and Crossnore and Beech Suite peralkaline granitic plutons. The Pumpkin Patch thrust sheet (Cullowhee terrane of Raymond et al., 1989; Mars Hill terrane of Bartholomew and Lewis, 1992), occurs immediately below the Spruce Pine thrust sheet, bounded by the Burnsville fault (Adams et al., 1995a). Beneath the Pumpkin Patch thrust sheet is the Beech Mountain thrust sheet (Sherwood terrane of Raymond et al., 1989), which contains the Neoproterozoic Crossnore-Beech intrusive suite. The lowermost thrust sheet is the Pardee Point thrust sheet, in which Cambrian Chilhowee Group sedimentary rocks unconformably overlie Grenville basement rocks.

The Blue Ridge thrust complex records multiple tectonothermal events. Basement thrust sheets were affected by Grenville-age

(1000-1200 Ma) metamorphism and deformation. Most regional syntheses of the Paleozoic tectonic evolution of the southern Appalachians begin with an Ordovician tectonothermal event correlated with the Taconic orogeny, followed by Acadian metamorphism and deformation, and major thrusting during the Alleghanian orogeny (e.g. Butler, 1973; Hatcher, 1987; Rankin et al., 1989). In the following discussion, age ranges used for these tectonothermal events are as follows: Taconic, 510-460 Ma; Acadian, 410-360 Ma; and, Alleghanian, 325-265 Ma (Butler, 1991).

SPRUCE PINE THRUST SHEET

The Spruce Pine thrust sheet is the uppermost unit in the Blue Ridge thrust complex, and contains rocks of the Neoproterozoic Ashe and Alligator Back Metamorphic Suites. Bryant and Reed (1970) and Abbott and Raymond (1984) postulated that the contact between the Ashe Metamorphic Suite (AMS) and underlying Cranberry Gneiss is a fault. The contact between the Spruce Pine and Pumpkin Patch thrust sheets was defined as a northwest-directed, post-metamorphic thrust fault (Goldberg et al., 1986a; Butler et al., 1987), and subsequent studies have verified these relationships adjacent to and northeast of the Grandfather Mountain window (Mies, 1988; 1990; Mies and Trupe, 1989). Along strike to the southwest, the contact between the AMS and basement is a syn- to post-peak-metamorphic dextral strike-slip fault that predates the thrust fault adjacent to the window (Trupe et al., 1991; Willard et al., 1991; Mallard et al., 1994; Willard and Adams, 1994; Adams et al., 1995a). Adams et al. (1995a) named this fault the Burnsville fault. Field relations indicate that the strike slip faulting is overprinted in the vicinity of the Grandfather Mountain window by Alleghanian shearing and thrust faulting (Adams et al., 1995a). Farther to the southwest, other workers have stated that the presumably equivalent contact is a pre-metamorphic thrust fault, correlative with the Hayesville fault (Hatcher, 1987; Merschat and Wiener, 1988; Eckert et al., 1989; Hatcher and Goldberg, 1991).

The Spruce Pine thrust sheet consists predominantly of amphibolite facies metasedimentary rocks including metapelitic schist, metasandstone, and mica gneiss. Also present are abundant amphibolite, minor dunite, altered ultramafic rocks, and Siluro-Devonian granitoid intrusions of the Spruce Pine Plutonic Suite (Rankin et al., 1973). Eclogite occurs at the base of the thrust sheet in the Bakersville, North Carolina area (Willard and Adams, 1994; Adams et al., 1995a). The association of metasedimentary rocks, amphibolite, and ultramafic rocks has been interpreted by several workers to represent a combination of metamorphosed oceanic crust and sediments formed east of the Laurentian margin, possibly as an accretionary mélange containing fragments of dismembered ophiolite (Hatcher, 1978; Abbott and Raymond, 1984; Horton et al., 1989; Raymond et al., 1989; Willard and Adams, 1994; Adams et al., 1995a). Geochemical analyses of mafic and ultramafic rocks in the eastern Blue Ridge generally support this interpretation (Hatcher et al., 1984; Misra and Conte, 1991).

GRADE AND TIMING OF METAMORPHISM

The Spruce Pine thrust sheet preserves evidence of several metamorphic events. Eclogite facies rocks occur near the base of the sheet, suggesting an early episode of high-pressure metamorphism. The metasedimentary and metavolcanic rocks of the Ashe Metamorphic Suite (AMS) contain amphibolite facies assemblages (kyanite grade). These rocks were subsequently affected by shearing in the Burnsville fault that deformed, but did not significantly retrograde, the amphibolite facies assemblages. To the northeast, near the Grandfather Mountain window, rocks of the AMS were overprinted by greenschist facies retrogression associated with northwest-directed thrust faulting.

Peak metamorphic assemblages in the AMS indicate amphibolite facies conditions of metamorphism. Published P-T estimates are consistent with conditions demonstrated by mineral assemblages (Table 1). Abbott and Raymond (1984) described evidence for multiple metamorphic events in the AMS rocks north of the Grandfather Mountain window, and estimated peak conditions of 7-10 kbar and 700 °C. McSween et al. (1989) presented estimates for metamorphic temperatures and pressures of in the AMS of 600-650 °C and 7.5 kbar. Satterfield (1992) reported estimates of 650 °C at a minimum pressure of 7.5 kbar for peak metamorphic conditions in AMS rocks north of the Grandfather Mountain window. Although these workers interpreted metamorphic conditions to represent Taconic metamorphism, none of these studies presented geochronologic constraints for the time of regional metamorphism.

Goldberg et al. (1992a, 1992b), Adams et al. (1995a), and Trupe (1997) reported P-T estimates for staurolite-kyanite-garnet mica schists and garnet amphibolites of the AMS. The assemblage in the schists constrains P-T estimates to the stability field of kyanite+staurolite+garnet+biotite+muscovite (Goldberg et al., 1992b). Fibrolite and chlorite

Table 1. Summary of quantitative P-T estimates for the Spruce Pine and Pumpkin Patch thrust sheets.

Thrust Sheet	Rock type	Pressure (kb)	Temperature (°C)
Spruce Pine	Pelitic schist and amphibolite	7-10[a]	700[a]
		7.5[b]	600-650[b]
		7-9 ("peak")[c]	640-700 ("peak")[c]
		4-6 (retrograde)[c]	550-610 (retrograde)[c]
		~7.5[d]	650[d]
		5-6.5[e,f] (retrograde)	550-610[e,f] (retrograde)
		8.5-11[e,f] (garnet amphibolite)	675-705 [e,f] (garnet amphibolite)
	Eclogite	13-17 (prograde)[g]	625-790 (prograde)[g]
		8.5-12 (retrograde)[g]	650-730 (retrograde)[g]
	Pelitic schist adjacent to eclogite	6-8 ("peak")[g,h]	580-640 ("peak")[g,h]
		5.5-6.5 (retrograde)[g,h]	565-610 (retrograde)[g,h]
Pumpkin Patch	Gneiss	6.5-8[i,j]*	750-847[i,j]*
		10-12[i]**	680-760[i]**
		7.5-9[j]**	700-740[j]**
	Meadlock Mtn. gneiss	~13 ("peak")[k]	725 ("peak")[k]
		~9 (retrograde)[k]	660 (retrograde)[k]

[a] Abbott and Raymond, 1984; [b] McSween et al., 1989; [c] Goldberg et al., 1992a; [d] Satterfield, 1992; [e] Adams et al., 1995a; [f] Trupe, 1997; [g] Willard and Adams, 1994; [h] Adams and Stewart, 1993; [i] Monrad and Gulley, 1983 ; [j] Gulley, 1985; [k] Adams et al., 1995b.

* Grenville metamorphism; ** Paleozoic metamorphism

that occur along grain boundaries of major minerals in the schists are interpreted to be late phases that grew after the peak of metamorphism. These authors interpreted these observations to indicate that final equilibration occurred near the kyanite-sillimanite phase boundary, indicating decompression and cooling. P-T estimates utilizing several geothermobarometers for core-rim assemblages are consistent with petrographic observations (Figure 2). Estimates for peak P-T conditions in metapelitic schists are approximately 7-9 kbar and 640-700 °C. Estimates from mineral rim compositions are 5-6.5 kbar and 550-610 °C. P-T estimates for garnet amphibolites are 8.5-11 kbar and 675-705 °C.

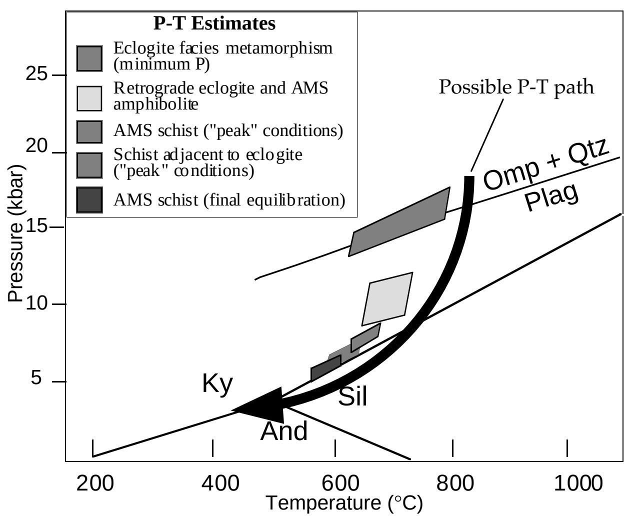

Figure 2. Petrogenetic grid showing P-T estimates for eclogite and associated rocks in the AMS (modified after Willard and Adams, 1994 and Adams et al., 1995a). P-T estimates suggest that the rocks record a continuous retrograde P-T path. Aluminum silicate phase boundaries after Holdaway (1971). Omphacite + quartz = plagioclase reaction boundary calculated from microprobe analyses of omphacite (Jd_{30}) and plagioclase (An_{30}) using the Holland (1980, 1983) jadeite-albite-quartz barometer. And=andalusite; Ky=kyanite; Omp=omphacite; Plag=plagioclase; Qtz=quartz; Sil=sillimanite.

Eclogite bodies occur at the base of the AMS within a sheared metapelitic matrix along the Burnsville fault near Bakersville, North Carolina. The peak eclogite assemblage consists of garnet, omphacite, quartz and rutile. Retrograde metamorphism variably affected the eclogite; the most retrogressed rocks have been altered to amphibolite. Willard and Adams (1994) reported minimum pressures of 13-17 kbar at 625-790 °C for the eclogite facies assemblage, and retrograde amphibolite facies conditions of 8.5-12 kbar and 650-730 °C. Adjacent sheared metapelitic rocks of the AMS record P-T estimates of 6-8 kbar and 580-640 °C for peak assemblages, and 5.5-6.5 kbar at 565-610 °C for final equilibration (Adams and Stewart, 1993; Willard and Adams, 1994).

Published isotopic ages for AMS rocks suggest that they experienced both Taconic and Acadian metamorphism (Table 2). Goldberg et al. (1993) reported Sm-Nd ages of 456-462 Ma from hornblende and epidote in the AMS. Rb-Sr mineral isochrons from amphibolites and metapelites yield dates of 395-419 Ma (Goldberg et al., 1992a; 1993). Goldberg and Dallmeyer (1997) reported ages for metamorphic minerals of the Spruce Pine and Pumpkin Patch thrust sheets. Garnet and hornblende ages (Rb-Sr, Sm-Nd, and $^{40}Ar/^{39}Ar$) yield both Ordovician and Devonian ages. These authors interpreted the two groups of ages to reflect discrete Taconic (Ordovician) and Acadian (Siluro-Devonian) metamorphic events.

Eclogite facies rocks from the Bakersville area give Silurian to Ordovician ages. Sm-Nd garnet - whole-rock ages from the eclogites range from approximately 410 to 450 Ma, with older ages recorded by abraded garnet cores (Adams et al., 1995b). Eclogite mineral separates of garnet and clinopyroxene yield a Sm-Nd mineral isochron age of 410±6 Ma (2σ) (Goldberg et al., 1994).

The Spruce Pine Plutonic Suite (Rankin et al., 1973) consists of pegmatites and alaskite bodies that intrude the AMS. Butler (1973)

Table 2. Summary of pertinent radiometric ages from the AMS and adjacent basement.

Location	Ages (Ma)	Method	Reference
Spruce Pine thrust sheet			
AMS			
Mineral isochron	397±14	Rb-Sr	a
Mineral isochron	375±27	Sm-Nd	a
Garnet	455-460	Rb-Sr & Sm-Nd	a
	386-393	Rb-Sr & Sm-Nd	a
	398-419	Rb-Sr	b
Hornblende	451-472	Rb-Sr & Sm-Nd	a
	379-394	Rb-Sr & Sm-Nd	a
	385-398	$^{40}Ar/^{39}Ar$	a
Hornblende & epidote	456-462	Sm-Nd	b
Sphene	467	U-Pb	b
Spruce Pine pegmatites	390-410	Rb-Sr & U-Pb	c, d, e
Eclogite (garnet)	410-450	Sm-Nd	f
Garnet - clinopyroxene	410±6	Sm-Nd	g
Pumpkin Patch thrust sheet			
Garnet	451-458	Rb-Sr & Sm-Nd	a
	375-397	Rb-Sr	b
Hornblende	455-472	Rb-Sr & Sm-Nd	a
	377±10	Rb-Sr	a
	366-407	$^{40}Ar/^{39}Ar$	a
	408	$^{40}Ar/^{39}Ar$	b
	368-500	$^{40}Ar/^{39}Ar$	h
Hornblende & epidote	370-384	Rb-Sr & Sm-Nd	b
Carvers Gap gneiss	1815±31	Rb-Sr whole-rock	i
Cloudland gneiss	807±26	Rb-Sr whole-rock	i

a - Goldberg and Dallmeyer (1997); b - Goldberg, Dallmeyer, and Su (1993); c - Lesure (1968); d - Kish (1983); e - summary by Butler (1991); f - Adams et al. (1995b); g .- Goldberg et al. (1994); h - Dallmeyer (1975); i - Monrad and Gulley (1983).

stated that these intrusions were closely related in time to amphibolite-grade metamorphism, based on their occurrence almost entirely in the kyanite and higher metamorphic zones, and the absence of contact metamorphic aureoles in AMS rocks. The pegmatites show both concordant and discordant relationships relative to the main metamorphic foliation. Rb-Sr whole-rock ages for the pegmatites fall in the range of 390-410 Ma (Kish, 1983; see summary by Butler, 1991). These dates therefore represent a minimum age for high-grade metamorphism of the AMS.

The Spruce Pine pegmatites also place constraints on the timing of deformation at the base of the Spruce Pine thrust sheet. Along the Burnsville fault, pegmatites intrude mylonitic rocks, and are themselves sheared, indicating that dextral strike-slip faulting was contemporaneous with intrusion of the pegmatites (Adams, 1995; Adams et al., 1995a). Additionally, peak metamorphic minerals are deformed, but not retrograded, in these mylonites. Near the Grandfather Mountain window, AMS rocks are retrograded and Spruce Pine pegmatites are deformed by greenschist-grade northwest-directed thrust faulting (Goldberg et al., 1986a; Mies, 1987). These observations suggest that the Burnsville fault is Acadian in age, and thrust faulting near the Grandfather Mountain window occurred later, presumably during Alleghanian thrusting.

PUMPKIN PATCH THRUST SHEET

Southwest of the Grandfather Mountain window, the Pumpkin Patch thrust sheet underlies the Spruce Pine thrust sheet and overlies the Beech Mountain thrust sheet (Figure 1). The Spruce Pine sheet-Pumpkin Patch sheet contact is represented by the Burnsville fault. The Pumpkin Patch sheet-Beech Mountain sheet contact is represented by an unnamed thrust fault. Northeast of the Grandfather Mountain window, the Pumpkin Patch thrust sheet is apparently absent. The lithology of the Pumpkin Patch thrust sheet is dominated by Mesoproterozoic gneisses and Neoproterozoic Bakersville intrusive rocks.

GRADE AND TIMING OF METAMORPHISM

The rocks of the Pumpkin Patch thrust sheet show evidence of multiple metamorphic events. The Mesoproterozoic basement rocks have a gneissic layering containing amphibolite to granulite facies assemblages (Gulley, 1985; Adams et al., 1995a). Additionally, these basement gneisses are migmatitic, indicating temperatures sufficiently high for anatexis. The gneissic layering in these basement rocks exhibits refolded folds, indicating multiple deformation. This gneissic layering is cross-cut by metadiabase dikes of the Bakersville Intrusive Suite. Thus, cross-cutting relationships of the Bakersville dikes indicate that the basement gneisses were metamorphosed prior to the intrusion of the dikes. The fact that the dikes are also metamorphosed provides evidence of multiple metamorphic events in the Pumpkin Patch thrust sheet. Evidence of retrograde, greenschist facies metamorphism is rare in the Pumpkin Patch sheet.

Monrad and Gulley (1983) and Gulley (1985) documented granulite facies conditions (6.5 - 8 kbar at 750 - 847°C) for the Cloudland and Carvers Gap gneisses in the Pumpkin Patch thrust sheet. These authors also reported Meso- to Neoproterozoic, Rb-Sr whole rock ages for these gneisses (ca. 1.8 Ga for the Carvers Gap gneiss; ca. 800 Ma for the Cloudland gneiss). These authors suggested that the 1.8 Ga age demonstrates the existence of continental crust prior to this date and the 800 Ma age represents limited isotopic equilibration of granulite facies assemblages during the waning stages of the Grenville orogeny. Monrad and Gulley (1983) also reported P-T estimates for a subsequent amphibolite facies metamorphic event (10 - 12 kbar at 680 - 760°C). They interpreted these conditions to record metamorphism during the Taconic orogeny.

Adams et al. (1995b) reported P-T estimates for the Meadlock Mountain gneiss. Microprobe analyses of cores from the peak assemblage yield estimates of ~ 13 kbar at 725° C, and rims give estimates of ~9 kbar at 660° C (Figure 3). These authors interpreted these estimates to represent “peak” and final equilibration conditions of metamorphism during a Paleozoic orogeny (either the Ordovician Taconic or Siluro-Devonian Acadian orogeny).

Goldberg and Dallmeyer (1997) documented radiometric ages for metamorphic minerals from Bakersville metagabbro in the Pumpkin Patch thrust sheet. They interpreted the Sm-Nd and most of the Rb-Sr isochrons to record Ordovician metamorphism. These authors also reported one Rb-Sr hornblende age and several $^{40}Ar/^{39}Ar$ hornblende ages that record Devonian dates. These authors suggest that the data indicate multiple metamorphic events during the Paleozoic, but temperatures during the Devonian metamorphism may have been below the closure temperature for Nd in hornblende.

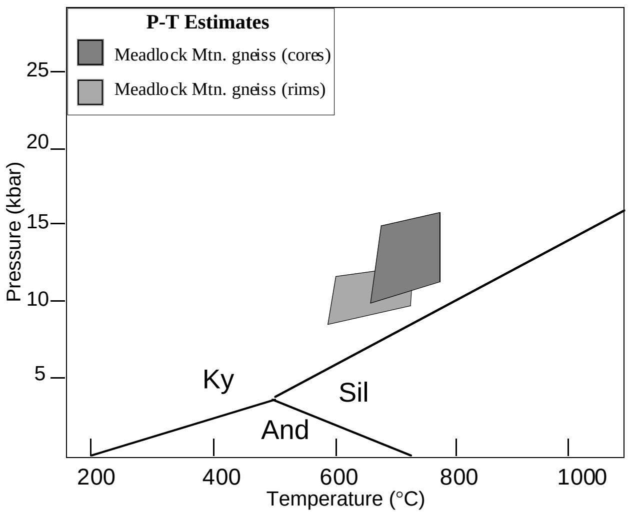

Figure 3. Petrogenetic grid showing P-T estimates of Adams et al. (1995b) for the Meadlock Mountain gneiss. Aluminum silicate phase boundaries after Holdaway (1971). P-T estimates are similar to those for amphibolite and retrogressed eclogite of the AMS, and the lower range of P-T estimates for eclogite as shown in Figure 2.

BEECH MOUNTAIN THRUST SHEET

The Beech Mountain thrust sheet directly overlies the Grandfather Mountain window and is bounded on the southeast by the Linville Falls fault and on the northwest by the Stone Mountain shear zone (Figure 1). The lithology of the thrust sheet is dominated by Mesoproterozoic gneisses, Neoproterozoic granitic plutons, and minor Neoproterozoic mafic dikes. The Mesoproterozoic gneisses include rocks that were metamorphosed or crystallized during the Grenville orogeny between approximately 1177 to 950 Ma. (Fullagar and Bartholomew, 1983). The Neoproterozoic granitic plutons include those of the Crossnore-Beech intrusive suite with crystallization ages of approximately 741 Ma. (Su et al., 1994). The Neoproterozoic mafic rocks include those of the Bakersville intrusive suite dated at approximately 734 Ma. (Goldberg et al., 1986b).

GRADE AND TIMING OF METAMORPHISM

Locally the rocks of the Beech Mountain thrust sheet show evidence of multiple metamorphic events. The Mesoproterozoic, Grenville age gneisses contain layers of garnet amphibolite, suggesting early metamorphic conditions of amphibolite facies. Additionally, migmatites are ubiquitous in the Cranberry Mine layered gneiss (Bartholomew and Lewis, 1984) or the Valle Crucis gneiss (Adams, 1990), indicating thermal conditions at least high enough to induce partial melting. Virtually all of the rocks in the Beech sheet show a late overprint of greenschist facies metamorphism evidenced predominantly by petrographic observations (greenschist facies equilibrium mineral assemblages) and operative deformation mechanisms in deformed rocks (Trupe, 1989; Adams, 1990; Adams and Su, 1996). Table 3 summarizes P-T estimates for rocks from the Beech Mountain thrust sheet.

Timing of metamorphism is constrained by cross-cutting relations and documented radiometric isotope dates. Crossnore-Beech granitic rocks and mafic dikes of the Bakersville suite intrude and cross cut gneissic layering in Grenville basement rocks. These intrusive rocks do not show evidence of the same high grade metamorphism that affected the basement rocks. Thus, the amphibolite facies metamorphism that affected the basement rocks must be older than the 741 to 734 Ma rocks of the Crossnore-Beech and Bakersville intrusive suites. Additionally,

Table 3. Summary of P-T estimates for the Beech Mountain and Pardee Point thrust sheets.

Thrust Sheet	Temperature	Pressure	Method	Reference
Beech Mountain*				
Beech Granite	350 - 450° C	4 kbar ±	1,2	a,b
mylonites in shear zones	350 - 450° C	4 kbar ±	1,2	a,b
mylonites in shear zones	350 - 450° C	4 - 5 kbar	1,2,3	c
mylonites in shear zones	310 - 400° C	4 - 6.5 kbar	3,4,8,9	d
mylonites in shear zones	~375° C	~4 kbar	1,2,5	e
Pardee Point				
basement gneiss*	675 - 775° C	NA	6	f
basement gneiss and Bakersville diabase**	sub- to lower greenschist	sub- to lower greenschist	7	g

1. Evaluation of operative deformation mechanisms. 2. Applying average geothermal gradient and average lithostatic pressure. 3. Phengite geobarometer. 4. Two feldspar thermometry. 5. Regionally restored cross sections. 6. Cation-exchange thermometry. 7. Petrographic observations (equilibrium mineral assemblage). 8. Fluid inclusions. 9. Biotite-muscovite-chlorite barometry.
a. Adams, 1990. b. Trupe, 1989. c. Goldberg and Dallmeyer, 1997. d. Schedl et al., 1992. e. Wojtal and Mitra, 1988. f. McCrary, 1997. g. Butler, 1991 and personal com.
*Mesoproterozoic conditions. **Paleozoic conditions.

Dallmeyer (1975), Fullagar and Bartholomew (1983) and Goldberg and Dallmeyer (1997) interpreted isotopic dates to represent metamorphic ages for basement rocks in the Beech sheet at approximately 1.0 Ga.

Timing of the greenschist facies metamorphism in the Beech sheet is constrained by field relations and radiometric dates. Field relations suggest that the pervasive metamorphic foliation in the Beech sheet is related to shearing along fault zones within and bordering the thrust sheet (Adams and Su, 1996). Mylonites within the Linville Falls shear zone, Long Ridge shear zone, and other minor shear zones within the Beech sheet record isotopic ages around 300 Ma (Van Camp and Fullagar, 1982; Schedl et al., 1992; Adams and Su, 1996). Goldberg and Dallmeyer (1997) report isotopic ages for mylonites from the shear zone along the Pumpkin Patch-Beech sheet contact at around 325 Ma. These data indicate that the Pumpkin Patch and Beech sheets were probably juxtaposed during early stages of the Alleghanian orogeny and the composite Blue Ridge thrust complex was transported along the Linville Falls fault during later stages of the Alleghanian.

Evidence for earlier Paleozoic metamorphism in the Beech sheet is somewhat ambiguous. Goldberg and Dallmeyer (1997) reported a Rb-Sr hornblende age of 451 Ma and $^{40}Ar/^{39}Ar$ age of 383 for a sample from the Beech sheet (their Sample 1). Geologic mapping (Adams, unpublished data) demonstrates that their Sample 1 is well within the Pumpkin Patch sheet (which is more consistent with the rest of their data). Dallmeyer (1975) also reported a biotite $^{40}Ar/^{39}Ar$ age of 518 Ma from a rock that may reside within the Beech sheet; however, analysis of hornblende from the same rock yields an age of 893 Ma. The 518 Ma biotite age is considered suspect for several reasons: 1) because of the discrepancy between the biotite and hornblende ages; 2) the 518 Ma biotite age does not appear to be related to any well-documented thermal event in the Blue Ridge: 3) Kish (1989) warns that biotite from the western Blue Ridge may contain excess ^{40}Ar and, thus, may be unreliable. Existing, unequivocal data suggest that the only Paleozoic metamorphic event that affected the rocks of the Beech sheet was the Alleghanian orogeny.

PARDEE POINT THRUST SHEET

The Pardee Point thrust sheet underlies the Beech Mountain thrust sheet along the Unaka Mountain-Stone Mountain fault system (Figure 1). As illustrated by King and Ferguson (1960), the Pardee Point thrust sheet is included in the Mountain City window. Crystalline rocks in this sheet include Mesoproterozoic basement gneiss, Neoproterozoic Bakersville Intrusive Suite, and minor pegmatites. Nonconformably overlying the crystalline rocks are basal clastic rocks of the Chilhowee Group and other Paleozoic sedimentary rocks (Shady and Rome Formations).

GRADE AND TIMING OF METAMORPHISM

Quantitative estimates of metamorphic conditions for rocks in the Pardee Point thrust sheet are sparse (Table 3). However, the crystalline rocks of the Pardee Point thrust sheet contain garnet amphibolite within the gneissic layering. Additionally, migmatization is prominent throughout these gneisses. These observations indicate that metamorphic conditions reached at least amphibolite facies and that temperature conditions were sufficient to induce anatexis. McCrary (1997) reported garnet-biotite temperatures for Pardee Point gneiss of 675-775 °C, interpreted as cooling temperatures following high-grade (granulite) Grenville metamorphism. Butler (1991) noted that thin sections indicate that the amphibolite facies minerals in the gneisses do not show significant retrogression by greenschist facies metamorphism.

Neoproterozoic Bakersville mafic rocks cross-cut the gneissic layering in the rocks of the Pardee Point sheet, indicating that the metamorphism and formation of the layering predates the intrusion of the 734 Ma Bakersville rocks. Virtually all of the documented radiometric ages from minerals from the gneisses are Precambrian (Long et al., 1959; Dallmeyer, 1975; McCrary, 1997), suggesting that the rocks of the Pardee Point sheet were not affected by Paleozoic metamorphism, or at least temperatures were not high enough to reset the isotope systematics in those minerals.

Locally, basal deposits of the Chilhowee group (Neoproterozoic ? or Lower Cambrian) rest unconformably on the crystalline basement rocks of the Pardee Point thrust sheet. Higher in the stratigraphic sequence, conglomerates above the Middle Ordovician unconformity in the Valley and Ridge province contain clasts of earlier Paleozoic sedimentary rocks (Kellberg and Grant, 1958), providing evidence for uplift and erosion during the Taconic orogeny. Uplift and erosion of rocks correlative with those in the Pardee Point sheet suggest that this thrust sheet was not deeply buried during the Taconic orogeny and, thus, the lack of evidence for Ordovician-age metamorphism is not surprising.

The Pardee Point thrust sheet was buried by overthrusting of the Beech sheet during the Alleghanian orogeny. As the rocks of the Chilhowee Group are anchimetamorphic (Butler, 1991), metamorphic conditions resulting from this burial probably was no greater than chlorite-grade. The data indicate that the Pardee Point thrust sheet was subjected to only very low grade metamorphism during the latest (Alleghanian) Paleozoic orogenic event.

SUMMARY

The earliest metamorphism recorded by basement thrust sheets of the Blue Ridge thrust complex resulted from the Mesoproterozoic Grenville orogeny. Mineral assemblages, the presence of migmatitic gneisses, and limited P-T data indicate upper amphibolite to granulite facies conditions of metamorphism. The timing of this metamorphism is constrained by Precambrian isotopic ages and ages of intrusive rocks (Neoproterozoic Crossnore-Beech and Bakersville suites) that cross-cut layering and folds in the gneisses. Grenville-age metamorphism affected the Pumpkin Patch, Beech Mountain, and Pardee point thrust sheets, but has not been recognized in the Spruce Pine thrust sheet.

Thrust sheets of the Blue Ridge thrust complex were variably affected by multiple Paleozoic tectonothermal events. The Pardee Point thrust sheet experienced only very low-grade metamorphism during Alleghanian thrusting, and Grenville metamorphic assemblages were not significantly retrogressed (Butler, 1991). The Beech Mountain thrust sheet was pervasively deformed during greenschist-grade Alleghanian thrusting. Isotopic ages for these fault-related rocks range from ~300-330 Ma (Van Camp and Fullagar, 1982; Goldberg and Dallmeyer, 1991; Schedl et al., 1992; Adams and Su, 1996; Goldberg and Dallmeyer, 1997). However, evidence for earlier Paleozoic metamorphism is somewhat ambiguous in the Beech Mountain thrust sheet.

