Geologic Studies in the Inner Piedmont, Brevard Zone, and Blue Ridge, South Carolina and North Carolina

Guidebook for the Seventy-fifth Anniversary of the Carolina Geological Society   October 12-14, 2012

Field Trip Leaders: John M. Garihan, William A. Ranson, Suresh Muthukrishnan, James L. Bridgeman, and Tom Goforth

CAROLINA GEOLOGICAL SOCIETY

2012 FIELD TRIP

Geologic Studies in the Inner Piedmont, Brevard Zone, and Blue Ridge, South Carolina and North Carolina

October 12-14, 2012

Greenville, South Carolina

Guidebook for the Seventy-fifth Anniversary of the Carolina Geological Society

73rd Annual Meeting

Founded at Furman University in 1937

FIELD TRIP LEADERS:

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Guidebook Editors: John M. Garihan and William A. Ranson

Carolina Geological Society

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Cover Photograph: Twin Falls (Reedy Cove Falls) along Eastatoe Creek, Eastatoe Gap quadrangle. Rock exposed is Henderson Gneiss. Falls is ~75 feet high.

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INTRODUCTION

National and international geological societies have a broad range of activities, most of which revolve around dissemination of research results through publications and annual meetings. Local geological societies tend to be oriented towards sponsoring field trips or field conferences. The Carolina Geological Society is no exception, for its focus is an annual field trip. There are no papers presented, and publications are limited to field guides. Simplicity as to organization has been a hallmark of the Society.

In 1987, when the Society marked the 50th anniversary of its founding, the Board of Directors asked the Secretary to write a brief history of the Society as one of the ways to celebrate the first half century. An earlier history was written in 1968 (Berry and Heron, 1968). The information in this history is based in part on both the 1968 and 1988 editions, the minutes of meetings and Executive Committee sessions, and papers in the files of the Society.

Figure 1. Wilbur C. Holland *circa* 1930, founding father of the Carolina Geological Society.

Figure 2. Willard Berry 1937, Secretary-Treasurer of the Society 1937-1965.

THE EARLY YEARS

Wilbur C. Holland (Figure 1) was the founding father for both the Carolina Geological Society and the Department of Geology at Furman University. He received his undergraduate degree at Marietta College in Ohio, studied a year at the University of Cincinnati, and then went to the University of Pittsburgh for another year where he received his M.S. degree in 1933. At Ohio State he worked on his Ph.D. degree into 1935. On May 22, 1935, he answered a letter from Furman President Bennette E. Geer and gave him details of his education. Presumably Geer was responding to a job inquiry from Holland. Thus Holland came to Furman in 1935 and left in 1942 for graduate school at Louisiana State University. He received his Ph.D. in 1943 and went to work as a field geologist for Carter Oil Company, a subsidiary of Standard Oil Company. Charles Cazeau (SUNY at Buffalo, retired) remembers Holland in the late 1950s as the overseer of the Humble Research Center library. “He was a most helpful and self-effacing gentleman who aided me greatly in my early report writing and research” (letter, July 27, 1987). Holland retired from Exxon in 1965.

Willard Berry (Figure 2) got his A.B. degree in 1924 and his Ph.D. in 1929, both from Johns Hopkins. He went to Ohio State in 1929 and remained as an instructor in geology until 1936. He must have known Holland at Ohio State. Apparently Berry knew that Holland had talked Furman into a geology department, for in 1936 Berry convinced Dean W. H. Wannamaker at Duke of the need of a geology department and his ability to form it.

Berry (Berry and Heron, 1968) recalled that Holland found little interest in geology in the Greenville, SC area. There were no active local geological societies in the Carolinas as there were in Ohio. He wrote in the fall of 1936 to Willard Berry about the idea of a local society. Berry tried "to help him all I could", but "Mr. Holland deserves much credit for the formation of the Society" (letter to B.E. Geer from Berry, June 4, 1937).

Holland sent a questionnaire to at least 50 people in higher education institutions, government agencies, and industry. Thirty-four responded favorably. The responses are of interest. As to the name of the organization, one respondent suggested the "Southeastern Geological Society," two others "The Carolina Geological and Geographical Society," but most liked the name Holland suggested, "The Carolina Geological Society."

As to who should be included as members, many favored making the membership as broad as possible to include geology undergraduate and graduate students, geographers, "those engaged in mining", soil scientists, and hobbyists. One unidentified person suggested that "some mining promoters" should be kept out. At least one favored full membership restricted to "those actively engaged professionally in geological and mining engineering work with a minimum of three years of active work in the field"; others could be associate or junior members.

The time of the meeting that Holland suggested was late May. Naturally, there was a variety of opinion, with some favoring the Spring and others the Fall. Two people suggested two meetings a year, and two others said that the meeting should be at the same time as the Academy of Sciences.

The original purpose of the meetings, as Holland envisioned it, was one full day meeting with presentation of papers in a morning session and the afternoon devoted to a field trip. Most favored this, but a few suggested the papers should be in the evening only. John Huddle (UNC) wanted "1 or 2 day field trip — papers in evening only — IF ANY." Most agreed that the place of the meeting should be varied from year to year. Holland suggested three officers for the society, a president, secretary-treasurer, and a corresponding secretary. The latter was to hold a two-year position and would "arrange the program". Most agreed, but Hubert O. DeBeck said that there should be a vice-president because "you should always have a Vice-President to anything."

Dues should be kept as low as possible in Holland's opinion, and most agreed that $1.00 or even fifty cents was the right amount. Two suggested $5.00.

The minutes of the organizational meeting on May 15 and the notice sent to charter members show that many of the current customs and practices were formulated at that time. The name Carolina Geological Society prevailed. The meeting time was approved for the Fall so as not to interfere with the Academies of Science in the two states. The concept of formal papers was dropped, and it was decided to hold a field trip and informal discussions. The field trip limit of 2 days was set. Dues of $1.00 per year were established and were not changed until 1986, when dues were increased to $2.00, which is still the current rate.

A decision made about a program committee at the organizational meeting was not followed by the Society, at least not in the latter post-war years. The program committee of three appointed by the President with a suggested term of three years was to "consider extended program areas desirable to study". At the second meeting in November of 1937, D.H. Eargle (Spartanburg, SC) was appointed chairman of the Program Committee with Raymond Binford (Guilford College) and B.C. Burgess (Spruce Pine) members. Their report listed eight two-day field trips along with a brief description of what might be seen in each of the localities. In a letter about the duties of the Program Committee to Jasper Stuckey (NC State), Willard Berry said that "if I may stick my oar into what is not my business, it comes to mind that it might be desirable for the program committee to fish around and see if they can get invitations for the Society to hold their programs at various places." The Program Committee with various members continued to function through at least 1948 (9th meeting). The contents of the Committee reports were "read and filed with the Executive Committee". Contrary to present custom, it was the Executive Committee that decided where the meeting would be held. In the 1952 meeting minutes, the Acting Secretary (Duncan Heron, Duke) referred to the field trip leader, Phil King (USGS), as Chairman of the Program Committee. After that time there was no program committee as originally defined.

There were 23 people at the organization meeting (shown as bold in Table 1). By suspension of the rules, the group approved as charter members those who had responded to Holland and said they wished to cooperate in the Society and had paid their $1.00 dues before the next meeting. The forty-three charter members of the Society are shown in Table 1.

Name	**Title, in 1937**	**Location, in 1937**
Bailey, Harry		Penland, NC
Barrett, H.P.		Charlotte, NC
Berry, E. Willard *	Asst. Prof., Duke University	Durham, NC
Binford, Raymond *	President Emeritus, Guilford College	Greensboro, NC
Bryson, H.J.	State Geologist of North Carolina	Raleigh, NC
Burgess, Blandford C. *	Manager, Tenn. Min. Products Co.	Spruce Pine, NC
Colburn, B.S.	Greystone Ct., Biltmore Forest	Biltmore, NC
Davis, Harry T.	NC State Museum	Raleigh, NC
De Beck, Hubert O. *	Consulting Geologist	Burnsville, NC
Eargle, D.H.		Spartanburg, SC
Edwards, Richard A. *	Grad. Student, UNC	Chapel Hill, NC
Emory, S.T.	UNC	Chapel Hill, NC
Grant, Leland F. *	Geologist , TVA	Murphy, NC
Grassy, Richard G. *	Asst. Geologist, Soil Conserv. Serv.	Greenville, SC
Gravaat, Marshall *	76 Arcade Bldg.	Asheville, NC
Holland, Wilbur C. *	Asst. Prof., Furman University	Greenville, SC
Huddle, John W. *	Professor, UNC	Chapel Hill, NC
Hunter, Charles E. *	TVA	Asheville, NC
Johnson, W. Ray (Jr.)		Chapel Hill, NC
Laird, Wilson	UNC	Chapel Hill, NC
LeBaron, P.M.	UNC	Chapel Hill, NC
MacCarthy, Gerald R. *	Assoc. Prof., UNC	Chapel Hill, NC
Marsh, Steve P.	Box 889	Durham, NC
Martin, Romeo *	Undergraduate, Furman University	Greenville, SC
McMurray, Lynn L. *	Geologist, TVA	Knoxville, TN
Mattson, V.L.		Burnsville, NC
Moneymaker, Berlen C. *	Geologist, TVA	Murphy, NC
Murray, Grover E. *	Undergraduate, UNC	Chapel Hill, NC
Parker, J.M.	State College	Raleigh, NC
Petty, Julian J.	Geology Dept., USC	Columbia, SC
Prouty,William F. *	Chmn. Geol Dept., UNC	Chapel Hill, NC
Reddie, Roy *	Consulting Geologist	Spruce Pine, NC
Rowell, William *	Undergraduate, Furman University	Greenville, SC
Smith, Laurence L.	Geology Dept., USC	Columbia, SC
Straley, H.W., III *	Grad Student, UNC	Chapel Hill, NC
Stroud, William *	Undergraduate, Furman University	Greenville, SC
Stuckey, J.L.	State College	Raleigh, NC

Taber, Stephen	Geology Dept., USC	Columbia, SC
Vail, Richard *		Burnsville, NC
Van Horn, Isaac	23 O'Henry Street	Asheville, NC
Ward, James B. *	TVA	Murphy, NC
Watkins, J.H.	The Citadel	Charleston, SC
White, Max	Dept. of Geology, Furman University	Greenville, SC

Table 1. The original Charter Members of the Carolina Geological Society. Those shown in bold (with asterisk) were members present at the first organizational meeting held at Furman University on May 15, 1937.

WORLD WAR II

The Executive Committee of CGS met by correspondence on September 5, 1941. Because of the gasoline shortage, the Executive Committee had to decide if there would be a meeting that fall. The trip was approved, but the meeting place was moved from Murphy, NC, to Asheville because of the lack of space in Murphy. The meeting was held on November 8 and 9, one month before the United States entered the war.

On September 14, 1942, a notice was mailed to the membership about the Executive Committee's action to postpone the annual meeting “for the duration”. In addition the membership was asked to vote on a proposal to amend the constitution so as to make the office of Secretary-Treasurer permanent. The idea of a permanent Secretary-Treasurer was to give the society a stable address, one where members could know that they could contact the organization. Berry (Berry and Heron, 1968) reported that 42 of the 50 members who responded wanted the Society to continue. The membership list at the time of the 1941 meeting had 118 names. Berry sent out 150 notices for the 1946 meeting. He extended an invitation to join the Society to “those known to be interested or whose names were sent to the Secretary by other members”. In the Report of the Secretary for 1946 Berry said, “The Secretary craves pardon for this unconstitutional act (asking people to join without formal approval) but it seemed necessary to clear up the disruption caused by the war.”

At the Shelby meeting the membership passed a resolution of appreciation to Willard Berry “for his contribution to keeping together of the membership during the war years” (Minutes, 1946 meeting).

PURPOSE OF THE SOCIETY

For 50 years the Carolina Geological Society has existed for the purpose of sponsoring an annual field trip. Yet the founders envisioned a broader scope for the Society. As the 1937 Constitution states the objective is: “...to promote the science of geography, geology, metallurgy, mining, ceramics, and soil science....to promote and encourage their study in the schools and colleges....to encourage research in these sciences and the presentation of its results; and to promote a spirit of friendship and cooperation among the earth scientists within the area named.”

Promote the Geosciences

Promotion is interpreted as public awareness of the earth sciences. The founders used the specific fields of geography geology, metallurgy, mining, ceramics, and soil science. Apparently, the inclusive terms, “geosciences” or “earth sciences”, were not in vogue in 1937.

The first examples of promotion are two resolutions passed at the 1939 meeting. The first resolved that “the Carolina Geological Society is in hearty accord with the proposal that the National Park Service establish and maintain a mineralogical museum in the Spruce Pine District”. Copies of the resolution were sent to Congressman Bulwinkle, Secretary of the Interior Harold Ickes, the National Park Service, and S.T. Henry. The idea of the resolution was that of S.T. Henry, who had sent a telegram to the Society asking for support of the museum.

Henry was the publisher of the *Tri- County News* in Spruce Pine, NC. Apparently, Congressman Bulwinkle was behind the project and Secretary Ickes had approved inclusion of the project in the 1941 budget. Perhaps World War II interfered with the museum, for it was not founded until 1955. The other resolution urged the South Carolina Public Service Authority to establish a natural history museum on the grounds of the Santee-Cooper project.

Press coverage of the annual meeting also promotes the Society and geology. Press coverage was good in the early years of the Society. Secretary Willard Berry wrote some press releases, especially after the annual meeting, containing a brief account of the field trips and a list of the new officers. Field trip leaders often gave the local newspaper word of the field trip. The *Tri-County News* of Spruce Pine and Burnsville, NC published an article on the front page of the October 19, 1939, issue with considerable details of the upcoming meeting including news of “nearly 100 expected”. The *Cheraw Chronicle* (SC) published on October 10, 1974, three pictures on the front page with the headline “Geologists Pick Way Around Country”. The best headline, “Geologists Go Perambulating During Conference Held Here”, refers to the 1938 meeting in South Carolina.

In a more recent example or public outreach, Society members Irene and Al Boland spearheaded an effort in 2004 to cover the costs of the replacement of a historical marker at Eutaw Springs, SC. The marker commemorates the Santee Limestone and the visit of Sir Charles Lyell in 1842 on one side and limestone and marl formations and its use for cement manufactory on the other. The original was destroyed by Hurricane Hugo in 1989. Through their efforts, twenty-six members contributed $900 and the Society contributed an additional $610 to replace the marker.

Also during 2004, thirty-one members contributed $1,255 and the Society an additional $500 towards exhibit construction of *Treasures Unearthed: North Carolina’s Spectacular Gems and Minerals*, a special display of minerals at the North Carolina Museum of Natural Science in Raleigh, NC.

Encourage the Study of Earth Science

The Society has encouraged the study of earth science in the schools by sponsoring an award for the best earth science-type exhibit at the North Carolina and South Carolina Science Fairs. North Carolina winners received a total of $325 between 1956 and 1971. South Carolina winners received a total of $50 in 1957 and 1958. A certificate to go with the cash award was approved in 1958, and a year's free membership was voted in 1970.

The minutes of the Executive Committee and the annual meeting reflect much discussion about the science fair awards. The money as approved in 1955 was intended as an unrestricted gift, but it was used by the North Carolina Fair as an award for the best earth science project. The 1957 minutes refer to the money as an award for the best earth science project. In 1969 Villard Griffin (Clemson) was appointed to look into the problem of no award for South Carolina. In 1970 he reported that there was no state science fair, but there were four regional fairs. The Society approved a $5.00 award for each regional fair, but no claim was ever presented to the Secretary for the money. In 1973 the Society voted to discontinue the award because there was no longer a science fair in North Carolina, and the South Carolina fairs were so fragmented into regional fairs that it was difficult to keep up with the nature and caliber of the earth science exhibits. Thus ended the only formal attempt to support the study of earth science in the schools of the Carolinas.

Promote Spirit of Friendship and Cooperation

The Society does by its annual gathering promote a spirit of friendship and cooperation among its members. The opportunity is always present to see old friends, make new friends, and discuss research or plan cooperative research. Naturally, there is no record as to how successfully the annual field trip promotes these activities.

Formal attempts at promoting friendship and cooperation are presented in the Society's newsletters. A newsletter was approved at the annual meeting in 1954. L.L. Smith (USC) and R.J. Councill (NC Survey) were appointed to coordinate the gathering of news in South Carolina and North Carolina. Other members were to be appointed from each state to represent academics, government, and industry.

The first newsletter was a summary of the 1954 meeting and a list of members. It reported that Dick Councill (NC Survey) aided by Roy Ingram (UNC- CH) and Mason Banks (Mineral Research Lab, Asheville) was to handle the North Carolina side of the newsletter. L.L. Smith (USC) with D.H. Eargle (Naval Base, SC) and R.W. Jones (Columbia) were to coordinate the South Carolina side. This newsletter was probably mailed in December, 1954.

Newsletter No. 2 was 5 1/2 legal-size pages long. News about faculty and students at the University of North Carolina, NC State, Duke, and the University of South Carolina included such things as recent publications, current research, and employment. News from Federal Surveys included only activities of the North Carolina Division of Mineral Resources. News of Members included one marriage announcement. General Activities of Mineral Industry announced the Museum of North Carolina Minerals and activities of some North Carolina mining companies, mostly abstracted from publications such as Mining World and Engineering and Mining Journal. All in all, the newsletter was more informative about activities of earth scientists in North Carolina; only five brief items about South Carolina were mentioned. The newsletter was mailed in midyear 1955.

The last issue of the newsletter was published in January, 1956. Like the first newsletter, it was a summary of the last meeting and gave list of officers and a membership list.

Encourage Research

The Society has never directly encouraged research. The Society's annual field trip has in most cases presented the results of original research on the geology of the Carolinas. The exceptions might be some of the early field trips that were nothing more than visits to mineral or mine sites with few new ideas or results of extensive study.

CGS field trips do serve a useful means of introducing new geological concepts to the profession. After years of field and lab work, it is only natural that the results should be communicated to the profession. Formal publication is the common method of consummating research. But few people take the time to read and study publications unless some revolutionary idea is presented. “Mundane” local geology publications seldom are read unless there is an immediate need. What better way to spread the word of local geology than a field trip? Changes in concepts and terminology can be promoted on the outcrop, where the evidence is available for all to judge. Personal gratification and development of a professional reputation are quickly earned as a leader of a major field trip. Young graduate students such as Stephen Kish (UNC) established a reputation after a successful field trip in 1975 on the geology of the Blue Ridge. More seasoned researchers have established reputations by repeated field trips in their areas of expertise. Thus, Bob Butler (UNC-CH) served as leader or assistant in '64, '65, '74 and '81 and Don Secor (USC) in '68, '78 and '87. Both are recognized as expert Piedmont geologists.

Encourage Publications

One purpose of the Society is to encourage research and the presentation of results. This includes the annual field trip (Table 3) with the auxiliary guidebook. The history of the Society's guidebooks probably parallels that of guidebooks in general; that is, increasing complexity and costs.

The early guidebooks were nothing more than a few mimeographed pages consisting mostly of a road log and perhaps a very brief description of each locality. The earliest “guidebook” in the files of the Society is that of the second annual meeting held in the Durham-Chapel Hill area on November 6-7, 1937. The leaders were W.F.Prouty (UNC) and Willard Berry (Duke). The guide consists of three mimeographed pages of road log, a page sketch map of the roads, and a generalized geologic map of parts of Orange, Durham, and Wake Counties. The Triassic area was hand-colored in yellow. Other early guides that are in the CGS files are for 1938, 1940, 1948, 1949, 1950, and 1951.

The first fancy guidebook was prepared by Phil King, Jerry Hadley, and Bob Neuman (all from the USGS) for the Great Smoky Mountains trip in 1952. But by today's standards, this book is primitive having 60 mimeographed pages bound in a press board binder with a large blueprint-type black and white map insert. It contains 5 tables, 11 figures, and 2 large maps. This was also the first guidebook sold to the field trip participants.

The guidebooks during the balance of the fifties, the sixties, and the early seventies never quite matched the book by King and others in length and in number of figures and maps. Of course, the printing quality improved and photographs were introduced.

The first multi-article guidebook came in 1961 with two articles, each with its own road log. The authors of each article (J.F. McCauley, USC, and Henry Johnson, SC State Geologist) were also the field trip leaders. The separate articles met the need of really two different field trips. The Saturday portion was in the Piedmont and the Sunday half-day trip was in the Coastal Plain. This was also the first guidebook published in a regular publication series, *Geologic Notes* of the Division of Geology, South Carolina State Development Board. Four other guidebooks were published in this series through 1969. All were single articles except the last one. "A Guide to the Geology of Northwestern South Carolina" by Villard Griffin and Bob Hatcher (Clemson) was the first guidebook with stand-alone articles and separate road log-and-locality descriptions.

The next major change in guidebook style was in 1978. Art Snoke (USC) initiated the first guidebook with invited papers. There were articles on regions not within the guidebook area and authored by some who were not field trip leaders. There are eleven articles on the general subject of eastern Piedmont geology by a total of 22 authors. This was a major change in style and content of a CGS guidebook.

This trend of invited papers continued through 1979 (Coastal Plain of North Carolina with 10 articles and 14 authors), 1980 (Triassic and Piedmont of Central North Carolina and Virginia with 13 articles by 18 authors), 1981 (Kings Mountain Belt of the Carolina with 21 articles by 27 authors), 1982 (Kaolin Mining District of South Carolina with 8 articles by 10 authors), and 1983 (Blue Ridge of Northwestern North Carolina with 8 articles by 15 authors). The largest guidebook ever produced was that for the 2000 meeting. The Savannah River Site guidebook runs 339 pages long containing 18 articles by 37 authors.

The Carolina Geological Society is the technical publisher for CGS guidebooks. They are printed and distributed by other organizations or individuals. In addition, all guidebooks are housed in the Duke University Perkins Library.

In preparation for the 50th anniversary of the Society in 1987, the Board of Directors formed a 50th Anniversary Committee, consisting of Ole Olson (as Chairman), Steve Conrad, Bob Hatcher and Wright Horton. In 1986, the 50th Anniversary Committee decided that a book should be compiled on the geology of the Carolinas. Wright Horton and Victor Zullo agreed to co-edit the book. Steve Conrad and Ole Olson (as State Geologists of North and South Carolina) helped raise $10,700 from various corporations and individuals in the two states to be applied toward publication costs. In addition, the membership contributed $1,000. After many delays, the hardcover book was published by the University of Tennessee Press in 1991. The 406-page volume contains 19 articles on just about every phase of the geology of the Carolinas. It is available for purchase for $50.00 from the North Carolina Geological Survey.

In 1995, the Society made its debut into the digital age with the creation of its first web site. Starting in 1999, a project began to put all of the CGS guidebooks on the web site. Through the concerted effort of dozens of members, all of the Society's guidebooks were scanned and converted into digital files. Today, all guidebooks from 1952 to 2011 (except 2009) are available for free download on the CGS web site.

INCORPORATION

The need for incorporation of the Carolina Geological Society did not arise until the lawsuit that arose out of the 1982 meeting in Aiken, SC. The Heart of Aiken Motel sued Norman K. Olson (SC State Geologist) and CGS for non- payment of rent on twenty motel rooms for two nights. According to the complaint the rooms were reserved in February for use on October 8 and 9. Because the rooms were not used, the Motel demanded payment. Of course the suit was unjustified because the rooms were to be held only up to a week or so before the meeting. If they were unreserved by a specific date, the room reservation was to be canceled. Olson was represented by the State Attorney General and the Society by a Lexington, SC law firm. The magistrates found that Norman K. Olson was acting as an agent for the South Carolina Geological Survey and that magistrate court does not have jurisdiction on a civil action against the State. The judge also ruled that the court did not have jurisdiction against an out-of-state unincorporated association and that Olson was not an officer of the Society or its registered agent. The plaintiff's lawyer did start proceedings for an appeal, but an appeal was never finalized. The cost to the Society for a totally frivolous suit was $250.

It was plain that the Society and its officers might be subject to litigation if an accident were to happen during the course of a field trip. Protection would best be afforded by incorporation and liability insurance. Furthermore, incorporation would allow for application to the IRS for tax-exempt status. Accordingly, the membership approved a motion on October 27, 1984, instructing the Secretary to take the necessary steps for incorporation and tax exemption.

In January 1985, Coralynn Y. Harward, an attorney in Durham, NC, drew up rough drafts of Certificate of Incorporation and By-Laws of the Carolina Geological Society, Inc. The Certificate of Incorporation was modified and signed by the seven incorporators of the Society: Don Secor (USC), Gail Gibson (UNC-Charlotte), Duncan Heron (Duke), Stephen Conrad (NC State Geologist), Norman Olson (SC State Geologist), Wallace Fallaw (Furman), and Kenneth Sargent (Furman). The first three were the current officers of the unincorporated Society and Kenneth Sargent was Chairman of the Membership Committee.

The organizational meeting of the Carolina Geological Society, Inc. was held in Cheraw, SC, on April 13, 1985. Of the seven incorporators, Stephen Conrad and Norman Olson, were absent. The elected officers of the new Society were, Don Secor, President; Gail Gibson, Vice-President; and Duncan Heron, Secretary-Treasurer. The proposed by-laws were modified and then adopted. Eight resolutions were adopted relating to the operation of the Secretary-Treasurer's office, liability insurance, and the annual field trip. President Secor appointed Ken Sargent as Chairman of the Membership Committee and Wally Fallaw as Chairman of the Nominating Committee.

In 1985 the Internal Revenue Service granted the Society federal income tax exemption under section 501(c)(3) of the Internal Revenue Code.

CAROLINA GEOLOGICAL SOCIETY GOVERNANCE

Before incorporation the Society's officers consisted of a President, Vice-President, and Permanent Secretary-Treasurer (as previously explained, the office of Secretary-Treasurer was made permanent during World War II). Up until 1952 the officers were nominated from the floor at the business meeting. In 1952 a nominating committee appointed by the President made the selection. This committee usually functioned on the outcrop during the Saturday field trip. The committee reported to the membership at the business meeting and the slate was elected by acclamation. The spirit of the nominating committee has been to try to rotate the officers between the two states.

The Constitution (1937-1984) of the Society provided for the election of a Chairman of the Membership Committee who is not an officer of the Society. The Chairman was directed to choose one member from each state "represented in the Society to serve as members". In practice the chairman served as the only member of the committee. He solicited names and presented them to the Executive Committee for approval. So far as known only one person has been turned down for membership by the Membership Committee and that was in 1938. No reason was given in the minutes of the Executive Committee. After incorporation, the Chairman of the Membership Committee is appointed by the President.

Since incorporation, the Society's affairs have been managed by a seven-member Board of Directors, elected by the membership at the annual meeting. The officers of the Board are elected by the Board immediately following the annual meeting. These officers, the President, Vice-President, and Secretary-Treasurer automatically remain as Directors of the Society for one year immediately following their term of office. This allows for continuity between boards and means that the membership elects four new Board members each year.

A complete list of all officers and members of the Board of Directors is shown in the attached Appendix B. In 1993, the Society was shocked by the sudden death of President Vic Zullo. Vice-President Steve Kish served out the remainder of Vic Zullo's term of office. There have been only three Secretary-Treasurers during the Society's seventy-five year history, Willard Berry (1937-1965), Duncan Heron, (1966-2009), and Tyler Clark (2010-present).

The by-laws provide for three standing committees: an Executive Committee, a Membership Committee, and a Nominating Committee. The President appoints all committee members except that the President, Vice-President, Secretary-Treasurer and immediate past President are automatically members of the Executive Committee.

The by-laws provide for an annual meeting to be held during the month of September, October, or November. Special called meetings are also possible. Membership in the Society only requires a serious interest in the geosciences.

Membership has increased from the original 43 charter members in 1937 to 363 today. Members reside in 20 states and 1 foreign country (Turkey). Past Secretary-Treasurer

Duncan Heron currently is the Society's longest, continuously-active member, currently in his 61st year as a member of the Carolina Geological Society.

APPENDIX A

Data About Carolina Geological Society Field Trips, 1937-2012

Date	Meeting Place	Trip Title	Leaders & Assistants	Attendance
1937, May 15	Greenville, SC	Geology in the Greenville-Caesars Head area	Wilbur C. Holland	22
1937, Nov. 6-7	Chapel Hill-Durham, NC	Geology in the Chapel Hill, Durham, Raleigh area and the Deep River Coal Field, Glendon Pyrophyllite	W.R. Prouty, E.W. Berry, J.L. Stuckey, H.J. Bryson	40
1938, Nov. 12-13	Columbia, SC	Piedmont and Coastal Plain Geology around Columbia, the Haile Gold Mine	Stephen Taber, L.L. Smith, Julian Petty	58
1939, Oct. 21-22	Spruce Pine, NC	Geology of the Spruce Pine area	B.C. Burgess,W.J. Alexander	70
1940, Oct. 19-20	Charleston, SC	Geology in the Charleston Area, the Santee-Cooper Project	J.H. Watkins, Stephen Taber, W.B. Cormack	52
1941, Nov. 8-9	Asheville, NC	Geology around Ashville	Charles Hunter	42
1946, Nov. 16	Shelby, NC	Kings Mountain Geology	Charles Hunter	54
1947, Oct. 25-26	Clemson, SC	Geology in Clemson, Elberton, Ga., area	F.H.H. Calhoun	65
1948, Oct. 30-31	Chapel Hill, NC	Geology of the Deep River Triassic Basin, pyrophyllite geology	J.A. Reinemund, J.L. Stuckey	70
1949, Nov. 5-6	Myrtle Beach, SC	Geology in the Coastal Plain between Elizabethtown and Myrtle Beach	W.A. White, B.W.Wells	
1950, Oct. 21-22	Albemarle, NC	Geology in the Albemarle area	H.E. LeGrand, W.A. White, J.L. Stuckey	75
1951, Oct. 20-21	Columbia, SC	Basement, Cretaceous, and Eocene Geology, Columbia-Aiken	Stephen Taber, L.L. Smith	50
1952, Nov. 1-2	Gatlinburg, TN	Geology of the Great Smoky Mountains	Phil King, J. Hadley, R. Neuman, R. Goldsmith, W. Hamilton, H. Malde	250
1953, Oct. 24-25	Shelby, NC	Geology of the Shelby area	W.C. Overstreet,P.K. Theobald, Jr., N.P.Cuppels	65
1954, Nov. 6-7	Asheville, NC	Geology in the Spruce Pine area	Charles Hunter	80
1955, Oct. 8-9	Wilmington, NC	Geology of the N.C. Coastal Plain	Harry LeGrand, Phil Brown	60
1956, Oct. 13-14	Gaffney, SC	Geology of the Kings Mountain area	Tom Kesler	100
1957, Nov. 16-17	Florence, SC	Geology of the S.C. Coastal Plain	George Siple	75
1958, Oct. 30-Nov. 1	Orangeburg, SC	Geology of the Basement and Eocene rocks of Central, South Carolina	H.S. Johnson, Jr., L.N. Smith, J.W. Clarke, S.D. Heron, Jr	69
1959, Oct. 24-25	Albemarle, NC	Geology of the Albemarle and Denton Quadrangles	Arvid Stromquist, James F. Conley	115
1960, Oct. 8-9	Morganton, NC	Geology of Grandfather Mountain	Bruce Bryant, John Reed, Jr.	80
1961, Oct. 21-22	Columbia, SC	Geology of Newberry Co. and Geology in the Sand Hills	John McCauley, H.S. Johnson, Jr.	102

1962, Oct. 19-20	Southern Pines, NC	Geology of Moore County	James F. Conley	100
1963, Oct. 26-27	Clemson, SC	Geology of Oconee and Pickens Cos.	Charles Brown, C.J. Cazeau	55
1964, Nov. 7-8	Durham, NC	Geology of the Slate Belt	George L. Bain, E.P. Allen, W.F. Wilson, Robert Butler	65
1965, Oct. 22-23	Rock Hill, SC	Geology of York County	Robert Butler	100
1966, Oct. 22-23	Concord, NC	Geology of Cabarrus County	Harry LeGrand, Henry Bell	124
1967, Oct. 14-15	Abingdon, V	Geology of the Mt. Rogers area	Doug Rankin	100
1968, Oct. 20-21	Columbia, SC	Stratigraphy, Structure and Petrology of the Piedmont in Central South Carolina	Don Secor, H.D.Wagener	100
1969, Oct. 4-5	Clemson, SC	Northwestern South Carolina	V.S. Griffin Jr., R.D. Hatcher, Jr.	125
1970, Oct. 24-25	Danville,V A	Stratigraphy, Sedimentology and Economic Geology of Dan River, North Carolina	Paul A. Thayer, Dewey S. Kirstein, Roy L. Ingram	125
1971, Nov. 13-14	Murphy, NC	Stratigraphy and Structure of the Murphy Belt, North Carolina	W. Robert Power, Joseph Forrest	161
1972, Oct. 7-8	Raleigh, NC	Geology of the Coastal Plain, New Bern to Wake County, North Carolina	R.B. Daniels, E.E. Gamble, W.H. Wheeler, C.S. Holzhey	100
1973, Oct. 13-14	Newberry, SC	Granitic Plutons of the Central and Eastern Piedmont of South Carolina	H.D. Wagener, D. E. Howell	150
1974, Oct. 5-6	Cheraw, SC	Geology of the Piedmont and Coastal Plain near Page- land, SC and Wadesboro, NC	H. Bell, III, R. Butler, D. Howell,W. Wheeler	175
1975, Nov. 8-9	Bryson City, NC	Geology of the Blue Ridge South of the Great Smoky Mountains, North Carolina	S. Kish, C. Merschat, D. Mohr, L. Wiener	260
1976, Oct. 23-24	Clayton, GA	Geology of the Eastern Blue Ridge of the Carolinas and nearby Georgia	Robert D. Hatcher, Jr.	190
1977, Oct. 8-9	Apex, NC	Geology of the Durham Triassic Basin	George L. Bain, Bruce W. Harvey, plus 10 others	209
1978, Oct. 7-8	Columbia, SC	Bedrock Geology of Central South Carolina	Arthur W.Snoke, Don Secor	175
1979, Oct. 20-21	Wrightsville Beach, NC	Structural and Stratigraphic Framework for the Coastal Plain of North Carolina	Gerald R. Baum, W. Burleigh Harris, Victor A. Zullo	208
1980, Oct. 11-12	Danville, VA	Bedrock Geology of South Central Virginia	V. Price, Jr., P.A. Thayer, W.A. Ranson	182
1981, Oct. 24-25	Gaffney, SC	Geological investigations of the Kings Mountain belt and adjacent areas in the Carolinas	J.W. Horton, Jr., J.R. Butler, M. Schaeffer, C. Murphy, John Conner, D Milton	318
1982, Oct. 9-10	Aiken, SC	Geological investigations related to the stratigraphy in the kaolin mining district,	Paul G. Nystrom, Jr., Ralph H. Willoughby	118
1983, Oct. 22-23	Boone, NC	Geologic Investigations in the Blue Ridge of Northwest- ern North Carolina	S. Lewis, M. Bartho- lomew, G. Feiss, G. Gul- ley, J. Monrad, J. Gryta	250
1984, Oct. 27-28	Albemarle, NC	A Stratigrapher's View of the Carolina Slate Belt, South- central North Carolina	Gail G. Gibson, Steven A. Teeter	162
1985, Nov. 16-17	Durham, NC	The Virgilina deformation: implications of stratigraphic correlations in the Slate Belt	Charles W. Harris, Lynn Glover, III	112
1986, Oct. 11-12	Columbia, SC	Cretaceous-Tertiary stratigraphy of the upper edge of the Coastal Plain between North Augusta and Lexington, SC	Paul G. Nystrom, Jr., Ralph H. Willoughby, Lucille E. Kite	118

Date	Meeting Place	Trip Title	Leaders & Assistants	Attendance
1987, Nov. 14-15	Hickory Knob Resort State Park, SC	Anatomy of the Alleghanian orogeny as seen from the eastern Piedmont of SC	Harmon Maher, Paul Sacks, Don Secor	160
1988, Nov. 12-13	Pilot Mountain, NC	Structure of the Sauratown Mountains Window, North Carolina	Keith McConnell, Teunis Heyn, Bob Hatcher	119
1989, Oct. 28-29	Fayetteville, NC	Campanian and Maastrichtian Depositional Systems of the Black Creek Group of the Carolinas	Jim Owens and Norm Sohl	77
1990, Sept. 29-30	Asheville, NC	Geology of Grenville-Age Basement and Younger Cover Rocks in the West Central Blue Ridge, North Carolina	Carl Merschat and Leonard Wiener	114
1991, Nov. 9-10	Murphy, NC	Studies of Precambrian and Paleozoic Stratigraphy in the Western Blue Ridge	Steve Kish and 11 others	240
1992, Nov. 14-15	Savannah River area, SC/GA	Geological Investigations of the Central Savannah River Area, South Carolina and Georgia	Wallace Fallow, Van Price, Walter Sexton	143
1993, Nov. 6-7	Hendersonville, NC	Studies of Inner Piedmont Geology with a Focus on the Columbus Promontory	Timothy Davis and Gregory Yanagihara	301
1994, Nov. 5-6	Raleigh, NC	Geology and Field Trip Guide, Western Flank of the Raleigh Metamorphic Belt, North Carolina	Skip Stoddard and David Blake	282
1995, Oct. 28-29	Greenville, SC	Geology of the Western Part of the Carolina Terrane in Northwestern South Carolina	Allen Dennis, Bob Butler, John Garihan, Bill Ranson, Ken Sargent	233
1996, Nov. 9-10	Onslow Bay, NC	Environmental Coastal Geology: Cape Lookout to Cape Fear, NC	Bill Cleary and Orrin Pilkey	253
1997, Sept. 27-28	Banner Elk, NC	Paleozoic Structure, Metamorphism, and Tectonics of the Blue Ridge of Western North Carolina	Kevin Stewart, Mark Adams, Charles Trupe, Rick Albert, Loren Raymond	261
1998, Nov. 14-15	Columbia, SC	The Carolina Terrane in Northeastern South Carolina: History of an Exotic Volcanic Arc	Don Secor, Chris Barker, Ken Gillon, Langdon Mitchell, Jerry Bartholomew, Bob Hatcher, Martin Balinsky	236
1999, Nov. 6-7	Emporia, VA	Geology of the Fall Zone along the North Carolina - Virginia State Line	Paul Sacks, Skip Stoddard, Rick Berquist, and Clay Newton.	165
2000, Nov. 4-5	Aiken, SC	Environmental Remediation Systems in Unconsolidated Upper Coastal Plain Sediments - Stratigraphic and Structural Considerations	Doug Wyatt and Allen Dennis	147
2001, Oct. 13-14	Greenville, SC	Geology of the Inner Piedmont in the Caesars Head and Table Rock State Parks Area, Northwestern South Carolina	John Garihan and Bill Ranson	192
2002, Oct. 19-20	Morganton, NC	Inner Piedmont Geology in the South Mountains-Blue Ridge Foothills and the southwestern Brushy Mountains, Central-western North Carolina	Bob Hatcher, Joseph Hill, Brendan Bream, Scott Giorgis, Scott Williams, James Kalbas, Arthur Merschat, and Russell Maps	226

Date	Meeting Place	Trip Title	Leaders & Assistants	Attendance
2003, Nov. 14-15	Raleigh, NC	Surficial Geology and Shallow Aquifer System of the Little Contentnea Creek Watershed, Neuse River Basin, North Carolina	Katheleen Farrell, Tyler Clark, Amy Keyworth, Steve Kraemer, and Tim Spruill	99
2004, Nov. 13-14	Charleston, SC	Macroseismic effects of the 1886 Charleston Earthquake	Pradeep Talwani and Michael Katuna	173
2005, Nov. 5-6	Maggie Valley, NC	Blue Ridge Geology Geotraverse East of the Great Smoky Mountains National Park, Western North Carolina	Robert D. Hatcher, Jr. and Arthur J. Merschat	311
2006, Nov. 4-5	Durham, NC	The Geology of the Chapel Hill, Hillsborough and Efland Quadrangles, Orange and Durham Counties, Carolina Terrane, North Carolina	Philip J. Bradley and Timothy W. Clark	264
2007, Nov. 10-11	New Bern, NC	Lee Creek Mine, Aurora, North Carolina : History, Mining Operations, Geology, Stratigraphy, and Paleontology	Lauck W. Ward	195
2008, Nov. 1-2	Little Switzerland, NC	Spruce Pine Mining District, North Carolina	Alex Glover and Kenneth Taylor	255
2009, Nov. 7-8	Columbia, SC	Rifting and Drifting in South Carolina: Fracture History in Alleghanian Granites and Coastal Plain Strata	Mervin J. Bartholomew, Mark A. Evans, Fredrick J. Rich, Brendan M. Brodie, and R. Daniel Heath	115
2010, Sept. 18-19	Charleston, SC	Coastal Processes Field Trip: Kiawah Island, Seabrook Island, and Edisto Beach State Park	Miles O. Hayes, Jacqueline Michel, and Tim Kana	135
2011, Oct. 22-23	Aberdeen, NC	Geology, Natural Gas Potential, and Mineral Resources of Lee, Chatham, and Moore Counties, North Carolina	Timothy W. Clark, Kenneth B. Taylor, and Philip J. Bradley	209
2012, Oct. 13-14	Greenville, SC	Geology of Upstate South Carolina in the Vicinity of Caesars Head and Keowee-Toxaway State Parks	Jack Garihan, Bill Ranson, Suresh Muthukrishnan, Jay Bridgeman, Tom Goforth	

APPENDIX B

Officers and Board Members of the Carolina Geological Society 1937-2012

1937
W.C. Holland (P) - Furman University
Berlin C. Moneymaker (VP) -TVA
E. Willard Berry (S-T) – Duke University

1938
H.W. Straley (P) - UNC
B.C. Burges (VP) - Tennessee Mineral Products
E. Willard Berry (S-T) – Duke University

1939
L.L. Smith (P) – USC
J.H. Watkins (VP) - Citadel
E. Willard Berry (S-T) – Duke University

1940
J.H. Watkins (P) - Citadel
W.H. Alexander (VP) - Bryson City, NC
E. Willard Berry (S-T) – Duke University

1941
G.W. Crickmay (P) - Univ. of GA
R.G. Grassy (VP) - USDA-SCS E.
Willard Berry (S-T) – Duke University

1942
R.G. Grassy (P) - USDA-SCS
E. Willard Berry (S-T) – Duke University

1946
J.W. Huddle[1] (P) – UNC
E. Willard Berry (S-T) – Duke University
[1]Acting President after Grassey withdrew owing to war work.

1947
J.L. Stuckey (P) - NC State
W.B. Cormack (VP) - USC
E. Willard Berry (S-T) – Duke University

1948
B.F. Buie (P) – USC
Mitchel H. Klein (VP) - Bureau of Mines
E. Willard Berry (S-T) – Duke University

1949
J.M. Parker, III (P) - NC State
C.E. Hunter (VP) - TVA
E. Willard Berry (S-T) – Duke University

1950
G.R. Graham (P) – USC
E.L. Miller, Jr. (VP) - NC State
E. Willard Berry (S-T) – Duke University

1951
G.R. MacCarthy (P) – UNC
W.H. Swanson (VP) - USC
E. Willard Berry (S-T) – Duke University

1952
Stephen Taber (P) – USC
Sam D. Broadhurst (VP) - NC Survey
E. Willard Berry (S-T) – Duke University

1953
Sam D. Broadhurst (P) - NC Survey
Virgil I. Mann (VP) - UNC
E. Willard Berry (S-T) – Duke University

1954
George Siple (P) – USGS
S.D. Heron, Jr. (VP) - Duke
E. Willard Berry (S-T) – Duke University

1955
S.D. Heron, Jr. (P) – Duke
W.J. Dukes (VP) - Augusta, GA
E. Willard Berry (S-T) – Duke University

1956
Roy L. Ingram (P) – UNC
E.S. Perry (VP) - USC
E. Willard Berry (S-T) – Duke University

1957
Harry LeGrand (P) – USGS
O.F. Stewart (VP) - Zonolite
E. Willard Berry (S-T) – Duke University

1958
Thomas L. Kesler (P) - Foote Mineral
Henry S. Johnson, Jr. (VP) - SC Survey
E. Willard Berry (S-T) – Duke University

1959
Henry S. Johnson, Jr. SC Survey
Walter Wheeler (VP) - UNC
E. Willard Berry (S-T) – Duke University

1960
Owen Kingman (P) - Tennessee Copper Co.
John F. McCauley (VP) - USC
E. Willard Berry (S-T) – Duke University

1961
John F. McCauley (P) – USC
Virgil I. Mann (VP) - UNC
E. Willard Berry (S-T) – Duke University

1962
Virgil I. Mann (P) – UNC
Charles Q. Brown (VP) - Clemson
E. Willard Berry (S-T) – Duke University

1963
Charles Q. Brown (P) – Clemson
Steve Conrad (VP) - NC Survey
E. Willard Berry (S-T) – Duke University

1964
Henry Brown (P) - NC State
George Siple (VP) - USGS
E. Willard Berry (S-T) – Duke University

1965
Donald Secor (P) – USC
Robert Butler (VP) - UNC
E. Willard Berry (S-T) – Duke University

1966
George Bain (P) – USGS
Bruce Nelson (VP) - USC
S.D. Heron, Jr. (S-T) – Duke

1967
William J. Furbish (P) – Duke
Marcie Magee (VP) - TN Copper Co.
S.D. Heron, Jr. (S-T) – Duke

1968
John Carpenter (P) – USC
David Dunn (VP) - UNC
S.D. Heron, Jr. (S-T) – Duke

1969
David Dunn (P) – UNC
Villard Griffin (VP) - Clemson
S.D. Heron, Jr. (S-T) – Duke

1970
Steve Conrad (P) - NC Survey
Ed Sharp (VP) - USC
S.D. Heron, Jr. (S-T) – Duke

1971
Ole Olson (P) - SC Survey
Walter Wheeler (VP) - UNC
S.D. Heron, Jr. (S-T) – Duke

1972
Walter Wheeler (P) – UNC
H.D. Wagener (VP) - Chiasma Consul.
S.D. Heron, Jr. (S-T) – Duke

1973
H.D. Wagener (P) - Chiasma Consul.
Charles Welby (VP) - NC State
S.D. Heron, Jr. (S-T) – Duke

1974
Paul Fullagar (P) – UNC
Robert Hatcher (VP) - Clemson
S.D. Heron, Jr. (S-T) – Duke

1975
Robert Hatcher (P) – Clemson
Jay Leith (VP) - NC State
S.D. Heron, Jr. (S-T) – Duke

1976
Jay Leith (P) – NC State
Charles J. Cazeau (VP) - Clemson
S.D. Heron, Jr. (S-T) – Duke

1977
Dave Snipes (P) – Furman
Neil Gilbert (VP) - Law Engineering
S.D. Heron, Jr. (S-T) – Duke

1978
Eldon Allen (P) - NC Survey
Wally Fallaw (VP) - Furman
S.D. Heron, Jr. (S-T) – Duke

1979
Art Snoke (P) – USC
Bob Lemon (VP) - UNC-C
S.D. Heron, Jr. (S-T) – Duke

1980
Bob Butler (P) – UNC
Van Price (VP) - E. I. DuPont
S.D. Heron, Jr. (S-T) – Duke

1981
Dick Chalcroft (VP) - College of Charleston
Malcom Shaeffer (VP) - Duke Power Co.
S.D. Heron, Jr. (S-T) – Duke

1982
Wright Horton (P) – USGS
Ed Sharp (VP) - USC
S.D. Heron, Jr. (S-T) – Duke

1983
Wally Fallaw (P) – Furman
John Chapman (VP) - Western Carolina
S.D. Heron, Jr. (S-T) – Duke

1984
Ed Burt (P) - NC Survey
Mike Katuna (VP) - College of Charleston
S.D. Heron, Jr. (S-T) – Duke

Society Incorporation in 1985
(first year w/ seven-member Board of Directors)

1985
Don Secor (P) – USC
Gail Gibson (VP) - UNC-C
S.D. Heron, Jr. (S-T) – Duke
Stephen Conrad, Wally Fallow
Norman Olson, Ken Sargent

1986
Gail Gibson (P) - UNC-C
Alexander Ritchie (VP) - College of Charleston
S.D. Heron, Jr. (S-T) – Duke
Neil Gilbert, Paul Nystrom,
Don Secor, Walter Wheeler

1987
Alexander Ritchie (P) - College of Charleston
Edward Stoddard (VP) - NC State
S.D. Heron, Jr. (S-T) – Duke
James Dockal, Gail Gibson,
Kenneth Gillan, Lucille Kite

1988
Kenneth Gillon (P) - Amselco Exploration
Jim Dockal (VP) - UNC-W
S.D. Heron, Jr. (S-T) – Duke
Bruce Idleman, Lee Mitchell, Alexander Ritchie
Edward Stoddard, Wayne Wilkinson

1989
Edward Stoddard (P) - NC State
Lee Mitchell (VP) - SC Water Resources Com.
S.D. Heron, Jr. (S-T) – Duke
Jim Dockal, Ken Gillon,
Jack Whisnant, Ralph Willoughby

1990
Lee Mitchell (P) - SC Water Resources Comm.
Jack Callahan (VP) - Appalachian State
S.D. Heron, Jr. (S-T) – Duke
Bruce Campbell, Geoffery Feiss,
E. F. Stoddard, Ralph Willoughby

1991
Jack Callahan (P) - Appalachian State
Paul Nystrom (VP) - SC State Survey
S.D. Heron, Jr. (S-T) – Duke
Donald Hathaway, Bill Hoffman,
Lee Mitchell, Victor Zullo

1992
Paul Nystrom (P) - SC State Survey
Victor Zullo (VP) - UNC Wilmington
S.D. Heron, Jr. (S-T) – Duke
Suellen Cabe, John Callahan,
Bill Hoffman, Van Price

1993
Steve Kish[2] (P) - Florida State
S.D. Heron, Jr. (S-T) – Duke
Suellen Cabe, Charles Clymer, Sharon Lewis,
Paul Nystrom, Van Price
[2]VP replaced Vic Zullo, deceased in office.

1994
Sharon Lewis (P) – SRC
Charles Clymer (VP) - AT&E
S.D. Heron, Jr. (S-T) – Duke
Fred Beyer, Jr., Andy Bobyarchick,
Irene Boland, Steve Kish

1995
Fred C. Beyer, Jr. (P) - Fayetteville Schools
Ralph Willoughby (VP) - SC Geological Survey
S.D. Heron, Jr. (S-T) – Duke
Jim Hibbard, Sharon Lewis,
William A. Pirkle, Ralph Willoughby

1996
Ralph Willoughby (P) - SC Geological Survey
Charles Gardner (VP) - NC State Geologist
S.D. Heron, Jr. (S-T) – Duke
Fred Beyer, Jr., Allen Dennis,
Geoff Feiss,

1997
Sue Ellen Cabe (P) - UNC – Pembroke
Allen Dennis (VP) - USC - Aiken
S.D. Heron, Jr. (S-T) – Duke
Dave Blake, Charles Gardner,
Dennis LaPoint, Ralph Willoughby

1998
Allen Dennis (P) - USC – Aiken
Dennis LaPoint (VP) - Chapel Hill
S.D. Heron, Jr. (S-T) – Duke
Dave Blake, Irene Boland,
Suellen Cabe, Dave Willis

1999
Dennis LaPoint (P) - Appalachian Resources
Dave Willis (VP) - Geraghty & Miller, Inc.
S.D. Heron, Jr. (S-T) – Duke
Allen Dennis, Bill Miller,
Don Privett, Ed Sharp

2000
Bill Ranson (P) - Furman University
Kevin Stewart (VP) - UNC-CH
S.D. Heron, Jr. (S-T) – Duke
Jim Furr, Dennis LaPoint,
Joe McMurray, Dave Willis

2001
Kevin Stewart (P) - UNC-CH
Neil Gilbert (VP) - Zapata Engineering
S.D. Heron, Jr. (S-T) – Duke
James Castle, Barbara Christian,
Dave Lown, Bill Ranson

2002
Neil Gilbert (P) - Zapata Engineering
Randy Cumbest (VP) - Westinghouse SRS
S.D. Heron, Jr. (S-T) – Duke
Jim Hibbard, Bill Powell,
Kevin Stewart, Doug Wyatt

2003
Randy Cumbest (P) - Westinghouse SRS
John Dennison (VP) - UNC-Chapel Hill
S.D. Heron, Jr. (S-T) – Duke
Neil Gilbert, Alex Glover,
Jim Hibbard, Bill Powell

2004
John Dennison (P) - UNC-CH
Irene Boland (VP) - Winthrop Univ
S.D. Heron, Jr. (S-T) – Duke
Randy Cumbest, Alex Glover,
Bill Powell, Frank Syms

2005
Ireland Boland (P) - Winthrop Univ.
Alex Glover (VP) - Zemex Industrial Minerals
S.D. Heron, Jr. (S-T) – Duke
Andy Bobyarchick, Tyler Clark,
John Dennison, Charles Trupe

2006
Alex Glover (P) - Zemex Industrial Minerals
Charles Trupe (VP) - Georgia Southern University
S.D. Heron, Jr. (S-T) – Duke
Andy Bobyarchick, Irene Boland,
Tyler Clark, Richard Wooten

2007
Charles Trupe (P) - Georgia Southern University
Rick Wooten (VP) - NC Geological Survey
S.D. Heron, Jr. (S-T) – Duke
Mike Armour, Andy Bobyarchick,
Bruce Campbell, Alex Glover

2008
Richard Wooten (P) - NC Geological Survey
Mike Armour (VP) - Shield Engineering
S.D. Heron, Jr. (S-T) – Duke
Andy Bobyarchick, Phil Bradley
Scott Howard, Charles Trupe

2009
Mike Armour (P) - Shield Engineering
Andy Bobyarchick (VP) - UNC-Charlotte
S.D. Heron, Jr. (S-T) – Duke
Phil Bradley, Scott Howard,
Mike Waddell, Richard Wooten

2010
Andy Bobyarchick (P) - UNC-Charlotte
Phil Bradley (VP) – NC Geological Survey
Tyler Clark (S-T) - consultant
S.D. Heron, Jr., Scott Howard,
Bill Ranson, Mike Waddell

2011
Phil Bradley (P) – NC Geological Survey
Scott Howard (VP) – SC Geological Survey
Tyler Clark (S-T) - consultant
Andy Bobyarchick, Bill Ranson,
Mike Waddell, Paul Johnstone

2012
Scott Howard (P) – SC Geological Survey
Mike Waddell (VP) – Univ. of South Carolina
Tyler Clark (S-T) – Wake Tech Community College
Phil Bradley, Bill Ranson,
Paul Johnstone, Angela Frizzell

GEOLOGY OF THE LOW-GRADE METAMORPHIC TERRANE IN NORTHERN SUNSET AND SOUTHERN EASTATOE GAP QUADRANGLES, GREENVILLE AND PICKENS COUNTIES, SOUTH CAROLINA

John M. Garihan, Earth and Environmental Sciences Department, Furman University, Greenville, SC 29613

INTRODUCTION

The purpose of the 2012 Carolina Geological Society Meeting is to celebrate its seventy-fifth anniversary and to showcase the geology in upstate South Carolina where the Society was originally founded. The Annual Field Trip will visit the historic Hagood Mill in Pickens County and view exposures of gneiss and metagabbro below a Piedmont thrust. Petroglyphs are well preserved at this site.

We will also examine the low-grade metamorphic rocks along a transect through the northern Sunset quadrangle, South Carolina (Fig. 1). The Saturday field trip will highlight the lithostratigraphic and structural relationships in the area of the Henderson Gneiss (Early Ordovician), Chauga River Formation (Cambrian to Lower Ordovician?), Poor Mountain Formation (Middle Ordovician), and the Table Rock gneiss (Middle Ordovician) (ages of Hatcher, 2002; Ranson and others, 1999). Within the field trip region, the Chauga River Formation contains button schist, metasiltstone, and metasandstone; the Poor Mountain Formation comprises amphibolite, schist, and metaquartzite; and Henderson Gneiss has a variably developed mylonitic fabric that preserves K-feldspar augen of different shapes and dimensions. As a result of polyphase folding, the individual thickness of each unit is unknown.

An important regional ductile thrust not visited on previous trips, the Eastatoee fault, will be described and examined at Dug Mountain. We also will visit an ultramafic body in Oconee County. The direct relationship between plant communities and soil chemistry related to rock lithology will be described along the transect. On Sunday we will visit geologic features and recent landslides in the vicinity of Jones Gap State Park.