Isotopic ages for metamorphic minerals from the Spruce Pine and Pumpkin Patch thrust sheets record both Ordovician and Siluro-Devonian metamorphism. Bakersville mafic intrusive rocks are metamorphosed, placing a lower age limit on post-Grenville metamorphism in the Pumpkin Patch sheet. High-pressure metamorphism is recorded by eclogite facies rocks and relatively high pressure estimates in the AMS and Meadlock Mountain gneiss. Amphibolite facies assemblages suggest a retrograde P-T path during cooling and decompression of the AMS. High-temperature dextral strike-slip shearing deformed but did not retrograde amphibolite-facies assemblages, and was broadly contemporaneous with intrusion of the Spruce Pine pegmatites. The similarity in metamorphic grade and isotopic ages in the Spruce Pine and Pumpkin Patch sheets suggests that they were juxtaposed no later than the Devonian. The greenschist-grade retrogression common in late Paleozoic shear zones of the Blue Ridge thrust complex is lacking in the Pumpkin Patch and Spruce Pine sheets southwest of the Grandfather Mountain window. However, near the window, high-grade assemblages are overprinted by greenschist-grade shearing associated with Alleghanian northwest-directed thrusting.

The available data are consistent with the following aspects of the Paleozoic tectonic evolution of the southern Appalachian Blue Ridge. Closure of an ocean basin and subsequent continental or arc-continent collision caused the Ordovician Taconic orogeny resulting in metamorphism of at least part of the AMS and formation of eclogite in the associated subduction zone complex. Subsequent or continued crustal thickening caused Siluro-Devonian amphibolite facies metamorphism. Dextral strike-slip faulting along the Burnsville fault occurred shortly after peak regional metamorphism, and the final juxtaposition of the AMS and underlying basement of the Pumpkin Patch thrust sheet occurred by the Devonian. The magnitude of displacement during this faulting is unknown. A southwestward progression of Devonian clastic wedges has been noted by several workers (e.g. Dennison, 1985; Ferrill and Thomas, 1988; Ettensohn, 1995). The absence of a large Devonian clastic wedge in the southern Appalachians and the southwestward progression of Devonian clastic wedges may be explained by Acadian dextral transpression (Ferrill and Thomas, 1988).

The late Paleozoic history of the Blue Ridge thrust complex was dominated by northwest-directed faulting. Thrust sheets within the thrust complex are typically separated by greenschist-grade mylonite zones with top-to-northwest sense of movement (e.g. Bryant and Reed, 1970; Trupe, 1989; Goldberg et al., 1989, 1992b; Trupe et al., 1990; Adams, 1990). Isotopic ages of mylonitic rocks from the Linville Falls and related shear zones are ~300 Ma (Van Camp and Fullagar, 1982; Schedl et al., 1992; Adams and Su, 1996), and represent final emplacement of the assembled thrust complex during the Alleghanian orogeny.

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REFERENCES

Abbott, R.N., Jr., and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic history. American Journal of Science, 284, 350-375.

Adams, M.G., 1990, The geology of the Valle Crucis area, northwestern North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 95 p.

Adams, M.G., 1995, The tectonothermal evolution of part of the Blue Ridge thrust complex, northwestern North Carolina: Ph.D. Dissertation, University of North Carolina, 193 p.

Adams, M.G., and Stewart, K.G., 1993, Tectonic implications of the occurrence of eclogite in the Blue Ridge, northwestern North Carolina. Geological Society of America Abstracts with Programs, v. 25, p. 424.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995a, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians: in Hibbard, J., van Staal, C.R., Cawood, P. and Colman-Sadd, S., editors, New Perspectives in the Appalachian-Caledonian orogen, Geological Association of Canada Special Paper 41, p. 21-42.

Adams, M.G., and Su, Q., 1996, The nature and timing of deformation in the Beech Mountain thrust sheet between the Grandfather Mountain and Mountain City windows in the Blue Ridge of northwestern North Carolina: Journal of Geology, p. 197-213.

Adams, M.G., Trupe, C.H, Goldberg, S.A., Stewart, K.G., and Butler, J.R., 1995b, Pressure-temperature history of high-grade metamorphic rocks along the eastern-western Blue Ridge boundary, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 27, p. 33.

Bartholomew, M.J., and Lewis, S.E., 1984, Evolution of Grenville massifs in the Blue Ridge geologic province, central and southern Appalachians, in Bartholomew, M.J., editor, The Grenville Event in the Appalachians and related topics, Geological Society of America Special Paper 194, p. 229-254.

Bartholomew, M.J., and Lewis, S.E., 1992, Appalachian Grenville massifs: pre-Appalachian translational tectonics: in Mason, R., editor, Basement Tectonics 7, Proceedings of the Seventh International Conference on Basement Tectonics, Kluwer Academic Publishers, Dordrecht, Netherlands, p. 363-374.

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

Butler, J.R., 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge thrust sheet, North Carolina: American Journal of Science, v. 273-A, p. 72-88.

Butler, J.R., 1991, Metamorphism, in Horton, J.W., Jr., and Zullo, V.A., editors, The geology of the Carolinas: Carolina Geological Society Fiftieth Anniversary Volume: Knoxville, The University of Tennessee Press, Carolina Geological Society, p. 127-141.

Butler, J.R., Goldberg, S.A., and Mies, J.W., 1987, Tectonics of the Blue Ridge west of the Grandfather Mountain window, North Carolina and Tennessee: Geological Society of America Abstracts with Programs, v. 19, p. 77.

Dallmeyer, R.D., 1975, 40Ar/39Ar ages of biotite and hornblende from a progressively metamorphosed basement terrane: Their bearing on the interpretation of release spectra: Geochimica et Cosmochimica Acta, v. 39, p. 1655-1669.

Dennison, J.M., 1985, Catskill Delta shallow marine strata, in Woodrow, D.L., and Sevon, W.D., editors, The Catskill Delta: Geological Society of America Special Paper 201, p. 91-106.

Ettensohn, F.R., 1995, Large-scale tectonic constraints on deposition of North American Devonian-Mississippian black shales: Geological Society of America Abstracts with Programs, v. 27, p. 400.

Eckert, J.O, Jr., Hatcher, R.D., Jr., and Mohr, D.W., 1989, The Wayah granulite-facies metamorphic core, southwestern North Carolina: High-grade culmination of Taconic metamorphism in the southern Blue Ridge: Geological Society of America Bulletin, v. 101, p. 1434-1447.

Ferrill, B.A., and Thomas, W.A., 1988, Acadian dextral transpression and synorogenic sedimentary successions in the Appalachians: Geology, v. 16, p. 604-608.

Fullagar, P.D., and Bartholomew, M.J., 1983, Rubidium-strontium ages of the Watauga River, Cranberry, and Crossing Knob gneisses, northwestern North Carolina, in Lewis, S.E., editor, Geologic Investigations in the Blue Ridge of Northwestern North Carolina: Carolina Geological Society Guidebook, North Carolina Geological Survey, Article II, 29 p.

Goldberg, S.A., Adams, M.G., Trupe, C.H., Stewart, K.G., and Butler, J.R., 1994, Sm-Nd isotopic constraints on a Blue Ridge eclogite, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 26, p. 196.

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

Goldberg, S.A., Butler, J.R., and Mies, J.W., 1986a, Subdivision of the Blue Ridge thrust complex, western North Carolina and adjacent Tennessee: Geological Society of America Abstracts with Programs, v. 18, p. 616-617.

Goldberg, S.A., Butler, J.R., Mies, J.W., and Trupe, C.H., 1989, The southern Appalachian orogen in northwestern North Carolina and adjacent states: International Geological Congress Field Trip T365 Guidebook, American Geophysical Union, Washington, DC, 55 p.

Goldberg, S.A., Butler, J.R., Trupe, C.H., and Adams, M.G., 1992b, The Blue Ridge thrust complex northwest of the Grandfather Mountain window, North Carolina and Tennessee, in Dennison, J.M., and Stewart, K.G., editors, Geologic field guides to North Carolina and vicinity: Chapel Hill, North Carolina, Department of Geology, University of North Carolina at Chapel Hill, Geologic Guidebook No. 1, p. 213 - 233.

Goldberg, S.A., and Dallmeyer, R.D., 1991, Rb-Sr and 40Ar/39Ar mineral ages from the Blue Ridge west of the Grandfather Mountain window: evidence for Late Mississippian thrusting and Devonian metamorphism: Geological Society of America Abstracts with Programs, v. 23, p. 35.

Goldberg, S.A., and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge thrust complex, North Carolina and Tennessee: American Journal of Science, v. 297, p. 488-526.

Goldberg, S.A., Dallmeyer, R.D., and Su, Q., 1993, Chronology of Paleozoic metamorphism and deformation in the southern Appalachian Blue Ridge based on Sr, Nd, Pb, and Ar isotopic systematics: EOS, v. 74, p. 122.

Goldberg, S.A., Trupe, C.H., and Adams, M.G., 1992a, Pressure-temperature-time constraints for a segment of the Spruce Pine thrust sheet, North Carolina Blue Ridge: Geological Society of America Abstracts with Programs, v. 24, p. 17.

Gulley, G.L., Jr., 1985, A Proterozoic granulite-facies terrane on Roan Mountain, western Blue Ridge belt, North Carolina - Tennessee: Geological Society of America Bulletin, v. 96, p. 1428-1439.

Hatcher, R.D., Jr., 1978, Tectonics of the western Piedmont and Blue Ridge, southern Appalachians: Review and speculation: American Journal of Science, v. 278, p. 276-304.

Hatcher, R.D., Jr., 1987, Tectonics of the southern and central Appalachian internides: Annual Review of Earth and Planetary Sciences, v. 15, p. 337-362.

Hatcher, R.D., Jr., and Goldberg, S.A., 1991, The Blue Ridge geologic province: in Horton, J.W., Jr., and Zullo, V.A., editors, The geology of the Carolinas: Carolina Geological Society Fiftieth Anniversary Volume: Knoxville, The University of Tennessee Press, Carolina Geological Society, p. 11-35.

Hatcher, R.D., Jr., Hooper, R.J., Petty, S.M., and Willis, J.D., 1984, Structure and chemical petrology of three southern Appalachian mafic-ultramafic complexes and their bearing upon the tectonics of emplacement and origin of Appalachian ultramafic bodies: American Journal of Science, v. 284, p. 484-506.

Holdaway, M.J., 1971, Stability of andalusite and the aluminum silicate phase diagram: American Journal of Science, v. 271, p. 97-131.

Holland, T.J.B., 1980, The reaction albite = jadeite + quartz determined experimentally in the range 600-1200°C: American Mineralogist, v. 65, p. 129-134.

Holland, T.J.B., 1983, The experimental determination of activities in disordered and short-range ordered jadeitic pyroxenes: Contributions to Mineralogy and Petrology, v. 82, p. 214-220.

Horton, J.W., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their boundaries in the central and southern Appalachians: in Dallmeyer, R.D., editor, Terranes in the Circum-Atlantic Paleozoic orogens: Geological Society of America Special Paper 230, p. 213-245.

Kellberg, J.M., and Grant, L.F., 1958, Coarse conglomerates of the Middle Ordovician in the southern Appalachian valley, Geological Society of America Bulletin, v. 67, p. 697-716.

King, P.B., and Ferguson, H.W., 1960, Geology of northeasternmost Tennessee with Description of the basement rocks by Warren Hamilton, United States Geological Survey Professional Paper 311, 160 p.

Kish, S.A., 1983, A geochronological study of deformation and metamorphism in the Blue Ridge and Piedmont of the Carolinas: Ph. D. Dissertation, University of North Carolina at Chapel Hill, 220 p.

Kish, S.A., 1989, Igneous and metamorphic history of the eastern Blue Ridge, southwestern North Carolina: K-Ar and Rb-Sr studies: in Fritz, W.J., Hatcher, R.D., Jr., and Hopson, J.L., editors., Geology of the eastern Blue Ridge of northeast Georgia and the adjacent Carolinas: Atlanta, Georgia, Georgia Geological Society, Inc., Georgia Geological Society Guidebooks, v. 9, no. 3, p. 41-74.

Lesure, F.G., 1968, Mica deposits of the Blue Ridge in North Carolina: United States Geological Survey Professional Paper 577, 124 p.

Long, L.E., Kulp, J.L., and Eckelmann, F.D., 1959, Chronology of major metamorphic events in the southeastern United States, American Journal of Science, v. 257, 585-603.

Mallard, L.D., Adams, M.G., and Stewart, K.G., 1994, Kinematic analysis of a possible suture in the southern Appalachians, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 26, p. 25-26.

McCrary, C.R., III, 1997, Pressure-temperature-time history of Grenville basement gneisses in the Pardee Point thrust sheet near Hampton, Tennessee: Geological Society of America Abstracts with Programs, v. 29, p. 57.

McSween, H.Y., Jr., Abbott, R.N., and Raymond, L.A., 1989, Metamorphic conditions in the Ashe Metamorphic Suite, North Carolina Blue Ridge: Geology, v. 17, p. 1140-1143.

Merschat, C.E., and Wiener, L.S., 1988, Geology of the Sandymush and Canton quadrangles, North Carolina: North Carolina Geological Survey Bulletin 90, 66 p.

Mies, J.W., 1987, An investigation of the Proterozoic basement-Ashe Formation boundary west of the Grandfather Mountain window, northwestern North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 74 p.

Mies, J.W., 1988, A major thrust at the base of the Ashe Formation in the Blue Ridge of northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 20, p. 280.

Mies, J.W., 1990, Structural and petrologic studies of mylonite at the Grenville basement - Ashe Formation boundary, Grayson County, Virginia to Mitchell County, North Carolina: Ph. D. Dissertation, University of North Carolina at Chapel Hill, 330 p.

Mies, J.W., and Trupe, C.H., 1989, Kinematic analysis in the Blue Ridge thrust complex, northwestern North Carolina and adjacent states: Geological Society of America Abstracts with Programs, v. 21, p. 50.

Misra, K.C., and Conte, J.A., 1991, Amphibolites of the Ashe and Alligator Back Formations, North Carolina: Samples of Late Proterozoic - early Paleozoic oceanic crust: Geological Society of America Bulletin, v. 103, p. 737-750.

Monrad, J.R., and Gulley, G.L., 1983, Age and P-T conditions during metamorphism of granulite-facies gneisses, Roan Mountain, NC-TN, in Lewis, S.E., editor, Geologic investigations in the Blue Ridge of northwestern North Carolina: Carolina Geological Society Field Trip Guidebook, 29 p.

Rankin, D.W., 1970, Stratigraphy and structure of Precambrian rocks in northwestern North Carolina, in Fisher, G.W., Pettijohn, F.J., Reed, J.C., Jr., and Weaver, K.N., editors, Studies of Appalachian geology-central and southern: Interscience, New York, p. 227-245.

Rankin, D.W., Drake, A.A., Jr., Glover, L.,III, Goldsmith, R., Hall, L.M., Murray, D.P., Ratcliffe, N.M., Read, J.F., Secor, D.T., Jr., and Stanley, R.S., 1989, Pre-orogenic terranes, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., editors The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 7-100.

Rankin, D.W., Espenshade, G.H., and Shaw, K.W., 1973, Stratigraphy and structure of the metamorphic belt in northwestern North Carolina and southwestern Virginia: A study from the Blue Ridge across the Brevard fault zone to the Sauratown Mountains anticlinorium: American Journal of Science, v. 273-A, p. 1-40.

Raymond, L.A., Yurkovich, S.P., and McKinney, M., 1989, Block-in-matrix structures in the North Carolina Blue Ridge belt and their significance for the tectonic history of the southern Appalachian orogen: in Horton, J.W., Jr., and Rast, N., editors, Melangés and Olistostromes of the U.S. Appalachians: Geological Society of America Special Paper 228, p. 195-215.

Satterfield, M.E., 1992, Investigation of the metamorphosed massive sulfide deposit at the Ore Knob mine, Ore Knob, North Carolina: Masters Thesis, University of North Carolina at Chapel Hill, 110 p.

Schedl, A., McCabe, C., Montanez, I., Fullagar, P.D., and Valley, J., 1992, Alleghenian regional diagenesis: A response to the migration of modified metamorphic fluids derived from beneath the Blue Ridge-Piedmont thrust sheet: Journal of Geology, v. 100, p. 339-352.

Su, Q., Goldberg, S.A., and Fullagar, P.D., 1994, Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia: Precambrian Research, v. 68, p. 81-95.

Trupe, C.H., 1989, Microstructural analysis of mylonites from the Blue Ridge thrust complex, northwestern North Carolina: M.S. Thesis, University of North Carolina at Chapel Hill, 101 p.

Trupe, C.H., 1997, Deformation and metamorphism in part of the Blue Ridge thrust complex, northwestern North Carolina: Ph. D. Dissertation, University of North Carolina at Chapel Hill, 176 p.

Trupe, C.H., Adams, M.G., Butler, J.R., and Willard, R.A., 1991, Geology of the Burnsville, NC quadrangle: Basement-cover relationships in the North Carolina Blue Ridge: Geological Society of America Abstracts with Programs, v. 23, p. 140.

Trupe, C.H., Butler, J.R., Mies, J.W., Adams, M.G., and Goldberg, S.A., 1990, The Linville Falls fault and related shear zone: Geological Society of America Abstracts with Programs, v. 22, p. 66.

Van Camp, S.G., and Fullagar, P.D., 1982, Rb-Sr whole-rock ages of mylonites from the Blue Ridge and Brevard zone of North Carolina: Geological Society of America Abstracts with Programs, v. 14, p. 92-93.

Willard, R.A., and Adams, M.G., 1994, Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61-70.

Willard, R.A., Trupe, C.H., Adams, M.G., and Butler, J.R., 1991, Transition in the character of the Ashe-Basement contact west of the Grandfather Mountain window: Geological Society of America Abstracts with Programs, v. 23, p. 150.

Wojtal, , S., and Mitra, G., 1988, Nature of deformation in some fault rocks from Appalachian thrusts, in Mitra, G., and Wojtal, S., editors, Geometries and Mechanism of Thrusting, with Special Reference to the Appalachians: Geological Society of America Special Paper 222, p. 17-33.

STRUCTURAL RELATIONSHIPS IN THE LINVILLE FALLS SHEAR ZONE, BLUE RIDGE THRUST COMPLEX, NORTHWESTERN NORTH CAROLINA

Charles H. Trupe*
Department of Geology
University of North Carolina
Chapel Hill, NC 27599-3315

ABSTRACT

The Linville Falls fault frames the Grandfather Mountain window, and separates crystalline thrust sheets of the Blue Ridge thrust complex from basement and metasedimentary rocks within the window. The fault is named for an exposure at Linville Falls, NC, where basement rocks overlie Paleozoic metasedimentary rocks of the Tablerock thrust sheet. Previous workers have described the fault at this exposure as a meter-scale mylonite zone, and have attempted to explain thickness variations between Linville Falls and exposures north of the Grandfather Mountain window. Detailed mapping shows that in the vicinity of Linville Falls, a ductile shear zone several hundred meters thick occurs immediately above the meter-scale mylonite zone. Field relationships indicate that the thin mylonite zone exposed at Linville Falls is a small part of the fault zone in general, and that there is no significant variation in shear zone thickness between this exposure and exposures north of the Grandfather Mountain window.

At Linville Falls, the hanging wall rock above the meter-scale shear zone is a slice of alkali feldspar granite structurally overlain by basement-derived mylonite of the Linville Falls shear zone. Shear zone mylonites record crystal-plastic deformation under greenschist-grade conditions, and kinematic indicators are consistent with top-to-northwest shear sense. Immediately below shear zone mylonites, cataclastic deformation overprints ductile fabric within the granite. The presence of cataclastic rocks in the Linville Falls shear zone indicates that movement continued under brittle conditions of deformation as the Blue Ridge thrust complex reached relatively shallow crustal levels.

INTRODUCTION

The Blue Ridge geologic province of the southern Appalachian orogen is one of the world's largest crystalline thrust terranes. In northwestern North Carolina, the crystalline thrust complex has been partially eroded to form the Grandfather Mountain window. The Linville Falls fault occurs at the base of the Blue Ridge thrust complex, and defines the border of the Grandfather Mountain window (Goldberg et al., 1992). The region adjoining the window provides a cross-section through the Blue Ridge thrust complex, and has been the focus of several important studies of faulting and fault-related rocks (e.g. Boyer and Elliott, 1982; Boyer and Mitra, 1988; Boyer, 1992; Schedl et al., 1992). However, most of these studies have been based upon relatively old, small-scale, rather than detailed, geologic mapping.

*Present address:
2619 Mt. Gilead Church Rd.
Pittsboro, NC 27312

Arthur Keith (1903, 1905) conducted the first mapping in the vicinity of Linville Falls and the Grandfather Mountain window on the Cranberry and Mt. Mitchell 30 minute quadrangles, but this did not include the exposure of the fault at Linville Falls. The Grandfather Mountain window was first interpreted as a window on the "Geologic Map of the United States" (Stose and Ljungstedt, 1932), and was subsequently named the Grandfather Mountain window by Stose and Stose (1944).

Mapping of 15 minute quadrangles was undertaken by the United States Geological Survey from 1956 to 1962, and resulted in several short reports and maps of the area in which the Linville Falls and Tablerock faults were named and described (see references in Bryant and Reed, 1970). These studies culminated in the publication of United States Geological Survey Professional Paper 615 (Bryant and Reed, 1970), which has since been regarded as the definitive geologic mapping in the area. Subsequent topical studies in the Linville Falls area have relied upon the 1:62,500-scale geologic map of Bryant and Reed (1970) as a basis for more detailed structural and petrologic studies (e.g. Boyer, 1978, 1992; Boyer and Elliott, 1982; Schedl, 1985, 1988; Wojtal and Mitra, 1988; Boyer and Mitra, 1988; Schedl et al., 1992; Newman and Mitra, 1993), but these studies did not present any new large-scale geologic mapping.

Detailed geologic mapping in the vicinity of Linville Falls fault has revealed relationships more complex than previously recognized. There are three main points that arise from this research. First, above the meter-scale Linville Falls fault zone (as originally defined, the Linville Falls fault sensu stricto), crystalline basement rocks are pervasively sheared to mylonite and ultramylonite (classification of Sibson, 1977) in a zone up to one kilometer thick. Trupe et al. (1990) termed this shear zone the Linville Falls shear zone, and described it as a thick, mixed-rock mylonite zone that everywhere lies just above the Linville Falls fault as originally mapped. Second, the hanging wall of the meter-scale shear zone at Linville Falls consists of a tectonic block (Berkland et al., 1972) of alkali feldspar metagranite similar in mineralogy and chemistry to Neoproterozoic Crossnore-Beech Suite granites. Third, the base of the Linville Falls shear zone is characterized by mylonitic rocks that are overprinted by cataclastic deformation. Cataclasite zones are most prominent in the lowest few meters of the hanging wall. These features are similar to those noted in exposures of the Linville Falls shear zone north of the Grandfather Mountain window (Trupe et al., 1990; Adams, 1990a, 1990b; Trupe and Adams, 1991; Goldberg et al., 1992; Adams and Su, 1996).

The present investigation is the result of detailed geologic mapping in the Linville Falls area. Preliminary reports have been presented by Trupe et al. (1990), Trupe and Adams (1991), and Goldberg et al. (1992), in which the nature of the Linville Falls shear zone and its relationship to the Linville Falls fault were discussed. The present paper constitutes the first publication of detailed new mapping in the Linville Falls area.

The purpose of this paper is to present new field, structural, and petrologic data in the vicinity Linville Falls. These data demonstrate the nature of structural relationships and deformation within the Linville Falls fault zone, which should be considered in interpretations of fault-related rocks in the vicinity of the Grandfather Mountain window.

GEOLOGIC SETTING

The Blue Ridge thrust complex of northwestern North Carolina (Figure 1) is a stack of crystalline thrust sheets separated by thick mylonite zones and characterized by different P-T and deformation histories (Butler, 1973; Abbott and Raymond, 1984; Goldberg et al., 1986, 1989, 1992; Butler et al., 1987). The

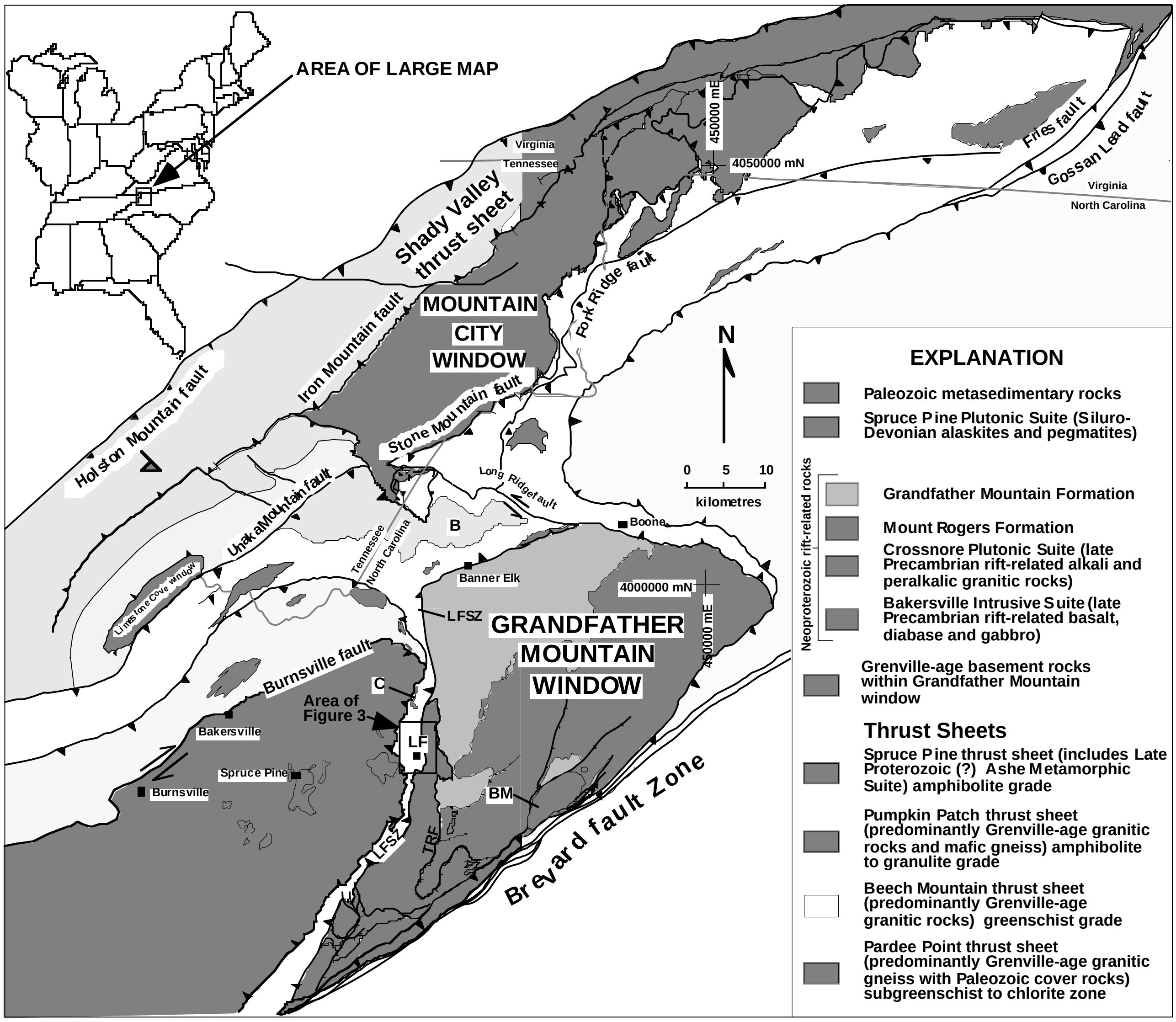


Figure 1. Generalized geologic and tectonic map of part of the Blue Ridge thrust complex in the vicinity of the Grandfather Mountain window, modifed from Adams et al., (1995). LFSZ - Linville Falls shear zone. TRF - Tablerock fault. LF - Linville Falls. Neoproterozoic Crossnore-Beech suite plutons indicated by B (Beech Granite), BM (Brown Mountain Granite), and C (Crossnore Granite). Registration coordinates are for Universal Transverse Mercator grid, zone 17.

base of the Blue Ridge thrust complex is marked by shear zones of the Linville Falls fault, a fault that defines the Grandfather Mountain window. Mylonitic rocks within and bounding the lower thrust sheets (which consist predominantly of Mesoproterozoic basement rocks) record top-to-northwest sense of movement and greenschist facies conditions (Goldberg et al., 1986, 1989, 1992; Mies et al., 1987; Mies and Trupe, 1989; Trupe, 1989a, 1989b; Adams, 1990b). Isotopic ages for these mylonitic rocks are ~300-330 Ma (Van Camp and Fullagar, 1982, Rb-Sr whole-rock age; Schedl et al., 1992, Rb-Sr whole-rock age; Goldberg et al., 1993, Rb-Sr and $^{40}Ar/^{39}Ar$ mica ages; Su, 1994, Rb-Sr whole-rock age; Su and Fullagar, 1995, Rb-Sr whole-rock age; Adams and Su, 1996, Rb-Sr whole-rock ages). The boundary between the uppermost unit and adjacent Mesoproterozoic basement, however, is marked locally by a syn-regional-metamorphic, dextral strike-slip fault formed under amphibolite grade conditions (Trupe et al., 1991; Willard et al., 1991; Mallard et al., 1994; Adams et al., 1995). Near the Grandfather Mountain window, this strike-slip deformation is overprinted by post regional-metamorphic mylonitization associated with the Linville Falls shear zone (Adams et al., 1995).

Within the Grandfather Mountain window, Neoproterozoic Grandfather Mountain Formation sedimentary and volcanic rocks overlie Mesoproterozoic basement gneisses, which are intruded by the Neoproterozoic Brown Mountain Granite (Bryant and Reed, 1970; Fetter and Goldberg, 1995). The Tablerock thrust sheet (Figure 1) is a tectonic slice of Cambrian Chilhowee Group metaquartzites and Shady Dolomite that occurs between the Blue Ridge thrust complex and the underlying Precambrian rocks of the Grandfather Mountain window (Bryant and Reed, 1970). The crystalline rocks overlying the Tablerock thrust sheet were mapped as Cranberry Gneiss by Bryant and Reed (1970), and consist of layered granodioritic gneiss, hornblende gneiss, biotite schist, and amphibolite.

LINVILLE FALLS SHEAR ZONE

The Linville Falls fault (sensu stricto) is named for an exposure on the west side of the Linville River, approximately 100 meters upstream of the National Park Service upper falls overlook. Bryant and Reed (1970, p. 163) described the fault as “marked by 6 to 18 inches of white to green finely laminated blastomylonite which is parallel to bedding in the quartzite and to foliation in the gneiss” (Figure 2). The “blastomylonite” separates “Cranberry Gneiss” in the hanging wall from Chilhowee Group quartzite of the Tablerock thrust sheet in the footwall. Bryant and Reed (1970) noted extensive shearing in basement rocks above the fault, and described slices of quartzite, amphibolite, and mica schist intercalated with mylonitic gneisses along the fault at several locations around the Grandfather Mountain window.

Figure 2. Exposure of the Linville Falls fault at Linville Falls. This is the exposure originally described by Bryant and Reed(1970). Hammer rests on sheared Chilhowee Group sericite-quartz mylonite; handle points northeast. Rock in the hanging wall is Linville Falls granite. Late, open folds with northeast-trending axes can be seen in the quartzite and laminated mylonite.

New mapping in the vicinity of Linville Falls reveals that the hanging wall of the Linville Falls fault (sensu stricto) consists of a thick mylonite zone, the Linville Falls shear zone (Figure 3). The base of the shear zone is defined by the Linville Falls fault (sensu stricto). The Linville Falls shear zone is approximately 800 meters thick near Linville Falls, and is well-exposed along the Blue Ridge Parkway west of the Linville River. The shear zone consists of mylonite and ultramylonite derived from basement gneisses (biotite gneiss, hornblende gneiss, and granitic gneiss), and contains tectonic blocks or slices of magnetite-hornblendite, amphibolite, and metagranite. The magnetite-hornblendite is similar to rocks of the Cranberry magnetite deposits that occur in the Beech Mountain thrust sheet along the northwestern margin of the Grandfather Mountain window (W. Ussler, personal communication). Mylonitic foliation in the shear zone wraps around these slices, suggesting tectonic emplacement of boudins or slices during thrusting.

This new mapping also demonstrates that the rock in the hanging wall of the Linville Falls fault (sensu stricto) is a tectonic slice of alkali feldspar metagranite, referred to hereafter as the Linville Falls granite. The "blastomylonite" of Bryant and Reed (1970) occurs between the granite and underlying Chilhowee Group quartzites and arkosic quartzites of the Tablerock thrust sheet. The granite consists of perthitic alkali feldspar, quartz, and minor plagioclase, with biotite, hornblende, fine-grained white mica, epidote, zircon, fluorite, apatite and opaque minerals (Table 1). The Linville Falls granite has not been isotopically dated, but is similar in outcrop appearance to the Beech Granite. It may be a tectonic slice of the latter unit. The Linville Falls granite is also similar in chemistry to the Beech, Brown Mountain, and Crossnore Granites (Table 2). Petrographically, the Linville Falls granite resembles the Beech Granite, as both contain abundant perthitic feldspar and accessory fluorite. The Linville Falls granite apparently lacks aegerine-augite, which is characteristic of the Crossnore Granite (Bryant and Reed, 1970; Su et al., 1994). The granite is variably sheared, ranging from weakly deformed to ultramylonitic; ductile fabric in the granite has been overprinted by cataclastic fabric. The granite is up to 50 meters thick, and extends 0.5 kilometers south and 1 kilometer north of the Linville Falls exposure. Basement-derived mylonite and ultramylonite of the Linville Falls shear zone structurally overlie the Linville Falls granite and locally occur below it. The contact between the granite and overlying mylonites may be seen just north of the National Park Service Linville Falls Campground, where a second slice of granite is

Table 1. Modal analyses of Linville Falls granite. Abbreviations after Kretz (1983).

Sample	8970	90-006	90-014	92-006
Kfs	45.30	52.90	56.23	55.56
Pl	1.42	7.74	1.82	0.62
Qtz	26.78	23.23	30.40	33.02
Ms	1.14	0.00	6.99	0.00
Bt	1.42	6.45	0.00	6.17
Ep	0.00	7.42	0.00	0.93
Opaque	0.85	0.00	3.65	2.47
Other*	23.08	2.26	0.91	1.23
Total	100.00	100.00	100.00	100.00

* Includes hornblende, zircon, apatite, fluorite, and cataclastic material too fine-grained to identify. In sample 8970, this is predominantly cataclastic material.

Table 2. Whole-rock analyses of granites. Linville Falls granite, 89-71, 90-006, 92-006: Beech Granite, 8729, BG-3: Brown Mountain Granite, BRM-1; Crossnore Granite, C-1.

Sample	8971	90-006	92-006	8729	BG-3	BRM-1	C-1
SiO_2	71.90	73.90	72.90	74.70	72.10	74.50	71.70
Al_2O_3	13.20	12.70	12.80	12.40	13.80	12.20	13.20
CaO	<0.01	0.90	0.25	0.50	0.85	0.52	0.98
MgO	0.34	0.25	0.10	0.08	0.24	0.13	0.18
Na_2O	3.20	4.27	3.60	3.73	4.16	4.01	4.32
K_2O	5.46	4.34	5.26	5.12	5.49	5.10	5.13
Fe_2O_3	3.70	1.78	3.42	1.15	1.69	1.61	3.23
MnO	0.04	0.05	0.07	0.02	0.05	0.04	0.09
TiO_2	0.42	0.26	0.37	0.13	0.17	0.11	0.22
P_2O_5	0.06	0.04	0.05	0.02	0.04	0.02	0.03
Cr_2O_3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
LOI	1.60	0.60	0.80	0.75	0.40	0.65	0.55
Total	100.2	99.3	99.8	98.7	99.1	99.0	99.8

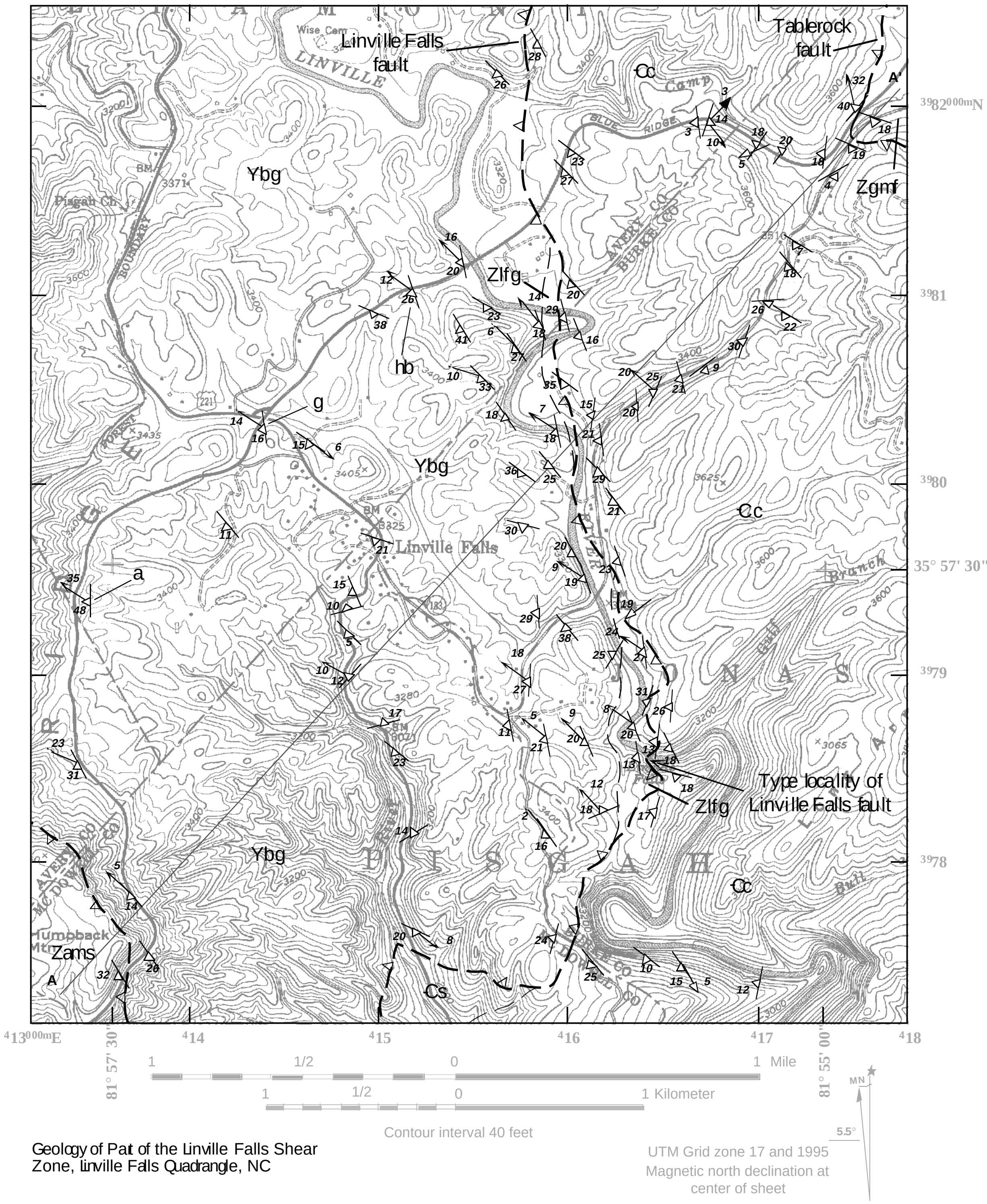


Figure 3. Geologic map and interpretive cross-section of part of the Linville Falls shear zone. The base map is a computer scan of part of the Linville Falls, NC 71/2 minute quadrangle. Portions of the Shady Dolomite and Ashe Metamorphic Suite contacts, and the southernmost part of the Linville Falls fault (above the Shady Dolomite) are modified after Bryant and Reed (1970).

EXPLANATION

Paleozoic

Ꞓs	Shady Dolomite: Massive, buff to light gray, fine-grained siliceous dolomite. Cataclastic deformation is prevalent near contact with the Linville Falls shear zone.
Ꞓc	Chilhowee Group, undivided: Meta-arkose, feldspathic quartzite, and quartzite, biotite grade. Typically sheared to mylonite and ultramylonite. Compositional layering generally parallel to mylonitic foliation.

Neoproterozoic

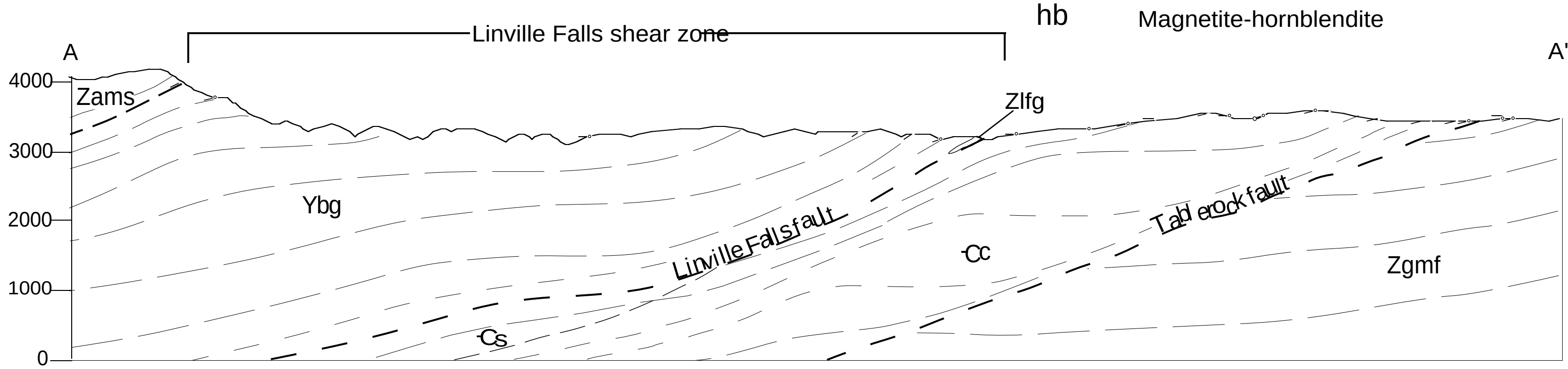
Zgmf	Grandfather Mountain Formation: Medium-grained arkose, massive, weakly foliated. Low greenschist-grade metamorphism.
Zams	Ashe Metamorphic Suite: Kyanite-garnet mica schist and amphibolite. Sheared and retrograded (greenschist grade) near fault contact with basement rocks in the Linville Falls shear zone.
Zlfg	Linville Falls granite: Medium- to coarse-grained alkali feldspar metagranite. Sheared to mylonite and ultramylonite, and overprinted by cataclasis.

Mesoproterozoic

Ybg	Biotite gneiss: Layered to nonlayered biotite gneiss and granitic gneiss, with minor hornblende gneiss, amphibolite, and epidote-biotite schist. Includes bodies of alkali feldspar granite and magnetite hornblendite. Strongly sheared to mylonite and ultramylonite in the Linville Falls shear zone.

Map Symbols

(dashed line)	Contact, dashed where approximate
(line with triangle)	Thrust fault, dashed where approximate
10	Trend and plunge of mineral stretching line
3	Trend and plunge of crenulation axis
5	Trend and plunge of minor fold axis
18	Strike and dip of mylonitic foliation
(dashed lines)	Form lines (cross section), closely spaced in areas of intense shearing
(tick symbol)	Dip direction (cross section)
a	Amphibolite
g	Alkali feldspar granite
hb	Magnetite-hornblendite



Interpretive Cross Section from A to A'

exposed (Figure 4). The Linville Falls granite pinches out to the north and south, where rocks of the Tablerock thrust sheet are juxtaposed against basement-derived mylonite of the Linville Falls shear zone along the Linville Falls fault (sensu stricto).

Figure 4. Contact between the Linville Falls granite (bottom) and ultramylonite of the Linville Falls shear zone (top). Hammer rests on the contact. Photograph taken facing west. Note platy weathering of finely laminated ultramylonite.

Structural data for the Linville Falls shear zone are summarized in Figure 5. Mylonitic foliation in the shear zone generally dips gently to moderately west and southwest. Mineral stretching lineations are very consistent, and plunge gently to the northwest and southeast. Foliation and lineation data for the Linville Falls granite and Chilhowee Group rocks of the Tablerock thrust sheet are similar to those for the Linville Falls shear zone, and suggest that they all experienced a common deformation history, as noted by Bryant and Reed (1970). Minor fold axes range from perpendicular to parallel to mineral stretching lineations. Bryant and Reed (1969, 1970) and Mies (1991) suggested that minor fold hinge lines were rotated during shearing toward

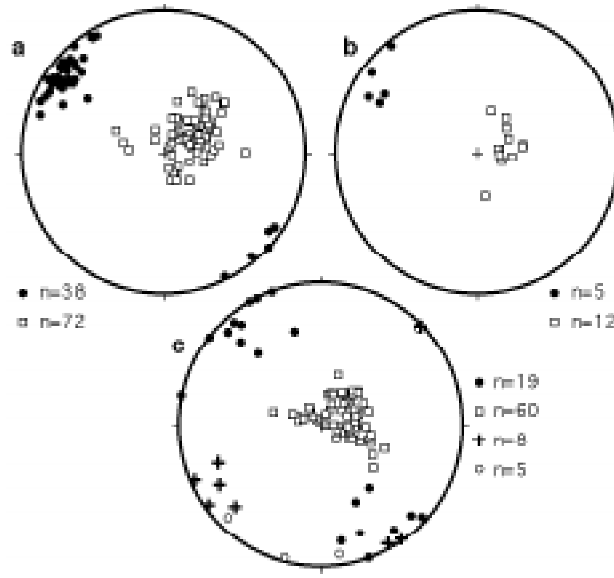


Figure 5. Equal area, lower hemisphere projections of structural data from the Linville Falls shear zone. Boxes = poles to mylonitic foliation; dots = mineral stretching lineations; crosses = minor fold axes; open circle = crenulation axis. a) Linville Falls shear zone; b) Linville Falls granite; c) Chilhowee Group metaquartzites.

parallelism with mineral stretching lineations. Axes to crenulation are perpendicular to mineral stretching lineations, and either post-date thrusting (Hatcher and Butler, 1986), or are related to late-stage movement in the Linville Falls shear zone (Bryant and Reed, 1970), possibly due to thrust imbrication and duplex formation within the Grandfather Mountain window (Boyer, 1992).

Cataclasite occurs within the Linville Falls granite, but has not been observed in Chilhowee quartzites. Mylonites near the base of the Linville Falls shear zone, immediately above the Linville Falls granite, have a minor cataclastic overprint confined to the first few meters above the granite. Cataclastic fabric in these mylonites consists of randomly sized and oriented angular fragments of mylonitic material in a very fine-grained matrix of quartz, feldspar, and mica. These cataclasite zones are predominantly normal microfaults. Cataclasites are also found at the base of the Linville Falls shear zone north of the Grandfather Mountain window near Banner Elk and Bowers Gap, NC (Trupe and Adams, 1991; Goldberg et al., 1992), and are also present in the Long Ridge, Unaka Mountain, and Stone Mountain fault systems (King and Ferguson, 1960; Bryant and Reed, 1970; Diegel and Wojtal, 1985; Adams and Trupe, 1991; O'Hara, 1992; Adams and Su, 1996). As at Linville Falls, the cataclasites overprint mylonitic fabrics, and occur at the base of the shear zone.

MICROSTRUCTURES AND CONDITIONS OF DEFORMATION ASSOCIATED WITH THE LINVILLE FALLS SHEAR ZONE

The Linville Falls shear zone consists of protomylonite, mylonite and ultramylonite derived from a variety of basement rocks. The predominant rock type is feldspar porphyroclastic mylonite (Figure 6). Most are L-S mylonites, with well-developed foliation defined by compositional layers of quartz and feldspar alternating with layers of fine-grained white mica. Lineation is defined by elongate quartz-feldspar aggregates or biotite streaks.

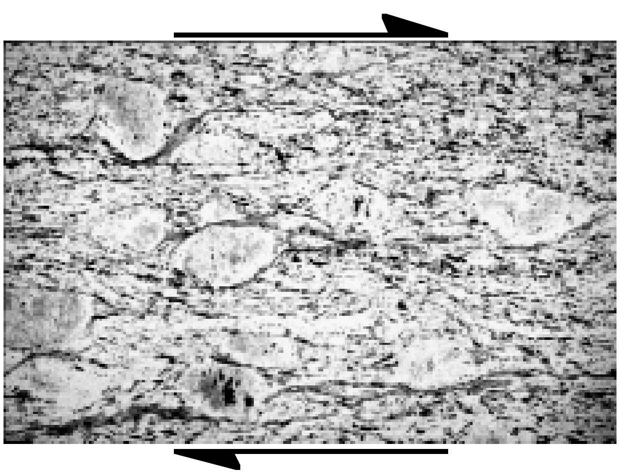


Figure 6. Photomicrograph (plane light) of basement-derived, feldspar porphyroclastic mylonite from the Linville Falls shear zone. Field of view is ~6.5 mm wide. σ-type asymmetric porphyroclasts give top-to-northwest sense of shear.

Feldspar in the mylonites is deformed primarily by cleavage-controlled fracture, with minor recrystallization along cracks and grain boundaries. Porphyroclast tails consist of fine-grained quartz, mica, and feldspar. In many basement-derived mylonites, plagioclase is the predominant feldspar, and it is typically sausseritic and altered to epidote, white mica, and quartz. This alteration suggests that hydrolysis of feldspars was an important mechanism in the reduction of feldspar porphyroclast size and the formation of quartz-mica matrix material.

Quartz is deformed by crystal-plastic mechanisms in all Linville Falls shear zone mylonites. Quartz forms ribbons or compositional layers of dynamically recrystallized grains that range from 10 µm to 100 µm in size and average ~50 µm. Grains range from highly strained with undulose extinction and irregular, serrated grain boundaries, to clear, polygonal, and strain-free with straight grain boundaries. These fabrics suggest deformation by dislocation creep accommodated by dynamic recrystallization and recovery (e.g. White, 1976, 1977; Kerrich and Allison, 1978; Urai et al., 1986).

LINVILLE FALLS GRANITE

In weakly sheared Linville Falls granite, a penetrative foliation did not develop. The predominant deformation mechanism was cleavage-controlled brittle fracture of feldspars, with minor recrystallization in quartz. Plagioclase deformed by crystal-plastic mechanisms as evidenced by bent or kinked twin lamellae and undulatory extinction. In more strongly sheared samples, feldspar grain-size is reduced, and a fine-grained matrix of quartz, mica, and recrystallized feldspar form a well-developed mylonitic foliation. In such mylonitic Linville Falls granite, quartz layers consist of aggregates of recrystallized grains averaging ~50 µm in diameter. K-feldspars exhibit minor recrystallization along fractures and grain boundaries. Mylonitic foliation is defined by fine-grained phyllosilicates and quartz-feldspar ribbons. Near the Linville Falls fault (sensu stricto), fluid-rock interaction is suggested by an increase in phyllosilicate content, and feldspar grain-size reduction apparently enhanced by hydrolysis. Previous studies have suggested that H_2O-rich fluids played an important role in the formation of Linville Falls shear zone mylonites (e.g., Bryant and Reed, 1970; Wojtal and Mitra, 1988; Schedl et al., 1992; Trupe, 1989b; Newman and Mitra, 1993).

Mylonitic foliation in the Linville Falls granite is cut by cataclasite zones (Figure 7). These zones consist of randomly oriented fragments of mylonitic granite in a very fine-grained matrix of quartz, epidote, chlorite, and opaque minerals. Much of the matrix material is dark red-brown to black, and apparently consists of very fine-grained iron oxide. Cataclasite zones do not appear to have been overprinted by subsequent ductile deformation. This sequence of deformation contrasts with relationships between brittle and ductile deformation in the Long Ridge fault and related shear zones north of the Grandfather Mountain window. Adams and Su (1996) noted that cataclasis was overprinted by ductile deformation in these shear zones, and suggested that these relationships could be explained by alternating episodes of brittle and ductile deformation enhanced by high fluid pressures within the Long Ridge fault.

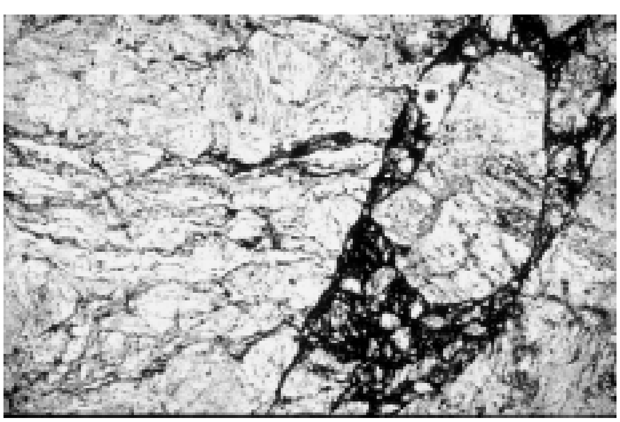


Figure 7. Photomicrograph (plane light) of mylonitic Linville Falls granite cut by cataclasite zones. Field of view is ~6.5 mm wide.

CHILHOWEE GROUP QUARTZITE

Quartzites and arkosic quartzites of the Chilhowee Group were strongly sheared in the Linville Falls shear zone to form feldspar-quartz-sericite mylonites. Mylonitic foliation is defined by fine-grained white mica and layers of recrystallized quartz. Opaque minerals (predominantly magnetite) are concentrated along the foliation. Alkali feldspar (microcline) forms small, rounded porphyroclasts with tails of quartz and white mica. Recrystallized quartz grains range from 10 μm to 100 μm, averaging about 30 μm.

There are some quartzites between the Linville Falls shear zone and the Tablerock fault that are not mylonitic. These rocks possess low-grade regional metamorphic fabric with weakly defined foliation and lineation. Relict sedimentary features are preserved in some of these less-deformed rocks. Shearing within the Tablerock thrust sheet is most intense near its bounding faults (Figure 3).

SUMMARY OF MICROSTRUCTURES AND CONDITIONS OF DEFORMATION IN THE LINVILLE FALLS SHEAR ZONE

Mylonitic rocks in the Linville Falls area all exhibit similar deformation features. K-feldspars were deformed predominantly by brittle fracture with minor recrystallization along cracks and grain boundaries. Plagioclase grains possess bent or kinked twin lamellae and undulose extinction. These features indicate that feldspars deformed by a combination of microcataclasis and intracrystalline slip (Tullis, 1983; Tullis and Yund, 1987). Quartz deformed by crystal-plastic mechanisms, with microstructures suggestive of deformation by dislocation creep accommodated by dynamic recrystallization (White, 1976, 1977; Urai et al., 1986). The features noted above are consistent with mid- to upper greenschist facies conditions (~350-450 °C) of deformation in the mylonitic rocks of the Linville Falls shear zone (e.g. Voll, 1976; Tullis, 1983; Simpson, 1985). Additionally, the mineral assemblages present in the mylonites reflect greenschist facies metamorphism. Similar estimates for conditions of deformation in the Linville Falls fault have been reported by Schedl (1985, 1988), Wojtal and Mitra (1988), and Trupe (1989b).

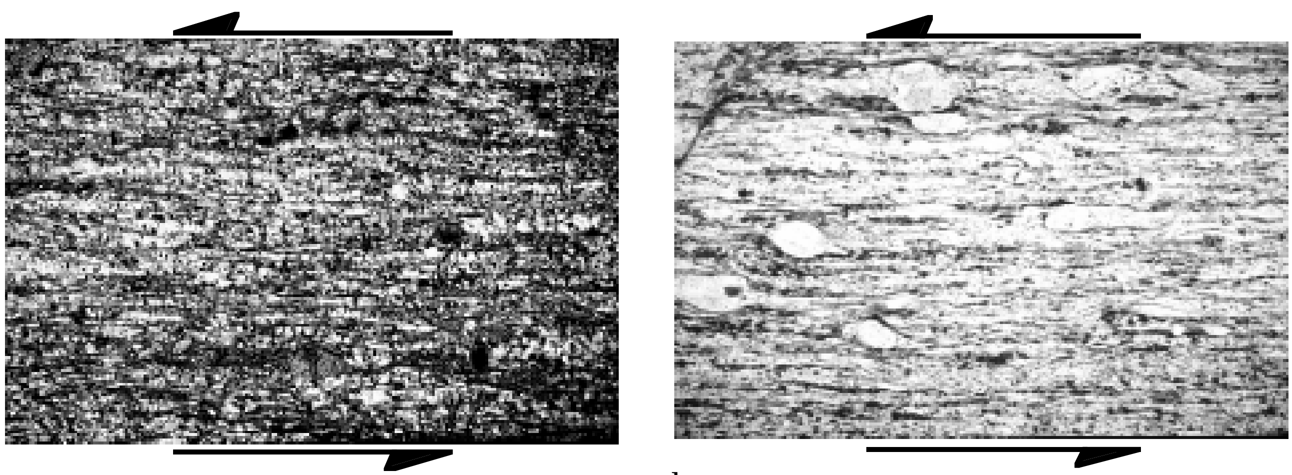
In weakly sheared Linville Falls granite, the abundant K-feldspars may have inhibited penetrative foliation development. Alternatively, the lack of penetrative mylonitic foliation in the less deformed granite may be the result of low strain within the granite block, while mylonitization was more intense along margins of the block. In any case, the majority of the granite is strongly mylonitic.

Cataclasite zones in the Linville Falls granite suggest deformation under different conditions than those noted above. Cataclasis could have been initiated by an influx of fluids into the Linville Falls shear zone, thus reducing the effective pressure (Hubbert and Rubey, 1959; Etheridge et al., 1984)). Alternatively, cataclastic deformation may represent overprinting by brittle deformation as the Blue Ridge thrust complex reached relatively shallow crustal levels during late stages of thrusting.

KINEMATIC ANALYSIS

Bryant and Reed (1970) interpreted the Linville Falls fault as a top-to-northwest thrust fault, and interpreted mineral stretching lineations in the sheared rocks to represent the direction of tectonic transport. Sense of movement derived from microscopic and mesoscopic kinematic indicators verifies this interpretation.

Examples of microscopic kinematic indicators from the Linville Falls shear zone and mylonitic Chilhowee Group quartzites are shown in Figure 8. Asymmetric porphyroclasts are present, and yield top-to-northwest shear sense. Dimensional preferred orientation in recrystallized quartz grains and composite



a b

Figure 8. Kinematic indicators in the Linville Falls shear zone. Field of view is ~6.5 mm wide in both photomicrographs. a) Photomicrograph (crossed polars) of Chilhowee-derived mylonite (sample 8968) 1 meter below the Linville Falls granite. Sample lies below granite slice shown in Figure 4. Top-to-northwest shear sense is shown by σ-type feldspar porphyroclast at bottom of photograph, composite planar fabric, and dimensional preferred orientation of recrystallized quartz grains. b) Photomicrograph of ultramylonite from the Linville Falls shear zone (sample 90-009) 1 meter above the Linville Falls granite contact shown in Figure 4. Top-to-northwest shear sense is shown by σ-type feldspar porphyroclasts. A small brittle microfault in upper left corner cuts mylonitic foliation and gives top-to-northwest sense of shear.

planar fabric (shear bands, S-C fabric) also give top-to-northwest sense of shear.

Quartz *c*-axes were measured in samples from the Linville Falls shear zone, Linville Falls granite, and Chilhowee-derived mylonite (Figure 9). Quartz *c*-axes in mylonite from the Linville Falls shear zone one meter above the Linville Falls granite describe a single girdle distribution with maxima near the pole to foliation, and parallel to the Y-direction. The quartz *c*-axis fabric is consistent with basal and prism slip in the <*a*> direction (Lister and Dornsiepen, 1982; Schmid and Casey, 1986). A sample of Linville Falls granite yields a diffuse crossed-girdle pattern. The fabric skeleton is consistent with top-to-northwest shear sense, as are other kinematic indicators within the granite (e.g., asymmetric porphyroclasts, dimensional preferred orientation in quartz, composite planar fabrics). Chilhowee-derived mylonite one meter below the Linville Falls granite exhibits a weakly defined pattern of *c*-axes similar to the shear zone mylonite above, with point maxima near the pole to foliation, consistent with top-to-northwest sense of shear. Additional analyses of quartz *c*-axis orientations in the Linville Falls shear zone and Tablerock thrust sheet (Trupe, 1989b, 1997) also indicate top-to-northwest shear sense.