REGIONAL GEOLOGIC RELATIONSHIPS

The regional structural framework of northwest South Carolina southeast of the Brevard fault zone (Fig. 2) involves a series of overlapping, northwest to

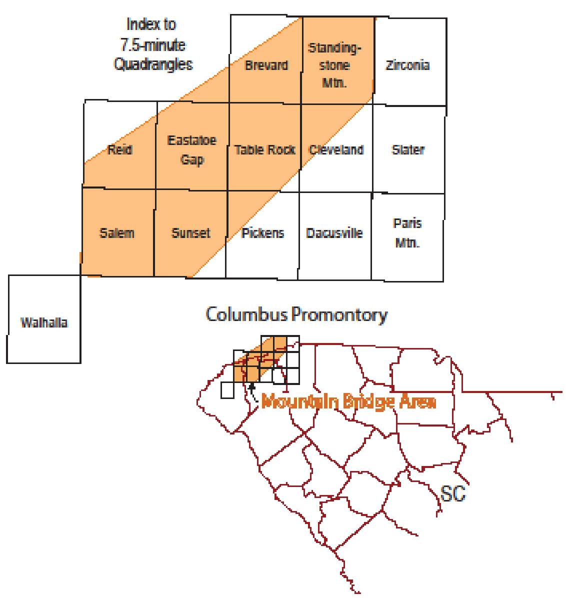

Figure 1. Index to 7.5-minute quadrangles of the Mountain Bridge Area.

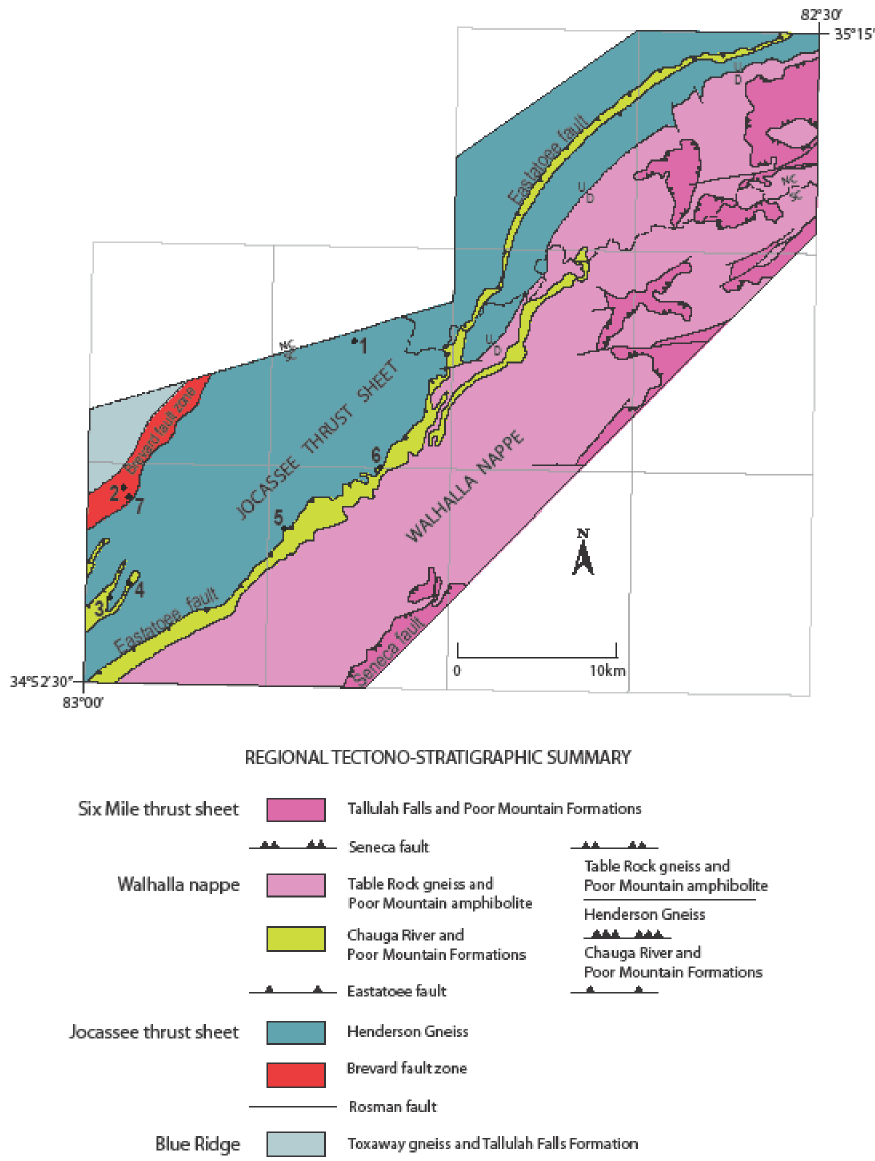

Figure 2. Regional tectono-stratigraphic summary, northwest South Carolina and adjacent North Carolina. Quadrangles are identified in Fig. 1.

southwest-emplaced thrust sheets (Griffin, 1971, 1978; Hatcher, 1972, 1993; Nelson and others, 1998; Merschat and others, 2005). Several versions of the Greenville 1°X 2° sheet covering the area were compiled and updated by the U. S. Geological Survey. These Inner Piedmont compilations emphasized the regional stacking of crystalline thrust sheets – each with its own lithostratigraphy and separated from the next by a fault at its base (Nelson and others, 1987, 1998; Horton and Dicken, 2001, and references therein). The bounding fault of each thrust sheet was proposed to be a ductile fault.

Each thrust sheet involves deformation of Early-Middle Paleozoic-age greenschist- or amphibolite-grade metasedimentary and meta-igneous rocks. Between Oconee and Greenville Counties, South Carolina, and in nearby Henderson and Transylvania Counties, North Carolina, the thrust stack sequence was originally referred to as the non-migmatitic Chauga belt (the lower grade part of the Inner Piedmont, according to Hatcher, 1972), the migmatitic Walhalla nappe (a fold-related thrust, according to Hatcher and Hooper, 1992), the amphibolite grade Six Mile thrust sheet (with the Seneca fault at its base), the Star nappe, and the Antreville nappe (Griffin, 1969, 1971, 1974a, 1974b). This sequence, northwest to southeast, was stacked structurally lowest to structurally highest, respectively. A relative order of thrust emplacement is not implied here. Hatcher (2002, and references therein) provided a summary of Inner Piedmont regional lithostratigraphic and structural relationships, and an interpretation of regional stratigraphic relationships of the Tallulah Falls, Chauga River, and Poor Mountain Formations between the Eastern Blue Ridge, Brevard Zone, Chauga belt, and North Carolina Western Inner Piedmont (Fig. 2-2, p. 31). In it a Middle Ordovician unconformity is recognized at the base of the Poor Mountain Formation.

In Walhalla 7.5-minute quadrangle (southwest of the Salem quadrangle, Fig. 1), Griffin (1974b, see his Plate 2 cross sections) mapped a series of complexly folded, non-migmatitic rocks. Structural relations indicated that Henderson Gneiss is preserved in cores of major overturned folds beneath the Chauga River Formation (Griffin (1974b). Hatcher (1969) had previously described the stratigraphic relationships and structures within the Chauga belt. In contrast to Griffin (1974b), he recognized significant faults within the Chauga belt, including those that emplaced Chauga River Formation rocks over Henderson Gneiss (Hatcher, 1969, see his Fig. 6 cross section). The Stumphouse Mountain fault is a "major high temperature thrust and strike-slip fault" in the South Carolina Chauga belt (Hatcher, 2002, p. 3). In the area west of Walhalla, South Carolina, Bobyarchick and others (1987) concluded that the original regional structural-stratigraphic succession was Henderson Gneiss above an early thrust fault, which emplaced that Henderson Gneiss over the Chauga River Formation. In their interpretation, the lithostratigraphic order of units was subsequently re-worked by Brevard zone faulting.

In Salem quadrangle outside the Brevard fault zone (Fig. 1), Hatcher and Acker (1984) interpreted the Chauga River Formation-Henderson Gneiss contact as an early pre-metamorphic fault that emplaced Henderson Gneiss over the Chauga River Formation. Northwest-verging overturned folds subsequently deformed that fault relationship. Hence, in localities such as on Smeltzer Mountain (Fig. 2, locality 4 of Garihan and Clendenin, 2007) where the Henderson Gneiss lies beneath Chauga River Formation rocks, the mapped relations presumably were interpreted as the overturned limb of an antiformal isocline (Hatcher and Acker, 1984). We suggest here a different interpretation for this type of structure.

Farther to the east in the rugged Inner Piedmont Columbus Promontory area in western North Carolina, Davis (1993) described Poor Mountain Formation and rocks of the Sugarloaf Mountain thrust sheet. Garihan (2001) demonstrated that the Sugarloaf Mountain thrust is the northeastern lateral continuation of the Seneca thrust at the base of the Six Mile thrust sheet in South Carolina. The Six Mile thrust sheet was emplaced over Walhalla nappe Henderson Gneiss along the knife-edge sharp, subhorizontal Seneca fault (Lemmon and Dunn, 1973; Davis, 1993). Both Davis (1993, in North Carolina) and Garihan (2002, in South Carolina) have interpreted the grain-size reduction in the footwall of the Seneca fault as the result of ductile deformation. Mica button schist and coarse-crystalline biotite gneiss are seen immediately above the Seneca fault (Griffin, 1974a; Garihan, 2005a, 2005b). In older studies, Griffin (1974b) described the Seneca fault as a tectonic slide (see discussion of this term by Fleuty, 1964), as he did the Chauga belt-Walhalla nappe boundary below it. In general, features associated with the Seneca fault (Garihan, 2001) provided insight into understanding the Eastatoee fault (Garihan and Clendenin, 2007).

GEOLOGY OF THE FIELD TRIP REGION

The sequence of map units in southern Salem (Clendenin and Garihan, 2007), northwest Sunset (Garihan, 2005a), and southeast Eastatoe Gap (Garihan and others, 2005) quadrangles (Fig. 1) is, northwest to southeast, Henderson Gneiss, Chauga River Formation, Poor Mountain Formation, and Table Rock gneiss (Fig. 3). Regional foliation

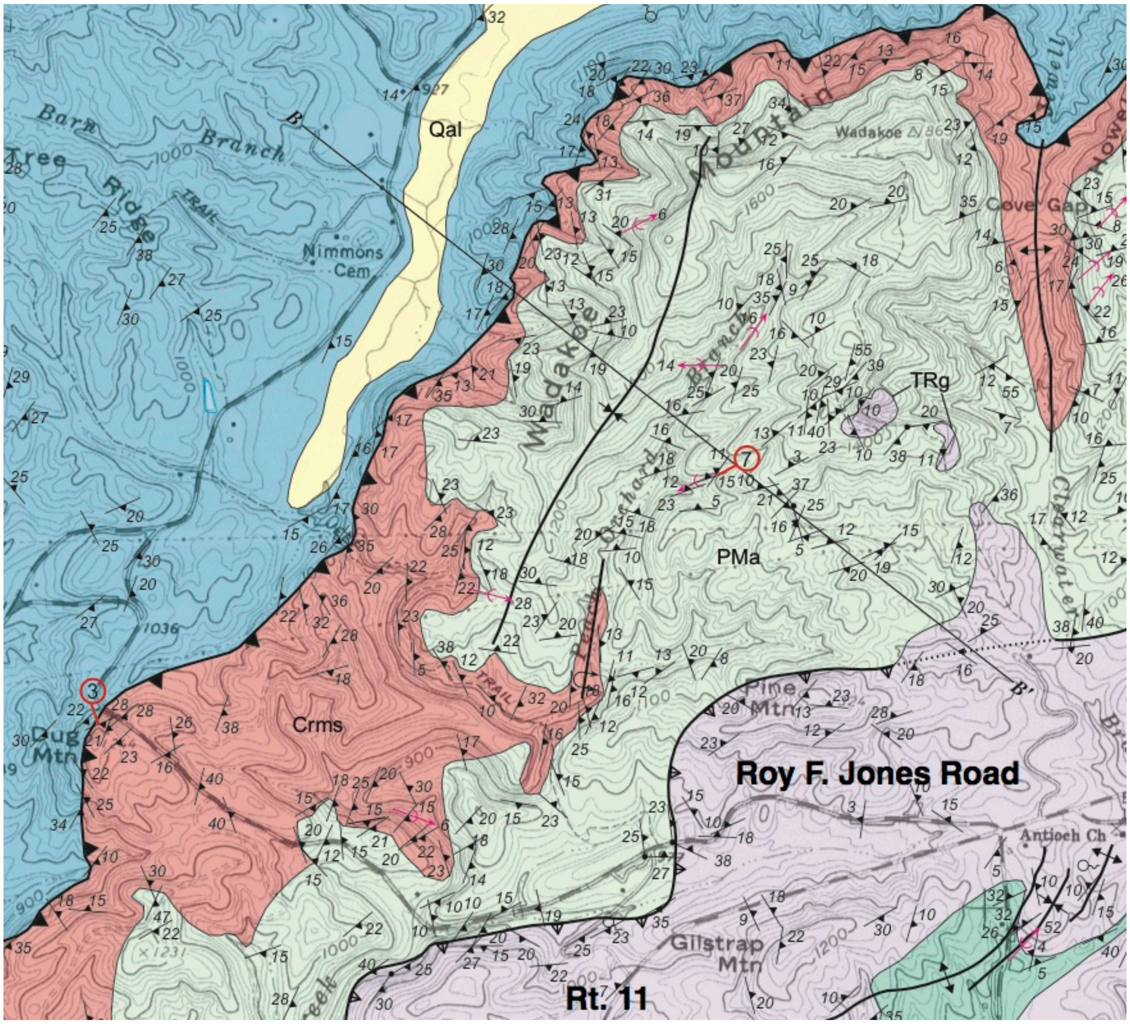

Figure 3. Geologic map of a portion of Sunset quadrangle. HGn (blue)- Henderson Gneiss; PMa- Poor Mountain Formation; PMp- Poor Mountain phyllonite; Crms- Chauga River Formation; Trg (pink)- Table Rock gneiss.

surfaces, although polyphase folded, generally dip to the southeast. Hence, Henderson Gneiss lies at the bottom and Table Rock at the top of the panel of rock that we will transect of the field trip.

Farther northeast in the Table Rock (Garihan and Ranson, 2001), Brevard (Cattanach and Bozdog, 2011), and Standingstone Mountain (Garihan and Ranson, 2002) quadrangles, the Chauga River Formation outcrop belt is flanked on both sides by Henderson Gneiss (Fig. 2). The Chauga River Formation in these latter three quadrangles is separated on its flanks from Henderson Gneiss by either 1) the Eastatoee thrust and another unnamed thrust, or 2) by the Eastatoee fault folded along with overlying Chauga River rocks into a laterally continuous, northwest-vergent, overturned, essentially non-plunging synform.

THE EASTATOEE FAULT

Our geologic mapping in the Sunset and Eastatoe Gap quadrangles (Garihan 2005; Garihan and others, 2005) is the basis for our subdivision of the western Inner Piedmont thrust stack into (northwest to southeast) the Jocassee, Walhalla, and Six Mile thrust sheets. Individual formations that are present on each thrust sheet are given in the regional tectono-stratigraphic summary of Figure 2. The ductile Eastatoee fault (Garihan and Clendenin, 2007) and the Seneca fault (Garihan, 2001 and references therein) lie, respectively, at the base of the Walhalla nappe and the base of the structurally higher Six Mile thrust sheet. Observations show that the Eastatoee fault is marked by a deformation style similar to the Seneca fault at the base of the Six Mile thrust sheet (Fig. 2). That is, progressive ductile deformation along both resulted in grain size reduction, shearing, and flattening fabrics. Those similarities led to the recognition that the Eastatoee fault is another of the major ductile structures that assembled the western Inner Piedmont. In Sunset quadrangle, the Eastatoee fault is exposed in saprolite at Dug Mountain (Fig. 4;

location 5 on Fig. 2), on the northwest flank of Horse Mountain (Fig. 5), and along Rt. 178 south of Beasley Gap (Fig. 6).

Figure 4. Henderson Gneiss–Chauga River Formation fault contact at Dug Mountain, Sunset quadrangle. Eastatoee fault contact is above and parallel to the pencil, between interlayered dark schist-metasiltstone and gray, fine-crystalline (grain-size reduced) gneiss. The rocks are saprolitic. View to southeast.

Figure 5. Eastatoee fault (above hammer) at contact between dark micaceous siltstone of the Chauga River Formation and gray Henderson Gneiss, northwest flank of Horse Mountain. View to the south.

Figure 6. The Eastatoee fault exposed along Rt. 178, south edge of Eastatoe Gap quadrangle. Fault is at hammer. Grain-size reduced Henderson Gneiss below and schistose metasiltstone of the Chauga River Formation above fault. View to northeast.

The identification of the Eastatoee fault expands the spatial distribution and lithostratigraphic character of the Walhalla nappe. The identification re-assigns the Chauga River Formation rocks of the Chauga belt above the fault to the Walhalla nappe. Hence the Walhalla nappe encompasses the thrusted rock package between the Eastatoee fault at its base and the overlying Seneca fault marking the base of Six Mile thrust sheet. The Jocassee thrust sheet is underlain by Henderson Gneiss here and in the Salem and Reid quadrangles. Excellent exposures of the Eastatoee fault there are found along the shores of Lake Jocassee (See Clendenin and Garihan paper, this volume) and Sharp Top Mountain in Sunset quadrangle (Fig. 7).

Figure 7. Imbricated Eastatoee thrust, Sharp Top Mountain. Hammerhead lies on Eastatoee thrust, between light gray Henderson Gneiss and darker Chauga River Formation rocks above. Both units are duplicated by an imbricate thrust.

A summary of information derived from Appalachian Deep Core Investigation Hole 2 (ADCOH-2), cored in the Brevard fault zone of northwest South Carolina and nearby North Carolina, indicates the fault that we interpret as the Eastatoee was encountered twice in the subsurface (O'Hara and Becker, 2004, and references therein). Their illustration of the lithologies encountered in ADCOH-2 (their Fig. 2, p. 568) shows the Chauga River Formation over Henderson Gneiss at 39.6 m and 167.6 m depth. They recognize the contacts as faults. In addition, the cross section A-A' of the bedrock geologic map of Holly Springs quadrangle by Hatcher and Liu (2001) shows a thrust at the Henderson Gneiss-Chauga River Formation contact in the core of a prominent sheath fold affecting garnet-staurolite grade rocks. This presumably also is the Eastatoee fault. Hence the Eastatoee is a regionally significant Inner Piedmont ductile thrust.

This discussion of the Eastatoee fault certainly does not rule out occurrences where Henderson Gneiss is thrust over rocks in the lower metamorphic grade terrane. Hatcher (2004), for example, described Henderson Gneiss thrust over Poor Mountain Quartzite along US 76 west of Westminster, South Carolina.

THE POOR MOUNTAIN-TABLE ROCK GNEISS CONTACT

The contact between the Chauga belt and the structurally overlying Walhalla nappe (cored in part by Table Rock gneiss) has been described as a metamorphic gradient and as a fault (Hatcher, 2004). In southwest Sunset quadrangle, the smoothly curving Poor Mountain Formation-Table Rock gneiss contact is interpreted to be an out-of-the-core thrust produced as a result of the tight folding in the core of a tight, northwest-vergent, overturned synform located just southeast of the thrust trace (See Garihan, 2005a, cross section B-B'). This fault at the Poor Mountain-Table Rock intersection is present but not exposed along our transect.

Elsewhere the trace of the Poor Mountain Formation-Table Rock gneiss contact is highly digitated, indicating an intrusive relationship. Table Rock gneiss there intruded the Chauga River Formation schist and metasiltstone (see Fig. 3, in the area west of Clearwater Branch, tracing the Table Rock-Poor Mountain amphibolite contact).

GEOLOGY OF THE BEASLEY GAP AREA

Chauga River Formation rocks and Poor Mountain Formation amphibolite in southeastern Eastatoe Gap quadrangle in the Beasley Gap-Horse Mountain area are thrust over Henderson Gneiss along the Eastatoee Fault (Fig. 5). Parallel to the Eastatoee is a northeast-striking brittle fault with reverse motion that displaces it (Fig. 8). A third set of faults with northwest strikes offsets both prominent northeast faults.

Intrusive and structural relationships in southeastern Eastatoe Gap quadrangle suggest a complex geologic history. Map patterns of the Chauga River, Poor Mountain, and Table Rock units indicate polyphase folding and intrusion (Fig. 3). In general, the early development of macroscopic folds in Chauga River and Poor Mountain rocks was interrupted by the intrusion of an irregular granitic body of the Mid-Ordovician Table Rock Plutonic Suite (Ranson and others, 1999). The irregular Table Rock intrusive contacts are markedly discordant to the formation contact between the Chauga River and Poor Mountain rocks. Subsequently the Table Rock gneiss and earlier folds in the two formations were tightly flattened into a system of northeast-trending, northwest-vergent isoclines and subjected to high-grade metamorphic conditions. Regional structural relationships, southwest-directed sheath folds, and gently plunging stretching lineations of northeast and southwest trends in the area suggest this took place in the Neoacadian (late Devonian to Mississippian) (Hatcher and Merschat, 2006). Transposition schistosity in the Chauga River rocks (Fig. 9) presumably dates from this deformational episode. Southeast of Beasley Gap, a possible klippe of Six Mile thrust sheet rocks is mapped lying above Chauga River and Poor Mountain rocks (Garihan and others, 2005). The tightly flattened system of northeast-trending, northwest-vergent isoclines was broadly folded along easterly trends subsequent to their development.

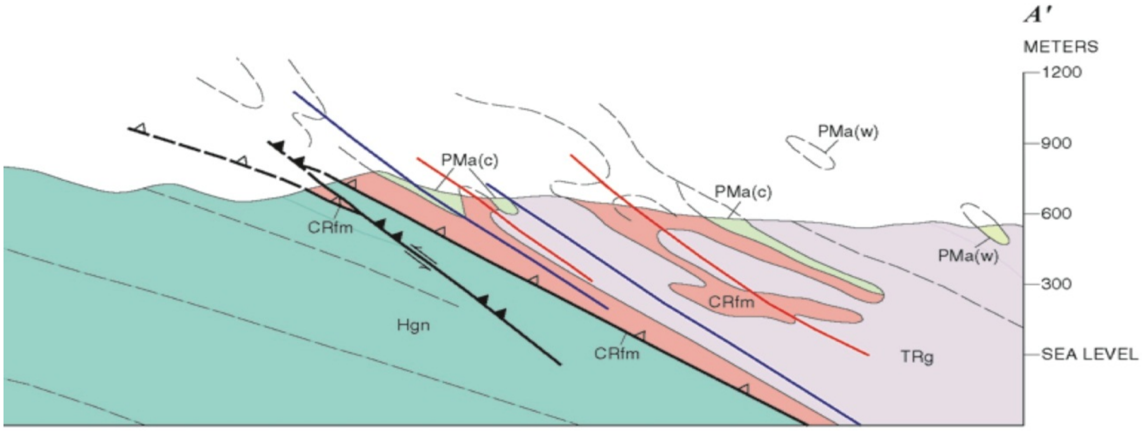

Figure 8. Cross section through Horse Mountain, southeast Eastatoe Gap quadrangle. Eastatoee fault with open saw tooth thrust symbol. Later thrust double closed sawtooth symbol. Map labels: Hgn- Henderson Gneiss; CRfm- Chauga River Formation; PMa(c), PMa(w)- Poor Mountain Formation; TRg- Table Rock gneiss. (From Garihan and others, 2005, cross section A-A').

Figure 9. Lenticular inclusion of epidote hornblende gneiss enveloped by regional S_2 schistosity (Hatcher, 1993) of button schist, Chauga River Formation, Horse Mountain. Note early tight folds of internal compositional layering are truncated by the surrounding transposing (secondary) schistosity, parallel to pencil.

GEOLOGY OF THE WADAKOE MOUNTAIN-COVE GAP REGION

Excellent exposures of rocks of the Chauga River and Poor Mountain Formations occur in northwest Sunset quadrangle in the Wadakoe Mountain-Cove Gap region (Fig. 3 and 10). Amphibolite and lesser garnet-muscovite-quartz phyllonite occur on Wadakoe Mountain (1,865 ft elev.) and along Peach Orchard Branch on its southeast flank. The amphibolite exposure belt is at its widest, about 2 km, between the latter and Winnie Branch (Garihan, 2003). Wadakoe Mountain is centered near the core of a large synform of Poor Mountain amphibolite. An open, north-trending antiform underlies Cove Gap. Structural relationships of the rock units and the associated folds, and the Eastatoee fault are shown in the cross section A-A' (Fig. 10).

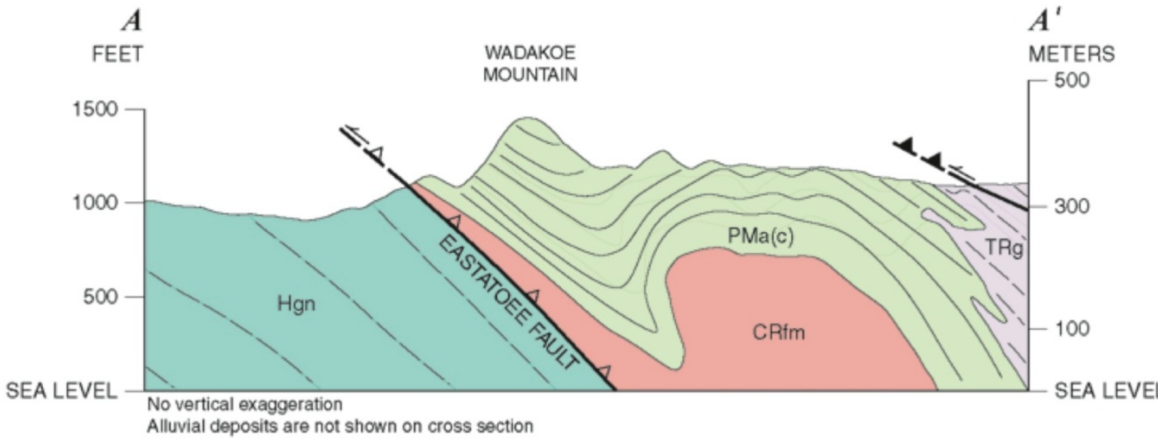

Figure 10. Cross section through the Wadakoe Mountain-Cove Gap area, northwest Sunset quadrangle. Intrusive relationship shown on right side. HGn- Henderson Gneiss; CRfm- Chauga River Formation; PMa(c)- Poor Mountain Formation; TRg- Table Rock gneiss. Wadakoe Mountain. (From Garihan, 2005, A-A'). This cross section is labeled B-B' on Fig.3)

DESCRIPTION OF ROCK UNITS
Walhalla Thrust Sheet
Poor Mountain Formation amphibolite. (Middle Ordovician)

Resistant amphibolite and minor interlayered metasiltstone, schist, and garnet-muscovite-quartz phyllonite occur in a belt of variable width from Lake Keowee (southwest Sunset quadrangle) to the southeast flank of Horse Mountain (southeast Eastatoe Gap quadrangle). Excellent exposures of amphibolite occur on Wadakoe Mountain and along Peach Orchard Branch on its southeast flank. Amphibolite occurs at Wadakoe Mountain (1,865 ft elev.) and in the area between Peach Orchard Branch and Winnie Branch, where the amphibolite exposure belt is at its widest (Garihan, 2003). Petrography indicates that amphibolites near Wadakoe Mountain were metamorphosed to the epidote amphibolite facies of metamorphism (Prince and Ranson, 2004). Contacts with Table Rock gneiss are sharp, whether intrusive and modified by folding or faulted.

Amphibolite is mafic, fine-crystalline, and thinly layered with leucocratic, fine- to coarse-crystalline pods and layers of quartz and feldspar parallel to foliation. Thin interlayers (a few centimeters thick) in amphibolite are composed of green, fine-crystalline, granoblastic feldspar, epidote, and quartz. Polyphase folding is observed in mesoscopic exposures. The map unit includes minor muscovite-biotite "button" schist. (The bent, tapered ends of lenses of mica in the schist produced by ductile deformation resemble "buttons" when weathered out of the rock onto the surface.) The Poor Mountain Formation amphibolite map unit also includes garnet-muscovite-quartz phyllonite, quartz-muscovite metasandstone, clinoamphibole schist, and garnet-hornblende gneiss. Chemical weathering of amphibolite forms a distinctive, limonite-rich rock, or it produces float with limonite rinds on fresher amphibolite cores.

Chauga River Formation metasiltstone and garnet schist. (Cambrian-Early Ordovician?)

Metasiltstone and schist constitute a thin, continuous belt of resistant rocks that crosses the quadrangles from Lake Keowee to Sharp Top Mountain (Sunset quadrangle), and from Beasley Gap to White Oak Mountain (Eastatoe Gap quadrangle). Ductile deformation features, folds, and boudinage are common in these cliff-forming rocks. Foliation in Chauga River Formation rocks is dominantly a secondary, transposition foliation (Fig. 9).