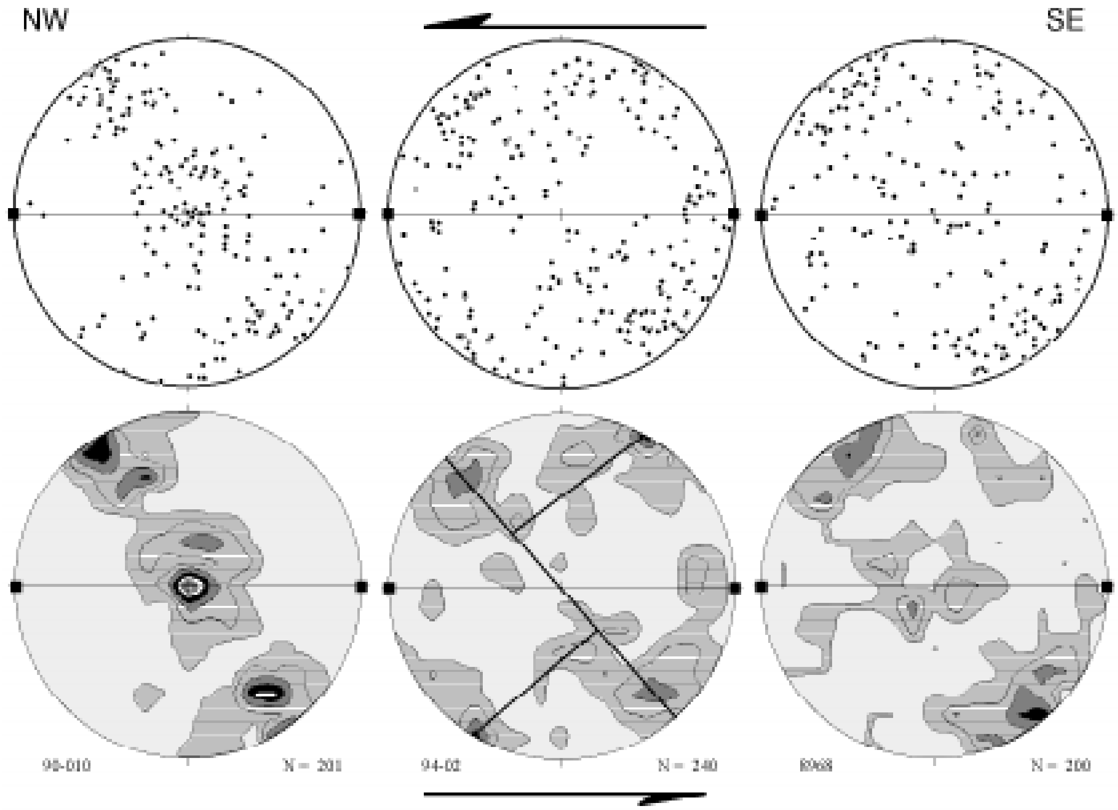


Figure 9. Equal area, lower hemisphere projections of quartz *c*-axes from the Linville Falls shear zone. All are XZ sections, plotted relative to vertical east-west foliation and horizontal mineral stretching lineation (boxes). Contour interval is 1% / 1% area. Sample 90-010 is Linville Falls shear zone mylonite 2 meters above the Linville Falls granite. Sample 94-02 is Linville Falls granite; sample occurs approximately midway between Linville Falls shear zone mylonites and Chilhowee Group quartzites. Sample 8968 is Chilhowee mylonite shown in Figure 8a. All give top-to-northwest shear sense. Sample 94-02 yields a crossed-girdle distribution; fabric skeleton asymmetry is consistent with interpreted sense of shear.

DISCUSSION AND CONCLUSIONS

The base of the Blue Ridge thrust complex comprises a thick ductile shear zone that contains tectonic blocks or slices of various lithologies in a matrix of sheared basement rocks. Mylonites were deformed under greenschist facies conditions, and all contain kinematic indicators consistent with top-to-northwest sense of shear. At Linville Falls, a slice of alkali feldspar granite overlies Chilhowee Group metaquartzites of the Tablerock thrust sheet. This granite is probably a slice of Neoproterozoic Beech Granite. Mylonites at the base of the Linville Falls shear zone were overprinted by cataclastic deformation fabrics. Field observations depicted schematically by closely spaced form lines in the cross section of Figure 3 suggest that the Tablerock thrust sheet is strongly sheared at its base and near the Linville Falls shear zone. Indeed, the volume of mylonitic rocks above and below the Linville Falls fault as originally defined, and the similarities in structural and microstructural features in the Linville Falls shear zone and underlying Tablerock thrust sheet may indicate that shearing associated with emplacement of the Blue Ridge thrust complex extends to the base of the Tablerock thrust sheet, at least in the vicinity of Linville Falls. Bryant and Reed (1970) interpreted the Tablerock thrust sheet as a tectonic slice incorporated during thrusting of Blue Ridge crystalline rocks over rocks of the Grandfather Mountain window.

In previously reported studies, geologists failed to recognize the magnitude of the Linville Falls shear zone; hence, their interpretations are based upon incomplete information. In particular, studies that have attempted to explain the variation in thickness of the Linville Falls fault from Linville Falls to exposures north of the Grandfather Mountain window (e.g. Wojtal and Mitra, 1988; Newman and Mitra, 1993) are flawed, because they did not recognize the considerable width of the Linville Falls shear zone. For example, Wojtal and Mitra (1988) described the Linville Falls fault at Linville Falls as an intensely deformed zone 10 to 15 meters thick, with most of the displacement confined to a 1-meter-thick mylonite zone along the fault. Newman and Mitra (1993) stated that a variation in fault thickness of >60 times occurs over a 20 kilometer distance from southeast to northwest along the Linville Falls fault, and attempted to explain this change by volume loss and fluid-rock interaction during shearing. While fluid-rock interaction was undoubtedly important in the deformation of the Linville Falls shear zone, a model that requires a large volume loss is unnecessary in this case, as there is no significant variation in thickness of the shear zone between Linville Falls and Banner Elk. Additionally, Newman and Mitra (1993) assumed that the protolith for fault zone mylonites at Banner Elk was a quartz-diorite gneiss, which is exposed 500 meters above zone they interpreted to be the fault. The quartz-diorite gneiss was shown to be an exotic slice within the Linville Falls shear zone by Adams (1990b) and Adams and Su (1996). Hence, at both Linville falls and Banner Elk, Wojtal and Mitra (1988) and Newman and Mitra (1993) not only failed to recognize the significant thickness of mylonite, they also overlooked the occurrence of exotic slices in the Linville Falls shear zone. Thus their interpretations are based upon incomplete field data. The Linville Falls shear zone is hundreds of meters thick both west and north of the Grandfather Mountain window, and the well-exposed laminated ultramylonite at Linville Falls is a high strain zone at the base of the shear zone. An alternate interpretation of this ultramylonite is that the ductility contrast between relatively competent mica-poor alkali feldspar granite in the hanging wall and the quartz-sericite rocks in the footwall resulted in a high strain zone between the two units.

The conclusions about the features of the Linville Falls shear zone and their implications are as follows. (1) The base of the Blue Ridge thrust complex comprises a thick mylonite zone produced under greenschist facies conditions, probably during the early Alleghanian orogeny. (2) Ductile fabrics of the mylonites have been overprinted by cataclastic fabrics. (3) Fluid flow perhaps contributed to mylonitization and cataclasis. Evidence for fluid involvement in the Linville Falls shear zone includes hydrolysis of feldspars, retrogressive metamorphism of sheared amphibolites and mylonitic hornblende gneisses, and local silicification of the Linville Falls granite. (4) The ductile fabrics probably formed as the Blue Ridge thrust complex developed at relatively great depth. (5) Near the Grandfather Mountain window, the Linville Falls shear zone appears to overprint earlier formed mylonite zones between thrust sheets within the complex (Goldberg et al., 1989). This suggests that the Linville Falls shear zone represents late movement of the Blue Ridge thrust complex along its base. (6) The large volume of mylonitic rocks associated with the Tablerock thrust sheet suggests that it accommodated high shear strain and essentially acted as a large shear zone, or as part of the Linville Falls shear zone. Mylonitization of is pervasive throughout the Tablerock thrust sheet, but cataclasites have not been observed in these rocks or in the Tablerock fault at the base of the thrust sheet (Trupe, 1997). Boyer (1992) suggested that the southern portion of the Linville Falls fault was active early in the deformation history, and that the Tablerock thrust formed later under generally brittle conditions of deformation and cut up-section to merge with the northern Linville Falls fault. In this interpretation, the Tablerock fault is an out-of-sequence thrust, and is not truncated by the Linville Falls shear zone. In contrast, Bryant and Reed (1970) state that the Tablerock fault is cut by the Linville Falls fault, and is therefore older. This issue remains unresolved. The existence of a Tablerock shear zone, however, could explain Boyer's interpretation that the two faults merged during their deformation history.

Tectonic blocks within the Linville Falls shear zone consist of Chilhowee Group metasandstone, granite bodies, and exotic rocks (e.g., Adams, 1990a, 1990b; Trupe et al., 1990; Adams and Trupe, 1991; Adams and Su, 1996). (7) The Linville Falls granite is one of these tectonic blocks, and may be a slice of Beech Granite, or possibly the Crossnore or Brown Mountain granites. The Beech and Crossnore granites both occur in the hanging wall of the Linville Falls fault. The Stone Mountain fault system has been interpreted to represent emergence of the Linville Falls fault north of the Beech Granite (e.g., Bryant and Reed, 1970; Harris et al., 1981; Boyer and Elliott, 1982), thus permitting the Beech Granite to locally define the base of the Blue Ridge thrust complex and to provide blocks to the shear zone. The Brown Mountain Granite is in the footwall of the Tablerock fault, which makes it geometrically difficult for it to have provided slices to the Linville Falls shear zone. However, if the base of the Tablerock thrust sheet is simply a sheared unconformity rather than a thrust fault with significant displacement (an explanation rejected by Bryant and Reed, 1970, p. 106), the Brown Mountain Granite could provide footwall slices to the Linville Falls shear zone. Alternatively, if the Brown Mountain Granite was originally farther southeast than its present location, the Linville Falls granite could be a footwall slice of Brown Mountain Granite carried along the base of the Linville Falls shear zone prior to emplacement of the Tablerock thrust sheet.

During Alleghanian thrusting, (8) the Blue Ridge thrust complex was emplaced along the Linville Falls shear zone. During the late Alleghanian orogeny, cataclastic fabrics overprinted ductile fabrics in mylonites at the base of the complex. Cataclastic deformation could result from an influx of fluids leading to reduction of effective stress (e.g., Hubbert and Rubey, 1959; Etheridge et al., 1984), or a change in strain rate at ductile depths (e.g., Hobbs et al., 1986). Alternatively, cataclastic deformation could be due to movement of the Blue Ridge thrust complex into relatively shallow crustal levels. Cataclasite zones were themselves overprinted by ductile deformation in other ~300 Ma faults north of the Grandfather Mountain window (Adams and Su, 1996), suggesting fluctuation of conditions (e.g., fluid pressure, temperature, strain rate) during later stages of movement. The ~300 Ma Rb-Sr whole-rock date for the Linville Falls fault (Van Camp and Fullagar, 1982; Schedl et al., 1992) indicates the age of closure of the Rb-Sr isotopic system, probably near the end of mylonite formation. Cataclasis may have been coeval with closure, or slightly younger. Adams and Su (1996) obtained similar ~300 Ma ages on mylonites overprinted by cataclastic fabrics in the Long Ridge fault, which they interpreted to be an Alleghanian feature associated with the Linville Falls shear zone. (9) The significance of the Linville Falls fault (sensu stricto) is that it defines the base of the Linville Falls shear zone, and records the last stages of movement of the composite Blue Ridge thrust complex.

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REFERENCES

Abbott, R.N., Jr., and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic history. American Journal of Science, 284, 350-375.

Adams, M. G., 1990a, Detailed mapping in the Valle Crucis area between the Grandfather Mountain and Mountain City windows, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 22, p. 1.

Adams, M. G., 1990b, The geology of the Valle Crucis area, northwestern North Carolina: Chapel Hill, North Carolina: MS Thesis, University of North Carolina at Chapel Hill, 95 p.

Adams, M. G., and Su, Q., 1996, The nature and timing of deformation in the Beech Mountain thrust sheet between the Grandfather Mountain and Mountain City windows in the Blue Ridge of northwestern North Carolina: Journal of Geology, v. 104, p. 197-213.

Adams, M. G., and Trupe, C. H., 1991, Significance of shear zones in the Beech Mountain thrust sheet, northwestern North Carolina and northeastern Tennessee: Geological Society of America Abstracts with Programs, v. 23, p. 2.

Adams, M. G., Stewart, K. G., Trupe, C. H., and Willard, R. A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting in the southern Appalachians, *in* Hibbard, J., van Staal, C., Cawood, P., and Colman-Sadd, S., editors, New Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 21-42.

Berkland, J.O., Raymond, L.A., Kramer, J.C., Moores, E.M., and O'Day, M., 1972, What is Franciscan?: American Association of Petroleum Geologists Bulletin, v. 56, p. 2295-2302.

Boyer, S. E., 1978, Structure and origin of Grandfather Mountain window, North Carolina: Ph.D. Dissertation, Johns Hopkins University, 279 p.

Boyer, S. E., 1992, Sequential development of the southern Blue Ridge Province of northwest North Carolina ascertained from the relationships between penetrative deformation and thrusting, *in* Mitra, S., and Fisher, G. W., editors, Structural Geology of Fold and Thrust Belts: The John Hopkins University Press, Baltimore, p. 161-188.

Boyer, S. E., and Elliott, D., 1982, Thrust systems: American Association of Petroleum Geologists Bulletin, v. 66, p. 1196-1230.

Boyer, S. E., and Mitra, G., 1988, Relations between deformation of crystalline basement and sedimentary cover at the basement/cover transition zone of the Appalachian Blue Ridge province, *in* Mitra, G., and Wojtal, S., editors, Geometries and Mechanisms of Thrusting, With Special Reference to the Appalachians: Geological Society of America Special Paper 222, p. 119-136.

Bryant, B., and Reed, J. C., Jr., 1969, Significance of lineation and minor folds near major thrust faults in the southern Appalachians and the British and Norwegian Caledonides: Geological Magazine, v. 106, p. 412-429.

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

Butler, J.R., 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge thrust sheet, North Carolina: American Journal of Science, v. 273-A, p. 72-88.

Butler, J. R., Goldberg, S. A., and Mies, J. W., 1987, Tectonics of the Blue Ridge west of the Grandfather Mountain window, North Carolina and Tennessee: Geological Society of America Abstracts with Programs, v. 19, p. 77.

Diegel, F. A. and Wojtal, S. F. 1985 Structural transect in SW Virginia and NE Tennessee, *in* Woodward, N. B., editor, Field Trips in the Southern Appalachians: University of Tennessee, Department of Geological Sciences, Studies in Geology 9, p. 70-143..

Etheridge, M. A., Wall, V. J., Cox, S. F., and Vernon, R. H., 1984, High fluid pressures during regional metamorphism and deformation: Implications for mass transport and deformation mechanisms: Journal of Geophysical Research, v. 89, p. 4344-4358.

Fetter, A.H., and Goldberg, S.A., 1995, Age and geochemical characteristics of bimodal magmatism in the Neoproterozoic Grandfather Mountain rift basin: Journal of Geology, v. 103, p. 313-326.

Goldberg, S. A., Butler, J. R., and Mies, J. W., 1986, Subdivision of the Blue Ridge thrust complex, western North Carolina and adjacent Tennessee: Geological Society of America Abstracts with Programs, v. 18, p. 616-617.

Goldberg, S. A., Dallmeyer, R. D., and Su, Q., 1993, Chronology of Paleozoic metamorphism and deformation in the southern Appalachian Blue Ridge based on Sr, Nd, Pb, and Ar isotopic systematics: EOS, v. 74, p. 122.

Goldberg, S. A., Butler, J. R.., Mies, J. W., and Trupe, C. H., 1989, The southern Appalachian orogen in northwestern North Carolina and adjacent states: International Geological Congress Field Trip T365 Guidebook, American Geophysical Union, Washington, D.C., 55 p.

Goldberg, S. A., Butler, J. R.., Trupe, C. H., and Adams, M. G., 1992, The Blue Ridge thrust complex northwest of the Grandfather Mountain window, North Carolina and Tennessee, *in* Dennison, J.M., and Stewart, K.G., editors, Geologic field guides to North Carolina and vicinity: Chapel Hill, North Carolina, Department of Geology, University of North Carolina at Chapel Hill, Geologic Guidebook No. 1, p. 213 - 233.

Harris, L.D., Harris, A.G., deWitt, W., Jr., and Bayer, K.C., 1981, Evaluation of southern eastern overthrust belt beneath Blue Ridge-Piedmont thrust: American Association of Petroleum Geologists Bulletin, v. 65, p. 2497-2505.

Hatcher, R. D., Jr. and Butler, J. R., 1986, Linville Falls fault at Linville Falls, North Carolina: Geological Society of America Centennial Field Guide, Southeastern Section, p. 229-230.

Hobbs, B.E., Ord, A., and Teyssier, C., 1986, Earthquakes in the ductile regime? Pure and Applied Geophysics, v. 124, n. 1-2, p. 309-336.

Hubbert, M. K. and Rubey, W. W., 1959, Role of fluid pressure in mechanics of overthrust faulting: Geological Society of America Bulletin, v. 70, p. 115-166.

Keith, A., 1903, Description of the Cranberry quadrangle, North Carolina-Tennessee: United States Geological Survey Geologic Atlas, Folio 90.

Keith, A., 1905, Description of the Mount Mitchell quadrangle, North Carolina-Tennessee: United States Geological Survey Geological Atlas, Folio 124.

Kerrich, R., and Allison, I., 1978, Flow mechanisms in rocks: Microscopic and mesoscopic structures, and their relation to physical conditions of deformation in the crust: Geoscience Canada, v. 5, p. 109-118.

King, P. B., and Ferguson, H. W., 1960, Geology of northeasternmost Tennessee: United States Geological Survey Professional Paper 311, 160 p.

Kretz, R., 1983, Symbols for rock-forming minerals: American Mineralogist, v. 68, p. 277-279.

Lister, G. S., and Dornsiepen, U. F., 1982, Fabric transitions in the Saxony granulite terrain: Journal of Structural Geology, v. 4, p. 81-92.

Mallard, L. D., Adams, M. G., and Stewart, K. G., 1994, Kinematic analysis of a possible suture in the southern Appalachians, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 26, p. 25-26.

Mies, J. W., 1991, Planar dispersion of folds in ductile shear zones and kinematic interpretation of fold-hinge girdles: Journal of Structural Geology, v. 13, p. 281-297.

Mies, J. W., and Trupe, C. H., 1989, Kinematic analysis in the Blue Ridge thrust complex, northwestern North Carolina and adjacent states: Geological Society of America Abstracts with Programs, v. 21, p. 50.

Mies, J. W., Butler, J. R., and Goldberg, S. A., 1987, Kinematic analysis of mylonite zones in the Blue Ridge, northwestern North Carolina and adjacent Tennessee: Geological Society of America Abstracts with Programs, v. 19, p. 118.

Newman, J., and Mitra, G., 1993, Lateral variations in mylonite zone thickness as influenced by fluid-rock interactions, Linville Falls fault, North Carolina: Journal of Structural Geology, v. 15, p. 849-863.

O'Hara, K., 1992, Major- and trace-element constraints on the petrogenesis of a fault-related pseudotachylyte, western Blue Ridge province, North Carolina: Tectonophysics, v. 204, p. 279-288.

Schedl, A., 1985, Deformation processes in the Linville Falls fault zone: Geological Society of America Abstracts with Programs, v. 17, p. 134.

Schedl, A., 1988, Possible geochemical implications of synthrusting growth of feldspar in the Linville Falls fault, North Carolina: Geological Society of America Abstracts with Programs, v. 20, p. 180.

Schedl, A., McCabe, C., Montanez, I., Fullagar, P. D., and Valley, J., 1992, Alleghanian regional diagenesis: A response to the migration of modified metamorphic fluids derived from beneath the Blue Ridge-Piedmont thrust sheet: Journal of Geology, v. 100, p. 339-352.

Schmid, S. M., and Casey, M., 1986, Complete fabric analysis of some commonly observed quartz *c*-axis patterns, *in* Hobbs, B. E., and Heard, H. C., editors, Mineral and Rock Deformation, Laboratory Studies: American Geophysical Union Geophysical Monograph 36, p. 263-286.

Sibson, R.H., 1977, Fault rocks and fault mechanisms: Journal of the Geological Society of London, v. 133, p. 191-213.

Simpson, C., 1985, Deformation of granitic rocks across the brittle-ductile transition: Journal of Structural Geology, v. 7, p. 503-511.

Stose, G. W., and Ljungstedt, O. A., 1932, Geologic map of the United States: United States Geological Survey, scale 1:2,500,000.

Stose, G. W., and Stose, A. J., 1944, The Chilhowee Group and the Ocoee Series of the southern Appalachians: American Journal of Science, v. 242, p. 367-390, 401-416.

Su, Q., 1994, Geochronological and isotopic studies of Later Proterozoic Crossnore-type plutons in the southern Appalachian Blue Ridge, North Carolina and Tennessee: Ph.D. Dissertation, University of North Carolina at Chapel Hill, 158 p.

Su, Q., and Fullagar, P.D., 1995, Rb-Sr and Sm-Nd isotopic systematics during greenschist facies metamorphism and deformation: Examples from the southern Appalachian Blue Ridge: Journal of Geology, v. 103, p. 423-436.

Su, Q., Goldberg, S. A., and Fullagar, P. D., 1994, Precise U-Pb zircon ages of Neoproterozoic plutons in the southern Appalachian Blue Ridge and their implications for the initial rifting of Laurentia: Precambrian Research, v. 68, p. 81-95.

Trupe, C. H., 1989a, Kinematic analysis and deformation mechanisms in mylonites from the Blue Ridge thrust complex, northwestern North Carolina: Geological Society of America Abstracts with Programs, v. 21, p. 62.

Trupe, C. H., 1989b, Microstructural analysis of mylonites from the Blue Ridge thrust complex, northwestern North Carolina: MS Thesis, University of North Carolina at Chapel Hill, 101 p.

Trupe, C. H., 1997, Deformation and metamorphism in part of the Blue Ridge thrust complex, northwestern North Carolina: Ph.D. Dissertation, University of North Carolina at Chapel Hill, 176 p.

Trupe, C. H., and Adams, M. G., 1991, Cataclastic deformation in the Linville Falls shear zone, western North Carolina Blue Ridge: Geological Society of America Abstracts with Programs, v. 23, p. 141.

Trupe, C. H., Adams, M. G., Butler, J. R., and Willard, R. A., 1991, Geology of the Burnsville, NC quadrangle: Basement-cover relationships in the North Carolina Blue Ridge: Geological Society of America Abstracts with Programs, v. 23, p. 140.

Trupe, C. H., Butler, J. R., Mies, J. W., Adams, M. G., and Goldberg, S. A., 1990, The Linville Falls fault and related shear zone: Geological Society of America Abstracts with Programs, v. 22, p. 66.

Tullis, J., 1983, Deformation of feldspars, *in* Ribbe, P. H., editor, Feldspar Mineralogy: Mineralogical Society of America Reviews in Mineralogy 2, p. 297-323.

Tullis, J., and Yund, R. A., 1987, Transition from cataclastic flow to dislocation creep of feldspar: Mechanisms and microstructures: Geology, v. 15, p. 606-609.

Urai, J. L., Means, W. D., and Lister, G. S ., 1986, Dynamic recrystallization of minerals, in Hobbs, B. E., and Heard, H. C., editors, Mineral and Rock Deformation: Laboratory Studies: American Geophysical Union Geophysical Monograph 36, p. 161-199.

Van Camp, S. G., and Fullagar, P. D., 1982, Rb-Sr whole-rock ages of mylonites from the Blue Ridge and Brevard zone of North Carolina: Geological Society of America Abstracts with Programs, v. 14, p. 92-93.

Voll, G., 1976, Recrystallization of quartz, biotite, and feldspars from Erstfeld to the Leventina Nappe, Swiss Alps, and its geological significance: Schweizerische Mineralogische und Petrographische Mitteilungen, v. 56, p. 641-647.

White, S., 1976, The effects of strain on the microstructures, fabrics, and deformation mechanisms in quartzites: Philosophical Transactions of the Royal Society of London, v. 283, p. 69-86.

White, S., 1977, Geological significance of recovery and recrystallization processes in quartz: Tectonophysics, v. 39, p. 143-170.

Willard, R. A., Trupe, C. H., Adams, M. G., and Butler, J. R., 1991, Transition in the character of the Ashe-Basement contact west of the Grandfather Mountain window: Geological Society of America Abstracts with Programs, v. 23, p. 150.

Wojtal, S., and Mitra, G., 1988, Nature of deformation in some fault rocks from Appalachian thrusts, *in* Mitra, G., and Wojtal, S., editors, Geometries and Mechanisms of Thrusting, With Special Reference to the Appalachians: Geological Society of America Special Paper 222, p. 17-33.

PETROLOGY AND TECTONIC SIGNIFICANCE OF ULTRAMAFIC ROCKS NEAR THE GRANDFATHER MOUNTAIN WINDOW IN THE BLUE RIDGE BELT, TOE TERRANE, WESTERN PIEDMONT ZONE, NORTH CAROLINA

Loren A. Raymond and Richard N. Abbott, Jr.
Department of Geology
Appalachian State University
Boone, NC 28608

ABSTRACT

Ultramafic rock bodies are scattered throughout the Ashe Metamorphic Suite, both northeast and southwest of the Grandfather Mountain Window in North Carolina. Of seven bodies examined northeast of the window and six bodies exposed southwest of the window, only two lack the older anhydrous, Eclogite (?) or Granulite (?) Facies olivine-pyroxene-chromite mineral assemblage recognized in many of these rock bodies. Two amphibolite facies assemblages characterized by hydrous amphibole and phyllosilicate phases, such as tremolite, anthophyllite, and chlorite, are recognized in all of the bodies; and one or two retrograde Greenschist Facies assemblages are reflected by serpentine-dominated assemblages in more than half of the bodies. A greenschist facies assemblage consisting of antigorite + chlorite + magnetite may reflect cooling after the peak of regional metamorphism, but the meaning of the textural relationship between this assemblage and an apparently younger anthophyllite-bearing assemblage and the thermodynamic implications of that relationship are unresolved. Overall, the sequence of assemblages reflects decreasing T with time. The particular sequence of phase assemblages developed during retrograde metamorphism is determined by the specific paths through P-T-a_{H2O}-time space.

All of the ultramafic bodies described herein occur in the Toe Terrane (= Spruce Pine Thrust Sheet), which lies within the Blue Ridge section of the Piedmont Zone of the Southern Appalachian Orogen. The structural settings, contact relations, and metamorphic histories of the ultramafic rock bodies indicate that they were emplaced tectonically into the enclosing rocks and were then metamorphosed and deformed during Taconic high pressure, Amphibolite Facies events. Later these rocks underwent retrograde metamorphism during Acadian Amphibolite Facies and Alleghenian (and perhaps younger) Greenschist Facies events. The structural setting, shape, distribution, and association with other exotic rock masses, including eclogite, at the western edge of the Piedmont Zone, suggest that these alpine ultramafic rocks represent mantle and ophiolite fragments within an accretionary, tectonic melange that marks the Taconic suture.

INTRODUCTION

Alpine ultramafic rock bodies are widely distributed, although not abundant, in the Eastern Blue Ridge Belt of North Carolina (Pratt and Lewis, 1905; Hess, 1955; Larrabee, 1966; Misra and Keller, 1978; Abbott and Raymond, 1984; Raymond, 1995, p. 667ff.). Rocks in these bodies contain several assemblages of minerals, most of which represent retrograde metamorphic events that occurred over Phanerozoic time. The oldest assemblages are dominated by olivine and orthopyroxene and contain Cr-spinel. Younger assemblages contain hydrous phases such as tremolite, anthophyllite, talc, and chlorite and the youngest assemblages, typically, are dominated by serpentine minerals.

The ultramafic rock bodies occur in two terranes within the Blue Ridge Belt (Fig. 1). The eastern terrane is called the Toe Terrane (Raymond, 1987; Raymond et al., 1989) or the Spruce Pine Thrust Sheet (Goldberg et al., 1989; Adams et al., 1995), and is included in the Jefferson Terrane of Horton et al. (1989; Rankin et al., 1993)(Figure 1). The western belt is referred to as the Cullowhee Terrane (Raymond, 1987; Raymond et al., 1989), the Mars Hill Terrane (Bartholomew and Lewis, 1988), or the Pumpkin Patch Thrust Sheet (Goldberg et al., 1989; Adams et al., 1995)(Figure 1). The western belt has also been included in the Jefferson Terrane of Horton et al. (1989; Rankin et al., 1993), and both terranes are assigned to the western part of the Piedmont Zone of Hibbard and Samson (1995). Herein, we refer to the the eastern and western belts as the Toe and Cullowhee terranes, respectively.

Near the Grandfather Mountain Window, both to the northeast and the southwest, ultramafic rock bodies occur in the Toe Terrane. Farther southwest, ultramafic rock bodies also occur in the Cullowhee Terrane. We have reviewed the literature on, examined, and here report on seven representative bodies northeast and six bodies southwest of the Grandfather Mountain Window, all in the Toe Terrane, in order to characterize the petrography, petrologic history, structure, and tectonic significance of the ultramafic rocks in this region.

LOCATIONS, STRUCTURAL RELATIONS, AND ROCK TYPES

The locations of the 13 bodies of ultramafic rock selected for this study are shown in Figure 2. All of the ultramafic rock bodies

Lithologic Belts of Brown et al., 1985	Terranes of Raymond, 1987; Raymond et al., 1989	Terrane & Massifs of Bartholomew and Lewis, 1988	Thrust Sheets of Goldberg et al., 1989; Adams et al., 1995	Terrane & Massif of Horton et al., 1989; Horton et al., 1991	Zones of Hibbard and Samson, 1995
Alligator Back Fm., Ashe Metamorphic Suite, & related rocks	Toe Terrane	----	Spruce Pine Thrust Sheet	Jefferson Terrane	Western Part of the Piedmont Zone
Migmatitic Biotite-Hornblende Gneiss & Biotite Gneiss (migmatitic)	Cullowhee Terrane	Mars Hill Terrane	Pumpkin Patch Thrust Sheet		
Biotite Granitic Gneiss & associated rocks (including Great Smoky Group)	Sherwood Terrane	Elk River Massif	Beech Mountain Thrust Sheet	Laurentia, including French Broad Massif	Cumberland Zone (Laurentian rocks)
Granodioritic Gneiss and associated rocks	---- (= Laurentian Basement rocks)	Watauga Massif	Pardee Point Thrust Sheet		

Figure 1. A comparison of recently assigned names for various structural and lithologic belts of rock within the North Carolina Blue Ridge Belt.

occur in the Ashe Metamorphic Suite of the Toe Terrane, although earlier some were assigned erroneously to the Cullowhee Terrane (shown as migmatitic biotite and migmatitic biotite-hornblende gneiss) on the Geologic Map of North Carolina (Brown et al., 1985). Bodies north of the Grandfather Mountain Window include the Edmonds Ultramafic Body, on the North Carolina-Virginia border; the Nathans Creek, Warrensville, and Todd bodies exposed in or near communities of those names; and the Greer Hollow and two Rich Mountain bodies exposed at those geographic locations. To the southwest, ultramafic rocks include the Frank, Spruce Pine, and Newdale bodies, near communities of those names, and the Blue Rock Road, Woody, and Day Book bodies (Appendix A contains locations of both northern and southern bodies).

In most cases, the contacts of the ultramafic bodies are concealed by soil, but in a few cases, the contacts are exposed. Typically, rocks on one or both sides of inferred contacts are exposed within a few meters of the contact. In

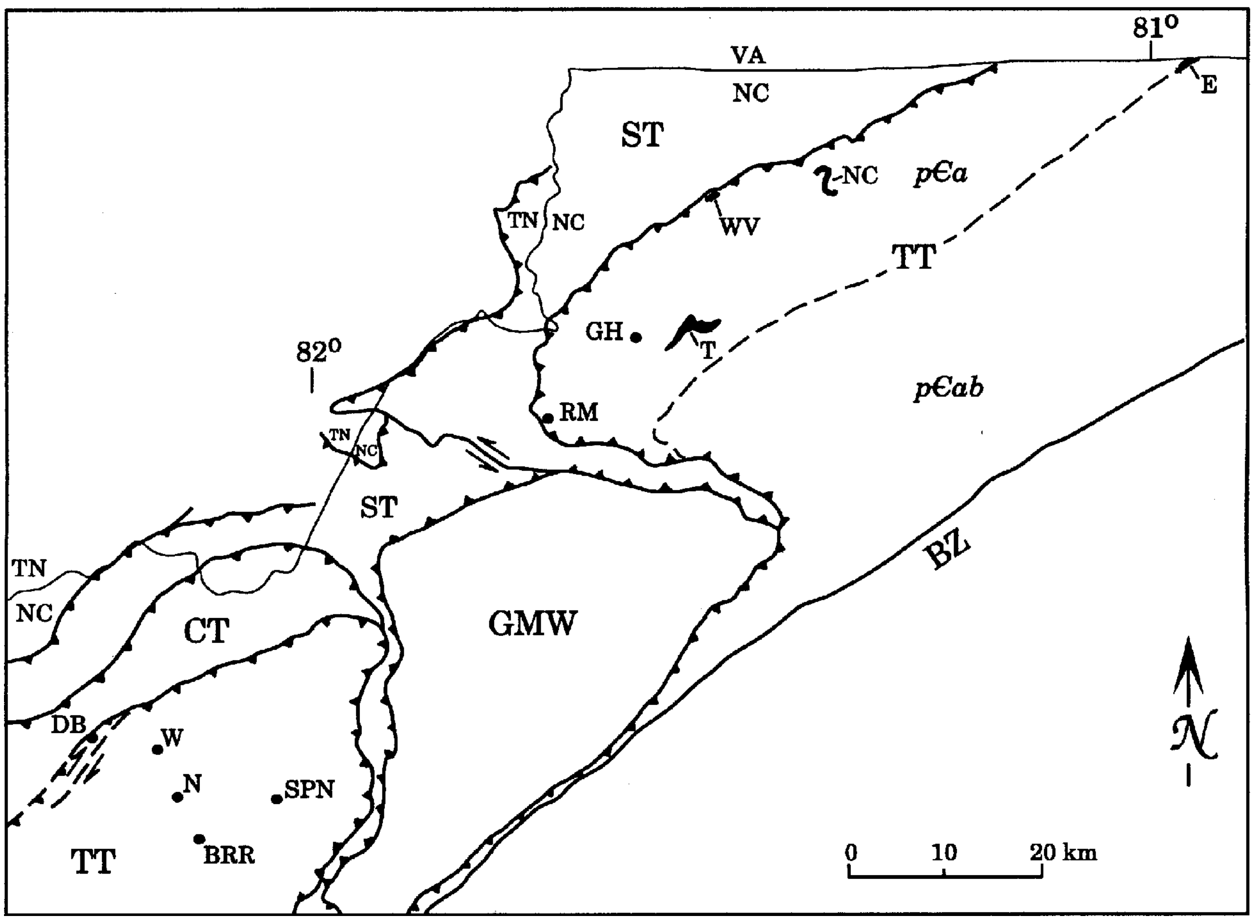

Figure 2. Generalized geologic map of northwestern North Carolina showing the structural belts bounded by major thrust faults and the locations of the ultramafic rock bodies described in this report (base map after Brown et al., 1985; and Adams et al., 1995). BZ = Brevard Fault Zone; CT = Cullowhee Terrane; GMW = Grandfather Mountain Window; pCa = Ashe Metamorphic Suite; pCab = Alligator Back Metamorphic Suite; ST = Sherwood Terrane; TT = Toe Terrane. Ultramafic bodies are BRR = Blue Rock Road; DB = Day Book; E = Edmonds; F = Frank; GH = Greer Hollow; RM = Rich Mountain; N = Newdale; NC = Nathans Creek; SPN = Spruce Pine North; T = Todd; W = Woody; WV = Warrensville.

no case is there preserved evidence of contact metamorphism, such as higher grade mineral assemblages, anhydrous phase assemblages, or localized migmatitic rocks adjacent to the ultramafic bodies in the surrounding country rocks. Where contacts are exposed, they are typically sharp and are marked by lower grade, hydrated mineral assemblages in the enclosing rocks. In some cases, schists with hydrous phase assemblages that suggest metasomatic reaction between ultramafic rock and adjacent schist and gneiss occur as a “blackwall” or reaction zones at the contact. No apophyses or dikes are known to extend from the ultramafic bodies into the surrounding rocks.

Each of the bodies selected for this study reveals some features typical of BlueRidge ultramafic rock bodies. General geologic maps of selected ultramafic bodies are shown in Figure 3 and others have been illustrated elsewhere (e.g., Stose and Stose, 1957; Swanson, 1981).

The *Edmonds Ultramafic Body*, mapped by Stose and Stose (1957) as a body of ultramafic rock complexly interfingered with rocks of the Lynchburg Gneiss (now included in the Ashe Metamorphic Suite), occurs at the boundary between the Ashe Metamorphic Suite and the Alligator Back Metamorphic Suite (Espenshade et al., 1975: Abbott and Raymond, 1984). The body contains serpentinite, chlorite-talc schist, chlorite-tremolite schist, anthophyllite-tremolite schist, actinolite-chlorite schist, and chlorite dunite (Stose and Stose, 1957; Scotford and Williams, 1983; this report). The details of internal structure and compositional variations are unmapped, but the body appears to contain a foliation parallel to the regional foliation. In addition, local folds in the foliation indicate post-metamorphic deformation of the body. Outcrops of this body occur along small road cuts in the vicinity of Edmonds on Highway 18 near the Virginia border, as well as locally to the north between Edmonds, North Carolina and Blue Ridge Mills, Virginia.

The *Nathans Creek Ultramafic Body* (= Shatley Springs body of Scotford and Williams, 1983) has a clearly folded map pattern (Fig. 3a; Rankin et al., 1972), indicating post-emplacement deformation. Foliation generally parallels that in the surrounding country rocks, which are mica schist, mica gneiss, and hornblende schist and gneiss. The body itself is composed of chlorite-tremolite schist and only locally contains remnant olivine (Scotford and Williams, 1983; this report). Good exposures of the Nathans Creek body occur northeast of Jefferson, North Carolina, along Highway 221 at Nathans Creek, as well as on private properties to the north.

Petrographically, the *Warrensville Ultramafic Body* is similar to the Nathans Creek body, in that chlorite-tremolite schists dominate (Scotford and Williams, 1983; this report). Local porphyroclasts of olivine occur in some samples. The body and the foliation within it generally parallel the foliation in the enclosing rocks, which consist of hornblende schist and gneiss (Jones, 1976). No internal structural features or petrographic variations have been mapped to date. The most easily accessible outcrop of the Warrensville Ultramafic Body occurs in a road cut, below a private yard, across from the park in the community of Warrensville, North Carolina, located on Highway 88, west of West Jefferson, North Carolina.

The *Todd Ultramafic Body,* like the Nathans Creek body, is folded with the surrounding rocks (Rankin et al., 1972). The body lies within a part of the Ashe Metamorphic Suite dominated by hornblende gneiss and schist, but containing some mica schists. Retrograded metadunite occurs locally within this body, harzburgite is reported by Larrabee (1966), and talc-tremolite schist is present, but the dominant rock type is chlorite-tremolite schist (Scotford and Williams, 1983; this report). As is the case with other bodies in this region, no detailed maps of internal structural or petrologic features have been published. The body is exposed in

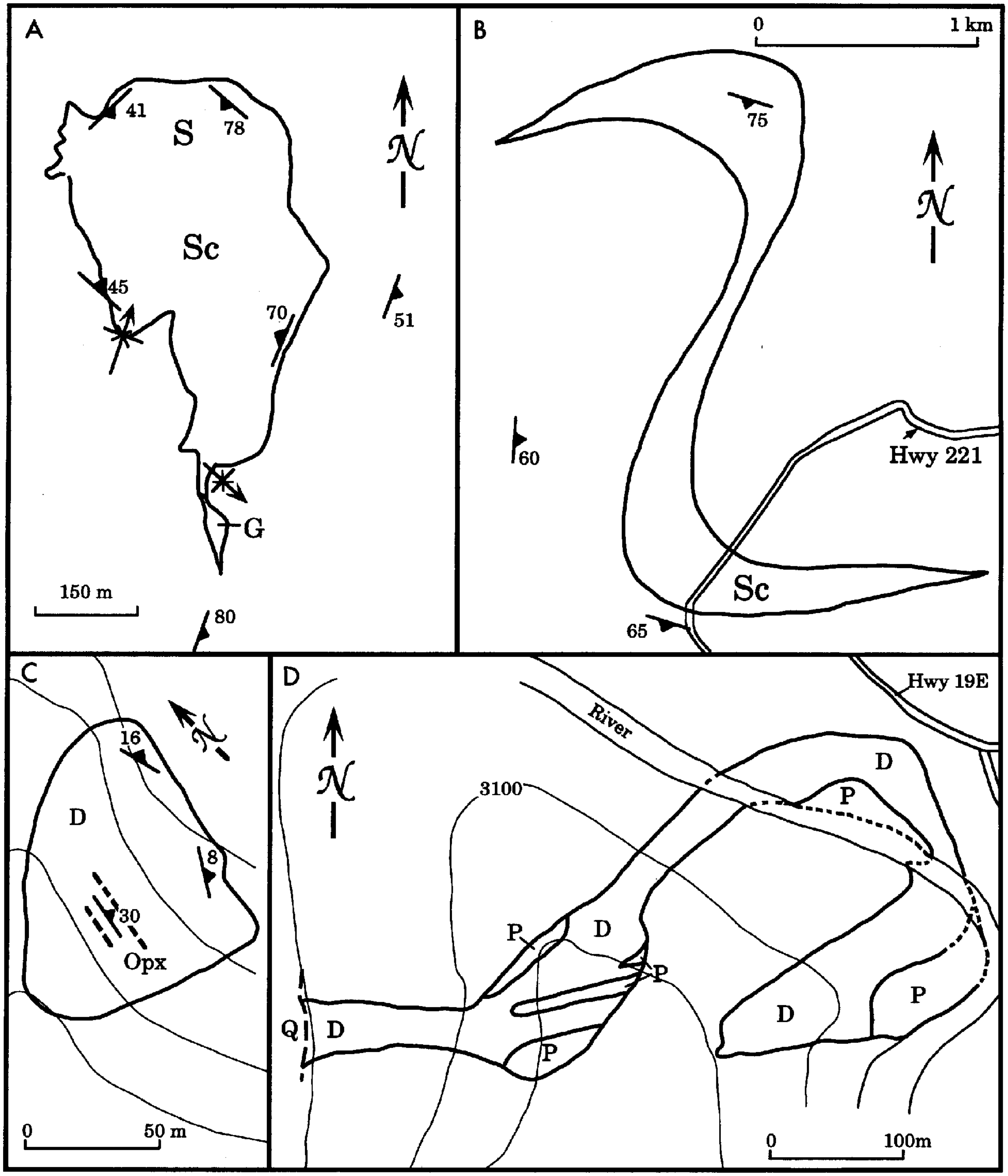

Figure 3. Maps of selected ultramafic rock bodies (note varying scales). A - Greer Hollow Ultramafic Body. Dark unit at southern end is magnetite-garnet-chlorite schist (in part, based on Raymond, 1995, p. 672). B - Nathans Creek Ultramafic Body (after Rankin et al., 1972). C - Hoots Ultramafic Body, Rich Mountain. Opx = orthopyroxenite bands. D - Frank Ultramafic Body . Pd = peridotite bands (modified from Vrona, 1979).

minor outcrops along Highway 194 and on adjoining roads, between Todd, North Carolina and the Baldwin and Fleetwood communities.

At *Greer Hollow*, the ultramafic body contains foliations and folds that are extensions of the same structures in the enclosing rocks (Raymond et al., 1988; Raymond, 1995; this report; Fig. 3b). Anthophyllite, tremolite, and chlorite schists dominate in the body, but a mappable mass of porphyroblastic magnetite-garnet-chlorite schist occurs at the southern end of the body. Minor porphyroclastic orthopyroxene-olivine-tremolite-anthophyllite-chlorite schist contains harzburgite microlithons. Late serpentinite veins cut the northern end of the body. Enclosing rocks are predominantly plagioclase-hornblende rocks, including gneiss, schist, and semi-schist. At the southeastern edge of the body, a small mass of pelitic schist crops out, separated from the ultramafic body by an approximately one meter-thick layer of actinolite-talc schist and diablastite. The Greer Hollow Ultramafic Body occurs near Todd, North, Carolina, on private property near Greer Hollow Road.

Two of several ultramafic bodies depicted by Pratt and Lewis (1905) and Larrabee (1966) in the Rich Mountain area north of Boone, North Carolina were later described by Hearn et al. (1977), Callahan et al. (1978), and Swanson (1980) as the Rich Mountain Ultramafic Bodies. These two bodies, the *Hoots Ultramafic Body* and the *McNeil Ultramafic Body*, occur within hornblende schist and gneiss and are located near outcrops of retrograded eclogite described in this volume by Abbott and Raymond (1997). Local float blocks of granitoid pegmatite and metadiorite suggest the presence of such rocks within the surrounding gneisses and schists (Swanson, 1980).

The *Hoots Ultramafic Body* is a small (96m X 98m) mass of dunite with local, discontinuous layers of orthopyroxenite and associated harzburgite (Fig. 3c). Minor veins of talc-amphibole diablastite and serpentine cut the dunite. The contacts are concealed by soil, colluvium, and block streams, but outcrops of hornblende schist and gneiss occur a few meters from them. Foliation and layering in the body are approximately parallel to the foliation in the surrounding hornblende schist and gneiss which have an average foliation trend of N30°W (Fig. 3c).

The *McNeil Ultramafic Body* is a very poorly exposed body composed primarily of dunite and represented in the field by a few outcrops and float blocks (locally piled up by the landowner). Minor harzburgite is reported here (Swanson, 1980), but the relationship between the harzburgite and dunite is not known. A "blackwall" alteration zone composed of tremolite-anthophyllite-talc schist is exposed in a pond bank at the north end of this ultramafic body. All other contacts are entirely concealed by soil. The surrounding country rocks consist of hornblende schist and gneiss. The approximate north-south trend of the McNeil Ultramafic Body parallels the generally north-south trend of foliation in the hornblende schist and gneiss. The body is located on private property near Junaluska Road, east of Zionville, North Carolina and permission must be obtained to visit the body.

South of the Grandfather Mountain Window, the *Frank Ultramafic Body* is exposed in the community of that name (Brobst, 1962; Bluhm, 1976). The body forms a folded mass that trends generally east-west (Fig. 3d). Bluhm (1976) mapped the contacts of the body as thrust faults. Foliation and layering within the body are not parallel to either the lithologic contacts in the country rock or the foliation in that rock, but Bluhm (1976) demonstrated that earlier fabrics in the ultramafic body have been overprinted by later fabrics produced by subsequent deformation of both the country rock and the ultramafic body. The east-west trend of the body roughly parallels the N80°E trend of a dominant foliation. Petrographically, the Frank Ultramafic Body consists of dunite, five "layers" of lherzolite, and associated retrograde metamorphic assemblages (Bluhm, 1976; this report). At the margins of the body, along veins and locally throughout the body, the dunite and lherzolite have been retrogressively metamorphosed to hydrous phase assemblages containing phases such as anthophyllite, tremolite, talc, chlorite, and serpentines. The enclosing rocks in contact with the ultramafic body consist of hornblende gneiss, garnet-hornblende schist, hornblende-biotite schist, garnet-muscovite schist, and muscovite schist of the Ashe Metamorphic Suite (Bluhm, 1976). A quarry for dunite has been developed and periodically activated within the center of the Frank body, and permission to visit the quarry must be obtained from the current mine owners. Outcrops of both of the principal rock types, dunite and lherzolite, and common metamorphic overprint assemblages, exist along the slopes of the North Toe River channel below Highway 19E at the road junction in Frank.

The *Spruce Pine North Ultramafic Body* is the northern of two bodies of ultramafic rock exposed north of a shopping center located in southern Spruce Pine on Highway 226 (Brobst, 1962). The body contains at least three retrograde mineral assemblages overprinted on an early dunite assemblage of chromite + olivine. The various retrograde assemblages are characterized by minerals such as anthophyllite, tremolite, talc, chlorite, magnesite, and serpentine. The body lies within a unit of the Ashe Metamorphic Suite dominated by mica schist and gneiss, and containing minor hornblende gneiss; and it occurs just north of a body of granitoid igneous rock of the Spruce Pine Plutonic Suite (Brobst, 1962; McSween et al., 1991; Wood, 1996). The long dimension of the body parallels the general ENE trend of the local foliation in the enclosing rocks. Good exposures of this ultramafic body occur less than 100m east of Highway 226 on a side road leading east, but they are now part of the landscaping of a residence that was constructed on the body. Sampling is not recommended.

The *Newdale Ultramafic Body* is located about 0.6km north of Highway 19E along Highway 80 in the Newdale community (Brobst, 1962; Vrona, 1979; this report). Road cuts, a water-filled quarry on the east, and a borrow pit on the west side of Highway 80 provide numerous exposures of the main rock, dunite, and retrograde veins cross-cutting it (permission is required to enter the quarry). The veins and associated zones of replacement minerals contain various assemblages composed of talc, anthophyllite, tremolite, chlorite, magnesite, serpentine, and magnetite. The ultramafic body is folded and shows three phases of deformation, including one that predates the two deformation events present in the surrounding rocks (Vrona, 1979). The long dimension of this elliptical ultramafic body parallels the general N60°E trend of the foliation in the enclosing rocks, but internal fabrics in the dunite show no relationship to this foliation (Vrona, 1979). Contacts with the enclosing rocks are not well exposed, but Vrona (1979) shows the contact as a fault that cross-cuts local structural and lithologic trends. The ultramafic body is entirely enclosed in hornblende gneiss and schist (amphibolite), but is in contact with an anthophyllite schist layer also enclosed within the hornblende gneiss and schist (Vrona, 1979).

The *Blue Rock Road Ultramafic Body* is exposed south of Newdale in a road cut on Blue Rock Road, just south of Blue Rock Branch, near a hill top east of the South Toe River. The body occurs within a mica schist and gneiss unit of the Ashe Metamorphic Suite and is cut at one end by a pegmatite of the Spruce Pine Plutonic Suite (Brobst, 1962). The rock here is anthopyllite-tremolite-talc-chlorite schist. The northeast trend of the long dimension of the body parallels the trend of the local foliation.

The *Woody Ultramafic Body* is one of several bodies in the Thunderstruck Knob area of Yancey County, North Carolina and is located about 4.5 miles (7.2 km) north of Micaville (Brobst, 1962; Kingsbury and Heimlich, 1978; Raymond, 1995, p. 667ff.). The body is a 300m long, elliptical mass composed of dunite, harzburgite, retrograded lherzolite, various $\pm$anthophyllite$\pm$tremolite$\pm$talc-chlorite schists, and serpentinites. Mineralogical layering is not evident in the body, in spite of the presence of peridotites within the dunite (Kingsbury and Heimlich, 1978). The long dimension of the elliptical body parallels the northeasterly trend of foliation in the enclosing rock, but the ends of the body are discordant to that foliation (Kingsbury and Heimlich, 1978). The enclosing rock consists of two mica-quartz-feldspar gneiss. Southeast of the ultramafic body, a granitoid pegmatite has intruded country rocks parallel to the foliation (Kingsbury and Heimlich, 1978). Inasmuch as the Woody Ultramafic Body is on private property, permission to examine the body must be obtained from the owner.

The *Day Book Ultramafic Body* is arguably the most studied ultramafic body in the North Carolina Blue Ridge Belt (e.g., Hunter, 1941; Kulp and Brobst, 1954; Brobst, 1962; McCormick, 1975; Swanson and Raymond, 1976; Swanson, 1981; Swanson et al., 1985; Raymond, 1995, p. 667ff., Swanson, 1996). The body is located north of Burnsville in the community of Day Book. The Day Book dunite has been mined for many years and the map pattern of the contacts has changed somewhat as mining progressed. In the 1970s, two bodies of rock, one substantially smaller than the other, existed end-to-end (Swanson, 1981), but recently developed exposures suggest that these bodies are connected at depth. At 1970s depths of exposure, the Day Book Ultramafic Body consisted of dunite, orthopyroxene-bearing dunite, chromite dunite, olivine chromitite, and chromitite. Layers of chromitite, some of which are folded, are the most recognizable layers in the dunite, but they are discontinuous and an internal structural and lithologic map of the body(ies) has not been produced. At mine levels in the mid-1990s, orthopyroxene was abundant enough in some quarry bottom exposures to make the exposed rock a harzburgite. A tabular granitoid pluton bounds the Day Book Ultramafic Body on the northwest and dikes extend from this pluton into and across the ultramafic body. Especially along these dike margins, but also in zones extending into the dunites and harzburgites, hydrous retrograde metamorphic assemblages containing vermiculite, phlogopite, talc, magnesite, anthophyllite, tremolite, chlorite, antigorite, lizardite, and other minerals replace the anhydrous minerals. The enclosing rocks at Day Book are mica gneiss and schist, hornblende gneiss and schist, and pegmatitic granodiorite, but the ultramafic body is only in contact with the first and last of these rock types (Swanson, 1981). Foliations in the mica schists and gneiss trend northeast, but locally wrap around the margins of the ultramafic body, the long dimension of which trends northeast parallel to the average foliation of the schist. Attitudes of veins in the dunite are unrelated to this northeast trend (Swanson, 1981). Permission to enter the Day Book quarries is required by the company that owns the body.

In summary, the ultramafic rock bodies occur in contact with hornblende schists and gneisses, mica schists, mica gneisses, related semi-schists, and granitoid igneous rocks. In some cases in the Toe Terrane, notably at Day Book, the granitoid rocks intrude the ultramafic rocks, constraining the emplacement of the ultramafic rocks to a pre-Taconic age (> 395 m.y.) (Swanson,1981; Kish, 1989; McSween et al., 1991). No evidence of magmatic emplacement of the ultramafic rock bodies exists and detailed structural studies (Bluhm, 1976; Kingsbury and Heimlich, 1978; Vrona, 1979) indicate that the ultramafic bodies were emplaced as solid masses, bringing with them relict structures and textures. The long dimensions of the bodies, in map views, generally parallel the foliation direction within the surrounding schists and gneisses. At Edmonds, Warrensville, Rich Mountain, Greer Hollow, Frank, and Newdale, it is clear that major foliation development, folding events, or both occurred after emplacement of the ultramafic bodies, because parallel structures occur in the surrounding rocks and the ultramafic rocks.

PETROLOGY

Previously published studies of Blue Ridge ultramafic rocks in North Carolina are numerous (e.g., Pratt and Lewis, 1905; Carpenter and Phyfer, 1969; Neuhauser and Carpenter, 1971; Dribus et al., 1976; Yurkovich, 1977; Kingsbury and Heimlich, 1978; Misra and Keller, 1978; Swanson, 1980; 1981; 1996; 1997; Raymond and Swanson, 1981; Huneycutt and Heimlich, 1980; Astwood et al., 1982; McElhaney and McSween, 1983; Scotford and Williams, 1983; Hatcher et al., 1984; Abbott and Raymond, 1984; Raymond and Abbott, 1985; Raymond et al., 1988; Raymond, 1995, Ch. 31; Tenthorey et al., 1996). Previously published syntheses of the data available on the ultramafic and associated rocks (e.g., Abbott and Raymond, 1984; Raymond, 1995, p. 571ff., p. 667ff.) suggest that at least five recrystallization events are represented by the various mineral assemblages and textures in the ultramafic rocks and at least three of these events have affected the associated schists and gneisses. Three major problems lack a consensus: (1) the sequence and nature of crystallization events; (2) the timing, nature, and significance of serpentinization; and (3) the nature of the tectonic history implied by the petrologic data.

PETROGRAPHIC OBSERVATIONS

The petrographic data from the 13 ultramafic bodies described briefly above reveal five mineral associations:

(A-1) olivine ± pyroxene(s) + chromite;
(A-2) olivine ± pyroxene(s) + chromite + tremolite + chlorite;
(A-3) ± tremolite ± anthophyllite ± chlorite ± talc ± phlogopite ± magnesite ± magnetite ± garnet;
(A-4) antigorite ± magnetite ± chlorite ± talc ± tremolite; and
(A-5) lizardite ± chrysotile ± magnetite ± chlorite ± talc ± tremolite ± magnesite.

The age sequence of these assemblages generally appears to be A-1 = oldest to A-5 = youngest. Some textural data suggest, however, that an A-4 association, consisting of antigorite ± chlorite + magnetite, formed locally between the formation of assemblages A-2 and A-3 (e.g., Swanson et al., 1985; Raymond et al., 1988; Swanson, 1996). The significance of these textural relationships is controversial (see below).

Table 1 lists the associations found in each of the bodies described above. Some bodies, such as the Nathans Creek Ultramafic Body, contain mineral assemblages representing only one of the associations, whereas others, such as the Day Book Ultramafic Body contain mineral assemblages representing all five associations. Northeast of the immediate vicinity of the Grandfather Mountain Window; anthophyllite, tremolite, and chlorite bearing assemblages are apparently more abundant, reflecting more pervasive, lower grade, fluid-richer metamorphism of the ultramafic rocks in this region.

The ultramafic rocks described herein, and in the original studies on which this review is based, show petrofabrics and textural relationships like those in many other deformed ultramafic rocks (e.g., Evans and Tromsdorff, 1974; Ave Lallement, 1976; O’Hanley, 1996), ultra-

TABLE 1. OBSERVED METAMORPHIC MINERAL ASSOCIATIONS IN TOE TERRANE ULTRAMAFIC ROCK BODIES

	ASSOCIATIONS					
LOCALITIES	A-1	A-2	A-3	A-4	A-5	SOURCES
EDMONDS	X		X	X		Scotford & Williams (1983); Raymond (1995)
NATHANS CREEK			X			Scotford & Williams (1983); This paper
WARRENSVILLE	X		X			Scotford & Williams (1983); This paper
TODD	X		X	X		Scotford & Williams (1983); This paper
GREER HOLLOW	X	X	X	X		Raymond et al. (1988); Raymond (1995)
RICH MOUNTAIN						
McNeil	X	X	X	X		Swanson (1980); This paper
Hoots	X	X	X	X		Swanson (1980); This paper
FRANK	X		X	X		Bluhm (1976); This paper
SPRUCE PINE	X	X	X	X		This paper
NEWDALE	X		X	X (?)	X	Vrona (1979); This paper
BLUE ROCK ROAD			X			This paper
WOODY	X		X	X	X	Kingsbury & Heimlich (1978); Raymond (1995); This paper
DAY BOOK	X	X	X	X	X	Swanson (1981; and others, 1985); Raymond (1995)

mafic xenoliths (Basu, 1977; Pike and Schwarzman, 1977), and experimentally deformed ultramafic rocks (e.g., Carter and Ave Lallement, 1970; Zeuch and Green, 1984). The general sequence of deformation in the Toe Terrane rocks, as revealed by rock textures, is also consistent with sequences in those deformed ultramafic materials. The textural sequence, from oldest to youngest textures, is:

(T-1) coarse porphyroclastic texture; replaced by
(T-2) equigranular-mosaic and equigranular-tabular texture; replaced by
(T-3) fine porphyroclastic and equigranular tabular texture; cross-cut and replaced by
(T-4) lepidoblastic, nematoblastic-foliated, and diablastic textures of several generations.

The first three textures are exhibited by rocks with association A-1 and A-2 mineral assemblages, whereas rocks of the fourth texture type (T-4) contain one or more mineral assemblages of the associations A-3, A-4, or A-5.

As noted above, the assemblage antigorite + magnetite + chlorite (of A-4) appears to have formed in some rocks (e.g., at Day Book) *before* an anthophyllite-bearing assemblage of A-3. Texturally, the antigorite-rich A-4 assemblage in these rocks occurs as rims on and along fractures in olivine grains that occur in equigranular-mosaic texture in dunite. Limited replacement of the olivine along grain boundaries and fractures results in a microscopic mesh-texture. The anthophyllite in these rocks occurs in both apparently compatible relationships and as cross-cutting grains with the serpentine that forms the mesh-texture. The ambiguity of the textural relations allows two likely possibilities: (1) that the anthophyllite and the mesh-textured assemblage serpentine + chlorite + magnetite formed under approximately the same conditions, which would require either that the fields of stability of antigorite and anthophyllite overlap (1a), or that anthophyllite crystallized metastably outside of its field of stability (1b); or (2) that the mesh-textured assemblage serpentine $\pm$ chlorite + magnetite formed after the development of the anthophyllite, but did not affect the grain margins of the anthophyllite in a noticeable way. Thermodynamic considerations make very unlikely a third alternative, (3) that the antigoritic mesh-textured assemblage developed *at a lower temperature* than the anthophyllite-bearing assemblage, and was overprinted by the anthophyllite-bearing assemblage *at a higher temperature* (Swanson et al., 1985). The issue is important, because, if the antigoritic mesh-textures did form at lower T than the anthophyllite-bearing assemblage, the thermal history of the mountain belt would include at least one cycle of cooling and reheating, which has significant tectonic implications.