Two end-member lithologies make up a range of compositional variation in this metapelitic map unit. Metasiltstone is dark gray, fine-crystalline, poorly layered, well foliated, locally schistose garnet-muscovite-biotite-porphyroclastic feldspar-quartz gneiss. With increased mica this lithology becomes a dark brown, fine- to medium-crystalline, garnet-muscovite-biotite “button” schist. Almandine garnet (1-5 mm) is idioblastic. Coarse muscovite flakes or aggregates of finer muscovite in the schist form conspicuous “fish” (lozenge-shaped bundles), in a groundmass of black, aligned, fine-crystalline biotite. Schistose rocks locally contain resistant layers and pods of medium- to coarse-crystalline granitoid material and pegmatite, locally foliated (sheared). The schist displays S-C fabric. Also present are finely laminated muscovite-quartz metasiltstone, biotite-quartz metasiltstone, mica metaquartzite, and minor amphibolite.

In southeastern Eastatoe Gap quadrangle, sillimanite-garnet-mica gneiss is locally encountered within presumably epidote amphibolite facies rocks of the Poor Mountain Formation. The index mineral sillimanite is indicative of a higher metamorphic grade. This sillimanite-garnet-mica gneiss lies near the regional contact with Table Rock gneiss. The sillimanite may be due to higher temperature effects of the adjacent large intrusive body of synkinematic granite.

Table Rock gneiss. (Middle Ordovician)

A suite of felsic, granitic rocks and related intrusional phases (both syn- and post-kinematic) with mafic rocks underlies the middle one-third of Sunset quadrangle (Garihan, 2005a), extending as a series of prominent rocky balds and rugged peaks northeastward into the Table Rock quadrangle (Garihan and Ranson, 2001) (Figure 1).

The main lithology of the Table Rock gneiss is a biotite quartzo-feldspathic gneiss, which locally is leucocratic. The gneiss is gray to tan, fine- to medium-crystalline, and moderately well layered compositionally. Foliation is defined by aligned micas or discontinuous, lenticular aggregates of quartz and feldspar. Sheared varieties of quartzo-feldspathic gneiss contain quartz ribbons a few millimeters thick defining foliation or muscovite, due to K-feldspar breakdown during ductile deformation. A well-developed mineral lineation occurs on foliation surfaces in many places.

The Table Rock gneiss map unit also includes muscovite-biotite-quartz-feldspar gneiss, micaceous biotite gneiss, biotite-feldspar augen presence of ultramylonitic Henderson Gneiss also indicates progressive ductile deformation. Biotite-gneiss, hornblende-quartz-feldspar gneiss, poorly layered, poorly foliated, biotite granitoid gneiss, and aplite, pegmatite with local biotite selvedges, and quartz veins. Mafic rocks are layered amphibolite, biotite amphibolite, hornblende gneiss, and schist.

Jocassee Thrust Sheet

Henderson Gneiss. (Early-Middle Ordovician)

The Henderson Gneiss has a variably developed mylonitic fabric that preserves microcline augen of different shapes and dimensions (Davis, 1993). Present throughout the Henderson are sigma and delta porphyroclasts, and S-C shear sense indicators. Recurrent ductile, dextral strike slip faulting along the Brevard fault zone accompanied by high grade metamorphic conditions occurred in the Neoacadian (Late Devonian-Mississippian) and Early Alleghanian (325 Ma) (Merschat and Hatcher, 2007).

Henderson Gneiss is part of a large regional igneous body that commonly shows distinctive large feldspar crystals (< 5 cm) in a finer quartz, feldspar, and mica matrix. The gneiss is exposed in the areas flanking Eastatoe Creek in Sunset quadrangle. All major peaks above Rocky Bottom, South Carolina at the headwaters of Eastatoe Creek have impressive balds formed on Henderson Gneiss.

Biotite-microcline augen gneiss (granodiorite to granite in composition) is gray to dark gray and fine- to coarse-crystalline. The gneiss generally is well foliated. Compositional layering includes discontinuous mafic layers and lenticular aggregates of quartz and feldspar. Conspicuous pink, porphyroclastic microcline (0.5 to 5 cm) has white myrmekite rims. Owing to its coarser, feldspathic character, Henderson Gneiss is somewhat less resistant to weathering than the more quartzose Table Rock gneiss. Mylonitic fabric development is variable: protomylonite in sheared pegmatite, mylonite, and thinly layered ultramylonite in proximity to ductile faults and high strain zones. Highly sheared varieties of Henderson Gneiss contain either 1) quartz or microcline ribbons, or 2) recrystallized, fine-crystalline muscovite. On the outcrop scale, S-C fabric and strain partitioning (alternation of zones with differences in strained fabric) are present. Henderson Gneiss L-tectonites display excellent mica and quartz-feldspar mineral lineations on foliation planes.

In many outcrops the Henderson Gneiss is a light gray, locally leucocratic, layered biotite augen gneiss. Sheared textures indicate that ductile deformation has produced a strongly layered rock from the originally heterogeneous granitoid. The augen gneiss is interlayered with resistant, light-gray, leucocratic, fine- to medium-crystalline, muscovite quartz-feldspar gneiss; quartz-feldspar gneiss; fine- to medium-crystalline, biotite quarto-feldspathic gneiss; aplite, pegmatite, and quartz veins; and minor biotite amphibole gneiss.

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PETROGRAPHY OF GNEISSES FROM THE WESTERN INNER PIEDMONT OF SOUTH CAROLINA: AN OVERVIEW FOR THE 2012 CAROLINA GEOLOGICAL SOCIETY FIELD TRIP

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Introduction

Biotite±muscovite-quartz-plagioclase-microcline gneisses constitute a major rock type in the Western Inner Piedmont of South Carolina and nearby North Carolina within a sixteen-quadrangle area mapped by Garihan (2001, 2002, 2003, 2005a, 2005b), Garihan and Ranson (2001, 2002), and Garihan and others (2005). Abundant, fresh gneisses crop out along the Blue Ridge Escarpment as exfoliation surfaces and within incised stream valleys. Although these gneisses are assigned to different mappable formations, no focused attempt has been made to systematically compare the mineralogy, texture, and major and trace element geochemistry of these lithologies. This paper summarizes some of the initial results of such a detailed study and focuses on the petrography of the gneisses.

In general, the rocks are mylonitic, granitic to granodioritic, calc-alkaline gneisses that occur in the Henderson Gneiss, the Tallulah Falls Formation, and the Table Rock gneiss. Henderson Gneiss and Table Rock gneiss. The Tallulah Falls Formation includes more muscovite-rich gneisses, schists, migmatites, and amphibolites, which occur in the Six Mile thrust sheet. Augen gneisses of uncertain affinity and granitoid gneisses constitute other rock units that could not be placed with certainty into the other formations based on field mapping.

Field Relations and Petrography

Mid-Ordovician magmatism and subsequent amphibolite facies metamorphism produced widespread biotite gneisses in the Jocassee, Walhalla, and Six Mile thrust sheets mapped in the study area in the Western Inner Piedmont of South Carolina (see discussion by Garihan, this volume). Gneisses were collected from the Henderson Gneiss, Table Rock gneiss, and Talullah Falls Formation map units. Also included are biotite augen gneiss of uncertain affinity and granitoid gneiss. Griffin (1974) described the distribution of metamorphic index minerals in the western Inner Piedmont. His study showed the Walhalla sheet contained kyanite-grade mineralogy. That sheet overrode a lower grade, “non-migmatitic” terrane. Prince and Ranson (2004), based on the mineralogy of associated amphibolites, reported that gneisses placed in the Walhalla sheet by Garihan (this volume) are lower amphibolite facies and those of the Six Mile thrust sheet are intermediate amphibolite facies.

Examination and point count analysis of 53 thin sections (30 stained and 23 polished for microprobe study) reveal many similarities and some differences among the major gneiss units outlined above. All units are recrystallized and mylonitic to varying degrees, granitic to granodioritic in composition, and geochemically calc-alkaline in nature.

Tallulah Falls Formation gneiss

The seven thin sections examined are mylonitic, exhibit varying degrees of recrystallization, and may or may not contain augen. On the modal quartz-alkali feldspar-plagioclase (QAP) diagram of Streckeisen (1976) (Fig.1), Tallulah Falls samples are split between the fields of granite and granodiorite.

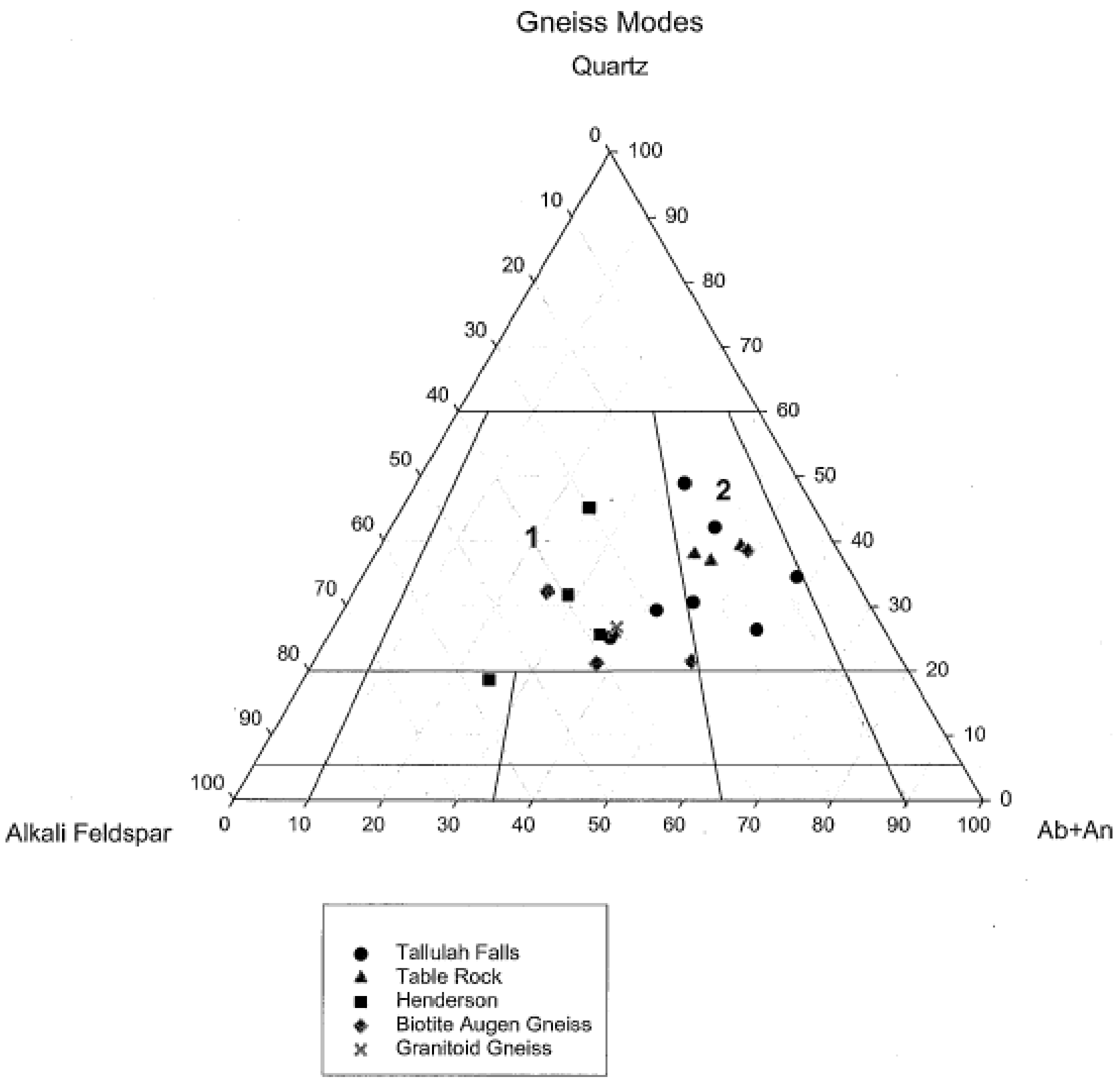

Figure 1. Modal plot of western Inner Piedmont gneisses on the quartz-alkali feldspar-plagioclase (QAP) diagram of Streckeisen (1976). All gneisses from each of the five categories plot in the field of granite (1) or granodiorite (2) with only one exception.

In thin section large quartz crystals (4-6 mm) tend to be anhedral and show undulose or sector extinction. Smaller, recrystallized quartz crystals (<1 mm) have clean, straight extinction and 120° crystal boundaries. These finer quartz crystals are typically part of quartz-feldspar ribbons and lenses that are abundant in all Tallulah Falls gneisses and along with the micas define the foliation and compositional layering.

Muscovite content ranges from less that 1% up to nearly 29% by volume and is more abundant in Tallulah Falls gneisses than any of the other gneisses examined. Coarse (2-4 mm) muscovite fish or tapered porphyroblasts are distinctive in some but not all Tallulah Falls samples (Fig. 2). Finer (<1 mm) muscovite and biotite aggregates wrap around coarser feldspars. Micas typically show sub-parallel alignment and define a single foliation.

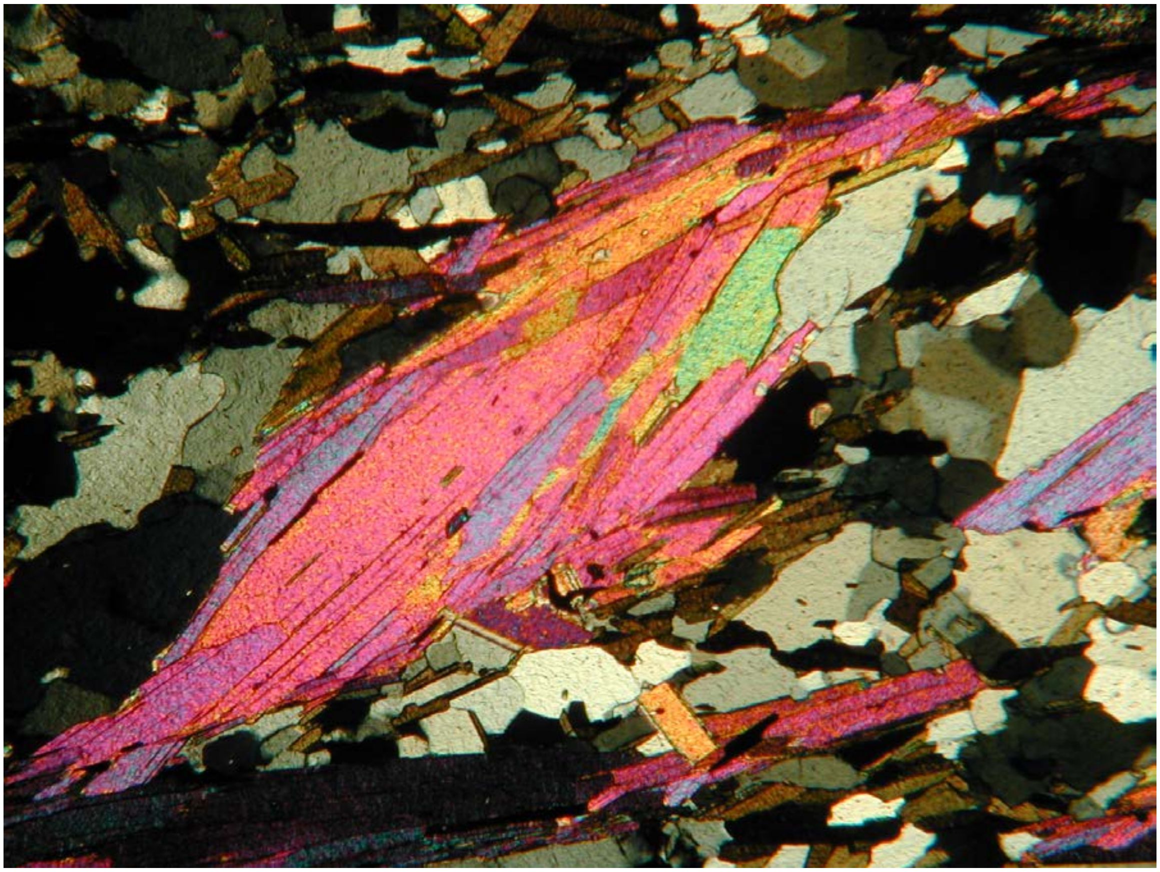

Figure 2. Tallulah Falls Formation gneiss. Photomicrograph of muscovite fish aggregate in matrix of finer crystalline quartz, microcline, biotite, and muscovite. Crossed polars. Field of view ~3 mm.

Plagioclase porphyroclasts (2-4 mm) are strained and exhibit undulose extinction. Commonly they are anhedral, zoned, and embayed by quartz and mica. Zoning suggests a volcanic origin for plagioclase porphyroclasts. Microcline porphyroclasts (3-5 mm) are also anhedral, strained, and embayed by quartz, and they are clearly breaking down to myrmekite at crystal margins.

Table Rock gneiss

Nine thin sections of Table Rock gneiss show widespread recrystallization and mylonitic texture. Quartz-feldspar ribbons are a common attribute. In general these rocks are more homogeneous and leucocratic, finer crystalline, and muscovite poor compared to other gneiss varieties. Although the following descriptions discuss feldspar porphyroclasts as part of the Table Rock gneiss, the more obvious augen gneisses are described in a subsequent section entitled "augen gneisses of uncertain affinity." Indeed, one of the questions to be answered is whether augen gneisses are part of the Table Rock gneiss, the Henderson Gneiss, or a separate mappable unit or generation of gneiss. On the modal QAP diagram (Fig. 1) Table Rock gneisses fall in the granodiorite field.

Quartz-feldspar ribbons and lenses are a hallmark of Table Rock gneiss texture. Coarse (3-6 mm) quartz crystals have undulose or sector extinction, suggesting partial annealing or recrystallization to form smaller crystals (Fig. 3). The more thoroughly recrystallized, finer (<1-2 mm) matrix quartz crystals show straight extinction and 120° crystal boundaries. Coarse feldspars have undulose extinction, and finer matrix feldspars are recrystallized with straight extinction and 120° margins.

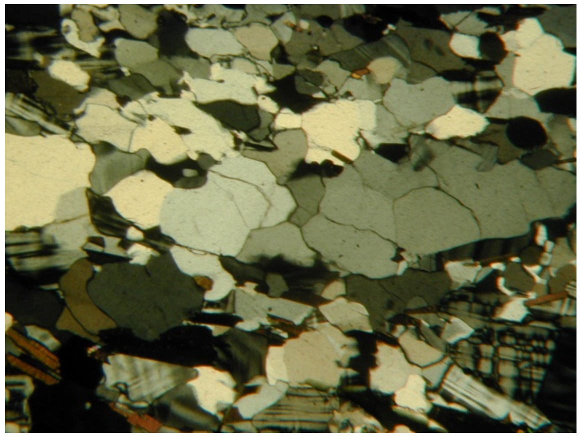

Figure 3. Table Rock gneiss. Photomicrograph of quartz ribbon (band across the center) in a matrix of quartz, microcline, muscovite, and biotite. Crossed polars. Field of view ~3 mm.

Biotite is finely crystalline and is concentrated into very thin, discontinuous layers that separate quartz-feldspar ribbons. These thin layers are fairly evenly distributed and define the foliation. Muscovite is much less common and may occur locally as a retrograde alteration product of plagioclase, with fine muscovite development along albite twin planes. Hornblende, though present in only two of the nine thin sections, replaces biotite as the most abundant mafic mineral in one rock.

Plagioclase porphyroclasts (2-4 mm) are embayed by quartz and reside in a matrix of finer (0.5-1 mm) feldspar and quartz. The plagioclase is not zoned but does have irregular curved fractures, suggesting a brittle phase of deformation after the peak of metamorphism and recrystallization. Microcline porphyroclasts (2-5 mm) are embayed by quartz and myrmekite (Fig. 4). Myrmekite is preferentially developed along the long dimensions of the crystals, perpendicular to foliation. The texture suggests stress-related K-feldspar breakdown (cf. discussion of Passchier and Trouw, 1996, p. 123-124). Microcline porphyroclasts are commonly polycrystalline aggregates, but the component microcline crystals remain significantly coarser than matrix crystals.

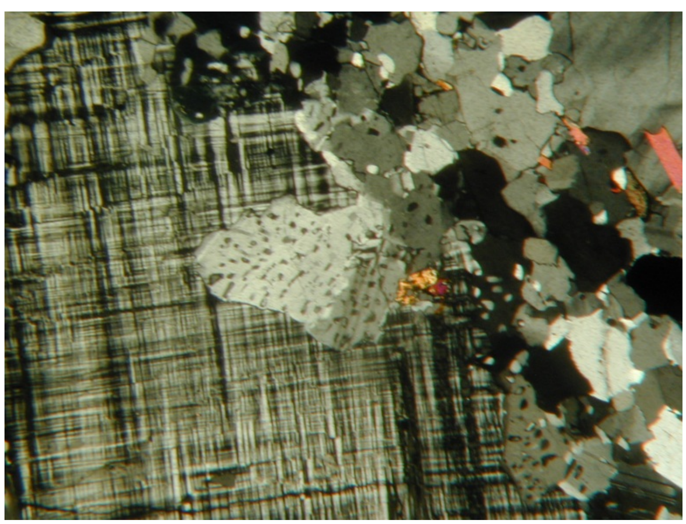

Figure 4. Table Rock gneiss. Photomicrograph of microcline porphyroclast (gridiron twin pattern) with margins embayed by myrmekite in a matrix of quartz, microcline, and biotite. Crossed polars. Field of view ~3 mm.

Henderson Gneiss

Henderson Gneiss is mylonitic to ultramylonitic with abundant augen. In addition to augen, common features of the seven thin sections examined are quartz-feldspar ribbons. On the modal QAP diagram, Henderson Gneiss samples plot in the field of granite and quartz syenite (Fig. 1). Henderson Gneiss is characteristically augen bearing with large (1-3 cm) microcline porphyroclasts, which in thin section commonly consist of polycrystalline aggregates of microcline (3-5 mm crystals) rimmed with myrmekite (Fig. 5). Moreover, microcline augen are flattened, embayed, and have tails that merge into quartz-feldspar ribbons. Plagioclase porphyroclasts 2-4 mm in length are similar in size to the microcline crystals making up the polycrystalline augen. Plagioclase may exhibit irregular cracks and fractures similar to those seen in the Table Rock gneiss, implying a later brittle history. Plagioclase alteration to sericite and calcite is common. All coarser feldspars have undulose extinction, whereas matrix feldspars and quartz have straight extinction, implying recrystallization and annealing.

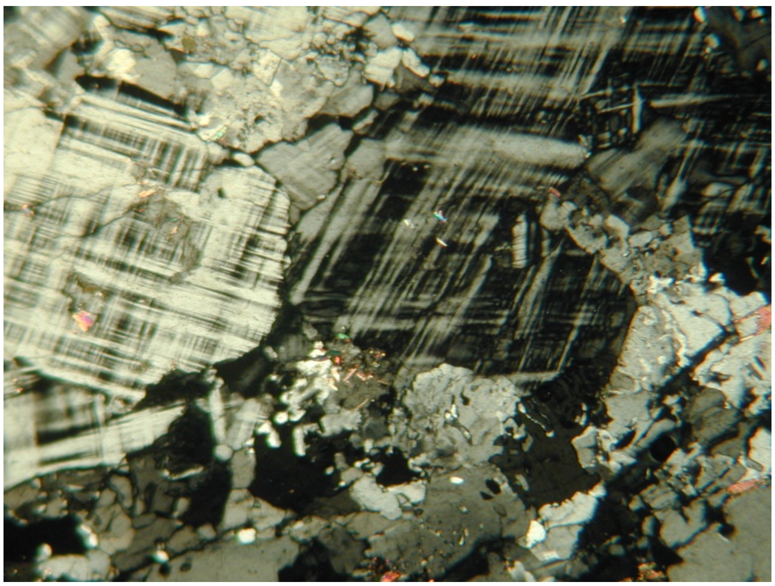

Figure 5. Henderson Gneiss. Photomicrograph of part of a polycrystalline microcline porphyroclast with margins embayed by myrmekite in a matrix of quartz, microcline, and biotite. Crossed polars. Field of view ~3 mm.

Biotite plus less abundant muscovite wrap around feldspar porphyroclasts, while away from porphyroclasts the micas define a foliation parallel to quartz-feldspar ribbons. Less commonly biotite defines two different foliations, perhaps associated with S and C structures.

Accessory minerals present in the Henderson Gneiss include epidote, garnet, titanite, zircon and opaques. Most notable are coarse (2-3 mm) wedge-shaped titanite crystals associated with biotite, muscovite, epidote, and opaque minerals.

Some Henderson Gneiss samples exhibit the texture of an ultramylonite, characterized in thin section by narrow zones of finely crystalline quartz+microcline+mica sandwiched between coarser, polycrystalline microcline and quartz ribbons (Fig. 6). Such ultramylonitic zones suggest strain partitioning within the rock. That is, higher strain has developed in select zones within the gneiss.

Figure 6. Henderson Gneiss. Photomicrograph of finely crystalline quartz+microcline+mica sandwiched between coarser, polycrystalline microcline and quartz ribbons. Crossed polars. Field of view ~3mm.

Biotite Augen Gneiss of Uncertain Affinity

Biotite augen gneiss is medium- to coarse-crystalline and mylonitic with abundant recrystallized microcline augen. In addition to augen, common features of the eleven thin sections examined are quartz and quartz-feldspar ribbons. On the modal QAP diagram (Fig. 1) biotite augen gneiss samples fall in the fields of granite and granodiorite.

Microcline augen, typically 2-3 cm in length, consist in thin section of polycrystalline aggregates of 6-8 mm microcline crystals with embayed, myrmekitic rims and tails. These porphyroclasts exist in a matrix of intermediate (1-3 mm) and fine (<1 mm) quartz, microcline, and plagioclase. Coarser crystals typically have undulose or sector extinction, whereas the finer crystals have straight extinction and 120° crystal boundaries suggestive of recrystallization. In particular coarse quartz (2-4 mm) displays multiple sub-grain boundaries that go extinct at different stage rotations (Fig. 7). Plagioclase porphyroclasts (2-4 mm) have ragged and embayed margins and may be altering to muscovite. Plagioclase, microcline, and quartz in the fine (<1 mm) size range form quartzo-feldspathic ribbons bordered by thin, discontinuous biotite±muscovite layers. The biotite layers define the foliation and wrap around augen. Accessory minerals associated with the biotite layers include epidote, titanite, zircon, apatite, and opaques. Coarse (2-3 mm) titanites are distinctive because of their size, subhedral wedge shape, and high relief.

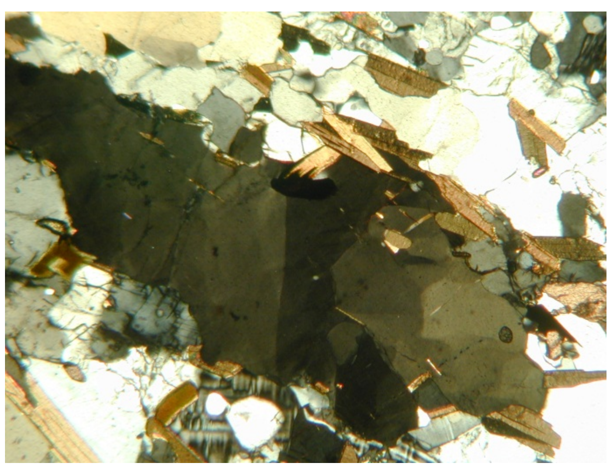

Figure 7. Biotite augen gneiss of uncertain affinity. Photomicrograph of coarse quartz crystal displaying multiple sub-grain boundaries, in a matrix of finer quartz, microcline, and biotite. Crossed polars. Field of view ~3 mm.

Biotite Granitoid Gneiss

Biotite granitoid gneiss is typically medium-crystalline (2-6 mm), leucocratic (CI<5), and hence poorly foliated and poorly layered to massive. Dispersed feldspar porphyroclasts up to 1 cm are present in about 20% of the rocks observed in the field and occur as blocky or augen shaped crystals. On the modal QAP triangular diagram (Fig. 1) biotite granitoid gneiss samples plot squarely in the field of granite.