Clearly, ambiguities and complexities involving associations A-3 and A-4 exist, as do some involving association A-5. The issue of the appearance of antigorite-bearing mesh-textured assemblages will be discussed further in the section below on phase relationships. Association A-3 has a complex set of minerals and the order of appearance of these minerals varies, depending on particular local conditions. Association A-4 is characterized by the appearance of serpentine minerals cross-cutting tremolite and other earlier formed minerals. Nematoblastic to lepidoblastic veins of serpentine minerals may cut one another. Association A-5 includes — in addition to the more common Mg-silicate phases — diablastic, nematoblastic, radial-planar, and lepidoblastic veins containing minerals such as aragonite and garnierite. It is clear from the available data, including the number of cross-cutting and partial replacement textures, that textural equilibrium was only attained locally.

PHASE RELATIONSHIPS AND THE PETROGENETIC GRID

The phase relationships in the system $MgO-SiO_2-H_2O$ have been debated and studied extensively since the pioneering work of Bowen and Tuttle (1949). Works by Chernosky et al. (1985) and Day et al. (1985) among others, have increased our present level of understanding with regard to this system. Reactions involving the stability of serpentine and anthophyllite are of particular importance to the ultramafic rock bodies described herein. Important controversies involving the MgO-SiO2-H2O system relate to the shape and size of the stability fields of anthophyllite and antigorite in P-T space (Day and Halback, 1979; Day et al., 1985; Chernosky et al., 1985; Spear, 1993, Ch. 13; O'Hanley, 1996). At issue are the field-limiting reactions:

talc + enstatite = anthophyllite
(reaction 1)

and

antigorite = olivine + talc + water
(reaction 2) (Fig. 4).

Depending on the locations of these reactions, the stability fields of anthophyllite and serpentine may or may not overlap. In the simple system MgO-SiO2-H2O, fields of stability for antigorite and anthophyllite do not overlap (Fig. 4).

The occurrence of serpentine and anthophyllite together in apparent equilibrium assemblages in some hydrated dunites suggests that an overlap of stability fields is possible (Sanford, 1977). Such an overlap provides one possible explanation for the ambiguous anthophyllite and mesh-texture antigorite combinations noted above. The possibility of overlapping stability fields is supported by some calculations and experiments (Delaney and Helgeson, 1978; Day et al., 1985), but not by others, especially those for the simple system (Spear, 1993, Ch. 13; see Fig. 4).

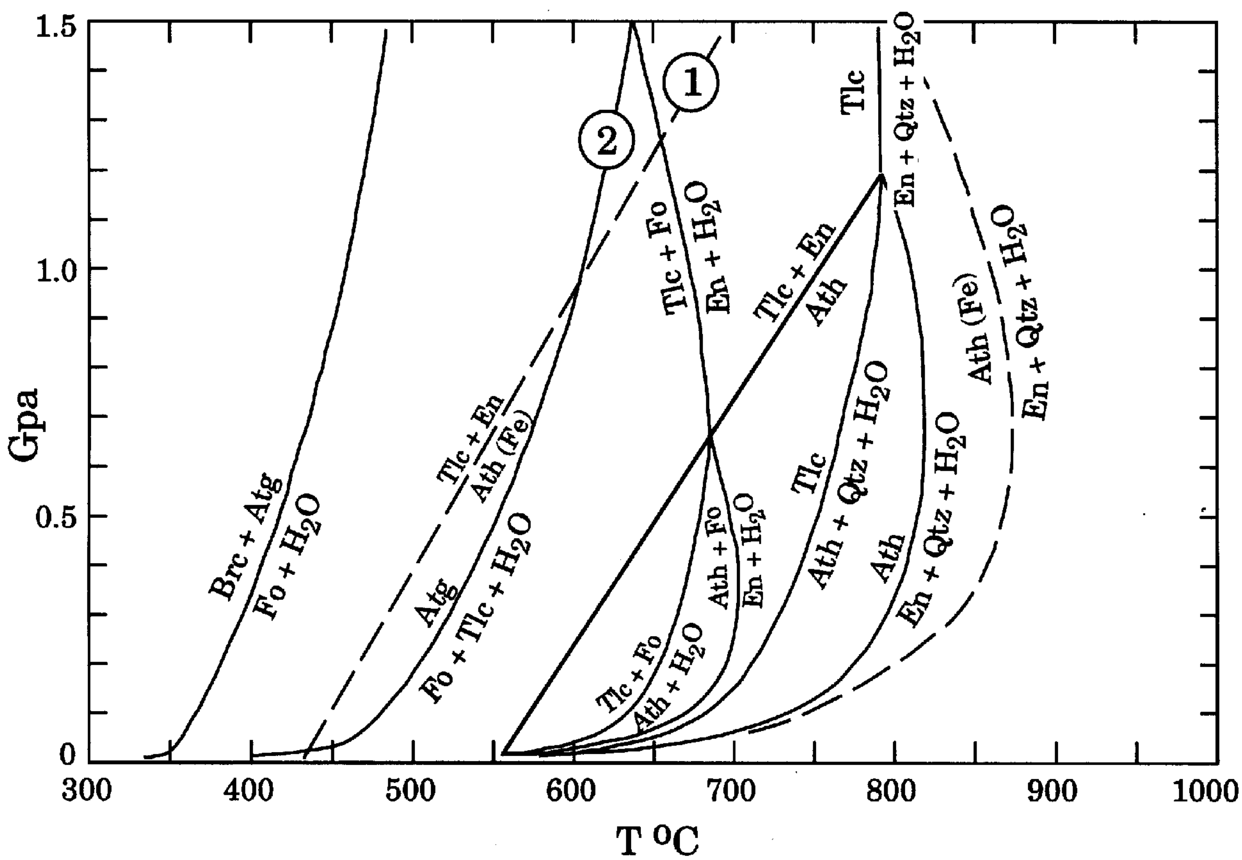

Figure 4. Petrogenetic grid for ultramafic rocks showing selected reaction curves involving either antigorite (Atg) or anthophyllite (Ath). Other minerals are brucite (Brc), enstatite (En), forsterite olivine (Fo), quartz (Qtz), and talc (Tlc). Solid lines for the pure ("simple") system. Dashed lines show changes resulting from the addition of iron to the system (also indicated by an (Fe) after the Ath symbol.)(Curves from Evans and Guggenheim, 1988; Spear, 1993).

Additional components in the system and variables affecting the system (e.g., the presence of Fe or Cl, or a low a_{H2O}) increase the likelihood of overlapping stability fields of anthophyllite and antigorite at high pressures. Changing phase associations resulting from changes in X_{H2O} have not yet been worked out, but the predicted effect of adding a relatively small amount of iron to the system is to reduce the temperature of reaction 1 by up to 140°C, creating an overlap in the stability fields at pressures of about 0.03 Gpa to 0.9 Gpa (Fig. 4; Evans and Guggenheim, 1988; O'Hanley, 1996). Other components that could have an affect on antigorite stability are chlorine and fluorine. Clearly, bulk composition and the composition of the fluid phase during metamorphism exercise significant control over mineral stability.

That anthophyllite can exist outside its field of stability at low T is obvious — it persists at the Earth surface. From a thermodynamic standpoint, metastable persistence is easily explained as a consequence of there being an inadequate amount of heat during uplift (and cooling) to drive the breakdown reaction. In contrast, from a thermodynamic perspective, it is unreasonable to expect antigorite to persist at higher T than its field of stability as defined by reaction 2 (alternative (3) above), insofar as excess heat would be abundant and readily available to drive the reaction during a prograde thermal event.

Considering the textural evidence and the thermodynamic considerations, it is likely that one or another of the possibilities (1a) — stable crystallization, (1b) — metastable crystallization, or (2) — sequential crystallization without alteration of anthophyllite grain margins, provides an explanation for the presence of anthophyllite in antigorite-bearing rocks. Inasmuch as anthophyllite persists at the Earth surface in euhedral crystals (i.e., there are no obvious signs of instability), the only certainty is that anthophyllite grew somewhere on a path of declining P-T, between the high T stability limit of anthophyllite and very low T at Earth surface conditions.

DISCUSSION and CONCLUSION

The stability fields of anthophyllite and serpentine are important in unraveling the metamorphic and tectonic history of the ultramafic rocks and the terranes in which they occur. Two hypotheses for the metamorphic history of the Toe Terrane in the eastern Blue Ridge Belt have been offered in recent years. One hypothesis posits alternating thermal peaks and valleys over time, with each thermal peak representing an orogenic (deformational and metamorphic) episode, specifically the Taconic, Acadian, and Alleghenian orogenies (Butler, 1973; Hatcher et al, 1979; McSween and Hatcher, 1985; Swanson et al., 1985; Goldberg and Dallmeyer, 1997). The alternative hypothesis suggests that there was monotonic cooling over time from a single thermal peak (reached during the Taconic Orogeny) in the Ordovician Period, with each mineral association marking the passage (in space) of the rocks through a reaction boundary reflecting specific P-T conditions (Abbott and Raymond, 1984; Raymond, 1995, p. 572ff.). To date, no definitive P-T-t curves have been determined that would allow discrimination between these possibilities.

If the stability fields of serpentine (antigorite) and anthophyllite for the events affecting the Toe Terrane were known, the petrologic data available would allow discrimination between the hypotheses. If it could be shown that the stability fields of antigorite and anthophyllite did not overlap and that development of association A-4 at lower temperatures occurred before develop- ment of association A-3 at higher temperatures, then the hypothesis of Butler (1973) would be supported. Thermodynamically, this scenario is quite unlikely. If instead, the stability fields of anthophyllite and antigorite did overlap due to a combination of factors such as the presence of iron, a low aH2O, or the presence of F or Cl in the fluid phase, or if anthophyllite grew metastably at lower T than its stability field would suggest for equilibrium conditions, then the monotonic cooling hypothesis is favored. The textural and thermodynamic data favor the latter possibilities at this time.

In both the Butler (1973) and Abbott and Raymond (1984) hypotheses, association A-1 and texture T-1 may represent mantle or lower crustal, pre-Taconic (pre-Ordovician) metamorphism and deformation, whereas mineral association A-2 and textures T-2 and T-3 would likely represent Taconic metamorphism and deformation. In the Butler hypothesis, mesh-textured association A-4 would represent a post-Taconic cooling of the terrane below temperatures of Devonian Acadian metamorphism. In the Abbott and Raymond hypothesis, post-Taconic cooling below the P-T level of Acadian metamorphism did not occur. Acadian metamorphism (association A-3) and deformation (represented by T-4 textures) at higher T is followed by lower T, post-Taconic cooling in the Butler hypothesis, whereas in the Abbott and Raymond hypothesis, Acadian metamorphism and deformation fall on an overall cooling trend from the Taconic thermal high. Alleghenian metamorphism and deformation are represented by associations A-4 and A-5 and textures of the T-4 type in both hypotheses.

Clearly, discrimination between the hypotheses requires an unequivocal demonstration that the rocks either did or did not cool below the temperatures of Acadian metamorphism prior to that event and after the peak Taconic metamorphic event. While the thermodynamic argument mitigates against such a cooling event, no direct evidence in support of either hypothesis is available.

The multiple textures and mineral assemblages in the ultramafic rocks record events not as clearly recorded in rocks less sensitive to mineralogical changes induced by a fluid phase. If the textures and mineral assemblages can be linked definitively to specific events, we can better understand the tectonic history of the Southern Appalachian Orogen. In particular, discrimination between the Butler (1973) and Abbott and Raymond (1984) hypotheses will allow us to understand whether the Acadian event in the Southern Appalachian Orogen was a more passive uplift event marked by local plutonism and reequilibration of metamorphic rocks or a more active tectonic event involving regional deformation accompanied by reheating to new, post-Taconic thermal high.

Together, the structural data, metamorphic histories of the ultramafic rocks, and the scattered distribution of ultramafic rock bodies and rare eclogites (Adams et al., 1995; Abbott and Raymond, 1997-this volume), marbles (e.g., Stose and Stose, 1957; Brobst, 1962), and metaconglomerates (Rankin et al., 1972) within a terrain dominated by hornblende schist, hornblende gneiss, mica schist and gneiss, and quartzo-feldspathic semischist suggest that the premetamorphic condition of the Toe Terrane was that of a tectonic melange (Raymond and Swanson, 1981; Abbott and Raymond, 1984; Raymond et al., 1989). The ultramafic rocks and some mafic rocks experienced metamorphism before or during emplacement into the surrounding rocks, but before the Taconic Orogeny and its associated amphibolite facies metamorphism (Vrona, 1979; Abbott and Raymond, 1984; Adams et al., 1995; Tenthorey et al. 1996). Acadian amphibolite facies metamorphism and Alleghenian greenschist facies metamorphism and deformational events associated with both of these later orogenies left their imprint on the rocks, locally resulting both in the total replacement of earlier formed fabrics and minerals and in folding and foliation development. Fluids injected by plutonism during the Acadian orogeny caused extensive replacement locally.

The series of tectonic and metamorphic events implied by the data obtained near the Grandfather Mountain Window and elsewhere in the Toe and Cullowhee terranes is consistent with collisional tectonic models for the southern Appalachian Orogen (e.g., Odom and Fullagar, 1973; Hatcher, 1978; Abbott and Raymond, 1984; Adams et al., 1995; Tenthorey et al., 1996). Pre-Taconic subduction and metamorphism of ophiolitic ultramafic and mafic oceanic crust in an accretionary complex, followed by Taconic emplacement, deformation, and metamorphism is consistent with both the metamorphic and the structural histories of the ultramafic rocks. The presently exposed accretionary melange of ultramafic rocks, eclogites, and associated rocks marks the Taconic suture. Acadian events were dominated by thermal and fluid induced changes, and there appears to have been local fabric development, as well. Finally, the Alleghenian Orogeny deformed and uplifted rocks across much of the orogen, while retrogressively metamorphosing rocks in the Blue Ridge core of the orogen.

REFERENCES

Abbott, R.N., Jr. and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic history: American Journal of Science, v. 284, p. 350-375.

Abbott, R.M., Jr. and Raymond, L.A., 1997, Petrology of pelitic and mafic rocks in the Ashe and Alligator Back metamorphic suites, northeast of the Grandfather Mountain Window: (this volume).

Adams, M.G., Stewart, K.G., Trupe, C.H. and Willard, R.A., 1995, Tectonic Significance of high-pressure metamorphic rocks and dextral strike-slip faulting along the Taconic suture: in Hibbard, J.P., van Staal, C.R., and Cawood, P.A.(eds.), Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 21-42.

Astwood, P.M., Carpenter, J.R. and Sharp, W.E., 1982, A petrographic study of the Dark Ridge and Balsam Gap Dunites, Jackson County, North Carolina: Southeastern Geology, v. 14, p. 183-194.

Ave Lallement, H.G., 1976, Structure of the Canyon Mountain ophiolite complex and its' implication for seafloor spreading: Geological Society of America Special Paper 173, 49 p.

Bartholomew, M.J. and Lewis, S.E., 1988, Peregrination of middle Proterozoic massifs and terranes within the Appalachian Orogen, eastern U.S.: Trabajos de Geologia, Universidad de Oveida, v. 17, p. 155-165.

Basu, A.R., 1977, Textures, microstructures and deformation of ultramafic xenoliths from San Quintin, Baja California: Tectonophysics, v. 43, p. 213-246.

Bluhm, C.T., 1976, The structure of the Frank, alpine-type dunite-lherzolite complex, Avery County, North Carolina: M.S. Thesis, Southern Illinois University, 153 p.

Bowen, N.L. and Tuttle, O.F., 1949, The system MgO-Si02-H20. Geological Society of America Bulletin, v. 60, p. 439-460.

Brobst, D.A., 1962, Geology of the Spruce Pine District Avery, Mitchell, and Yancey counties North Carolina: U.S. Geological Survey Bulletin 1122-A, 26p.

Brown, P.M., et al., 1985, Geologic Map of North Carolina: North Carolina Geological Survey, Raleigh, N.C.

Butler, J.R., 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge Thrust Sheet, North Carolina: American Journal of Science, v. 273-A, p. 72-88.

Callahan, J., Hearn F., Heron, S., III, Schumaker, D., and Swanson, S., 1978, Utilizing soil geochemistry, ground magnetic, and radiometric surveys to outline a Blue Ridge ultramafic body in North Carolina: Journal of Geochemical Exploration, v. 10, p. 53-61.

Carpenter, J.R. and Phyfer, D.W., 1969, Proposed origin for the alpine-type ultramafics of the Appalachians: Geological Society of America Abstracts with Programs, v. 7, p. 261-263.

Carter, N.L., and Ave Lallement, H.G., 1970, High temperature flow of dunite and peridotite: Geological Society of America Bulletin, v. 81, p. 2181-2202.

Chernosky, J.V., Jr., Day, H.W., and Caruso, L.J., 1985, Equilibria in the system MgO-SiO2-H20: Experimental determination of the stability of mg-anthophyllite: American Mineralogist, v. 70, p. 223-236.

Day, H.W. and Halbach, H., 1979, The stability of anthophyllite: The effect of experimental uncertainty on permissible phase diagram topologies: American Mineralogist, v. 64, p. 809-823.

Day, H.W., Chernosky, J.V., Jr. and Kumin, H.J., 1985, Equilibria in the system MgO-SiO2-H20: A thermodynamic analysis: American Mineralogist, v. 70, p. 237-248.

Delaney, J.M., and Helgeson, H.C., 1978, Calculation of the thermodynamic consequences of dehydration in subducting oceanic crust to 100 Kb and >800C: American Journal of Science, v. 278, p. 638-686.

Dribus, J.R., Godson, W.L., Hahn, K.R., Kammer, T.W., Lawton, D.L., Pesch, H.G., Schick, J.T., and Tata, S.S., 1976, Comparative petrography of some alpine ultramafic plutons in western North Carolina: Compass, v. 53, p. 33-45.

Espenshade, G.H., Rankin, D.W., Shaw, K.W., and Neuman, R.B., 1975, Geologic map of the east half of the Winston-Salem Quadrangle, North Carolina-Virginia: U.S. Geological Survey Map I-709-B.

Evans, B.W. and Guggenheim, S., 1988, Talc, pyrophyllite, and related minerals, in Bailey, S.W. (ed.), Hydrous Phyllosilicates: Mineralogical Society of America, Reviews in Mineralogy, v. 19, p. 225-294.

Evans, B.W., and Tromsdorff, V., 1974, Stability of enstatite + talc, and CO2-metasomatism of metaperidotite, Val d'Efra, Lepontine Alps: American Journal of Science, v. 274, p. 274-296.

Goldberg, S.A., Butler, J.R., Mies, J.W., and Trupe, C.H., 1989, The southern Appalachian Orogen in northwestern North Carolina and adjacent states: IGC Field Trip T365, American Geophysical Union, Washington, D.C., 55p.

Goldberg, S.A. and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge Thrust Complex, North Carolina and Tennessee: American journal of Science, v. 297, p. 488-526.

Hatcher, R.D., Jr., 1978, Tectonic of the western Piedmont and Blue Ridge, Southern Appalachians: Review and Speculation: American Journal of Science, v. 278, p. 276-304.

Hatcher, R.D., Butler, J.R., Benedict, G.L., Harris, L.D., Merschat, C.E., Milici, R.C., Walker, K.R., and Wiener, L.S., 1979, Guidebook for Southern Appalachian Field Trip in the Carolina, Tennessee, and Northeastern Georgia: International Geological Correlation Program, The Caledonides in the U.S.A., 117 p.

Hatcher, R.D., Jr., Hooper, R.J., Petty, S.M., and Willis, J.D., 1984, Structure and chemical petrology of three southern Appalachian mafic-ultramafic complexes and their bearing upon the tectonics of emplacement and origin of Appalachian ultramafic bodies: American Journal of Science, v. 284, p. 484-506.

Hearn, F., Heron, S.D., III, Shumaker, D., and Swanson, S.E., 1977, Petrology of the Rich Mountain alpine ultramafic, Watauga Co., North Carolina: Geological Society of America Abstracts with Programs, v. 9, p. 146-147.

Hess, H.H., 1955, Serpentines, orogeny, and epeirogeny: in A. Poldervaart (ed.)., Crust of the Earth. Geological Society of America Special Paper 62, p. 391-408.

Hibbard, J.P. and Samson, S.D., 1995, Orogenesis exotic to the Iapetan cycle in the southern Appalachians: in Hibbard, J.P., van Staal, C.R., and Cawood, P.A. (eds.), Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, p. 191-205.

Horton, J.W., Drake, A.A., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians: in Dallmeyer, R.D. (ed.), Terranes in the Circum-Atlantic Paleozoic orogens: Geological Society of America Special Paper 230, p. 213-245.

Horton, J.W., Drake, A.A., Jr., Rankin, D.W., and Dallmeyer, R.D., 1991, Preliminary tectonostratigraphic map of the central and southern Appalachians: U.S. Geological Survey Map I-2163.

Huneycutt, F.M. and Heimlich, R.A., 1980, Petrology of the Balsam Gap Dunite, Jackson County, North Carolina: Southeastern Geology, v. 21, p. 251-260.

Hunter, C.E., 1941, Forsterite olivine deposits of North Carolina and Georgia: North Carolina Division of Mineral Resources Bulletin Number 41, 117p.

Jones, T.Z., 1976, Petrography, structure, and metamorphic history of the Warrensville and Jefferson Quadrangles, southern Blue Ridge, northwestern North Carolina: Ph.D. Dissertation, Miami University, Oxford, Ohio, 130 p.

Kingsbury, R.H., and Heimlich, R.A., 1978, Petrology of an ultramafic body near Micaville, Yancey County, North Carolina: Southeastern Geology, v. 20, p. 33-46.

Kish, S.A., 1989, Paleozoic thermal history of the Blue Ridge in southwestern North Carolina — Constraints based upon mineral cooling ages and the ages of intrusive rocks: Geological Society of America Abstracts with Programs, v. 21, No. 3, p. 45.

Kulp, J.A., and Brobst, D.A., 1954, Notes on the dunite and the geochemistry of vermiculite at the Day Book deposit, Yancey County, N.C.: Economic Geology, v. 49, p. 211-220.

Larrabee, D.M., 1966, Map showing distribution of ultramafic and intrusive mafic rocks from northern New Jersey to eastern Alabama: U.S. Geological Survey Map I-476.

McCormick, G.R., 1975, A chemical study of Kammererite, Day book body, Yancey County, North Carolina: American Mineralogist, v. 60, p. 924-927.

McElhaney, M.S., and McSween, H.Y., Jr., 1983, Petrology of the Chunky Gal Mountain mafic-ultramafic complex, North Carolina: Geological Society of America Bulletin, v. 94, p. 855-874.

McSween, H.Y., Jr. and Hatcher, R.D., Jr., 1985, Ophiolites (?) of the southern Appalachian Blue Ridge: in Woodward, N.E. (ed.), Field Trips in the Southern Appalachians: University of Tennessee, Department of Geological Sciences, Studies in Geology 9, p. 144-170.

McSween, H.Y., Jr., Speer, A., and Fullagar, P.D., 1991, Plutonic rocks, in Horton, J.W., and Zullo, V.A. (eds.), The Geology of the Carolinas: The University of Tennessee Press, Knoxville, p. 109-129.

Misra, K.C., and Keller, F.B., 1978, Ultramafic bodies in the southern Appalachians: A Review: American Journal of Science, v. 278, p. 389-418.

Neuhauser, K.R., and Carpenter, J.R., 1971, A structural and petrographic analysis of the Bank's Creek (North Carolina) serpentine: Southeastern Geology, v. 13, p. 151-165.

Odom, A.L. and Fullagar, P.D., 1973, Geochronologic and tectonic relationships between the Inner Piedmont, Brevard Zone, and Blue Ridge Belts, North Carolina: American Journal of Science, v. 273-A, p. 133-149.

O'Hanley, D.S., 1996, Serpentinites: Oxford University Press, New York, 277p.

Pratt, J.H. and Lewis, J.V., 1905, Corundum and the Peridotites of North Carolina: North Carolina Geological Survey, v. 1, 464p.

Pike, J.E.N., and Schwarzman, E.C., 1977, Classification of textures in ultramafic xenoliths: Journal of Geology, v. 85, p. 49-61.

Rankin, D.W., Espenshade, G.H., and Neuman, R.B., 1972, Geologic map of the west half of the Winston-Salem Quadrangle, North Carolina, Virginia, and Tennessee: USGS Map I-709-A.

Rankin, D.W., Drake, A.A., Jr., and Ratcliffe, N.M., in Rankin, D.W. (ed.), 1993, Proterozoic rocks east and southeast of the Grenville Front: in Reed, J.C., Jr, Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and van Schmus, W.R. (eds.), Precambrian: Conterminous U.S.: Geological Society of America, The Geology of North America, v. C-2, p. 378-422.

Raymond, L.A., 1987, Terrane amalgamation in the Blue Ridge Belt, Southern Appalachian Orogen: Geological Society of America Abstracts with Programs, v. 19, p. 125.

Raymond, L.A., 1995, Petrology: The Study of Igneous, Sedimentary, and Metamorphic Rocks: Wm.C. Brown Publ., Dubuque, 742p.

Raymond, L.A., and Abbott, R.N., Jr., 1985, Metamorphism of alpine ultramafic rocks, North Carolina Blue Ridge: I - Observed metamorphic histories: Geological Society of America Abstracts with Programs, v. 17 , p 695.

Raymond, L.A., Leatherman, L.E., Vance, K., Cook, T. and Abbott, R.N., Jr., 1988, The Greer Hollow Ultramafic Body, eastern Blue Ridge Province, North Carolina: Petrography, field relations, and implications for metamorphic history of the Blue Ridge Province: Geological Society of America Abstracts with Programs, v. 20, No. 4, p. 310.

Raymond, L.A., and Swanson, S.E., 1981, Deformation history of ultramafic rocks, Blue Ridge Belt, southern Appalachian Mountains: Correlations with Appalachian tectonic events: Geological Society of America Abstracts with Programs, v. 19, p. 125.

Raymond, L.A., Yurkovich, S.P., and McKinney, M., 1989, Block-in-matrix structures in the North Carolina Blue Ridge belt and their significance for the tectonic history of the southern Appalachian Orogen, in Horton, J.W., Jr. & Rast, N. (eds.), Melanges and Olistostromes of the U.S. Appalachians: Geological Society of America Special Paper 228, p. 195-215.

Sanford, R.F., 1977, The coexistence of antigorite and anthophyllite in ultramafic rocks: Geological Society of America Abstracts with Programs, v. 9, p. 1154-1155.

Scotford, D.M., and Williams, J.R., 1983, Petrology and geochemistry of metamorphosed ultramafic bodies in portion of the Blue Ridge of North Carolina and Virginia: American Mineralogist, v. 68, p. 78-94.

Spear, F.S., 1993, Metamorphic Phase Equilibria and Pressure-Temperature-Time Paths: Mineralogical Society of America, Washington, D.C., 799p.

Stose, A.J. and Stose, G.W., 1957, Geology and mineral resources of the Gossan Lead District and adjacent areas in Virginia: Virginia Division of Mineral Resources, Bulletin 72, 233p.

Swanson, S. E., 1980, Petrology of the Rich Mountain ultramafic bodies and associated rocks, Watauga County, North Carolina: Southeastern Geology, v. 21, p. 209-225.

Swanson, S.E., 1981, Mineralogy and petrology of the Day Book Dunite and associated rocks, western North Carolina: Southeastern Geology, v. 22, p. 53-77.

Swanson, S.E., 1996, Metamorphic history of ultramafic rocks from the Spruce Pine Thrust Sheet, Western North Carolina: Geological Society of America Abstracts with Programs, v. 28, no. 2, p. 46.

Swanson, S.E., 1997, Mineral compositions from ultramafic rocks from the Spruce Pine Thrust Sheet, western North Carolina: Geological Society of America Abstracts with Programs, v. 29, No. 3, p. 72.

Swanson, S.E., Naney, M.T., and Sturnick, M.A., 1985, Polyphase metamorphism in the Blue Ridge of western North Carolina: Evidence from the Day Book Dunite Geological Society of America Abstracts and Programs, v. 17, p. 138.

Swanson, S.E. and Raymond, L.A., 1976, Alteration of the Day Book dunite, Spruce Pine District, western

North Carolina: Geological Society of America Abstracts with Programs, v.8, p. 282.

Tenthorey, E.A., Ryan, J.G., and Snow, E.A., 1996, Petrogenesis of sapphirine-bearing metatroctolites from the Buck Creek ultramafic body, southern Appalachians: Journal of Metamorphic Petrology, v. 14, p. 103-114.

Vrona, J.P., 1979, Structure of the Newdale ultramafite, Yancey County, North Carolina: M.S. Thesis, Southern Illinois University, 115 p.

Wood, P.A., 1996, Petrogenesis of the Spruce Pine Pegmatites, North Carolina: M.S. Thesis, Virginia Polytechnic Institute and State University, 99 p.

Yurkovich, S.P., 1977, The Corundum Hill Dunite, Macon County, North Carolina: Southeastern Geology, v. 19, p. 55-68.

Zeuch, D.H., and Green, H.W., II, 1984, Experimental deformation of a synthetic dunite at high temperature and pressure. I. Mechanical behavior, optical microstructure and deformation mechanisms: Tectonophysics, v. 110, p. 233-262.

APPENDIX A. LOCATIONS OF ULTRAMAFIC BODIES

Edmonds Ultramafic Body. Cumberland Knob 7 1/2' Quadrangle, VA–NC. Small outcrops are present in road cuts along Hwy 18, within 0.5 km, both east and west of Edmonds and south of the NC/VA state line. Also, ultramafic rock underlies the Big Spring Church vicinity northeast of Edmonds on VA Road 613. Road cuts provide access, but much of the body lies on private property.

Nathans Creek Ultramafic Body. Jefferson, NC 7 1/2' Quadrangle. The unincorporated community of Nathans Creek is located in the east central part of the Jefferson Quadrangle on Highway 221. The Nathans Creek Ultramafic Body is exposed approximately 0.6 km north of the Hwy 221 – Nathans Creek School Road junction on Hwy 221. Small outcrops occur on the east side of the road and bold outcrops occur on the west at the spot where a Nathans Creek tributary and Hwy 221 start to parallel one another. The road cuts provide access, but much of the body lies on private property.

Warrensville Ultramafic Body. Warrensville, NC 7 1/2’ Quadrangle. The Warrensville Ultramafic Body is best exposed in a road cut across from the park in the town center of Warrensville, which is located at the Hwy 88–194 bifurcation approximately 9 km northwest of West Jefferson, NC.

Todd Ultramafic Body. Todd, NC 7 1/2' Quadrangle. The body is exposed in road cuts and field outcrops in Ashe County, northeast of the community of Todd, located on Hwy 194. Exposures occur east of Laurel Knob Church at BM 3247 on Hwy 194 and between Laurel Knob Gap and Mill Creek Church.

Greer Hollow Ultramafic Body. Todd 7 1/2' Quadrangle. The Greer Hollow Ultramafic Body underlies a small stream valley and the adjoining hill between the Ashe–Watauga County line and Greer Hollow Road, which leads north from Highway 194 approximately 1 km west of the Todd exit from Hwy 194. This body is on private property and should not be visited without permission of the landowner or local overseer.

Rich Mountain Ultramafic Bodies. Zionville, NC 7 1/2' Quadrangle.
The McNeil Ultramafic Body is exposed in a pasture, on private property, in the drainage depression immediately east of Buckeye Knob on Cove Creek Ridge in the SW 1/4 SW 1/4 of the quadrangle. The site is approximately 1 km south of

the Junaluska Road – Potato Hill Road junction, located at approximately 36° 16' 40" North latitude.

The Hoots Ultramafic Body is located south of the saddle between Wolf Ridge and Cove Creek Ridge at about 36° 15' 46" North latitude. Access is restricted and requires permission to pass over at least two parcels of private property. Recently, access has been denied by one of those two property owners.

Frank Ultramafic Body. Carvers Gap 7 1/2' Quadrangle, NC–TN. The Frank Ultramafic Body is located at the west edge of the Carvers Gap Quadrangle, south and west of Hwy 19E, southwest of the community of Frank, on the north end of Copperas Bald, and along the North Toe River Banks. Copperas Bald and the mine there are on private property.

Spruce Pine North Ultramafic Body. Spruce Pine 7 1/2' Quadrangle, NC. The Spruce Pine North Ultramafic Body occurs on the hill immediately east of the junction of Graveyard and Grassy creeks, east of Hwy 226, in southern Spruce Pine, North Carolina. The body is exposed in road cuts <100 m east of Hwy 226 on the road that leads to Carter Ridge.

Newdale Ultramafic Body. Micaville 7 1/2' Quadrangle, NC. The Newdale Ultramafic Body straddles Hwy 80 in the Newdale Community, about 0.6 km north of the Hwy 80–Hwy 19E junction. Exposures occur along the highway, in a pit west of the highway, and in a restricted access, water filled quarry east of the highway.

Blue Rock Road Ultramafic Body. Micaville 7 1/2' Quadrangle, NC. This small body is located just north of the crest of the hill on Blue Rock Road, south of Blue Rock Branch, a few kilometers south of Hwy 19E. The rock is exposed in a road cut on the grade <100 m north of the crest of the hill.

Woody Ultramafic Body. Micaville 7 1/2' Quadrangle, NC. The Woody Ultramafic Body is located at an elevation of about 2700'+ 100' on the northeast flank of Chestnut Mountain in the NW 1/4 of the Micaville Quadrangle. The body, and an adjoining body, cap the hills flanking a small north draining creek line at 35° 58' 30" N latitude. The property is privately owned and permission is required for access.

Day Book Ultramafic Body. Burnsville 7 1/2' Quadrangle, NC. The Day Book Ultramafic Body is located on Mine Fork, about 1.5 km southeast of Day Book. The body has been mined extensively and an obvious mill is on the site. The body straddles the road here. Mine workings are located northwest of the road along Mine Fork and a mine office is located east of the road. Permission is required to enter the mine.

PETROLOGY OF PELITIC AND MAFIC ROCKS IN THE ASHE AND ALLIGATOR BACK METAMORPHIC SUITES, NORTHEAST OF THE GRANDFATHER MOUNTAIN WINDOW

Richard N. Abbott, Jr. and Loren A. Raymond
Department of Geology
Appalachian State University
Boone, NC 28608

ABSTRACT

Pelitic and mafic rocks dominate the Ashe and Alligator Back Metamorphic Suites north of the Grandfather Mountain window. New information on phase relationships in pelitic rocks allows re-interpretation of metamorphic gradients in P and T. The gradient in P suggests that the highest metamorphic pressures were achieved near the base of the Ashe Metamorphic Suite, immediately southwest and immediately north of the Grandfather Mountain window.

The location of previously described eclogites (ECG1) in the Ashe Metamorphic Suite southwest of the Grandfather Mountain window and the location of recently discovered, retrograded eclogite (ECG2) in the Ashe Metamorphic Suite north of the Grandfather Mountain window are consistent with the highest-pressure zone, inferred from relationships in the pelitic rocks. We report here a preliminary description of the retrograded eclogite (ECG2) north of the Grandfather Mountain window. ECG2 is in the same structural position as ECG1, i.e., near the base of the Ashe Metamorphic Suite. ECG2 differs from ECG1, in two important ways: (1) the presence of epidote in ECG2, and (2) the sequence of retrograde changes recognized in the mineral assemblage. Samples examined so far indicate that omphacite in ECG2 has been completely replaced by symplectitic diopside+plagioclase. The original (highest grade) mineral assemblages in ECG2, however, are believed to have been omphacite+garnet+quartz and omphacite+garnet+epidote+quartz. Most likely the presence of epidote indicates a higher fugacity for O_2 than in ECG1.

Textural relationships suggest the following retrograde paragenesis for ECG2:

(a) Omp(I) + Gar + Qtz, and Omp(I) + Gar + Epi + Qtz;
(b) Omp(II) + Gar + Epi + Qtz,
(c) (Dio + Pla) + Gar + Epi + Qtz, where (Dio + Pla) is symplectite,
(d) (Dio + Pla) + Gar + Epi + Hnb + Qtz,
(e) Pla + Gar + Epi + Hnb + Qtz.

Distinctive plagioclase + quartz coronas around garnet were presumably formed by reaction of garnet with omphacite during the change from assemblage (b) to assemblage (c). Similar coronas around garnets in pyroxene-free hornblende schist (e) suggest that large areas of the mafic rocks in the Ashe Metamorphic Suite may have been retrograded from eclogite.

Observations support a growing body of evidence for the following general conclusions: (1) The Ashe Metamorphic Suite has an ensimatic origin. (2) The Ashe Metamorphic Suite is a subduction-related accretionary melange. (3) This melange marks the Taconic suture between the North American Craton and the Inner Piedmont.

In a palinspastic reconstruction the thrust fault at the structural base of the Ashe Metamorphic Suite appears to have intercepted the greatest depths (i.e., the highest-P metamorphic rocks) beneath parts of the Ashe and Alligator Back Metamorphic Suites now exposed imme-

diately north and immediately southwest of the Grandfather Mountain window. The greatest volume of mafic rock is in these same parts of the Ashe Metamorphic Suite. We offer the possibility that the nascent, subduction-related, basal thrust fault was deflected downward quite simply by an obstacle, in the form of an isolated, mafic volcanic edifice on oceanic crust — a seamount.

INTRODUCTION

The Ashe Metamorphic Suite (AMS), the Alligator Back Metamorphic Suite (ABMS), and their inferred lithostratigraphic equivalents in the Blue Ridge Belt of the southern Appalachian Orogen (Figure 1), were metamorphosed to the amphibolite facies of regional Barrovian Facies Series metamorphism during the Taconic Orogeny (Goldberg and Dallmeyer, 1997). The AMS is exposed northeast and southwest of the Grandfather Mountain window (Rankin et al., 1973; Goldberg et al., 1989), where it forms a principal Neoproterozoic to Early Paleozoic (?) sequence of sedimentary and volcanic rocks in the southern Blue Ridge Belt. The AMS structurally overlies Mesoproterozoic basement (including the Cranberry Mines Gneiss) and is

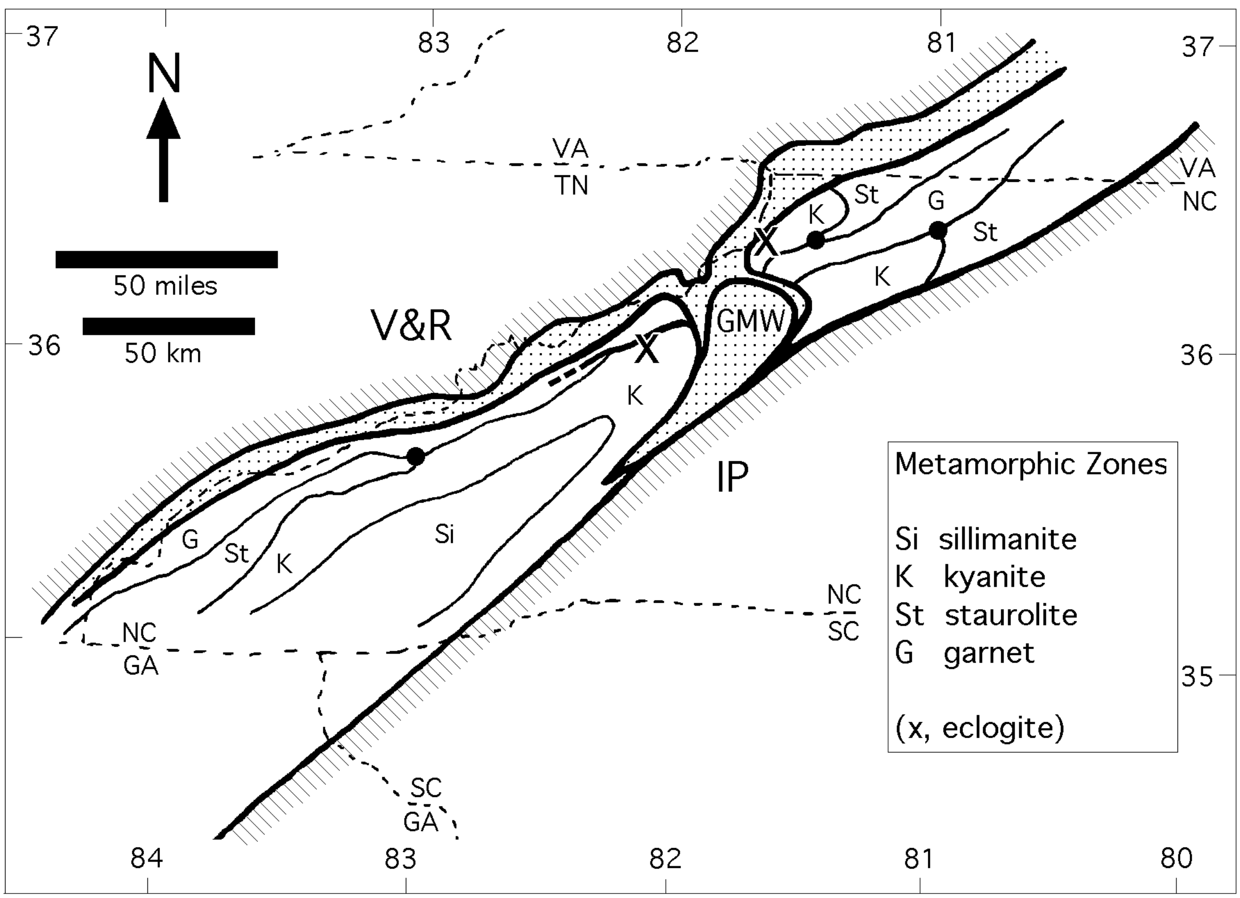

Figure 1. Metamorphic zones in the eastern Blue Ridge (modified from Drake *et al*., 1989). Bold lines are major thrust faults separating the Blue Ridge Belt from the Valley and Ridge Province (V&R) to the northwest and the Inner Piedmont (IP) to the southeast. Thrust faults within the Blue Ridge Belt separate the western Blue Ridge (stippled) from the eastern Blue Ridge, and also form the borders of the Grandfather Mountain window (GMW). The Ashe and Alligator Back Metamorphic Suite are the principal constituents of the eastern Blue Ridge Belt. Three pseudo-invariant points are indicated by filled circles, where the garnet, staurolite, and kyanite zones meet.

structurally overlain by the ABMS (Rankin et al., 1973; Fullagar and Odom, 1973; Fullagar and Bartholomew, 1983; Abbott and Raymond, 1984). The Ashe and Alligator Back Metamorphic Suites are confined to the Spruce Pine thrust sheet of Goldberg et al. (1989). The Cranberry Mines Gneiss is confined to the Beech Mountain thrust sheet of Goldberg et al. (1989). These thrust sheets structurally overlie a deeper, basement-cover sequence of lower metamorphic grade. The latter sequence includes the Neoproterozoic Grandfather Mountain Formation and underlying Mesoproterozoic Blowing Rock and Wilson Creek Gneisses, which are exposed in the Grandfather Mountain window (Figure 1; Bryant and Reed, 1970).

Major rock types in the AMS include hornblende schist and gneiss, pelitic schist, and quartzofeldspathic schist and gneiss. The hornblende schist and gneiss are interpreted to be metabasalt (e.g., Rankin, 1970; Misra and Conte, 1991). Minor components of the suite include eclogite (Willard and Adams, 1994; Adams et al., 1995) and ultramafic rocks. The ultramafic rocks are variously interpreted to be residual mantle blocks, ophiolite fragments, or intrusions (e.g., Rankin et al., 1973; Abbott and Raymond, 1984; McSween and Hatcher, 1985; Wang and Glover, 1991). The ABMS is dominated by pelitic rocks, but also contains hornblende schists and rare ultramafic rocks (Rankin et al., 1973; Conley, 1987).

Well to the southwest of the Grandfather Mountain window, the Mesoproterozoic (?) basement gneisses and schists are structurally overlain by a different group of rocks—gneisses and schists of the Neoproterozoic (?) Great Smokey Group (Hadley and Nelson, 1971; Brown et al., 1985). These rocks are dominantly pelitic to quartzofeldspathic schists and gneisses, but slates and metaconglomerates also occur in the unit.

The allochthonous Neoproterozoic rocks, especially the AMS and ABMS, have been affected by at least three metamorphic and deformational events (e.g., Butler, 1972, 1973; Abbott and Raymond, 1984; Adams et al., 1995). The major prograde event has generally been assigned to the Ordovician Taconic Orogeny (Abbott and Raymond, 1984; Miller et al., 1997; Goldberg and Dallmeyer, 1997). Incomplete retrograde recrystallization is widely developed.

The objectives of this paper are: (1) to review the metamorphic petrology of pelitic and mafic rocks in the AMS and ABMS northeast of the Grandfather Mountain window, (2) to discuss new constraints on metamorphic conditions (P,T), and regional metamorphic gradients in P and T, (3) to describe previously unreported, retrograded eclogites in the mafic rocks of the AMS, northeast of the Grandfather Mountain window, (4) to re-evaluate the P-T-t (t=time) path of the AMS, and (5) to discuss the likely origin of the AMS.

PELITIC ROCKS

General statement. North of the Grandfather Mountain window, pelitic rocks in the AMS are mainly muscovite schists. The essential minerals are muscovite, quartz, and plagioclase. Where quartz and plagioclase dominate, the rocks are properly called quartzofeldspathic schists or gneisses. Depending on the grade of metamorphism and bulk composition, other minerals include various combinations of biotite, garnet, chlorite, staurolite, and kyanite. Accessory mineral included Fe-oxides, apatite, and tourmaline. The distribution of mineral assemblages is consistent with a Barrovian Metamorphic Facies Series.

Regional and detailed metamorphic maps (Figure 1) of the central Blue Ridge Belt (Hadley and Nelson, 1971; Espenshade et al., 1975; Brown et al., 1985; Abbott and Raymond, 1984; McSween et al., 1989; Abbott et al., 1991; Butler, 1991) reveal three occurrences of an AFM (A=Al_2O_3-Na_2O-K_2O-CaO, F=FeO, M=MgO; Thompson, 1957) pseudo-invariant point (intersection of isograds). Pseudo-invariant points of the type described here have not been recognized elsewhere, although Labotka (1981) has predicted their existence in theory, and thermodynamic calculations (Spear et al., 1995) indicate reasonable crustal conditions (P, T) for their existence. Thus, the southern Blue Ridge Belt affords an opportunity to characterize a possibly unique, relatively high-pressure regime of amphibolite facies metamorphism.

Each of the pseudo-invariant points is located at the intersection of the three mapped isograds. The three isograds that define the point of intersection, correspond to the AFM reactions

Gar + Chl = Bio + Sta, [Kya]
Sta = Bio + Kya + Gar, [Chl]
and Gar + Chl = Bio + Kya. [Sta]

Mineral abbreviations are explained in Table 1. Mapping of reaction isograds suggests invariance (with respect to P and T) only within the limits of resolution permitted by the spatial distribution of relevant, observed mineral assemblages. Spear et al. (1995) have shown that conditions at such an intersection of reactions depend on, among other factors, the CaO and MnO content of the rock. Indeed, while the point of intersection of the reaction isograds cannot actually be invariant, the point of intersection has characteristics of invariance in the context of a limited range of bulk compositions in pelitic rocks. That the intersection can be identified at all on the basis of the distribution of mineral assemblages suggests that the CaO and MnO contents, among other bulk compositional factors, are more or less uniform in relevant rock types in the AMS and ABMS. Theoretically, two other reactions,

Sta = Gar + Kya + Chl, [Bio]
and Sta + Chl = Bio + Kya, [Gar]

Table 1. Abbreviations used for minerals, components, and metamorphic zones.

	mineral (components)
And	andalusite
Bio	biotite
Chl	chlorite
Dio	diopside (Di = $CaMgSi_2O_6$, Hd = $CaFeSi_2O_6$)
Epi	epidote
Gar	garnet
Hnb	hornblende
Kya	kyanite
Omp	omphacite (Di = $CaMgSi_2O_6$, Hd = $CaFeSi_2O_6$, Jd = $NaAlSi_2O_6$, Ts = $CaAl_2SiO_6$)
Pla	plagioclase (Ab = $NaAlSi_3O_8$, An = $CaAl_2Si_2O_8$)
Qtz	quartz (In Figure 6, this is $3SiO_2$)
Sil	sillimanite
Sta	staurolite
	metamorphic zones (Figures 1 and 4)
G	garnet zone
St	staurolite zone
K	kyanite zone
Si	sillimanite zone

are involved at each intersection, but corresponding isograds apparently were not produced, probably because of inappropriate bulk compositions. As noted above, P-T conditions for this kind of intersection remain poorly constrained, for reasons just noted (Spear et al., 1995). Based on determinations near one of the invariant points in the AMS (McSween et al., 1989) northeast of the Grandfather Mountain window, P and T are estimated to be ~0.75 GPa and 600-650 °C.

Characterizing the point of intersection northeast of the Grandfather Mountain window. The pseudo-invariant point, immediately north of Boone, North Carolina, has already been described by us in considerable detail (Abbott and Raymond, 1984; McSween et al., 1989; Abbott et al., 1991). We defined three metamorphic zones surrounding the psedu-invariant point as Ip, IIp, and IIIp (Figure 2; Abbott and Raymond, 1984; McSween et al., 1989), for which the mineral assemblages, coexisting with quartz and muscovite, are given in Figure 2. Diagnostic assemblages are Gar+Bio+Chl in zone Ip, Gar+Sta+Bio and Gar+Sta+Chl in zone IIp, and Gar+Bio+Kya in zone IIIp. Rankin et al. (1972, 1973) showed that the staurolite zone (hatched region, Figure 2), which is bounded to the southeast and northwest by garnet and kyanite zones respectively, ceases to be recognizable southwest of a point (marked 'i', Figure 2) where the staurolite and kyanite isograds converge. Southwest of the point, garnet-grade rocks are juxtaposed with kyanite-grade rocks. The relationships might otherwise be explained by a fault, separating the kyanite and garnet grade rocks south of point i, but there is no indication of what should be a fairly obvious post-metamorphic fault.

Northeast of the point of intersection, the staurolite isograd is due to the AFM reaction [Kya] (see above), and the kyanite isograd is due to the reaction [Chl]. Hence, kyanite appears in response to the disappearance of staurolite. These reactions are common in other terranes (e.g., Guidotti, 1970; Abbott, 1979; Thompson and Norton, 1968; Albee, 1968). The five minerals involved in these two reactions are also involved in the equilibrium where the two isograds meet. Interpreted as an "invariant point," three other four-phase AFM equilibria must be involved at the invariant point, one each for the non-involvement of staurolite, biotite, and garnet. Using Schreinemakers method, it is a straightforward matter to determine the missing reactions and to locate them properly around the invariant point. The reaction for the non-involvement of stauro-

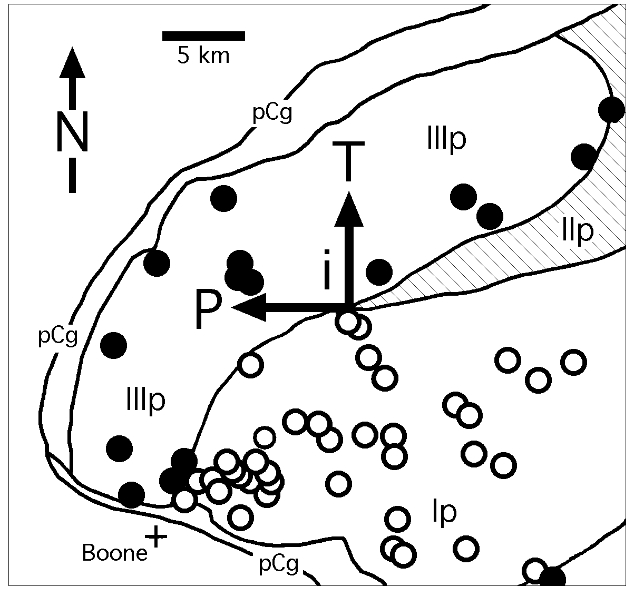

Figure 2. Metamorphic zones in pelitic rocks of the AMS and ABMS, north of the Grandfather Mountain window. Open circles indicate AFM mineral assemblages in the garnet zone (Ip). The common assemblage is Gar+Bio+Chl. The shaded region is the staurolite zone (IIp). The diagnostic AFM asemblages are Sta+Bio+Gar and Sta+Bio+Chl. Filled circles indicate mineral assemblages in the kyanite zone (IIIp). The common assemblage is Gar+Bio+Kya. Isograds bounding the staurolite zone meet at the pseudo-invariant point marked "i." Southwest of "i," garnet zone (Ip) assemblages are juxtaposed with the kyanite zone (IIIp) assemblages. General direction of increasing P and direction of increasing T are indicated by arrows. See Figure 3.

lite, [Sta], must necessarily extend southwest from the point of intersection, and is presumably responsible for the appearance of kyanite. The remaining two reactions, [Bio] and [Gar], though theoretically possible, are not observed because of inappropriate bulk rock compositions.

Relationships around the point of intersection are shown schematically in Figure 3. P-T slopes of the various reactions are consistent with calculations by Spear et al. (1995). Significantly, the slope (dP/dT) of reaction [Kya] is positive, but very steep to nearly vertical, while the slope of reaction [Chl] is negative.

In Figure 2, we have superimposed schematically on the mapped relationships an arrow for increasing P (at constant T) and an arrow for increasing T (at constant P) by direct analogy with the relationships shown in Figure 3. The pressure of metamorphism, as recorded and preserved by the distribution of the mineral assemblages, increases toward the west, and the temperature of metamorphism increases toward the north.

Two other pseudo-invariant points. The regional metamorphic map, shown here as Figure 4 (from Drake et al., 1989), illustrates relationships that can be found on various more detailed maps (Hadley and Nelson, 1971; Rankin et al., 1972; Espenshade et al., 1975). On this map, we have marked, by means of the arrows for increasing P and increasing T, the probable locations of two other pseudo-invariant points involving the same isograds.

The northeasternmost of the points is approximately on the boundary between the geologic maps for the west and east halves of the Winston-Salem 2° sheet, in the vicinity of the town of Devotion, NC. The pseudo-invariant point is implicit in the mineral assemblages reported on these geologic maps by Rankin et al. (1972) and Espenshade et al. (1975). Unfortunately, neither detailed mapping nor petrography has been performed to verify the precise location of the intersection and the precise trends of the traces of the reaction isograds.

The southwesternmost (third) pseudo-invariant point, some 100 miles SW of the Grandfather Mountain window, appears near the town of Cove Creek on the metamorphic map of the geologic map of North Carolina (Brown et al., 1985), which is based on the earlier work of Hadley and Nelson (1971). Here the pseudo-invariant point appears to lie within rocks of the Great Smoky Group. Again, neither detailed

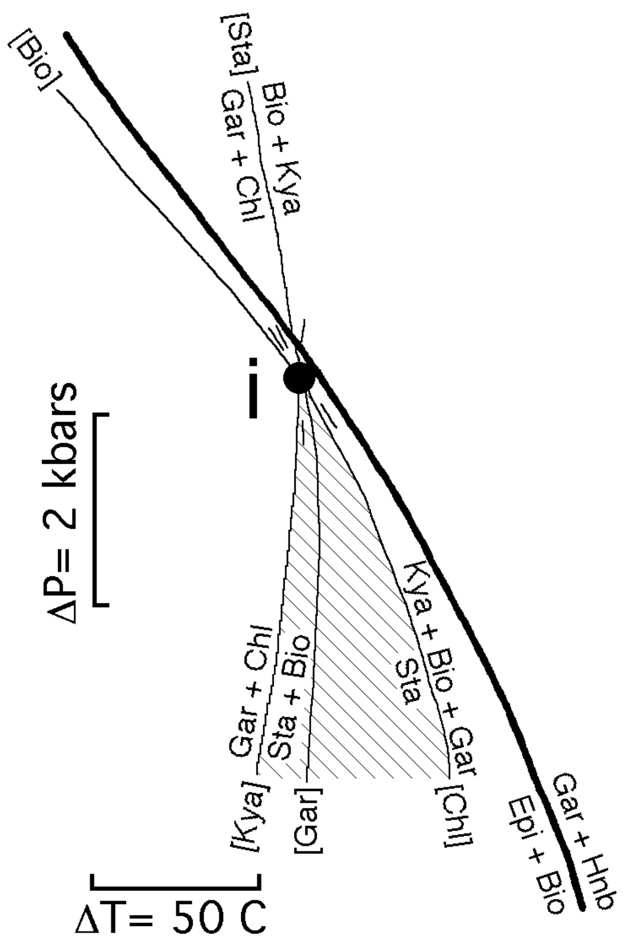

Figure 3. Schematic phase relationships in pelitic rocks (fine lines) and mafic rocks (bold line) in AMS and ABMS. Slopes of AFM reactions (pelitic rocks) are consistent with calculations by Spear et al. (1995) for conditions at pseudo-invariant point of P = 7.5 kbars, T = 640 °C, X_{Mn}(Gar) = 0.25. The shaded region is the staurolite zone of a typical Barrovian Metamorphic Facies Series.

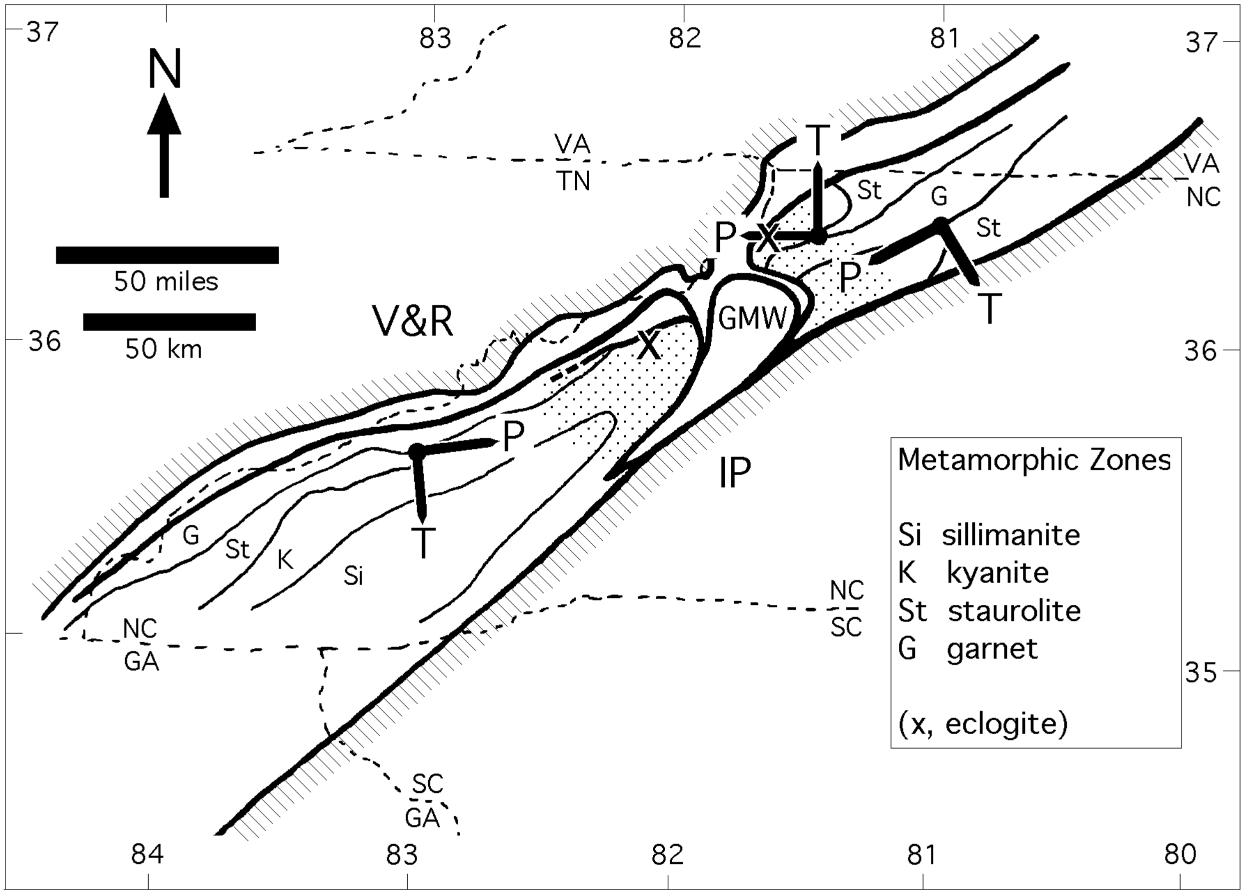

Figure 4. Direction of increasing metamorphic pressure and direction of increasing metamorphic temperature in the Eastern Blue Ridge Belt at each of the pseudo-invariant points. Inferred regions of high pressure metamorphism are stippled. Eclogite locales are indicated by X's. Eclogite southwest of Grandfather Mountain window has been described by Willard and Adams (1994). Retrograded eclogite immediately north of Grandfather Mountain window is described in the report. (modified from Drake et al., 1989.)

mapping nor petrography has been performed to determine the precise location of the inferred pseudo-invariant point and the precise trends of the traces of the reaction isograds.