Although these rocks are not well foliated or mylonitic, in thin section they display textures indicative of metamorphic recrystallization. Such textures include well-developed 120° crystal boundaries, quartz-feldspar ribbons composed of fine crystals (<1 mm) with straight extinction, coarser (2-4 mm) quartz and feldspar crystals with undulose or sector extinction, and microcline porphyroblasts (2-6 mm) with embayed, myrmekitic margins (Fig. 8). Sparse biotites (0.5-1 mm) wrap around microcline porphyroclasts and may define a weak foliation. Epidote-biotite-muscovite-quartz symplectites form mafic segregations that punctuate the largely felsic matrix (Fig. 9) and alter coarse plagioclase crystals.

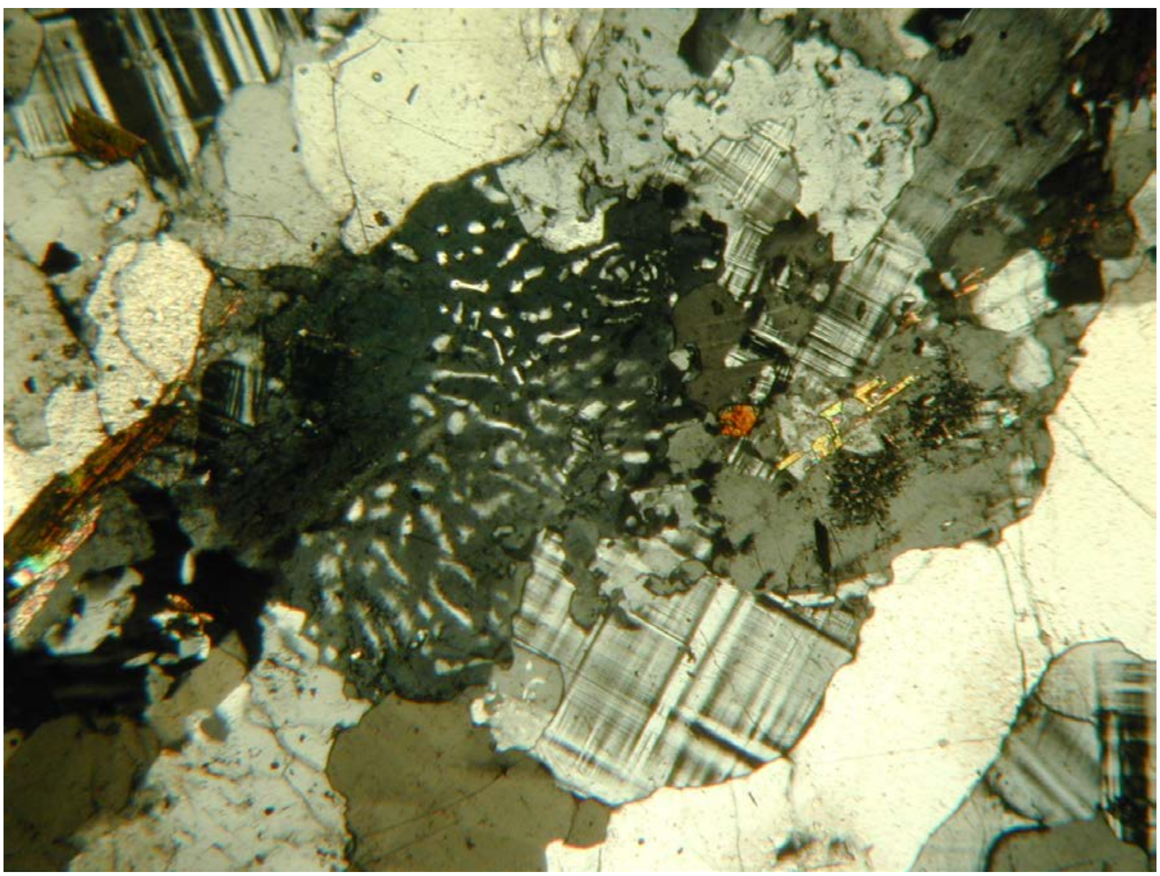

Figure 8. Granitoid gneiss. Photomicrograph of typical granitoid gneiss texture consisting of microcline, quartz, and plagioclase with minor biotite and muscovite. Note lack of foliation. Crossed polars. Field of view ~ 3 mm.

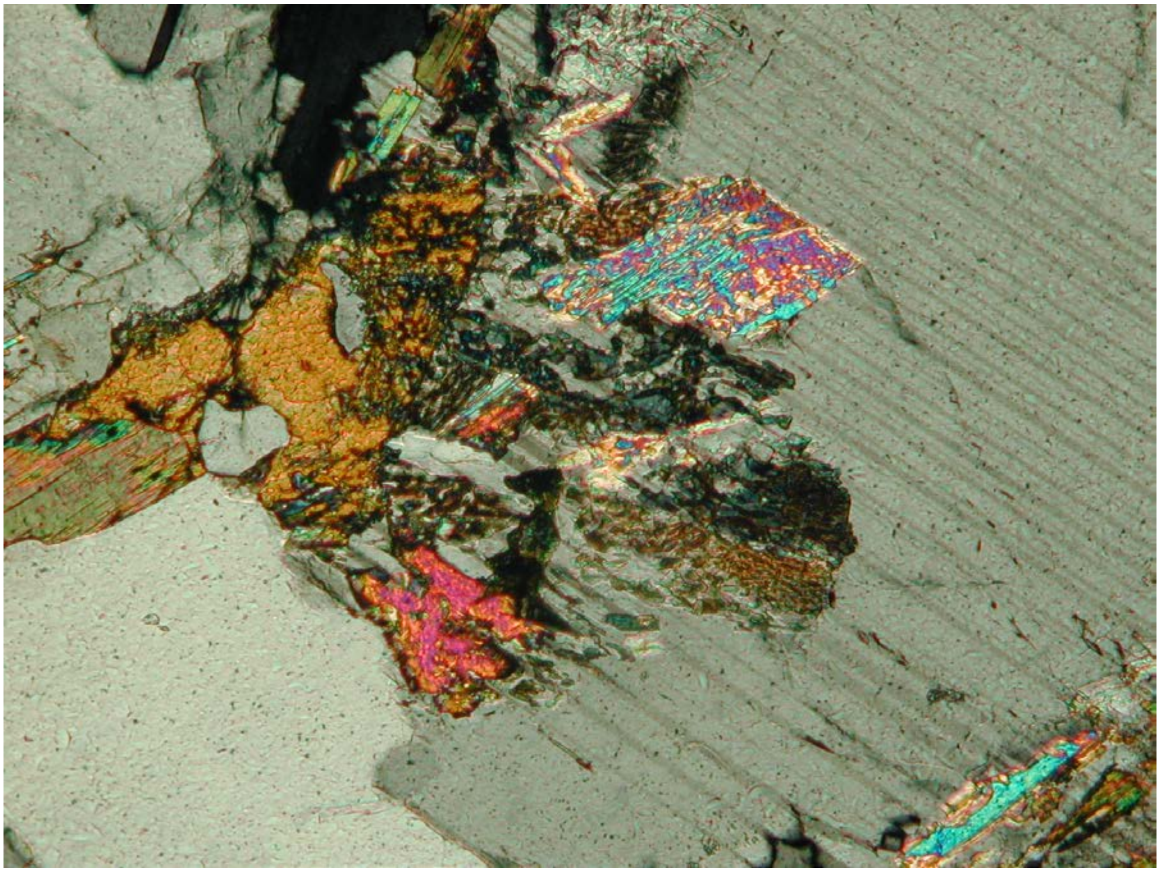

Figure 9. Granitoid gneiss. Photomicrograph of epidote-biotite-muscovite-quartz symplectite occurring as a mafic segregation within the largely felsic matrix and altering a coarse, albite-twinned plagioclase crystal. Crossed polars. Field of view ~1 mm.

Summary and Comparison of Gneiss Petrography

The five varieties of biotite gneiss identified by mapping have many commonalities with regard to mineralogy and texture in thin section. 1) All contain microcline, plagioclase, and quartz porphyroclasts in a quartzo-feldspathic plus biotite matrix and show evidence of microcline breakdown to myrmekite. 2) All show evidence of metamorphic recrystallization. 3) All but the biotite granitoid gneiss are mylonitic and contain quartz-feldspar ribbons. Being more leucocratic and less well foliated, the biotite granitoid gneiss has an igneous texture in hand specimen. It characteristically weathers to an iron-stained appearance with chalky feldspars. Tallulah Falls gneiss is a distinctively a two-mica gneiss. It is more aluminous and mafic than the other gneisses. Distinguishing petrographically among the various augen gneisses - Henderson augen Gneiss, Table Rock gneiss, and biotite augen gneiss of uncertain affinity - on the basis of texture and mineralogy remains problematic. Future studies will focus on geochemistry as a possible means of distinguishing the augen gneisses from one another.

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GEOLOGIC MAPPING IN THE CLEMSON EXPERIMENTAL FOREST, PICKENS AND OCONEE COUNTIES, SOUTH CAROLINA

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ABSTRACT

The Clemson Experimental Forest mapping program has been deciphering the metamorphic history of the rocks that crop out in the Forest through whole rock analysis, petrographic studies, and microprobe characterization of their mineral assemblages. The pressure-temperature data retrieved from the metamorphic minerals provides a framework for interpreting the complex tectonic history of rocks in the Six Mile thrust sheet.

INTRODUCTION

As part of the undergraduate research initiative at Clemson University, mentor-led student groups started mapping the northern half of the Clemson Experimental Forest (Fig. 1) in 2007. While most of the area had been previously mapped by Griffin (1993) and Brown and Cazeau (1964), our focus was on training students in identifying and characterizing the different kinds of metamorphic rocks, determining the metamorphic history, and creating a detailed digital geologic map of the forest.

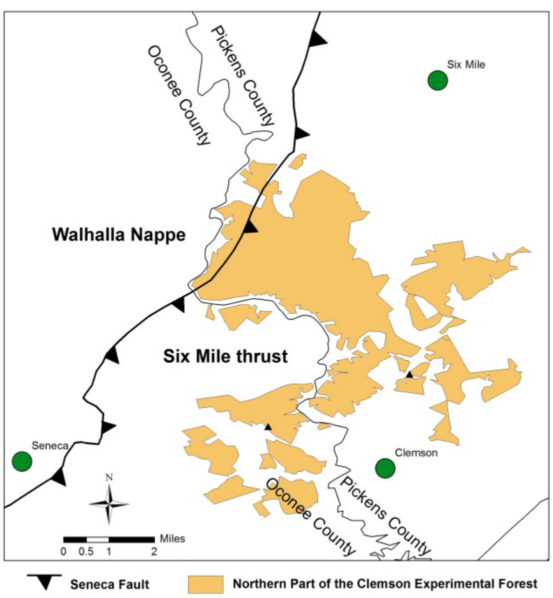

Figure 1. Location of the Clemson Experimental Forest in the upstate of South Carolina.

TECTONIC SETTING

The Clemson Forest is situated to the east of the Seneca fault, which lies at the base of the Six Mile thrust sheet (Fig. 1). The sillimanite-grade rocks of the Six Mile sheet have been subjected to high-grade metamorphism and are migmatitic.

ROCK TYPES

The predominant rock type is a biotite gneiss that is medium- to coarse-grained, with a moderately distinctive foliation due to the subparallel alignment of the biotite. Quartz and plagioclase are the light-colored minerals. Garnet, commonly present, occurs as more or less equant porphyroblasts (Fig. 2).

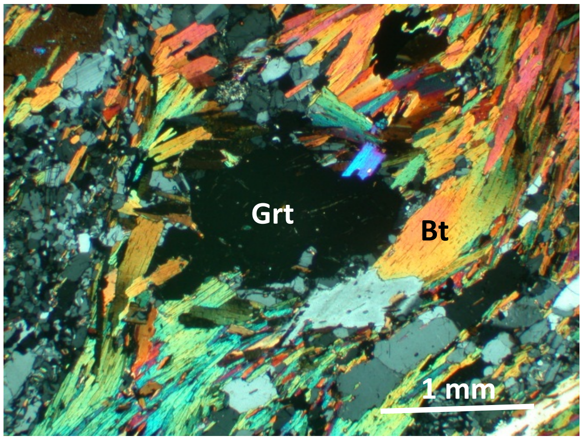

Figure 2. Photomicrograph of a garnetiferous biotite gneiss under crossed polars. Grt = Garnet; Bt = Biotite.

Muscovite is a common accessory mineral, and sillimanite (Fig. 3) is found in some samples. Where the biotite gneiss is migmatitic, it is intermixed with masses of granitoid rocks. The gneiss occasionally occurs with abundant augen (Fig. 4). The augen are composed of plagioclase (or more rarely quartz) porphyroblasts.

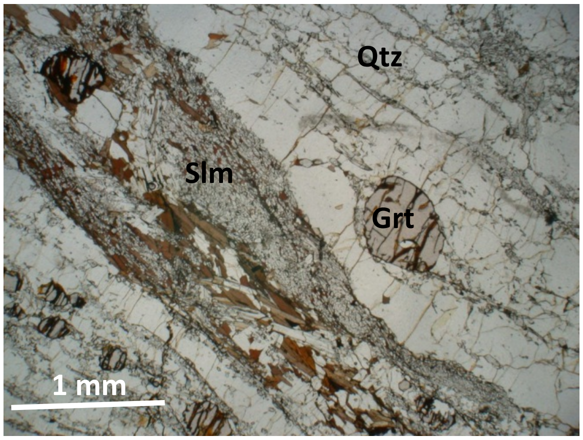

Figure 3. Photomicrograph of sillimanite-garnet gneiss in plane polarized light. Grt = Garnet; Qtz = Quartz; Slm = Sillimanite.

Figure 4. Biotite augen gneiss with plagioclase (and/or quartz) porphyroblasts.

Amphibolite and hornblende gneiss are common and typically occur interbedded with the biotite gneiss or as boudins. In a few areas, the amphibolite occurs as larger pods that represent mappable units. Hornblende, plagioclase, and subordinate quartz are the main minerals. Hornblende gneiss is visibly foliated, and amphibolite is weakly foliated or nonfoliated.

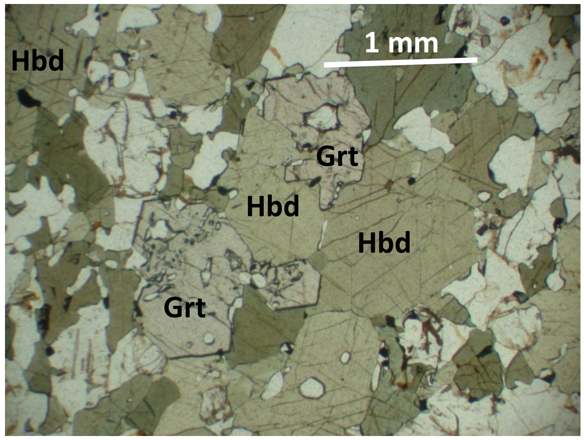

Figure 5. Photomicrograph of garnetiferous amphibolite in plane polarized light. Grt = Garnet; Hbd = Hornblende.

Migmatites occur throughout the Forest. Migmatites consist of various proportions of dark, ferromagnesian mineral-rich rock and light quartz- or feldspar-rich rock. When rocks reach the temperature of granitic partial melting, lighter minerals like quartz and feldspar melt and flow away from the darker minerals. The light-shaded rock is referred to as the leucosome, whereas the dark-shaded rock is referred to as the melanosome. Leucosomes (Fig. 6) commonly have a non-foliated, igneous-like appearance, whereas melanosomes are usually foliated.

Figure 6. Outcrop of migmatite with folded leucosome (light colored, quartz and feldspar-rich).

Other rocks types encountered in the Forest include a typically coarse-grained mica (primarily muscovite) schist, metaquartzite, and an ultramafic rock body.

GEOLOGIC MAP

Most of the northern half of the Clemson Experimental Forest has been mapped (Fig. 7.) While the biotite gneiss dominates the Forest, there is considerable variation within the gneiss including interbedded amphibolites, schists, granitic gneisses, and quartzites that are too small to be mapped at this scale. Some areas remain unmapped due to a lack of adequate outcrop control.

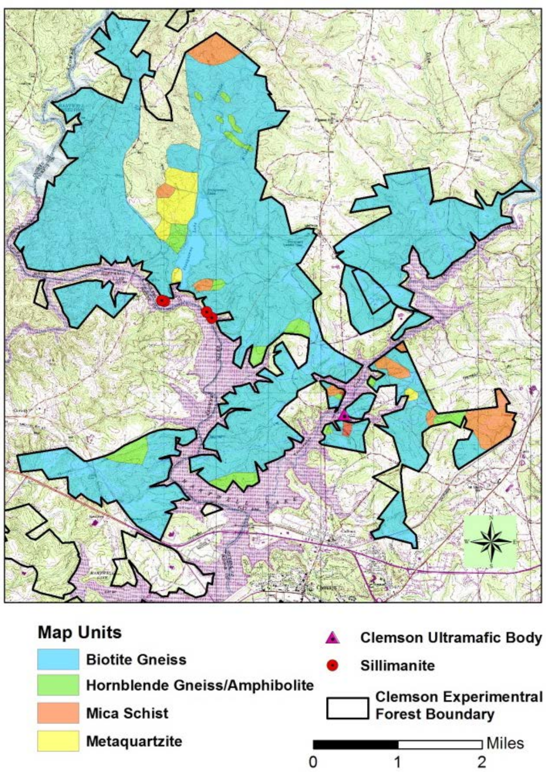

Figure 7. Geologic map of the northern half of the Clemson Experimental Forest.

POSSIBLE ORIGINS

Biotite Augen Gneiss

Whole rock analysis of the augen gneiss was used to calculate the CIPW weight norm, a geochemical calculation in which the idealized mineral composition is produced for each selected rock sample. Using the weight norm composition, a quartz alkali-feldspar plagioclase diagram was constructed (Fig. 8).

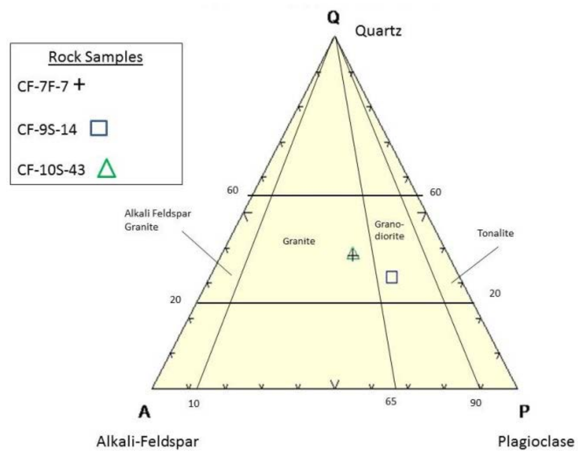

Figure 8. QAP diagram that plots the composition of selected biotite augen gneiss samples according to their possible source rocks.

The results indicate that the augen gneiss samples collected are broadly granitic in composition. This suggests that the biotite augen gneiss found in the experimental forest has an igneous origin.

Amphibolite

Whole rock analysis was conducted on eight amphibolite samples collected from different parts of the Forest. The results are summarized in Table I.

Table I. Major elemental percentages of eight amphibolite samples.

Oxide	7F-4	8F-12	9S-1	9S-6	9S-9	9S-12A	9F-18	10s-40
SiO_2	52.79	44.73	44.79	51.62	50.99	49.19	45.9	46.7
TiO_2	1	2.01	1.06	1.62	0.43	2.74	1.07	0.99
Al_2O_3	13.69	15.21	16.62	13.5	17.14	13.01	16.28	15.3
Fe_2O_3	11.42	14.71	16.46	16.2	11.26	16.55	10.34	11
MnO	0.19	0.19	0.34	0.34	0.2	0.26	0.17	0.26
MgO	7.74	7.51	6.23	5.99	6.64	5.99	7.02	6.92
CaO	9.28	11.95	10.98	9.12	11.56	9.2	14.7	14.7
Na_2O	1.01	2.09	1.63	0.62	1.41	0.97	1.79	2.53
K_2O	0.25	0.33	0.36	0.27	0.33	0.56	0.3	0.56
P_2O_5	0.1	0.28	0.17	0.15	0.04	0.27	0.1	0.1

CIPW norms for each sample were calculated to yield theoretical mineralogies based on the elemental percentages. Four of the samples are quartz normative, and four of the samples are olivine normative. The range of plagioclase in the samples is 40-50%. Of the total plagioclase, albite makes up

25%, and anorthite comprises the remaining 75%. Pyroxene ranges from 25%-40% and occurs mainly as diopside and hypersthene.

Trace metal and rare-earth elemental compositions were used to plot the tectonic origin of the amphibolites. The rubidium and ytterbium/tantalum percentages were used to construct Figure 9. This plot indicates that the amphibolites originated in a volcanic arc system.

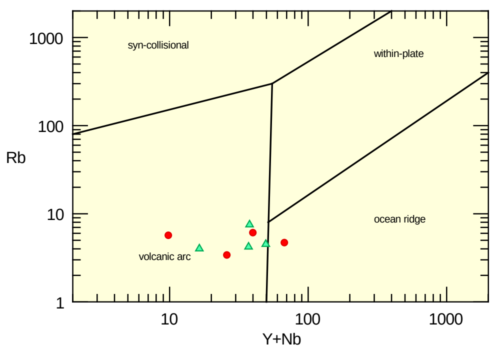

Figure 9. Discrimination diagram for tectonic origin of amphibolite using Rb and Yb/Tb percentages. The red circles represent quartz normative samples, and the green triangles represent olivine normative samples.

The titanium, zircon, and yttrium percentages were used to construct Figure 10. This plot indicates that the amphibolites are derived from island-arc basalts and ocean-floor basalts.

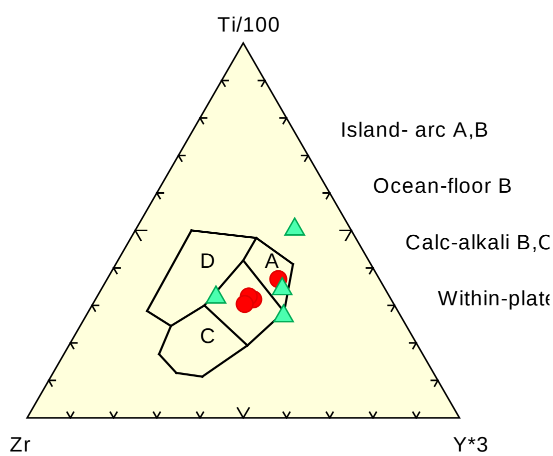

Figure 10. Discrimination diagram for tectonic origin of amphibolites using Ti/100, Zr, and Y*3 percentages. The red circles represent quartz normative samples, and the green triangles represent olivine normative samples.

These results indicate that the Clemson Experimental Forest amphibolites are dominantly island-arc basalts with lesser ocean-floor basalts. The island arcs originated in the proto-Atlantic (Iapetus) Ocean and were accreted onto the continent during Devonian time (Acadian Orogeny).

Migmatite

Whole rock element analyses were conducted on three samples of the leucosome. Table II shows the analyses for the major oxides. The important numbers in the table are those for K_2O, SiO_2, and Al_2O_3. Low K was not expected because there was muscovite mica present in the leucosome. High silica was expected because only the quartz and feldspar were melted. The levels of Al were not expected but could be attributed to the feldspar that was created.

Table II: Whole rock analysis of leucosome samples. Note high SiO_2 and low K_2O.

Oxide	**11S-27A**	**11S-27B**	**11S-27C**
SiO_2	73.35	71.25	74.41
Al_2O_3	15.46	17.42	15.23
Fe_2O_3	1.26	0.71	0.92
CaO	3.21	4.06	3.21
Na_2O	3.8	5.17	3.95
K_2O	1.12	0.45	1

The weight percents of the oxides were used to calculate CIPW norms to get theoretical mineralogy. These norms are presented in Table III. The norms indicate that the leucosomes are peraluminous, having enough aluminum to be assigned to corundum.

Table III: CIPW normative mineral percentages.

Mineral	**11S-27A**	**11S-27B**	**11S-27C**
Quartz	39.58	30.34	40.03
Orthoclase	6.62	2.66	5.91
Albite	32.15	43.75	33.42
Anorthite	15.73	20.01	15.92
Corundum	2.23	1.09	1.81
Hypersthene	2.02	0.98	1.4
Magnetite	0.28	0.16	0.2
Ilmenite	0.23	0.08	0.19
Apatite	0.07	0.05	0

The CIPW normative mineral percentages were used to construct a QAP ternary diagram that classifies plutonic rocks (Fig. 11). Using this diagram, the migmatite samples are classified as granodiorites and tonalites. The rocks do not contain enough alkali feldspar to be considered granites. This result was unexpected, because if partial melting caused the migmatites to form, one would expect a granitic compostion for the migmatites. Perhaps the partial melting process was incomplete when the rocks cooled, preventing alkali feldspar from forming.

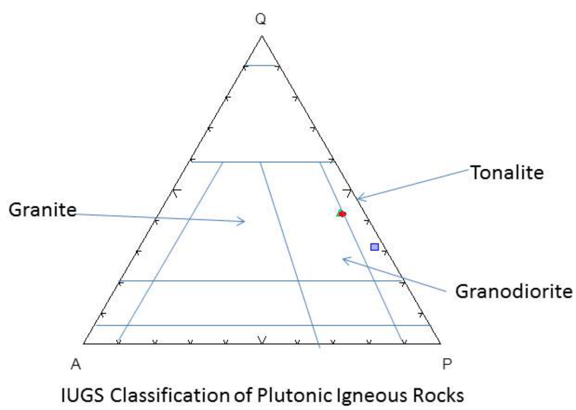

Figure 11: Classification of the leucosome samples using a QAP diagram. Two samples were classified as granodiorite, while one sample was classified as a tonalite. Q = quartz; A = alkali-feldspar; P = plagioclase.

Temperatures of Metamorphism

The presence of sillimanite in biotite gneiss places peak metamorphic conditions in the sillimanite zone. The occurrence of migmatites indicates that the temperatures were in excess of 650-670^{o}C. The coexistence of anthophyllite and olivine in the ultamafic schist body suggests a metamorphic temperature between 670-700°C (and a pressure below 6 kbar).

Temperatures of metamorphism can be derived from compositions of co-existing garnet and biotite through application of the garnet-biotite Fe-Mg exchange geothermometer (Ferry and Spear, 1978). The highest temperatures obtained from this method are in the range 660-710^{o}C, which possibly represent peak metamorphic conditions. The results from the analysis of biotite-garnet pairs from the same sample often yield temperatures more than one hundred degrees apart. We interpret the lower temperatures found in the same rocks as an indication that the Fe-Mg exchange between biotite and garnet continued during retrograde metamorphism.

The presence of garnet in some hornblende gneiss/amphibolite samples provides another method to determine temperature using the garnet-hornblende geothermometer of Graham and Powell (1984). The results obtained using this method were more consistent with little variance within individual samples or between different samples. Garnet-hornblende temperatures range from 637-673^{o}C and are thus in good agreement with those indicated by the presence of migmatites.

A sample collected in the spring of 2012 was used to estimate the pressure regime. Sample CF-11S-2 contained an abundance of sillimanite and alkali feldspar, along with muscovite mica. This was interpreted as the retrograde reaction kfs+als→ms, meaning that the opposite reaction must have taken place when the rock was heating up. Using this information, we estimated a pressure of 5 kbar. We were then able to acquire a range for temperature of metamorphism between 670 and 700°C using the phase diagram in Figure 12.

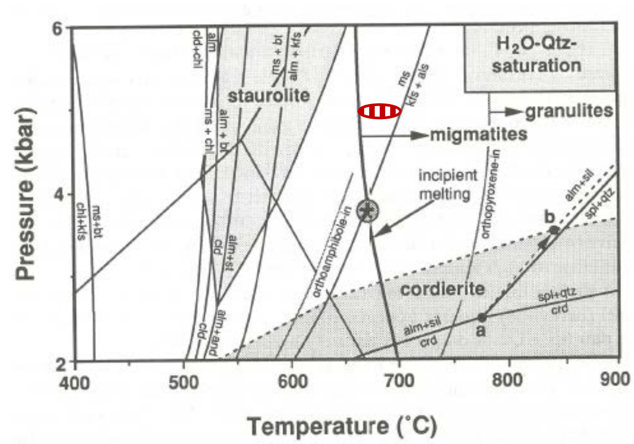

Figure 12: Phase diagram showing the beginning of melting curve where migmatites occur, and the reaction curve for ms→kfs+als. The red striped oval indicates the temperature range constrained by this reaction.

Migmatites have provided a new constraint on temperatures of metamorphism in the Clemson Experimental Forest. These rocks provide a lower limit on temperature, showing that rocks in the Forest must have experienced temperatures at least 650°C. This narrows the range of temperatures considerably, as we have not had a lower limit before.