If the relationships just described are even qualitatively correct, important conclusions naturally follow:

1. Inferred gradients in P (at constant T), Figure 4) indicate that the highest pressure of metamorphism in the AMS and ABMS should be recorded near the base of the Spruce Pine thrust sheet, close to the Grandfather Mountain window (stippled areas in Figure 4). Significantly, the locations of eclogites southwest of the Grandfather Mountain window (Willard and Adams, 1994) and northeast of the Grandfather Mountain window (this report) support this general interpretation (Figure 4).
2. These areas, with evidence for the highest pressures of metamorphism, do not coincide with the areas that experienced the highest temperatures. This follows from inferred gradients in P and T.
3. The geothermal gradient, at the time of metamorphism, varied systematically from place to place laterally across the volume of crust affected by the metamorphism. In the highest-pressure regions (close to Grandfather Mountain window), the temperatures were comparatively low; thus, the geothermal gradient was comparatively steep (i.e., a cool geotherm). To the northeast and to the south-

west, away from the Grandfather Mountain window, comparable temperatures correspond to lower pressures; thus, the geothermal gradient was comparatively shallower (i.e., a hot geotherm).

METABASITES

Hornblende schist and gneiss. The essential minerals in the mafic rocks of the AMS and ABMS are hornblende, quartz, and plagioclase. Varieties of amphibolite are distinguished by various combinations of garnet, biotite, epidote-ziosite, and magnetite. Locally, extreme variants, dominated by epidote (epidotites) or dominated by garnet (garnetites), occur as lenses (dm-scale) and thin (mm- to cm-scale) layers, parallel to the foliation. Accessory minerals include sphene, apatite, ilmenite, zircon, and iron sulfides. Late replacement minerals include white mica, calcite, chlorite, and ferric oxides.

Abbott and Raymond (1984) identified two metamorphic zones in the mafic rocks of the AMS-ABMS northeast of the Grandfather Mountain window (Figure 5). In terms of CFM minerals (C=CaO+K2O+Na2O-Al2O3, F=FeO-Fe2O3, M=MgO; Abbott, 1982), the zones are separated by a reaction isograd,

Bio + Epi = Gar + Hnb.

Quartz, plagioclase, and Fe-oxide are involved in the reaction. The lefthand side corresponds to the low-grade (zone Im), where the common CFM mineral assemblage is Hnb+Bio+Epi (coexisting with quartz, plagioclase, Fe-oxide). Garnet and hornblende are not compatible. On the high-grade side (zone IIm), diagnostic CFM assemblages are Gar+Hnb, Gar+Hnb+Epi, and Gar+Hnb+Bio. The isograd passes practically through the AFM pseudo-invariant point, in such a way that the P-T slope (dP/dT) of the reaction is constrained to be negative (Figure 3).

Gar-Hnb and Gar-Bio geothermometry is consistent with Gar-Bio geothermometry for the pelitic rocks (McSween et al., 1989). Temperatures range from 530 to 622°C in zone Im; and from 611 to 729 °C in zone IIm. The map distribution of estimated temperatures (McSween et al., 1989) is consistent with the general direction of the increasing T, inferred from relationships in the pelitic rocks.

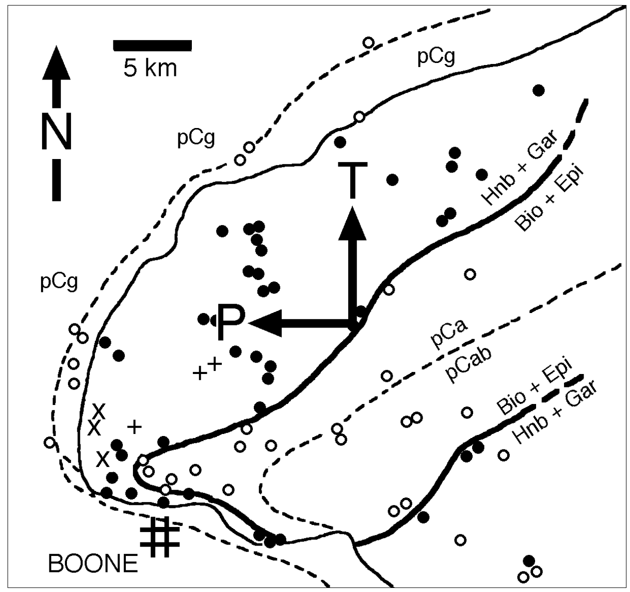

Figure 5. Metamorphic zones in mafic rocks north of the Grandfather Mountain window (from Abbott and Raymond, 1984; McSween et al., 1989). Filled circles indicate mafic assemblages with Gar + Hnb; the common, diagnostic CFM assemblage is Hnb+Gar+Epi. Open circles indicate mafic assemblages with Epi + Bio (Hnb and Gar are incompatible). The common, diagnostic CFM assemblage is Hnb+Bio+Epi. Non-eclogitic mafic assemblages containing clinopyroxene (diopside, mentioned in McSween et al., 1989) are indicted by +'s. Eclogite sites are indicated by X's:

NCA 5: lat. N 36° 15' 34", long. W 81° 43' 22", Junaluska Rd.

NCA 170: lat. N 36° 16' 44.2", long. W 81° 43' 41", Howard Creek Rd., 50-100 m NE of junction with Tater Hill Rd.

(No sample): lat. N 36° 16' 46.6", long. W 81° 43' 38", Howard Creek Rd., 250 m NE of junction with Tater Hill Rd. Boulders from upslope, to north.

Eclogite. This is the first description of retrograded eclogites from northeast of the Grandfather Mountain window. There are actually three sites (Figure 5, precise locations given in caption), which are close to each other and in nearly the same structural position, close to the base of the AMS, at its westernmost edge. It is not possible to know, at this time, if the three sites are parts of a contiguous area of retrograded eclogite, because mapping is incomplete. The locations are coincident, however, with the area of highest metamorphic pressures in the AMS, as inferred from the general direction of increasing P in the pelitic rocks.

The retrograded eclogites occur as thin (cm-scale), granoblastic layers in otherwise typical amphibolite. The essential minerals are symplectic intergrowths of diopside and plagioclase (representing former omphacite), generally euhedral to subhedral garnet (<1mm), polygonal epidote, and quartz. Symplectic grains retain simple polygonal shapes, and are related to one another in such a way that the mosaic texture of the original omphacite is recognizable. Boundaries between layers of retrograded eclogite and amphibolite are gradational, showing a progressive replacement of the eclogite by hornblende schist. Locally the vermicular texture of the original symplectite is preserved in the hornblende. Plagioclase occurs only in symplectite and with quartz in coronas around garnets. Presumably the coronas formed in response to a retrograde reaction between garnet and surrounding symplectite (Adams et al., 1995). The distinctive coronas are very common in the symplectite-free hornblende schist, especially near the base of the AMS, along the southern and western margin of the thrust sheet. Interpreted as relict features inherited from an earlier, higher-grade condition of the rock, the coronas suggest that a significant volume of the amphibolite in the AMS is retrograded (amphibolitized) eclogite (Adams et al., 1995).

These inferred eclogites northeast of the Grandfather Mountain window are distinguished from those described by Willard and Adams (1994) by the presence of epidote. In some samples epidote occurs in thin (mm-scale), nearly monomineralic layers or lenses, bounded by the symplectic diopside+plagioclase and garnet. Individual grains of epidote are free of inclusions. Aggregates contain variable amounts of garnet, grains of symplectic diopside-plagioclase, or both. By itself or with lesser amounts of other minerals—mainly garnet and symplectic diopside+plagioclase—the epidote forms aggregates that show a well-devoloped, equigranular mosaic texture. A second type of epidote (with quartz) occurs between garnet and symplectic diopside-plagioclase in some samples, as crude coronas, suggesting that it resulted from an early retrograde reaction involving garnet and omphacite. Locally, euhedral garnets are embedded in symplectite (diopside+plagioclase) with only minor quartz, no epidote, and no hornblende, suggesting an original metamorphic assemblage of omphacite and garnet.

Hornblende seems not to have any special site for nucleation. Grains of hornblende occur along every kind of grain boundary involving combinations of garnet, epidote, and symplectite. Hornblende also develops at boundaries between grains of symplectic diopside+plagioclase, cutting across the vermicular texture of the symplectite.

Based on textural relationships, the following sequence of assemblages (excluding accessory minerals) is envisioned, starting with the earliest, highest-grade assemblage,

(a) Omp(I) + Gar + Qtz, and Omp(I) + Gar + Epi + Qtz,
(b) Omp(II) + Gar + Epi + Qtz,
(c) (Dio + Pla) + Gar + Epi + Qtz, where (Dio + Pla) is symplectite,
(d) (Dio + Pla) + Gar + Epi + Hnb + Qtz, and
(e) Pla + Gar + Epi + Hnb + Qtz.

Reactions relating assemblage (a) to (b), and assemblage (b) to (c) can be conveniently represented in the compositional space defined by principal components of omphacite (Omp) plus quartz, that is Jd = $NaAlSi_2O_6$, Ts = $CaAl_2SiO_6$, Di-Hd = $Ca(Mg,Fe)Si_2O_6$, and Qtz = 3 SiO_2 (Figure 6). Assuming the rock system is open with respect to H_2O and O_2, epidote plots in the same place as garnet, in this simplified representation. The appearance of epidote is thought to be controlled mainly by the availability of O_2 and H_2O, according to one or both of the following reactions involving components of an original, slightly tschermakitic omphacite, Omp(I), components of garnet, or both.

$$\underbrace{CaFeSi_2O_6 + CaAl_2SiO_6}_{\text{Hd and Ts in Omp(I)}} + 0.5\,H_2O + 0.25\,O_2 = \underbrace{Ca_2FeAl_2Si_3O_{12}(OH)}_{\text{Epi}}$$

$$\underbrace{Ca_2FeAl_2Si_3O_{12}}_{\text{in Gar}} + 0.5\,H_2O + 0.25\,O_2 = \underbrace{Ca_2FeAl_2Si_3O_{12}(OH)}_{\text{Epi}}$$

The Ts-content of most omphacites (Deer et al., 1992; Cameron and Papike, 1980) is very low, typically much less than 10%. Omphacites analyzed by Willard and Adams (1994) from eclogite in the AMS contain less than 9% Ts-component. Presumably, production of epidote from omphacite by the first reaction is less important than production of epidote from garnet by the second reaction. The reader will note that the component of garnet in the second reaction is chemically equivalent to combined chemical components of Omp(I) in the first reaction. The first reaction has the effect of changing the composition of the omphacite toward the (Di-Hd)-Jd join, directly away from epidote. In the context of Figure 6, the reaction may be written simply,

$$Omp(I) + H_2O + O_2 = Omp(II) + Epi.$$

The bulk composition of the rock is in the triangle Qtz-Gar(Epi)-Omp(II). The absence of epidote from the paragenesis of the eclogite southwest of the Grandfather Mountain window (Willard and Adams, 1994) may be due simply to lower fugacity of O_2.

Based on optical properties and X-ray diffraction characteristics, the clinopyroxene in the symplectite is diopside, close to the Di-Hd apex in Figure 6; the plagioclase is oligoclase (~An_{20}). Volumetric proportions of oligoclase and diopside in the symplectite suggest that the Jd-content of original omphacite was at least 35%. A line connecting the diopside and the

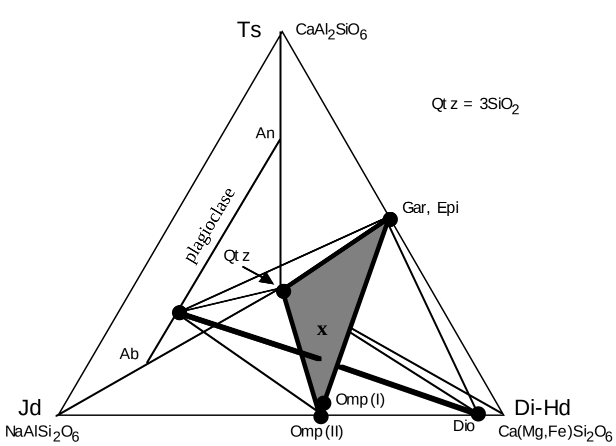

Figure 6. Eclogite tetrahedron (designed by one of us, RNA), defined by components, Jd = $NaAlSi_2O_6$, Di-Hd = $Ca(Mg,Fe)Si_2O_6$, Ts = $CaAl_2SiO_6$, and Qtz = $3SiO_2$. The Qtz component is taken as 3 units of SiO_2, so that all compositions in the tetrahedron are normalized to 6 oxygen atoms. In this way, all compositions represent approximately the same volume; hence, modal relationships are preserved (approximately). The bulk composition of typical eclogite is in the shaded plane, e.g., composition marked X. Oxidation of the initial omphacite Omp(I) and compositionally equivalent components in Gar produce epidote, driving the composition of the omphacite to Omp(II). Symplectic Dio+Pla forms by the reaction Om(II) + Qtz + Gar (or Epi) -> Pla + Dio. The final mineral assemblage is Dio + Pla + Gar/Epi + Qtz.

plagioclase of the symplectite pierces the Qtz-Gar(Epi)-Omp(II or I, ~Jd_{35}) plane. Hence, the reaction producing the symplectite necessarily takes the form,

Omp(II or I) + Gar(or Epi) + Qtz = Dio + Pla,

defining the compatibility tetrahedron Dio-Pla-Qtz-Gar(Epi), within which the bulk composition resides. Admittedly, the amount of Gar(or Epi) involved in the reaction may be small.

At this writing, chemical analyses are being performed by electron microprobe (J. Greenwood, Univ. of Tennessee, Knoxville) on the minerals in the eclogite. Results are not yet available. Using mass balance calculations on the analyses of symplectic diopside and plagioclase, we hope to recover the composition of the original omphacite. Using relevant geothermometers and geobarometers, we then hope to obtain quantitative estimates of the original P and T.

Hornblende cannot be plotted in Figure 6. However, assemblage (c), Dio + Pla + Gar + Epi + Qtz, is amenable to a CFM representation (Abbott, 1982), wherein the appearance of hornblende can at least be understood qualitatively. The relationships relevant to assemblage (c) are shown schematically in Figure 7a. A hypothetical bulk composition is indicated in the Gar+Dio+Epi field. Upon uplift, cooling, and hydration, the 2-phase Gar-Epi field rotates clockwise, shifting the Gar-Cpx-Epi field toward the CF sideline and increasing the area of the Hnb-Gar-Epi field, such that in Figure 7b the same bulk composition resides in the latter field. Relevant multivariant CFM reactions operating on the bulk composition could be,

Cpx (+ H_2O) = Gar + Epi, first,

followed by,

Gar + Epi (+ H_2O) = Hnb.

H_2O necessarily appears on the left side of each reaction; hence, the reactions are driven by the availability (activity) of H_2O. Of course, the combined reaction,

Cpx (+ H_2O) -> Hnb,

is permissable if, for reasons of disequilibrium, any diopside should persist when conditions are appropriate for the relationships in Figure 7b.

In the eclogites southwest of the Grandfather Mountain window, described by Willard and Adams (1994), hornblende starts to form in a different way, earlier in the paragenesis, before the breakdown of omphacite to symplectic Dio+Pla. Willard and Adams (1994) suggest the reaction,

3 Gar + 7 Omp + 2 H_2O = 2 Hnb + 4 Pla.

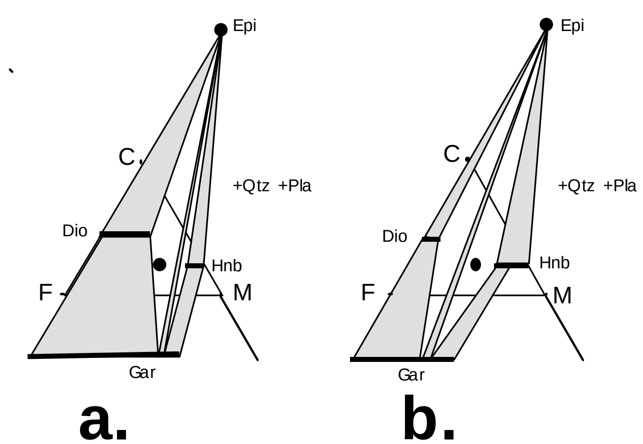

Figure 7. CFM diagrams (C = CaO+Na_2O+K_2O-Al_2O_3, F = FeO-Fe_2O_3, M = MgO, Abbott, 1982), illustrating schematically the retrograde conversion of eclogite to amphibolite. A hypothetical bulk composition is indicated by the filled circle, expressed at high grade (a) by symplectic (Dio+Pla) + Gar + Epi + Qtz (see Figure 6). At lower P-T conditions (b) in the presence of H_2O, the same bulk composition is expressed by Hnb + Gar + Epi + Pla + Qtz.

DISCUSSION

A hypothetical retrograde P-T path is given in Figure 8. The stippled region encloses P and T conditions estimated by McSween et al. (1989) for amphibolites and pelitic schists in the AMS. Without knowing precise compositions for omphacite (I or II) and garnet in the original eclogite, P can be constrained only crudely. As noted earlier, a conservative estimate of the Jd-content of the omphacite (I or II) is at least 35%. The reaction Omp(Jd_{30}) + Qtz = Pla(An_{20}) (Holland, 1980, 1983) places a lower limit on P for omphacite (I or II). Lacking any meaningful constraints on T, but assuming a retrograde P-T path of positive slope ($dP/dT > 0$) passing through the AFM pseudo-invariant point i, the minimum T would be approximately 600 °C, and the minimum P would be approximately 1.3 Gpa. These conditions are comparable to those estimated for the eclogites in the AMS, southwest of the Grandfather Mountain window (Willard and Adams, 1994; Adams et al., 1995).

The distribution of eclogites in the AMS (immediately southwest and northeast of the Grandfather Mountain window) is consistent with the metamorphic pressure gradients preserved in the pelitic rocks. Parts of the AMS that experienced the greatest uplift; hence, originated at the greatest depths; are adjacent to the Grandfather Mountain window. In a palinspastic reconstruction, this means the basal thrust fault intercepted the greatest depths beneath parts of the AMS now exposed immediately north and immediately southwest of the Grandfather Mountain window. The greatest volume of mafic rock is in these same parts of the AMS. Early during subduction (Abbott and Raymond, 1984; Willard and Adams, 1994; Adams et al., 1995) along what would become the basal thrust fault of the AMS, downward deflection of the surface of the fault would explain the interception of the highest-P parts of the AMS. Downward deflection of the nascent fault suggests that the effected parts of the AMS were different from other parts of the eastern Blue Ridge (i.e, further away from the general vicinity of the Grandfather Mountain window) with regard to physical properties of the crust at the time. Perhaps the most significant, distinguishing feature of the AMS-ABMS adjacent to the Grandfather Mountain window is the great volume of mafic rocks. We offer the possibility that the nascent thrust fault was deflected downward quite simply by an obstacle, in the form of what was originally an isolated mafic volcanic edifice on oceanic crust — a seamount. Trace element and REE geochemistry of AMS-ABMS amphibolites (Misra and Conte, 1991) are generally consistent with this interpretation. Misra and Conte (1991) describe three composi-

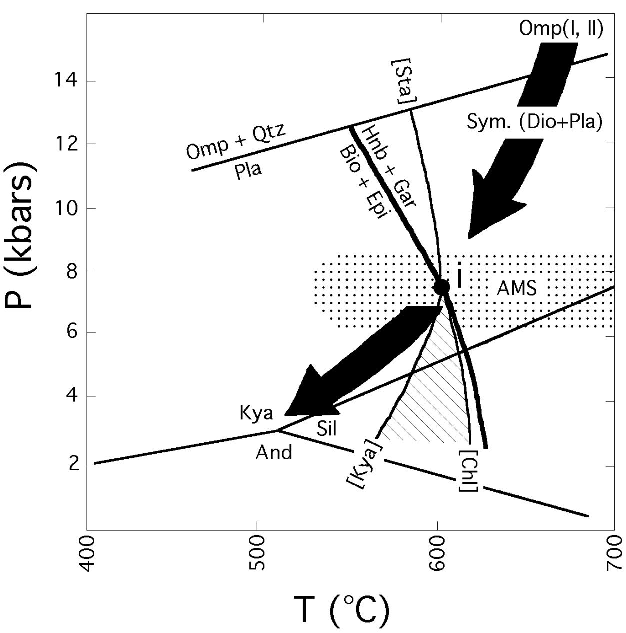

Figure 8. P-T diagram illustrating schematically the retrograde path of eclogites in the AMS. Phase relationships from Figure 3 are positioned such that point i is consistent with conditions estimated by McSween et al. (1989). Slopes of reactions are consistent with calculations by Spear et al. (1995). Omp + Qtz = Pla reaction (Omp, Jd_{30}; Pla, An_{20}) is from Holland (1980, 1983). Al_2SiO_5 polymorphic transformations, involving And, Kya, and Sil, are from Holdaway (1971). Stippled region encloses range of P-T conditions in AMS, as estimated by McSween et al. (1989).

tional groups of basalts. The paleotectonic setting for Group I is back-arc or plume; for group II, spreading center (N-MORB); and for group III, transitional between spreading center and plume (T-MORB).

CONCLUSIONS

With regard to the origin of the AMS-ABMS, the findings reported here support the three main conclusions of Willard and Adams (1994) and Adams et al. (1995), for the same reasons. Summarizing their conclusions:

1. The discovery of eclogites in the eastern Blue Ridge helps to resolve controversy regarding the origin of this part of the southern Appalachian Orogen.

2. The collected body of evidence strongly supports an ensimatic origin for the AMS, as a subduction-related melange. Subduction was most likely toward the east, such that the melange accumulated along the western edge of Piedmont terrane.

3. The AMS marks the suture between the ancient North American Craton and the Piedmont terrane.

We offer an additional, fourth conclusion:

4. The Grandfather Mountain window may mark the site where a seamount was incorporated into the subduction melange.

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REFERENCES

Abbott, R.N., Jr., 1979, Polymetamorphism in the Siluro-Devonian Goshen Formation of western Massachusetts: Geological Society of America Bulletin, v. 90, p. 871-876.

Abbott, R.N., Jr., 1982, A petrogenetic grid for medium and high grade metabasites. American Mineralogist: v. 67, p. 865-876.

Abbott, R.N., Jr., and Raymond, L.A., 1984, The Ashe Metamorphic Suite, northwest North Carolina: Metamorphism and observations on geologic history: American Journal of Science, v. 284, p. 350-375.

Abbott, R.N., Jr., Raymond, L.A., and McSween, H.Y., Jr., 1991, Taconic invariant points in the central Blue Ridge Belt and their structural/tectonic implications: Geological Society of America Abstracts with Program, v. 23, p. 1.

Adams, M.G., Stewart, K.G., Trupe, C.H., and Willard, R.A., 1995, Tectonic significance of high-pressure metamorphic rocks and dextral strike-slip faulting along the Taconic suture, in Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., Current Perspectives in the Appalachian-Caledonian Orogen: Geological Association Canada, Special Paper 41, p. 21-42.

Albee, A.L., 1968, Metamorphic zones in northern Vermont, in Zen, E-an et al., eds., Studies in Appalachian Geology - Nothern and Meritime: New York, Interscience Publishers, p. 329-341.

Brown, P.M., 1985, Geologic Map of North Carolina, Department of Natural Resources and Community Development, Division of Land Resources, North Carolina.

Bryant, B., and Reed, J.C., Jr., 1970, Geology of the Grandfather Mountain window and vicinity, North Carolina and Tennessee: U.S. Geological Survey Professional Paper 615, 195 p.

Butler, J.R., 1972, Age of Paleozoic regional metamorphism in the Carolinas, Georgia, and Tennessee, southern Appalachians: American Journal of Science, v. 272, p. 319-333.

Butler, J.R., 1973, Paleozoic deformation and metamorphism in part of the Blue Ridge thrust sheet, North Carolina: American Journal of Science, v. 273-A, p. 72-88.

Butler, J.R., 1991, Metamorphism, in Wright, J.W., Jr. and Zullo, V.A., eds., The Geology of the Carolinas: University of Tennessee, Knoxville, ch. 8, p. 127-141.

Cameron, M., and Papike, J.J., 1980, Crystal chemistry of silicate pyroxenes. in Prewitt, C.T, ed., Pyroxenes: Mineralogical Society of America, Reviews in Mineralogy, v. 7, p. 5-116.

Carmichael, D.M., 1978, Metamorphic bathozones and bathograds: a measure of the depth of post-metamorphic uplift and erosion on the regional scale: American Journal of Science, v. 278, p. 769-797.

Conley, J.F., 1987, Geology of the Piedmont of Virginia - Interpretations and problems, in Contributions to Virginia Geology - III: Virginia Division of Mineral Resources Publication 7, p. 115-149.

Deer, W.A., Howie, R.A., and Zussman, J., 1992, An Introduction to the Rock-Forming Minerals, 2nd Edition: New York, John Wiley and Sons, 606 p.

Drake, A.A., Jr., Sinha, A.K., Laird, J., and Guy, R.E., 1989, The Taconic orogen, in Hatcher, R.D., Jr., et al., eds., The Appalachian-Ouachita Orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 101-177.

Espenshade, G.H., Rankin, D.W., Shaw,, K.W., and Neuman, R.B., 1975, Geologic Map of the east half of the Winston-Salem quadrangle, North Carolina-Virginia: U.S.Geological Survey, Miscelaneous Geologic Investigations, Map I-709B.

Fullagar, P.D., and Bartholomew, M.J., 1983, Rubidium-Strontium ages of the Watauga River, Cranberry, and Crossing Knob Gneisses, northwestern North Carolina, in Lewis, S.E., ed., Geological Investigations in the Blue Ridge of Northwestern North Carolina: 1983 Guidebook for the Carolina Geological Society: North Carolina Division of Land Resources, Article II, 29 p.

Fullagar, P.D., and Odom, A.L., 1973, Geochronology of Precambrian gneisses in the Blue Ridge province of northwestern North Carolina and adjacent parts of Virginia and Tennessee: Geological Society of America Bulletin, v. 84, p. 3065-3080.

Goldberg, S.A., Butler, J.R., Mies, J.W., and Trupe, C.H., 1989, The southern Appalachian Orogen in northwestern North Carolina and adjacent states, in Goldberg, S.A., and Butler, J.R., leaders, Geological Cross-section Through Part of the Southern Appalachian Orogen: American Geophysical Union, Field Trip Guidebook T365, 55 p.

Goldberg, S.A., and Dallmeyer, R.D., 1997, Chronology of Paleozoic metamorphism and deformation in the Blue Ridge thrust complex, North Carolina and Tennessee: American Journal of Science, v. 297, p. 488-526.

Guidotti, C.V., 1970, Metamorphic petrology, mineralogy and polymetamorphism in a portion of N.W. Maine, in Boone, G.M., ed., New England Intercollegiate Geological Conference Guidebook, B-2, p. 1-29.

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

Holdaway, M.J., 1971, Stability of andalusite and the aluminum silicate phase diagram: American Journal of Science, v. 271, p. 97-131.

Holland, T.J.B, 1980, The reaction albite = jadeite + quartz determined experimentally in the range 600-1200 °C: American Mineralogist, v. 65, p. 129-134.

Holland, T.J.B, 1983, The experimental determination of activities in disordered and short-range ordered jadeitic pyroxenes: Contributions to Mineralogy and Petrology, v. 82, p. 214-220.

Labotka, T., 1981, Petrology of an andalusite-type regional metamorphic terrane, Panamint Mountains, California: Journal of Petrology, v. 22, p. 261-296.

McSween, H.Y., Jr., Abbott, R.N., Jr., and Raymond, L.A., 1989, Metamorphic conditions in the Ashe Metamorphic suite, North Carolina Blue Ridge: Geology, v. 17, p. 1140-1143.

McSween, H.Y., Jr., and Hatcher, R.D., Jr., 1985, Ophiolites (?) of the southern Appalachians Blue Ridge, in Woodward, N.B., ed., Field Trips in the Southern Appalachians: University of Tennessee, Department of Geological Sciences, v. 9, p. 144- 170.

Miller, C.F., Hatcher, R.D., Gorisch, E.B., Harrison, T.M., and Coath, C., 1997, Ages of plutonism, granulite facies metamorphism, and oldest basement in the southern Appalachian Orogen, NC - GA: High resolution ion probe dating of zircon and monazite: Geological Society of America Abstracts with Programs, v. 29, p. 58.

Misra, K.C., and Conte, J.A., 1991, Amphibolites of the Ashe and Alligator Back Formations, North Carolina: Geological Society of America Bulletin, v. 103, p. 737-750.

Rankin, D.W., 1970, Stratigraphy and structure of Precambrian rocks in northwestern North Carolina, in Fisher, G.W. et al., eds., Studies in Appalachian Geology - Central and Southern: New York, Interscience Publishers, p. 227-245.

Rankin, D.W., Espenshade, G.H., and Newman, R.B., 1972, Geologic map of the western half of the Winston-Salem quadrangle, N.C., Va., Tenn.: U.S. Geological Survey, Miscelaneous Investigations, Map I-709A.

Rankin, D.W., Espenshade, G.H., and Shaw, K.W., 1973, Stratigraphy and structure of the metamorphic belt in northwestern North Carolina and southwestern Virginia: A study from the Blue Ridge across the Brevard Fault Zone to the Sauratown Mountains Anticlinorium: American Journal of Science, v. 273-A, p. 1-40.

Spear, F.S., Kohn, M.J., and Paetzold, S., 1995, Petrology of the regional sillimanite zone, west-central New Hampshire, U.S.A., with implications for the development of inverted isograds: American Mineralogist, v. 80, p. 361-376.

Thompson, J.B., Jr., 1957, The graphical analysis of mineral assemblages in pelitic schists: American Mineralogist, v. 42, p. 842-858.

Thompson, J.B., Jr., and Norton, S.A., 1968, Paleozoic regional metamorphism in New England and adjacent areas, in Zen, E-an, et al., eds., Studies of Appalachian Geology - Northern and Maritime: New York, Interscience Publishers, p. 319-328.

Wang, P., and Glover, L., III, 1991, Late Precamb. mafic-ultramafic rocks of the VA Blue Ridge: Geochemical signatures and tectonic setting compared with Jurassic of eastern U.S.: Geological Society of America Abstracts with Programs, v. 23, p. A145.

Willard, R.A., and Adams, M.G., 1994, Newly discovered eclogite in the southern Appalachian orogen, northwestern North Carolina: Earth and Planetary Science Letters, v. 123, p. 61-70.