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PETROLOGY OF THE SALEM ULTRAMAFIC BODY, OCONEE COUNTY, SOUTH CAROLINA

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INTRODUCTION AND REGIONAL GEOLOGY

The Salem quadrangle ultramafic body was the subject of two undergraduate theses by Rutledge (2008) and Bridgeman (2012). This body is one of numerous small pods, typically less than 1km in size, of metamorphosed ultramafic rock that occur in the Western Inner Piedmont of South Carolina.

Early work by Misra and Keller (1978) has provided a general overview of Inner Piedmont ultramafics. The bodies of the South Carolina Inner Piedmont are characterized as either altered dunite or magnesian schist and consist of varying proportions of talc, chlorite, and amphibole. They typically are conformable to local and regional foliation and are heavily deformed. As inferred from their concordant geometry and intense alteration, the Inner Piedmont bodies tend to belong to an older group of ultramafics when compared to those of the Blue Ridge. Their maximum age is thought to be late Precambrian to early Paleozoic.

Butler (1989) grouped ultramafic rocks within the lithotectonic belts of the Carolinas into four main types. The Inner Piedmont contains small pods and lenses, usually less than 200m long, of Alpine-type altered dunite and peridotite. The south-central Inner Piedmont contains potassic ultramafic rocks, presumably metamorphosed lamproites. The western Charlotte and Kings Mountain belts contain peridotite, clinopyroxenite, and hornblende-bearing ultramafics that grade into gabbroic complexes that extend over tens of square kilometers. Finally, along the Inner Piedmont-Kings Mountain belt boundary, the flanks of the Raleigh belt, and in the Kiokee belt lie several occurrences of ultramafic and related rocks interpreted to be dismembered ophiolites or ophiolitic mélanges (Butler, 1989).

The bodies of this study lie in the western Inner Piedmont in the Tugaloo terrane (Hatcher, 2002) in northwestern South Carolina. The Inner Piedmont is characterized by a stack of westward-vergent fold-thrust nappes that have undergone polyphase deformation and metamorphism of middle to upper amphibolite facies (Hatcher 1993, 2002). The Inner Piedmont is separated from the Blue Ridge province by the Brevard fault zone followed by the non-migmatic Chauga belt. To the southeast, the Walhalla fold nappe is overlain by the Six Mile thrust sheet. Griffin (1974) originally described the Walhalla fold-nappe (Hatcher and Hooper, 1992) as consisting of amphibolite and amphibole gneiss interlayered with variable amounts of granitoid gneiss. The northwestern margin is non-migmatic but becomes migmatic moving southeast (Griffin, 1974). Griffin identified a number of small ultramafic pods in the Walhalla fold-nappe and described these bodies as chlorite-amphibole-talc rocks. These bodies are commonly schistose and lie sub-parallel to the country rock foliation. He suggested that they might represent altered dunites or olivine pyroxenites (Griffin, 1974). Such occurrences are dispersed throughout the Walhalla nappe with a few bodies cropping out in the Six Mile nappe. Northeast of the rocks mapped by Griffin, Garihan (2004) mapped the rock units of the Walhalla nappe as Table Rock gneiss and Poor Mountain Formation amphibolite. The Six Mile nappe is a sillimanite grade autochthonous thrust sheet comprised predominantly of biotite gneiss, mica schist, granitoid gneiss, and amphibolite (Griffin, 1974, Hatcher, 1978).

MINERALOGY AND PETROLOGY

The Salem Body (Fig. 1) is contained in the Salem 7.5-minute quadrangle as mapped as by Clendenin and Garihan (2008). The body is lenticular, northeast trending, and 0.7 km long by 0.1 km wide. Petrographically, it is a well-foliated, lepidoblastic chlorite-amphibole schist composed of approximately 50-60% chlorite, 40-50% amphibole, and ~10% other minerals including accessory magnetite and relict olivine. Fresh hand samples are gray-green to dark green with rust colored weathering. They vary slightly in crystal size from sub-mm scale up to 5 mm. The amphiboles appear as dark green needles or blades that are parallel to unoriented. The chlorite appears as thin, flat books or laths and commonly defines the schistosity. In thin section, chlorite exhibits colorless to pale green pleochroism in plane light. In cross-polarized light chlorite is abnormal gray-brown to gray-white. Olivine is present in some of the samples but usually in amounts less than 10%. Figures 2, 3, 4, and 5 show representative photomicrographs of Salem body thin sections. See figure captions for explanation.

Polished thin sections from the Salem ultramafic body were probed on the University of

Georgia's Jeol JXA-8600 electron microprobe housed in the Geology Department and using a 15 KV accelerating voltage and a 15 nA beam current. Results confirm that the chlorite is magnesian with Mg numbers ranging from 0.72 to 0.84. Olivine is also Mg rich with compositions averaging Fo_{78}. Amphiboles classified using the Probe-AMPH Microsoft Excel spreadsheet designed by Tindle and Webb (1994) include tremolite, tremolitic hornblende, magnesio-hornblende, ferrian-magnesio-hornblende, and magnesio-cummingtonite. Probe analyses of Salem amphiboles are plotted on the amphibole quadrilateral in Figure 6. The tie line connects coexisting amphiboles within sample SA-UM-1. A few representative amphibole analyses are posted in Table 1.

Four whole rock samples from the Salem body were chemically analyzed at Acme Analytical Labs by Inductively Coupled Plasma Emission Spectroscopy (ICP-ES) after a lithium metaborate/tetraborate fusion at 1000°C and dilute nitric acid digestion. Analysis of trace and rare earth elements was determined by Inductively Coupled Plasma Mass Spectroscopy (ICP-MS) after the same fusion and digestion preparation. The major element analyses (Table 2) for the Salem body highlight certain elements that compositionally define the body. The body has a range of Al_2O_3 values between 6-10%, MgO values of mostly 21-28%, Fe_2O_3 between 11-13%, and CaO values mostly between 4 and 7%. Table 2 also includes whole-rock chemistry for other nearby ultramafic bodies from the Inner Piedmont and the Blue Ridge. The data were plotted on several tectonic discrimination diagrams with limited success.

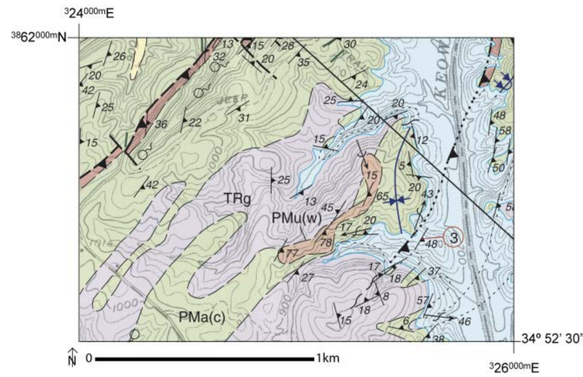


Figure 1. Geologic map showing the Salem body from the Salem Quadrangle (Clendenin and Garihan, 2008) PMa(c) = Poor Mountain Formation amphibolite (light green); TRg = Table Rock gneiss (light purple); PMu(w) = Poor Mountain Formation ultramafic schist (orange). To the east of the body is Lake Keowee. Below is an aerial view from Google Earth.

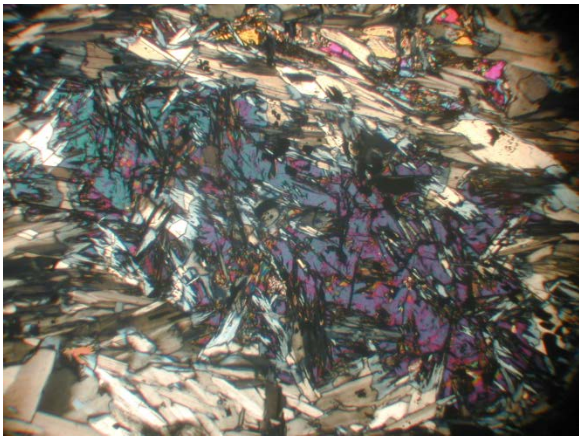
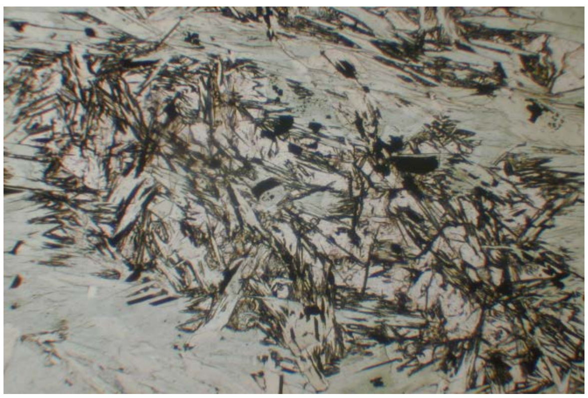


Figure 2. Salem body sample SA-UM-5 showing tremolite crystal (blue-purple) cut by smaller chlorite crystals. Cross-polarized light (top), plane light (bottom) with field of view ~2mm.



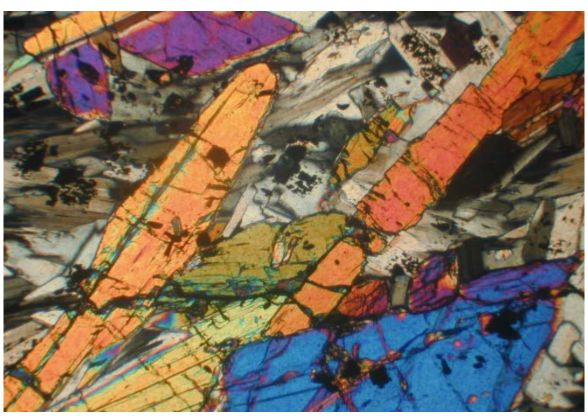


Figure 3. Large, colorful tremolite crystals in matrix of chlorite in sample SA-UM-25. Cross-polarized light, field of view ~2mm.

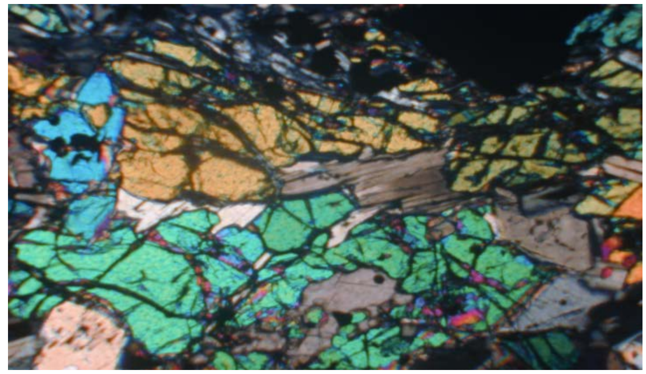


Figure 4. Fractured olivine crystals in matrix of chlorite in sample SA-UM-25. Cross-polarized light, field of view ~2mm.

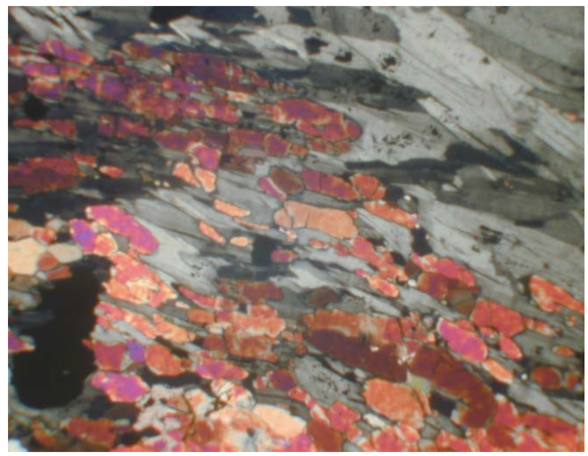


Figure 5. Amphiboles (tremolite or magnesio-cummingtonite) shown dismembered by gray chlorite crystals in sample SA-UM-1. Note the well-developed schistosity. Cross-polarized light, field of view ~2mm.

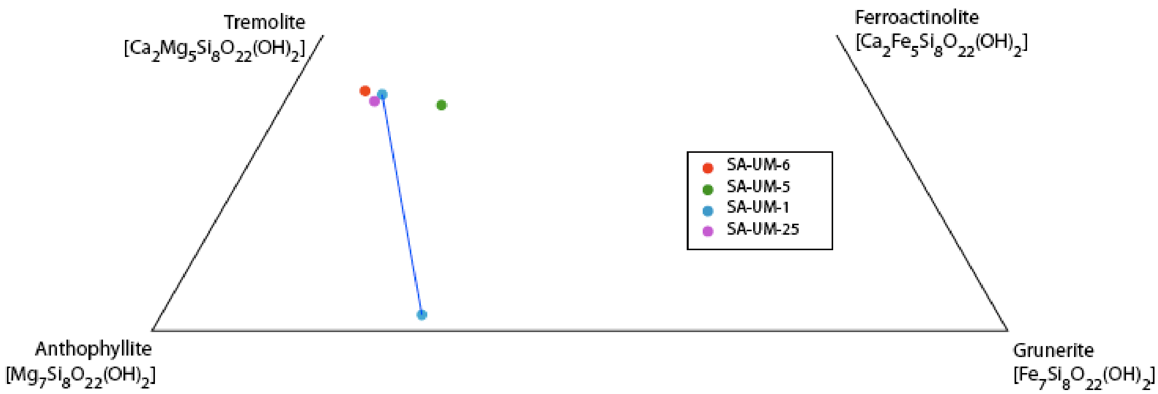


Figure 6. Amphibole quadrilateral showing selected amphibole compositions from the Salem ultramafic body. Tie line connects coexisting amphiboles in sample SA-UM-1.

Table 1. Microprobe analyses of selected amphiboles from the Salem ultramafic body.

Sample	SA-UM-5	SA-UM-5	SA-UM-5	SA-UM-5	SA-UM-5	SA-UM-25
SiO2	51.73	56.69	56.3	51.09	51.58	57.04
TiO2	0.1558	0.0695	0.1212	0.132	0.2522	0.068
Al2O3	4.67	0.8302	1.6621	6.57	5.5	0.7422
MgO	19.68	23.39	22.78	18.65	18.49	21.83
FeO	7.18	3.34	4.39	7.94	7.51	3.83
CaO	11.8	12.95	12.59	12.51	12.22	12.16
MnO	0.36	0	0.0603	0.0942	0.1371	0.0604
K20	0.0985	0.0429	0.0715	0.1104	0.0918	0.0286
Na2O	0.8302	0.1121	0.2907	1.2335	1.0008	0.156
Cr2O3	0.1758	0.1547	0.1185	0.2925	0.2928	0.0712
Total	96.69	97.59	98.37	98.62	97.08	95.99
name	ferrian-magnesio-hbd	tremolite	tremolite	magnesio-hbd	tremolitic hbd	tremolite

Table 2. Whole rock chemistry

	SA-UM-1	SA-UM-5	SA-UM-7	SA-UM-25	SLD-UM-2	SLD-UM-5	SU-UM-2011	(SU-UM) 2037	SU(UM) 2203	(SU-UM) 2094	(SU-UM) 2051	(SU-UM) 879A
SiO2	39.70	37.08	42.50	39.84	45.26	48.55	39.32	44	43.29	43.42	40.51	41.17
Al2O3	7.33	5.95	9.77	7.30	13.51	7.96	10.73	9.2	10.55	8.09	6.88	13.73
Fe2O3	12.35	11.12	11.57	13.08	12.66	9.81	11.45	9.8	9.16	14.11	10.4	11.14
MgO	27.68	26.42	20.76	27.03	8.87	20.24	22.91	26.83	21.96	22.34	30.58	20.75
CaO	4.42	7.15	6.97	4.80	15.58	7.42	5.87	2.99	7.44	4.58	4.6	6.14
Na2O	0.07	0.07	0.32	0.09	0.55	0.49	0.32	0.08	0.56	0.29	0.1	0.6
K2O	0.01	0.02	0.06	0.02	0.15	0.08	0.04	0.04	0.07	0.04	0.04	0.06
TiO2	0.39	0.38	0.48	0.45	0.64	0.14	0.40	0.36	0.34	1.02	0.15	0.55
P2O5	0.04	0.06	0.05	0.05	0.08	0.03	0.02	0.01	0.04	0.13	0.03	0.06
MnO	0.17	0.18	0.19	0.21	0.25	0.17	0.26	0.17	0.2	0.21	0.16	0.19
Cr2O3	0.373	0.319	0.304	0.323	0.094	0.312	0.314	0.25	0.244	0.217	0.391	0.179
Ni	1104	958	816	1071	170	621	743	341	722	728	1051	495
Sc	19	17	21	19	39	27	25	23	27	24	15	17
LOI	6.8	10.7	6.5	6.2	2.1	4.3	7.8	6.2	6	5.4	6	5.3
Sum	99.50	99.53	99.59	99.49	99.76	99.64	99.58	99.95	99.94	99.91	99.96	99.93

	SU(UM) 2174	(SU-UM) S188B	SU range	SA Range	SLD Range	Clemson Body WGC-1	Lherzolite	Plagioclase Lherzolite	Garnet Lherzolite	Peridotite	Greer Hollow UM Body	Buck Creek Dunite
SiO2	40.65	42.48	39.32-44.0	37.08-42.50	45.26-48.55	42.34	42.52	43.61	44.36	42.26	27.2	37.78
Al2O3	6.32	7.98	6.32-13.73	5.95-9.77	7.96-13.51	6.98	4.11	2.93	3.49	4.23	19.6	2.72
Fe2O3	11	10.54	9.16-14.11	11.12-13.08	9.81-12.66	13.11	11.78	1.09	8.29	10.19	35.3	13.08
MgO	29.21	26.03	20.75-30.58	20.76-27.68	8.87-20.24	27.42	28.37	39.86	39.38	31.24	10.4	46.07
CaO	4.62	5.23	2.99-7.44	4.42-7.15	7.42-15.58	5.7	5.32	2.66	2.96	5.05	0.6	0.34
Na2O	0.03	0.29	0.03-0.56	0.07-0.32	0.49-0.55	0.2	0.55	0.26	0.28	0.49	0.05	0.01
K2O	0.04	0.04	0.04-0.07	0.01-0.06	0.08-0.15	0.01	0.25	0.01	0.01	0.34	0.04	0.01
TiO2	0.31	0.24	0.15-1.02	0.38-0.48	0.64-0.14	0.3	0.42	0.06	0.12	0.63	0.95	0.01
P2O5	0.06	0.03	0.01-0.13	0.04-0.06	0.03-0.08	≤0.01	0.11	0	0.01	0.1	0.03	
MnO	0.17	0.14	0.14-0.26	0.17-0.21	0.17-0.25	0.26	0.17	0.11	0.14	0.41	10.4	0.16
Cr2O3	0.317	0.336	0.179-0.391	0.304-0.373	0.094-0.312	0.14						
Ni	975	671	341-1051	816-1104	170-621							
Sc	19	21	15-27	17-21	27-39							
LOI	7	6.5					1.07			3.91		3.77
Sum	99.81	99.93				96.7	94.67	100.5	101.99	98.85	99.8	100.17
						Warner et al, 1986	Le Maitre, 1976 Average of 179 lherzolites	Raymond, 1995	Raymond, 1995	Le Maitre, 1976 Average of 108 peridotites	Raymond, 1995	Peterson et al, 2009

DISCUSSION

Rutledge (2008) concluded that the protolith for the Salem body was most likely a peridotite of intrusive origin, whereas Bridgeman (2012) suggested a sub-oceanic mantle slab origin**.** According to Butcher and Grapes (2011), ultramafic rocks formed from fractional crystallization of gabbroic or basaltic magmas are relatively rare, and most of the ultramafic rocks are mantle fragments from either sub-oceanic crust, often lherzolitic in bulk composition, or mantle fragments from sub-contintental mantle, usually harzburgitic or dunitic in composition. Indeed, the whole rock chemistry of these samples is similar to published lherzolite compositions.

The Salem body rocks are very similar to the Clemson Group of ultramafics, studied by Warner et al. (1986). Butler (1989) summarized the Clemson Group as widely distributed bodies of two main types: altered dunite or chlorite-amphibole schist. The altered dunite bodies have retrograded to a point where the olivine has either been partially or completely replaced by talc, actinolite-tremolite, chlorite, and serpentine. He notes that the main difference between the two types may be the degree of deformation and alteration (Butler, 1989). The Clemson bodies are spatially close to the body in this study, contained in adjacent or proximal quadrangles to the Salem quadrangle. Warner and others (1986) concluded that the Clemson Group bodies had a probable protolith of lherzolitic composition or a hornblende- or plagioclase-bearing peridotite, which fits well with the proposed protolith of the Salem body of this study.

Bridgeman (2012) suggested a model of emplacement for the Salem body that began with a lherzolite or plagioclase-lherzolite protolith from a mantle derived sub-oceanic crustal setting. This lherzolitic protolith underwent sea-floor hydrothermal metamorphism in which the olivine, pyroxene, and plagioclase recrystallized to chlorite and actinolitic amphibole. The bodies were then tectonically emplaced. Subsequent faulting, folding, and amphibolite facies metamorphism dismembered the obducted slab of lower oceanic crust and mantle. As temperature and pressure ramped up, chlorite remained stable as a result of its high Mg content and the amphiboles became more aluminous, some eventually stabilizing as hornblende.

These conclusions are supported by the studies of the amphibolites of the Walhalla nappe and Six Mile thrust sheet by Prince (2004) and Strom (2005), which enclose the Salem body ultramafic rocks. Their results revealed a tholeiitic composition for the amphibolites and pointed to an origin as either a mid-ocean ridge basalt or an island arc basalt. The presence of oceanic crustal basalts in the same geologic terrane and in close proximity support the claim of a dismembered ophiolite or sub-oceanic mantle underpinnings related to obducted oceanic crust.

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THE EFFECT OF DAM REMOVAL ON TRANSPORT OF SEDIMENT IN TWELVE-MILE CREEK, PICKENS COUNTY, SOUTH CAROLINA

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ABSTRACT

Two dams on Twelve-Mile Creek were removed in 2011 as part of a Superfund remedial action involving PCBs in Lake Hartwell. The purpose of this study is to examine sediment transport following removal of Woodside II dam in July 2011. The approach was to measure the volume of sediment stored in selected reaches as a function on time. This was done by identifying five reaches, establishing benchmarks at each reach, and making topographic surveys of the streambed and bank. A measuring rod and hand level were used to survey a bank of sand in the site of the former impoundment upstream from the former dam. Four observation sites are located downstream from the former dam and were surveyed over multiple transects using a laser level. The initial survey was made June 2011, and additional surveys were made every month or two since then. Elevation data from each survey were integrated and the surfaces were subtracted from the initial topographic surface to estimate the volume change. The volume change was divided by the area of the streambed to estimate the average change in the height of the bed.

The sand bed upstream from the former dam was roughly level, more than 1 m thick and more than 10 m wide. During the first survey the initial volume was estimated to be more than 25000 m^3. After 3 months more than 8000 m^3 had been eroded, and after 8 months the eroded volume roughly doubled. The first measurement station downstream from the dam had an average bed elevation increase of roughly 1 m. Most of sand appears to be within 1 km downstream of the dam as of June 2012.

INTRODUCTION

Twelve-Mile Creek near Clemson, SC has been the focal point of community interest and an EPA Superfund project in recent years as PCB-contaminated sediment is remediated (Brenner and others, 2004). As part of the final step in the EPA's remediation plan two dams located on the creek were removed. The goal for the removal of the dams was to release clean sediment to overlie and isolate the remaining contaminated sediment in Lake Hartwell. After this stage the environmental system will be monitored during natural recovery. When a dam is installed the natural flow is disrupted, allowing sediment to settle out of the water and accumulate upstream behind the dam (Williams, 1977). After a dam is removed there is an increase in shear stresses attributed to the drop in the water level. These stresses cause sediment behind the dam to be eroded. The stream channel cuts down through the sediment and removes it until eventually reaching a new state of dynamic equilibrium (Doyle and others, 2002).

Monitored natural recovery is a method of reducing the risk contaminated sediment presents by using natural processes to contain, destroy, or reduce the bioavailability and toxicity of contaminants in sediment (Magar and Wenning, 2006). In this process clean sediment will overly the remaining contaminated sediment and hopefully effectively separate the hazardous properties from the environmental system.

Woodside II dam was removed in June 2011 as part of the remediation plan for Twelve-Mile Creek. The main objective for this project is to characterize how the sediment moves after the removal of the dam. The approach has been to make topographic surveys of the streambed at five sites at multiple times and calculate the change in volume of sediment upstream and downstream from the dam.

STUDY SITE CHARACTERISTICS

One study site is located upstream from the former dam area, and four sites are downstream to emphasize the redistribution of the impoundment. Site A stretches for 820 m upstream of the former dam (Fig. 1), with an average width of 31 m. Sand was absent from the area between the dam and Site A during our first measurement, and it may have been removed by dredging prior to removal of the dam.

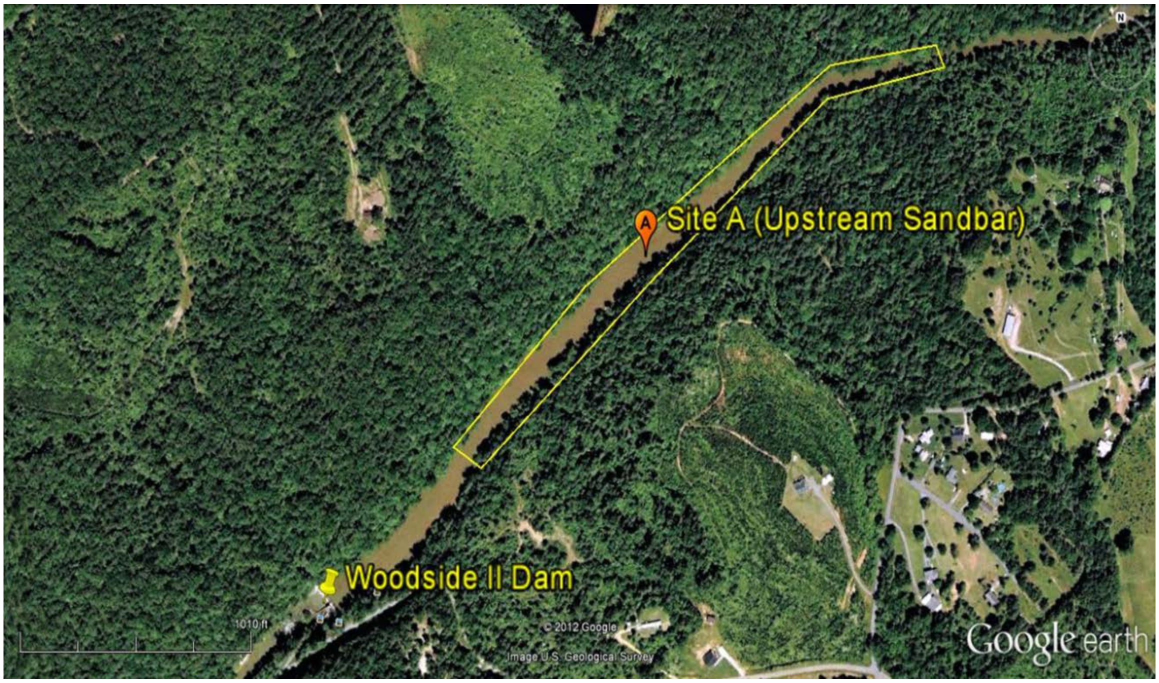

Figure 1. Location of the sand deposit at Site A upstream of the Woodside II dam near Norris, SC.

Site B (Fig. 2) is the site closest to the former location of the dam. It is located on a bend in the channel where the water flows at the highest velocity of any of the study areas. Site C is located on a straight reach of the creek where the flow velocity has greatly decreased from Site B. Site D is located along a sharp bend in the channel where a notable cut bank and point bar occur. Site E, the farthest downstream and closest to Lake Hartwell, has the slowest flow velocity and greatest average width. Benchmarks were selected at each survey location. A point on a large boulder or prominent tree was selected and used each time a survey was made.

The study sites range from 0.24 km upstream to 3.6 km downstream of the dam (Table I). The sites downstream from the dam cover lengths of several tens of meters, but the upstream site (Site A) is much longer. Also, it is important to notice that Site E was added late in the study, approximately 5 months after the first sites were surveyed. When the initial measurements of Sites A-D were taken the water level in the area of Site E was too deep to collect data.

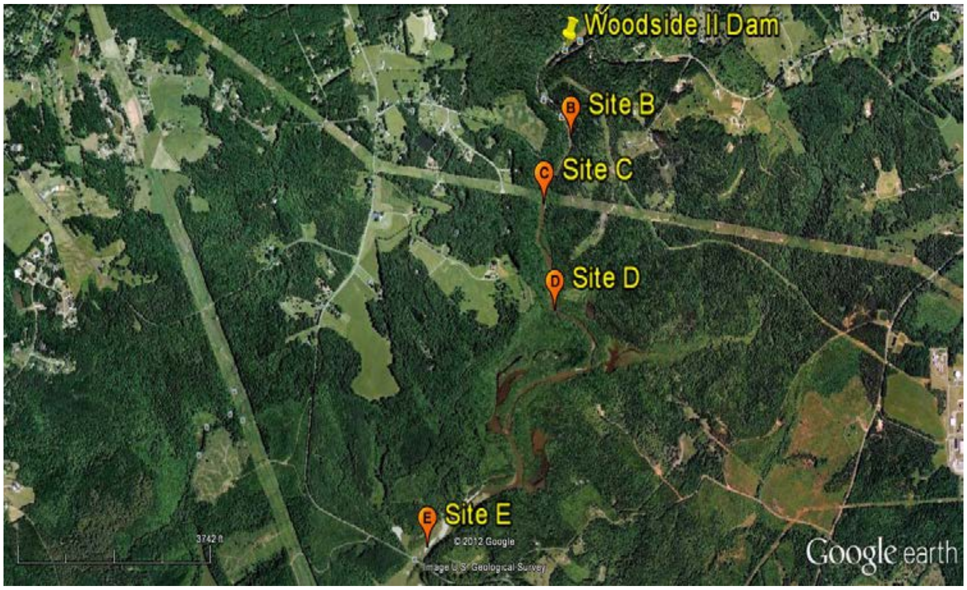

Figure 2. Locations of the study sites on 12-mile Creek, Pickens County, SC.

Table I. Locations and specifications of study sites.

	Distance (km)	Reach Length (m)	Width (m)	Date of Initial Measurement
Site A	-0.24	820	31	October 2011
Site B	0.6	40	26	June 2011
Site C	1.0	45	29	June 2011
Site D	1.6	30	23	June 2011
Site E	3.6	55	52	November 2011

METHODS

The sites were surveyed from June 2011, one month prior to removal of the dam, to June 2012. The team that was surveying the sites would measure a series of topographic profiles of the streambed at each site. The data at Site A, located upstream, was collected using a measuring tape, hand level and stadia rod. A reach of the sandbar (15 m long) was measured, and a measurement was also taken across the width of the valley (former impounded area). These two measurements in addition to a thickness of the sandbar allow approximate volumes to be calculated. Topographic profiles were measured at 30-m intervals unless there was a large change in the sediment, topography, or other feature. This resulted in approximately 35 profiles in Site A. The depositional sites downstream were surveyed by measuring 3 transverse profiles spaced approximately 10 m apart (Fig. 3). A Topcon RL-H3CL rotating laser was used to obtain the elevation profiles in relationship to the base point at each site. The laser was set up on a tripod and a measuring rod was coupled with a laser receiver to obtain an accurate height. We would generally make measurements every 3 m along a profile, although more closely spaced measurements were made where the bed topography changed sharply. All elevations for a site were then related to the elevation of a base point (Fig. 3).

The elevations at each site were integrated to obtain a volume of sediment relative to the site benchmark, and this volume was normalized to the area of the site to obtain an average sediment depth. Change in sediment depth relative to the initial measurement was used to characterize erosion or deposition.

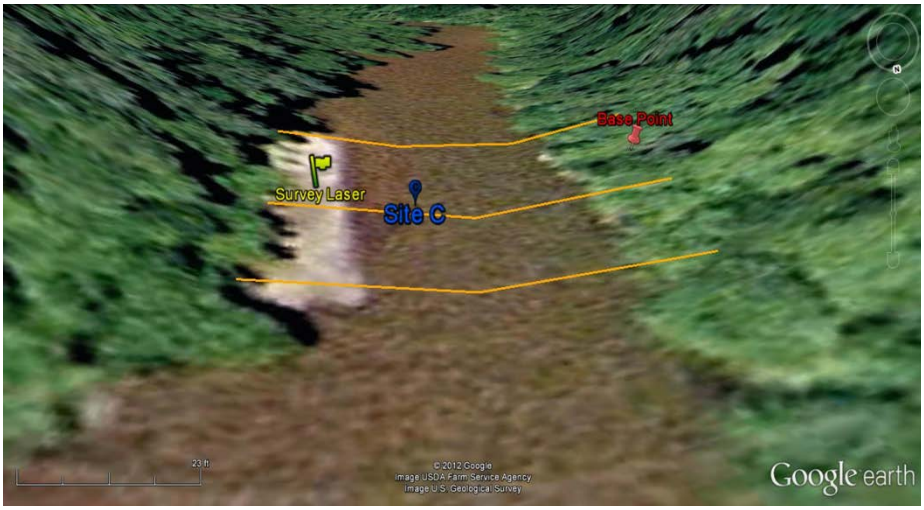

Figure 3: Profile lines for surveying and benchmark base point at Site C.

RESULTS AND CONCLUSION

Sediment was eroded from Site A, and the average height of the bed was reduced by approximately 1 m over the first 6 months of monitoring. Sand was deposited predominantly at Site B, where the average height of the bed increased by 0.9 m (Fig. 4). Bed elevations were variable at Site C, 1 km from the dam (Fig. 4, Table II), with erosion occurring during August through September, followed by deposition of up to 0.4 m of sediment through the winter. Sediment levels dropped during the last measurement. This could indicate erosion in the summer, following a pattern similar to the previous summer. The elevation at Site D was roughly constant until the last two measurements during March and June. Increases in bed height of roughly 0.1 m were measured during these two sampling times. (Fig. 4). The site closest to Lake Hartwell, Site E, was added late into the study, and only three measurements were taken. In the month of February there was slight amount of sediment deposited, followed by erosion in March. In June deposition occurred again.

The general finding of the study is that the majority of the sediment that was in the impounded area behind the dam was removed within 1 year. This resulted in significant increase in height of the streambed due to accumulation of sediment within 0.6 km downstream of dam site. The increase in sediment started soon after the dam was removed and may have stabilized between the March and June measurements, roughly 7 to 10 months after the dam was removed.

Some sediment appears to have accumulated further downstream, but the details depend on the location. Site C is the most dynamic, with increases of 0.3 and decreases of -0.5 m of average height. In general, sediment does not appear to be accumulating at Site C. In contrast, sediment may be accumulating at Site D, with increases in bed height of 0.1 m or more, 1.5 km from the dam site. It is possible that some sediment has arrived at Site D, 3.6 km from the dam, but the data are too sparse for this to be conclusive.

The bulk of the sediment that was initially behind the dam appears to have moved 1 km or less since August 2011. At this rate, it appears that several more years will be required before this sediment reaches the lake where it can contribute to the PCB remediation effort. The streambed is largely sand, and it is possible that finer-grained sediment fractions have already arrived at the lake.

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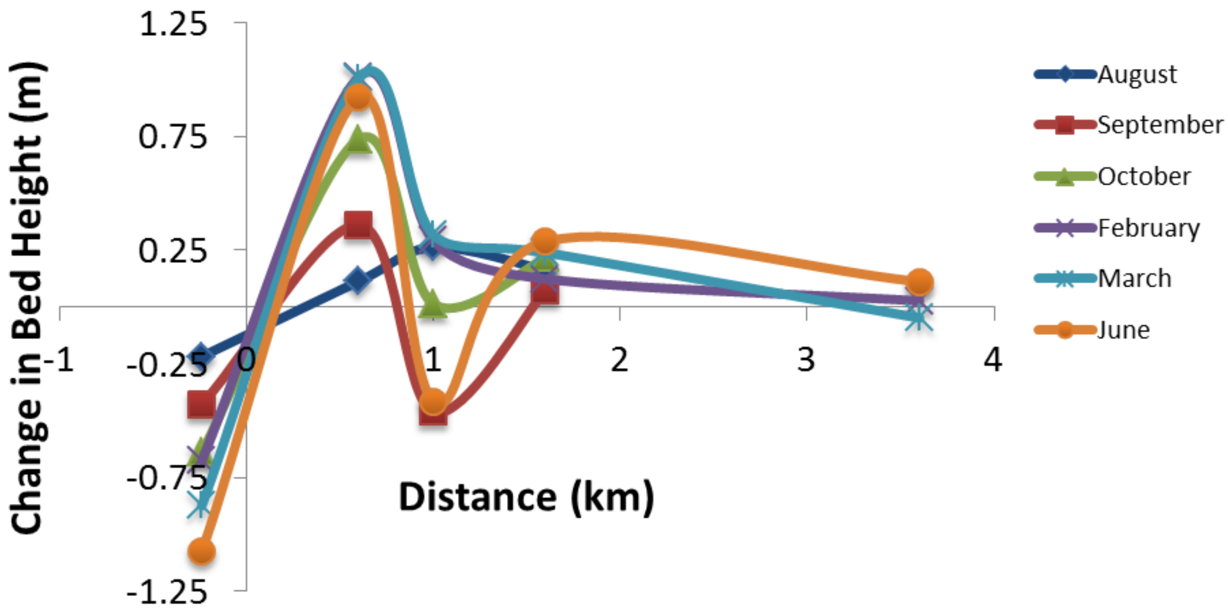

Figure 4: Change in average height of the streambed as functions of time and distance downstream from Woodside II dam. Data from August 2011-June 2012.

Table II. Change in average bed height at survey locations, determined as the difference between the first and last measurements. Three out of the four sites (Sites B, D, and E) indicate sediment accumulation; deposition and erosion have occurred at Site C.

	Distance (km)	Reach Length (m)	Width (m)	Date of Initial Measurement	Δheight in Sediment (m)
Site A	-0.24	820	31.1	October 2011	-1.08
Site B	0.6	40	26	08 June 2011	0.93
Site C	1.0	45	29	08 June 2011	-0.42
Site D	1.6	30	22.8	08 June 2011	0.29
Site E	3.6	55	52.4	01 Nov 2011	0.11

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CONNECTIONS BETWEEN GEOLOGY AND PLANT COMMUNITIES

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Botanists have long recognized the connection between plant occurrences and substrate geology and typically include either general site geology or regional geologic information in plant survey and other biological literature. Plants have adapted and are adapting to variable soil chemistry that is derived from substrate lithologies and/or sediments and aqueous solutions transported locally or from afar. Some plant species, called specialists, occur exclusively in habitats with soils derived from specific rock types. Non-specialist plants, called cosmopolitans, occur in habitats with different substrates. Where vigorous specialists are observed in a habitat, the substrate can be inferred as occurring directly below or close by. Infrequent and stunted plant species may be encountered within a substrate that does not readily support the specialist.

Along a transect where variable substrate lithologies are exposed, different plant specialists occur that reflect the different minerals and soils produced by the weathering of a particular rock type. Plant specialists and the soils in which they reside cane be used as indicators of substrate when outcrops are few or absent. Lithologic contacts are sometimes slightly to moderately blurred by the effects of local topography, hydrology, sedimentation, or metasomatism in metamorphic terrain. Human land use may significantly modify and even preclude making geologic/plant correlations where soil profiles have been lost, depleted, or artificially amended.

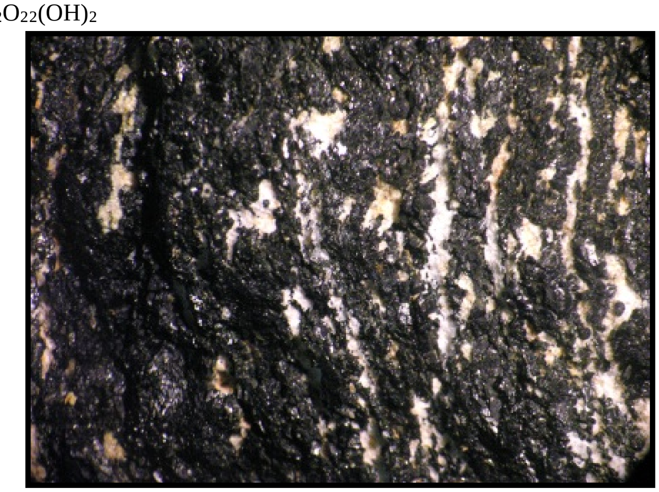
BEDROCK MINERALOGY

Bedrock mineralogy is the primary source of surface soil. The composition and characteristics of the soil directly influences the variety of organism and the habitat composition. The Inner Piedmont of South Carolina is underlain by felsic, mafic, and intermediate metamorphic rocks composed chiefly of alumino-silicate minerals. Mineralogy of rock units varies primarily in metal content and metals are key components in soil character development we well as plant community structure and vigor. Below is a list of the general mineralogy of three rock types that will be encountered in this field trip. The percentages of metals in minerals in these rocks vary and thus influence the characteristics of soils they produce and the availability of plant nutrients. In general, mafic rocks produce richer soils and higher plant diversity compared to felsic rocks.

Dominant rock types encountered in the field trip area

<u>Poor Mountain Amphibolite (mafic)</u>

Hornblende….$(Ca,Na)_{2-3}(Mg,Fe,Al)_5\ Si_6(Si,Al)_2O_{22}(OH)_2$
Anorthite….$CaAl_2Si_2O_8$
Quartz….SiO_2
Biotite….$K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$
Epidote….$Ca_2(Al,Fe)Al_2O(SiO_4)(Si_2O_7)(OH)$



Henderson Gneiss/Table Rock gneiss (felsic)

Orthoclase....$KAlSi_3O_8$
Quartz….SiO_2
Muscovite….$KAl_2(AlSi_3O_{10})(OH)_2$
Biotite….$K(Mg,Fe)_3(AlSi_3O_{10}(OH)_2$

Chauga River Formation (intermediate)

Muscovite….$KAl_2(AlSi_3O_{10})(OH)_2$
Biotite….$K(Mg,Fe)_3(AlSi_3O_{10}(OH)_2$
Almandine….$Fe_3Al_2Si_3O_4$
Orthoclase....$KAlSi_3O_8$
Quartz….SiO_2

WEATHERING

Substrate weathering is both mechanical and chemical. It depends on the availability of water and its acidity, oxygen, carbon dioxide, nitrogen, micro-organisms, higher organisms, and humus. Mineral components of rocks weather at different rates.

In a mature forest setting weathering results in a soil profile depicted below. Many components of soil, including solids, dissolved ions, and molecules are mobile in the soil column both vertically and laterally. Plants absorb nutrients from the soil for metabolism and growth and return those nutrients initially as leaf litter and dead plant stems. Since lants can only absorb simple mineral compounds and ions, the organic molecules and complex minerals must be decomposed to make them available for uptake by plants. Weathering proceeds through the formation of new minerals, acids, bases, and oxides, the release of stable minerals (mainly quartz), and ultimately exchangeable cations and anions that are available to plants.

Rock Type	Weathering Potential
quartz and muscovite	very slow
feldspars and biotite	slow
calcite, hornblende, and augite	rapid

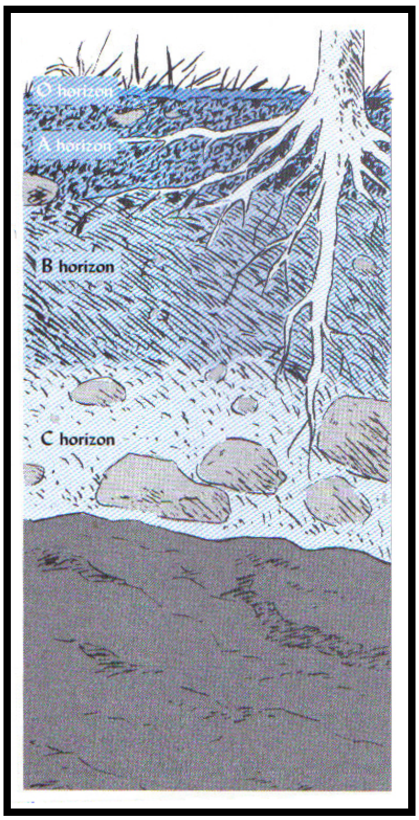
The activities of soil micro-organisms and fungi are largely responsible for late stage chemical weathering and the recycling of dead organic matter. In mature O and A horizons in a forest (see figure below), upwards of 11 trillion micro-organisms exist in a space of one square meter that is 15 centimeters deep. These organisms consume and decompose dead organic matter and change organic molecules into molecules and ions. The byproducts of micro-organism activities are organic acids that cause the breakdown of clays and the release of ions strongly bound to clays.

In a mature soil profile, cation concentration is highest in the A horizon, and some of those cations migrate down into the B horizon where most are bound to clays. In this situation, surplus cations buffer the pH of the B horizon in an upward direction.

If the O and A horizons, including most micro-organisms, are removed through erosion or human development, the pH and richness of the surface soil will be lowered, and the occurrences of substrate specific plants will be strongly decreased. This is particularly true in mafic substrate terrain.

Mafic rocks produce circum-neutral pH soils and felsic rocks produce strongly acidic soils. The soil components most responsible for pH are acidic metals (Al) and alkaline metals (Ca, Mg, Mn, Na, and K). The relative proportions of these metals in the substrate mineralogy determine soil pH. Surface soil characteristics are a function of soil maturity and disturbance.

Plant specialist species that require strongly acid soils are called **acidophiles**, and specialist species that require low acidity or circum-neutral conditions are called **calciphiles**. Plants that occur in many different substrate terrains are **cosmopolitans**. The following pages contain photos of specialist species that are likely to be observed in felsic or mafic terrains.



Felsic Terrain Plant Indicator Species

Royal Fern
Osmunda regalis

New York Fern
Thelypteris noveboracensis

Robin's Plaintain
Erigeron pulchellus

Mountain Laurel
Kalmia latifolia

Canadian Hemlock
Tsuga canadensis

Catesby's Trillium
Trillium catesbaei

Azaleas
Rhododendron spp

Pines
Pinus spp

Cinnamon Fern
Osmunda cinnamomea

Xanthorhiza simplicissima

Blueberry
Vaccinium spp

Indicator species: Felsic terrain, low pH 4.6-5.2

Mafic Terrain Indicator Plant Species

Acute leaf Hepatica
Hepatica acutiloba

Northern Maidenhair Fern
Adiantum pedatum

Narrow Glade Fern
Diplazium pycnocarpon

Paw Paw
Asimina triloba

Redbud
Cercis canadensis

Wild Geranium
Geranium maculatum

Spice Bush
Lindera benzoin

Broad Beech Fern
Phegopteris hexagonoptera

Blue Cohosh
Caulophyllum thalictroides

Bloodroot
Sanguinaria canadensis

Trillium rugelii

Allegheny Spurge
Pachysandra procumbens

Indicator species: Mafic terrain pH 6.5-7.0+

SOIL pH AS A PROXY FOR SUBSTRATE LITHOLOGY

pH is the negative logarithm of the H^+ ion concentration in soils on a scale of 1 to 14. Another way to express pH is the relative proportions of H^+ and OH^- ions in soils. Soils with a pH range of 1 to 6.99 are acidic, those with a pH of 7.01 to 14 are alkaline, and those with a pH of 7 are neutral. The pH of soils in the Carolinas ranges from ~4.5 to 7.2, with values above 7.2 only around marble outcrops and shell middens.

Soil pH is determined by the chemical composition of substrate lithology, substrate weathering, hydrology, the activities of soil micro-organisms and fungi, resident plants and animals, climate conditions, and site history. Foremost in soil pH formation is the relative quantity of acidic metals (primarily Al and Si) and alkaline metals (Ca, Mg, Na, K, and Mn) in the parent rock. Acidic cations such as Al^{+3} readily exchange with H^+ ions in the soil solution and act to increase H^+ concentration and acidity. Alkaline cations such as Ca^{+2} attract OH^- ions and raise alkalinity. When there is a balance in acidic and alkaline metals in a lithologic unit, the resultant soil pH will be circum-neutral. Imbalance will produce either acidic or alkaline soil.

Since weathering progresses in stages, different layers in a soil profile can have a different pH. These differences are summarized in Table 1. Because of the activities of soil micro-organisms, a mature A horizon contains the most exchangeable cations for affecting pH and providing plant nutrients. B horizon soils typically have a lower pH.

In mature habitats with either mafic or felsic substrates, A horizon soils are dark gray to black colored and thick due to the high concentration of humus. An A horizon soil with a mafic substrate will have a soil pH of 6.4 to 7.2 depending on the amount and composition of mafic minerals. The pH of B horizon soil will be in the range of 5.8 to 6.0. In a felsic terrane, A horizon soils will have a pH of 4.8 to 5.1 depending on the proportions of feldspar, quartz, and micas. The B horizon pH will be only slightly different. The presence of epidote in felsic rocks will increase soil pH by a few tenths.

In a disturbed area where the A horizon is essentially absent, surface pH will be substantially lower above mafic rocks (~5.5). This occurs because basic cations are bound to clays and colloids and there is a paucity of soil micro-organisms. The soil micro-organisms are the agents responsible for releasing ions from the mineral matrix. In disturbed felsic terranes, surface pH will be similar to mature A horizon pH.

Soil texture and color are also correlated with substrate lithology in disturbed areas. B horizon surface soils above mafic rocks will typically be dominated by dense red clay with sparse quartz sand. B horizon surface soils above felsic rock will be sandy and light to medium tan or reddish.

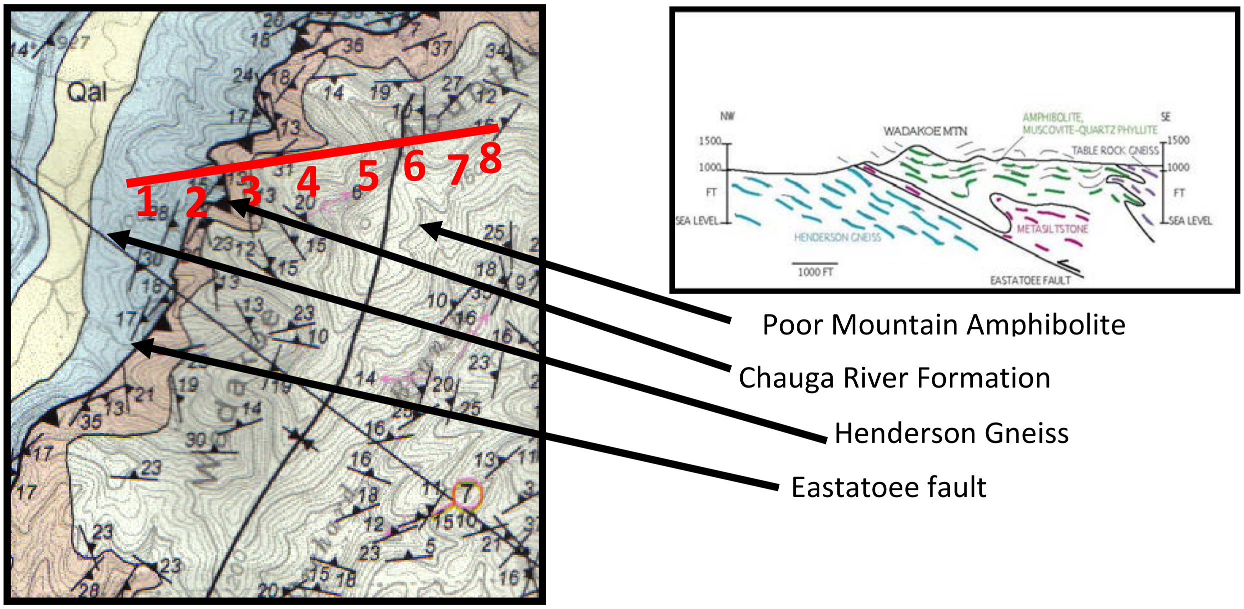
In an area with variable lithologies and scarce outcrops, soil can be physically examined and pH determined and this will often reveal substrate lithology. In some cases though, soil characteristics and plant specialist occurrences do not correlate with nearby outcrops. These anomalies likely indicate the presence of a nearby lithologic boundary, rock units with variable mineralogy, discrete pods or layer, or where ions have migrated downslope or persist from overlying rocks that have been removed by erosion or man.

Table I. Differences in soil pH as a function of horizon integrity

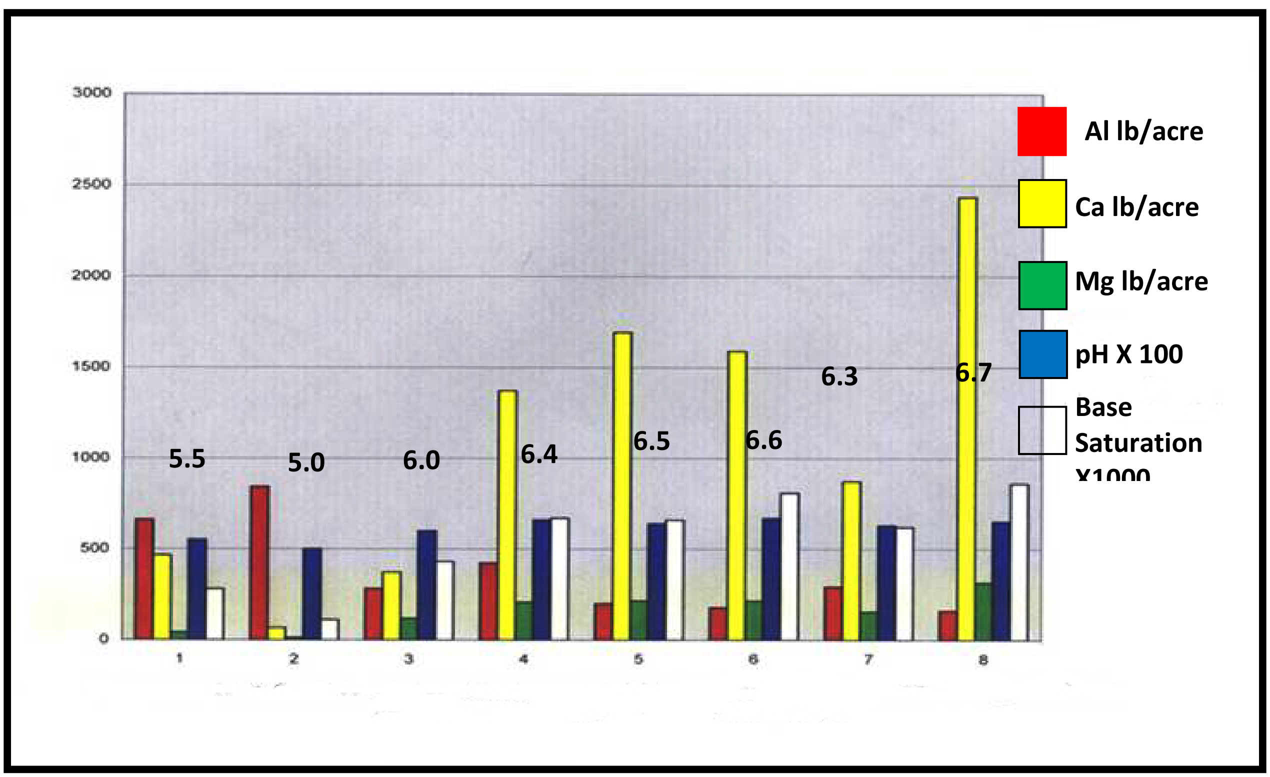
Substrate	Soil Horizon	pH	Color
Felsic	Mature A horizon	4.8-5.1	dark gray to black and humus rich
	B horizon pH below mature A horizon	4.8-5.1	medium tan to reddish and sandy
	B horizon pH with absent A horizon	4.8-5.1	light to light reddish and sandy
Mafic	Mature A horizon pH	6.4-7.2	dark gray to black and humus rich
	B horizon below mature A horizon	5.8-6.0	red clay dominant
	B horizon pH with absent A horizon	~5.5	red clay dominant
Intermediate	Mature A horizon pH	5.7-6.3	dark gray to black and humus rich
	B horizon below mature A horizon	5.3-5.7	depends on biotite content
	B horizon with absent A horizon	5.2-5.6	depends on biotite content

SOIL ANALYSIS TRANSECT

A 1400 meter long soil analysis transect was conducted on the northwest side of Wadakoe Mountain. Samples of the A soil horizon were collected at approximate intervals of 200 meters. The transect began in the Henderson Gneiss, crossed the Eastatoee fault into the Chauga River Formation, and ended below the summit of Wadakoe Mountain in the Poor Mountain amphibolite. The graph shows significant changes in pH, base saturation, and Al, Ca, and Mg concentrations.



Soil analyses for samples collected along the northwest side of Wadakoe Mountain



NEW GEOLOGIC MAPPING OF THE HORSE SHOE, PISGAH FOREST, AND BREVARD QUADRANGLES, HENDERSON AND TRANSYLVANIA COUNTIES, NORTH CAROLINA, GREENVILLE COUNTY, SOUTH CAROLINA: A PRELIMINARY REPORT

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INTRODUCTION

This paper summarizes the North Carolina Geological Survey's (NCGS) field mapping activities in the Horse Shoe (2007-2008), Brevard (2010-2011), and Pisgah Forest (2011-2012) quadrangles, Henderson and Transylvania Counties, NC, and Greenville County, SC. These quadrangles were completed under the auspices of the National Cooperative Geologic Mapping Program, STATEMAP component administered by the United States Geological Survey. The generalized geologic maps and cross sections for these quadrangles are shown in Figures 1A and 1B, respectively.

The NCGS identifies quadrangles to be mapped in the STATEMAP program based on criteria including population, projected population growth, status of existing geologic mapping, access to transportation corridors, water supply considerations, requests from municipalities or other governmental agencies, and economic resources. The Horse Shoe, Brevard, and Pisgah Forest quadrangles are within commuting distance of the population centers of Asheville, Brevard and Hendersonville, areas of expanding growth with development extending into the surrounding rural countryside. Other than mapping by Worley (2000) in a portion of the Pisgah Forest quadrangle, these quadrangles had little detailed geologic control but were bordered by published maps of Standingstone Mountain (Garihan and Ranson, 2007), Zirconia (Garihan and Ranson, 2008), Fruitland (Lemmon and Dunn, 1973), Skyland (Dabbagh, 1981), Rosman (Horton, 1982), Eastatoe Gap (Garihan and others, 2005) and Table Rock (Garihan and Ranson, 2003). Additional detailed geologic mapping on bordering quadrangles includes: Hendersonville (Lemon, 1978), Dunsmore Mountain (Dabbagh, 1976), Cruso (Morrow, 1978), and Shining Rock (Acker, 1982).

During the course of the mapping these three quadrangles, over 9,500 structural measurements were collected at over 5,300 stations. These data are georeferenced and available to anyone with an interest in the geology of the region. The mapping area includes parts of three distinctive geologic domains: 1) The eastern Blue Ridge province; 2) the Brevard Zone; and 3) Paleozoic granitoids and metasediments of the western Inner Piedmont.

EASTERN BLUE RIDGE

Within the study area the eastern Blue Ridge (EBR) is comprised of rocks of the Ashe Metamorphic Suite-Tallulah Falls Formation (AMS-TFF) that have been variably intruded by Paleozoic granitoid bodies. The AMS-TFF is structurally the lowest of the rock packages in the map area. Map units identified within the AMS-TFF include metagraywackes, schistose metagraywackes, and schists, with minor interlayers of amphibolite, calc-silicate and altered ultramafic assemblages. These rocks are interpreted to be a thick sequence of metamorphosed sandstones, siltstones, and shale along with basalt flows and tectonically emplaced oceanic crust (Rankin and others, 1973; Abbott and Raymond 1984; Hatcher and others, 1984). AMS-TFF protoliths were metamorphosed to upper-amphibolite facies within the study area. Many outcrops are migmatitic. Mylonitic fabrics attributed to the Brevard fault are dominant in these rocks within 700 m northwest of the Brevard Zone, and consistently present within 4,000 m northwest of the Brevard Zone.

Metamorphic ages of detrital monazite and zircon grains from AMS-TFF within the EBR are dominantly ca 450 Ma (Moecher and others, 2011). Crystallization age dates from regional trondhjemite dikes that cross-cut metamorphic layering range from 420 to 400 Ma (Mapes, 2002; Miller and others, 2000; Kish and others, 1975). We therefore interpret that the dominant metamorphic fabrics and peak metamorphism of the AMS-TFF in the eastern Blue Ridge to be the result of middle Ordovician Taconian orogenesis.

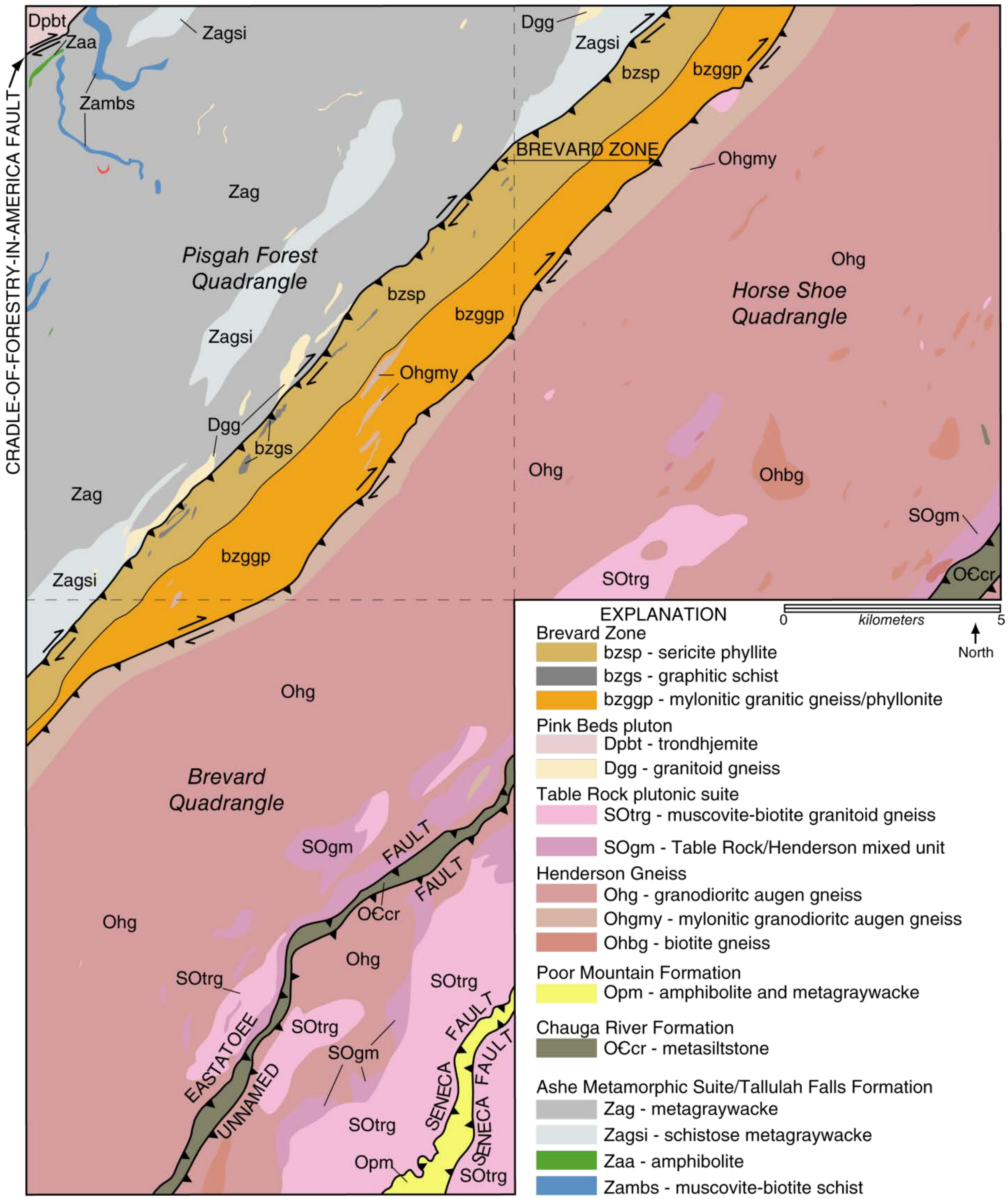

Figure 1A. Generalized geologic map of the Horse Shoe, Pisgah Forest, and Brevard quadrangles, NC-SC. Geology by Bart Cattanach, Nick Bozdog, Rick Wooten, Carl Merschat, and Brad Worley.

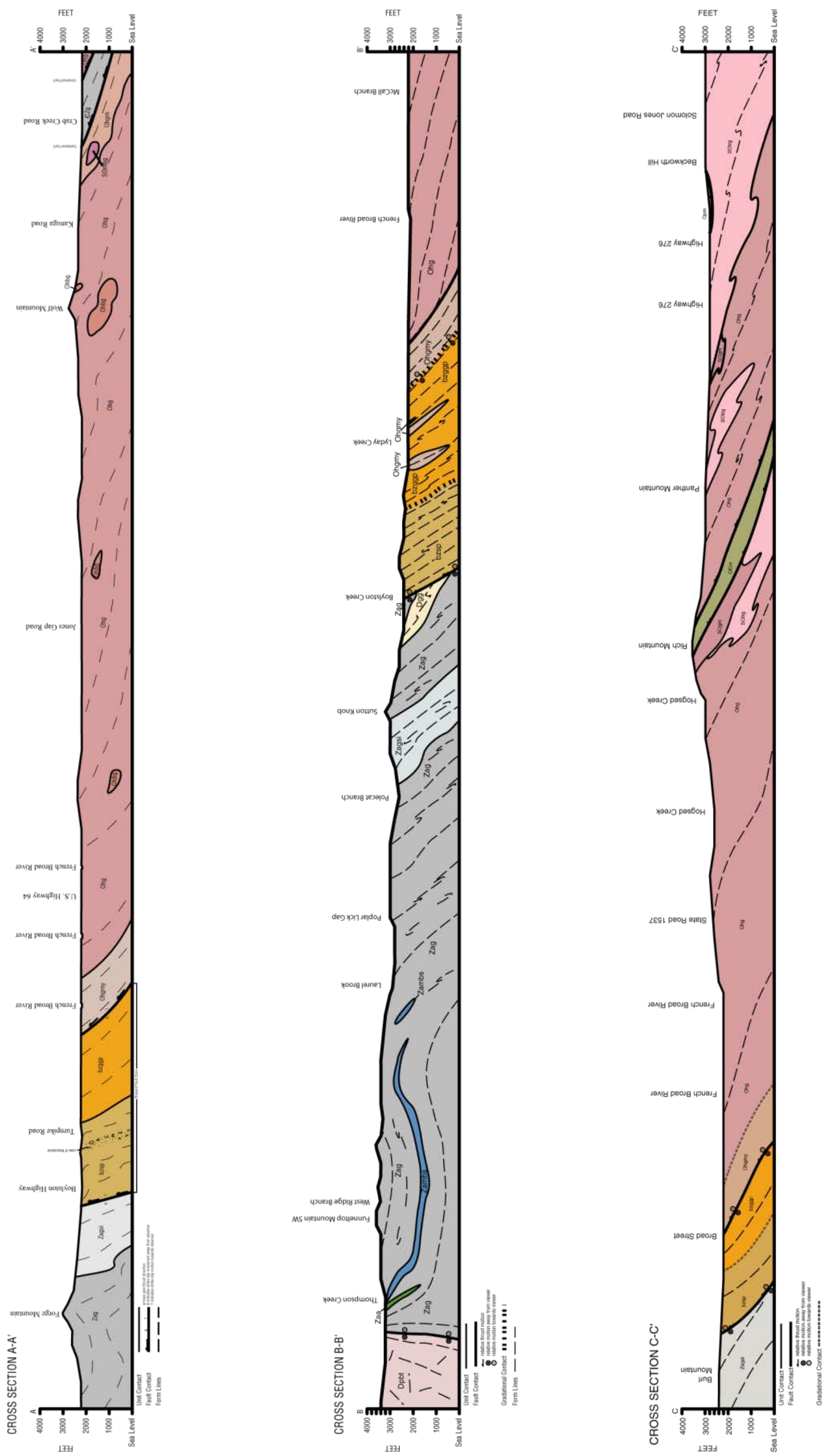

Figure 1B. Geologic cross-sections for the Horse Shoe (A-A'), Pisgah Forest (B-B'), and Brevard quadrangles (C-C'). See Figure 1A for map unit explanations.

Map units were delineated based upon the predominant rock type observed in the field. It should be noted that the AMS-TFF is very heterogeneous and almost all other rock types within the AMS-TFF may be interlayered within a given unit. For example, it is not uncommon to find a unit composed predominantly of metagraywacke but with scattered outcrops of schistose metagraywacke, garnet-mica schist, and amphibolite.

Outcrops of the main body of the Pink Beds pluton (Dpbt) and scattered smaller bodies of granitoid intrusive were mapped in the NW corner of the Pisgah Forest quadrangle. The Pink Beds pluton is typically trondhjemitic in composition and has reported crystallization ages of 388 +- 5 Ma (Miller and others, 2000) and 371.3 +-4.2 Ma (Jubb, 2010). Weak NE-SW trending foliations were observed in the Pink Beds Pluton outcrops in the field area and are interpreted to reflect late Devonian to Mississippian deformation relating to Neoacadian-Acadian orogenesis.

The contact between the Pink Beds pluton and the AMS-TFF is unexposed or buried by colluvium on the Pisgah forest quadrangle but is reported to be the Cradle-of-Forestry-in-America (CFA) fault, a polyphase ductile and ductile-brittle dextral strike-slip fault active during Neoacadian and/or Alleghanian events and present in the Shining Rock and Pisgah Forest quadrangles (Dockal, 2007). Jubb (2010) reports that the CFA fault in the Shining Rock quadrangle extends southwest into the Lake Toxaway quadrangle. The presence of mylonitic fabric and mylonitic granitoid gneiss in the contact area of the Pink Beds pluton and the AMS-TFF leads us to believe the Cradle of Forestry in America fault is present in the Pisgah Forest quadrangle. The outcrop pattern of folded schist units in the northwest corner of the Pisgah Forest quadrangle could be interpreted as the CFAA fault truncating the northwest limb of a northeast-plunging synform. This synform is part of a complimentary synform-antiform structure interpreted to be the northeast extension of similar folds in the Shining Rock quadrangle (Acker, 1982, and Dockal, 2007).

New mapping has also identified a cross-cutting granitoid unit within the AMS-TFF along and/or near the contact with the Brevard Zone (Dgg). It is medium- to coarse-grained, granoblastic to well-foliated to mylonitic, and trondhjemtic to granitic in composition (Fig. 2). The bodies range in size from less than a meter to over 40 meters thick in some outcrops. We do not yet have absolute age data for this granitoid but it cross-cuts fabrics probably of Taconian age within the AMS-TFF. Additionally, it appears to be overprinted by Late Paleozoic Brevard Zone deformation which suggests an Acadian-Neoacadian crystallization age and possible correlation with the Pink Beds and Looking Glass plutons.

Figure 2. Granitoid gneiss (Dgg) cross-cutting the dominant foliation in AMS-TFF schistose metagraywacke in the Pisgah Forest quadrangle Location: long. -82.6839, lat. 35.2967.

BREVARD ZONE

Much work has been done on the Brevard zone over the years by numerous workers. Although a formalized stratigraphy of Chauga River Formation rocks exists for the Brevard Zone farther to the SW (Hatcher, 1969) we have not connected our units to these with detailed mapping. For this reason we have assigned units within the Brevard Zone informal lithologic names (bzsp, bzm, bzgs, bzggp). This does not represent disagreement with previous workers but rather an uncertainty that will hopefully be cleared up by future work.

The Brevard zone within the map area is defined by two main structural packages. The first package consists of an internal stratigraphy of greenschist to lower amphibolite facies metasedimentary phyllites, schists, graphitic schists, arkoses and marbles (Fig. 3-5). These rock types are correlatives with metasediments identified within the BZ to the SW. Conrad (1960) reported two locations of marble workings in the area; however, outcrops of marble at these locations could not be located. Dolomitic marble and graphitic schist well cuttings

(Fig. 5) from beside Boylan Creek indicate that the marble is structurally below the graphitic schist unit (bzgs) within the Brevard Zone.

Figure 3. Brevard Zone mylonitic meta-arkose and phyllite in the Pisgah Forest quadrangle. Hammer handle is36cm long. Location: long. -82.6792, lat. 35.2729.

Immediately southeast of these metasediments is the second structural package of the Brevard Zone, a 1 to 1.5 km-thick zone of mixed lithologies (bzggp) including outcroppings of highly mylonitized Henderson Gneiss and Brevard zone metasedimentary phyllonites. In many cases it is impossible to determine the protolith, and a rock name of "mylonite" is ascribed to these outcrops. The bzggp is interpreted to be a heterogeneous ductile shear zone with fault panels of both Brevard Zone metasediments and Henderson Gneiss. Brevard Zone deformation is strongest in these two structural packages but extends to the northwest into recognizably AMS-TFF rocks, and to the southeast into the Henderson Gneiss. The southeastern flank of the Brevard Zone in the study area is defined by a zone of highly mylonitic, but recognizable, Henderson Gneiss.

Several localities within the Brevard Zone (BZ) have been extensively brecciated. We attribute these brittle fabrics to late-stage faulting along the Rosman fault identified by Horton (1982). It should be noted that on the map area, these breccia zones are not restricted to the NW boundary of BZ lithologies but are also present within the central portion of the BZ.

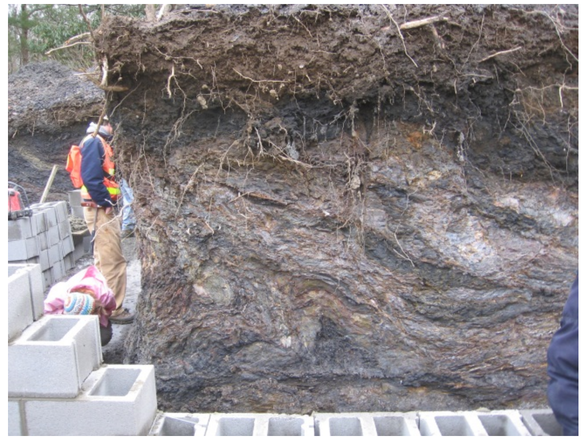

Figure 4. Complexly folded and faulted graphitic schist layers within the Brevard Zone in the Pisgah Forest quadrangle. Location: long. -82.6258, lat. 35.3389.

Figure 5. Marble and graphitic schist well cuttings from beside Boylan Creek within the Brevard Zone, structurally below graphitic schist in Figure 4. The well casing is ~15cm in diameter. Pisgah Forest quadrangle. Location: long. -82.6273, lat. 35.3386.

WESTERN INNER PIEDMONT

Henderson Gneiss (Ohg)

The vast majority of the western Inner Piedmont in the study area is underlain by Henderson Gneiss. It forms the southeastern border of the BZ in these three quadrangles. The HG is a strongly lineated augen gneiss composed of feldspar, quartz, biotite, and accessory minerals (Fig. 6). Moecher and others (2011) reported a U-Pb zircon age of 447.6 +-5.4 Ma for a sample of the HG. Mylonitic fabric within the HG decreases with distance from the BZ. Minor rock types within the main body of Henderson gneiss include medium-grained biotite granodioritic gneiss (Ohbg), fine-grained augen gneiss, and layered biotite granitoid gneiss.

Figure 6. Typical Henderson Gneiss (Ohg) as seen in the Penrose Quarry (location: long. -82.6426, lat. 35.2772), Pisgah Forest quadrangle. The lengths of the long axes of the feldspar augen range from about 5 mm to 25 mm.

Table Rock Gneiss (SOtrg)

In the southeastern Brevard quadrangle, there are large outcroppings of Table Rock granitic gneiss. Most commonly, it is white to medium-gray, medium- to coarse-grained, weakly foliated to locally mylonitic, and composed of approximately 30-35% quartz, 25-30% plagioclase, 25-30% potassium feldspar, 1-5% biotite, 1-5% muscovite, and minor amounts of opaques, epidote, and chlorite. Many outcrops contain prominent tight to isoclinal folds (Fig. 7).

In the central portions of the Brevard and Horse Shoe quadrangles, northwest of the main body of Table Rock gneiss, we have identified scattered bodies of granitic gneiss that we tentatively correlate with the Table Rock Gneiss. We do not yet have age data for these bodies but feel they are texturally and compositionally similar enough to the Table Rock gneiss to make such a correlation.

There are also areas of poor exposure where outcrops resembling Henderson gneiss occur in close proximity to outcrops resembling Table Rock gneiss. Because we could not reasonably separate these rock types at 1:24,000-scale we created the Mixed unit (SOgm) to depict these areas. SOgm is an interlayered unit consisting of nearly equal amounts of protomylonitic Henderson Gneiss and Table Rock plutonic suite granitic gneiss with minor biotite gneiss and mylonite. It is characterized by its outcrop-scale heterogeneity in contrast with both the Henderson and Table Rock gneisses. It is interpreted to be a mixed intrusive suite with Table Rock gneiss intruding the Henderson gneiss (Fig. 8).

Figure 7. Folds in Table Rock Gneiss (SOtrg) in the Brevard quadrangle. Field of view is about 23 cm x 30 cm. Location: long. -82.6625, lat. 35.1337.

Figure 8. Granitic gneiss (Table Rock SOtrg?) cross-cutting Henderson Gneiss (Ohg) on the Horse Shoe quadrangle. Hammer head is 18 cm long.

Chauga River Formation (OCcr)

There is a thin slice of metasiltstone extending through the central portion of the Brevard quadrangle onto the Standingstone Mountain quadrangle and then onto the southeastern corner of the Horse Shoe quadrangle. It is olive-gray to black, fine- to medium-grained metasiltstone consisting of plagioclase, biotite, quartz, muscovite, potassium feldspar and minor garnet. A diagnostic feature of this unit is the presence of small muscovite porphyroblasts within a fine-grained, dark matrix. It is locally interlayered with muscovite-biotite schist and metagraywacke. The unit is highly sheared and bounded by a fault on the lower contact interpreted as a continuation of the Eastatoe fault in the Standingstone Mountain quadrangle (Garihan and Ranson, 2007), and an unnamed thrust on the upper contact. The OCcr ranges in map thickness from 150 to 950 m. We have adopted the interpretation of Garihan and Ranson (2007) who mapped this unit as a sliver of the Chauga River formation on the Standingstone Mountain quadrangle.

The footwall of the OCcr thrust slice is predominantly the SOgm mixed-plutonic unit but is Henderson Gneiss on the south-central portion of the Brevard quadrangle. The hanging wall of the upper thrust fault bounding the OCcr block is made up of Henderson Gneiss but with bodies of the Table Rock gneiss and SOgm mixed unit in close proximity southeast of the fault contact.

Poor Mountain Formation (OPM)

There is a small slice of metasedimentary and metavolcanic rocks in the SE corner of the Brevard quadrangle. It is an interlayered unit consisting of amphibolite, metagraywacke, biotite gneiss (lithic tuff?), biotite schist, and quartz-sericite schist. Compositional layers are generally meter-scaled with most rocks being fine- to medium-grained, and well foliated to mylonitic. Amphibolite is locally sulfidic. We interpret this to be the continuation of the Seneca thrust sheet from the adjoining Table Rock and Standingstone Mountain quadrangles (Garihan and Ranson, 2003; 2007).

SUMMARY

The mapping area includes parts of three distinctive geologic domains from the northwest to southeast: 1) The eastern Blue Ridge province; 2) Rocks of the Brevard Zone; and 3) Paleozoic granitoids and metasediments of the western Inner Piedmont. The eastern Blue Ridge province is made up of the trondhjemitic Pink Beds pluton, and amphibolite facies rocks of the Ashe Metamorphic Suite-Tallulah Falls Formation (AMS-TFF). Although not exposed in the map area, the CFAA fault appears to be present in the northwest corner of the Pisgah Forest quadrangle, and separates the trondhjemitic Pink Beds pluton from rocks of the AMS-TFF. Further work in the Dunsmore Mountain quadrangle will be needed to determine the extent and nature of the CFAA fault to the northeast of the map area. A cross-cutting, trondhjemitic to granitic gneiss unit occurs within the AMS-TFF along and/or near the contact with the Brevard Zone. An absolute age is not known for this granitoid but it cross-cuts fabrics of probable Taconian age within the AMS-TFF. Additionally, it appears to be overprinted by Late Paleozoic Brevard Zone deformation which suggests an Acadian-Neoacadian crystallization age and possible correlation with Pink Beds and Looking Glass plutons. Mylonitic fabrics attributed to the Brevard fault are dominant in AMS-TFF rocks within 700 m of the Brevard Zone, and consistently present within 4,000 m of the Brevard Zone.

Rocks of the Brevard Zone consist of two structural packages, one of mylonitized metasedimentary rocks, and another zone of mixed lithologies including highly mylonitized Henderson Gneiss and Brevard zone metasedimentary phyllonites. Rocks of the Brevard Zone are greenschist to lower amphibolite facies. The width of the Brevard Zone ranges from about 1 to 3.3 km wide in the map area.

Rocks of the western Inner Piedmont southeast of the Brevard Zone are the Henderson and Table rock orthogneisses, and lower amphibolite to amphibolite facies metasedimentary and metavolcanic rocks correlated with the Chauga River and Poor Mountain Formations. The southeastern flank of the Brevard Zone here is defined by a -0.25 to 1km-wide zone of highly mylonitic, but recognizable, Henderson Gneiss. Map patterns and field observations in the Brevard and Pisgah Forest quadrangles indicate that the Table Rock Gneiss intrudes the Henderson Gneiss. Garihan and Ranson (2007), however, interpret these units to be in thrust contact in the Standingstone Mountain quadrangle. Additional work will be needed to resolve the contact relationships between the Table Rock and Henderson Gneisses. Other major structures interpreted to be present to the southeast of the Brevard Zone are continuations of the Eastatoe and Seneca faults as delineated by rocks correlated with the Chauga River and Poor Mountain Formations respectively.

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INSIGHTS INTO THE BREVARD ZONE IN THE LAKE JOCASSEE AREA

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INTRODUCTION

The northeast-striking Brevard zone (BZ) can be traced over 700 km from Alabama to Virginia (Hatcher, 2001) and separates the Blue Ridge from the Piedmont geological province along its trace. In general terms, the structure has been described as a gently to moderately southeast-dipping, 1- to 3-km wide fault zone. Although commonly thought of as a fault zone, BZ is one of the more complicated structures in the southern Appalachians. A history of diachronous, polyphase deformation produced and overprinted its geology.

Disparate viewpoints have interpreted that history as resulting from synclinal folding, left-lateral strike-slip, right-lateral strike slip, back-limb thrusting, stratigraphically controlled thrusting, and suturing (Hatcher, 2001, and references therein). Here observations made during mapping of the Lake Jocassee area in Salem and Reid 7.5-minute quadrangles, Oconee and Pickens County, South Carolina (See Clendenin and Garihan, 2007a), and subsequent interpretations are presented to provide insight into BZ.

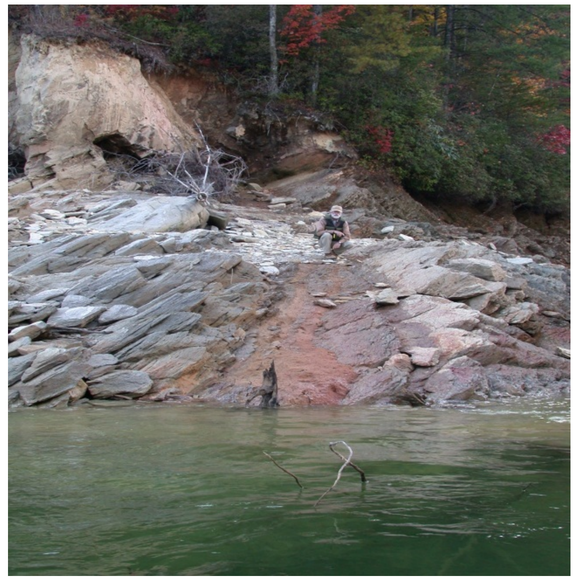

Figure 1. South Boundary Fault of BZ. Henderson Gneiss thrust over Chauga River Formation. Jack Garihan acts as scale. View is to west.

FIELD RELATIONS

In the Lake Jocassee area, the southern margin of BZ is marked by grain-size reduced Henderson Gneiss thrust over Chauga River Formation phyllonite (Fig. 1). The colors of the two units make the thrust contact easy to recognize, as the light gray-white Henderson Gneiss changes abruptly to the red brown, S-C' deformed Chauga River Formation below the moderately southeast-dipping fault. Thrusting is defined on the basis of regional mapping that has established Chauga River Formation overlies grain-size reduced Henderson Gneiss, above the Eastatoee fault (Fig. 2; Garihan and Clendenin, 2007).

Northwest of the thrust, the BZ can be subdivided into two, northeast-striking subdomains. Deformation produced distinct structural styles in each, with the southern subdomain characterized by an imbricate stack of repeated Chauga River Formation-Henderson Gneiss slices (Fig. 2) and the northern one characterized by asymmetric northwest-vergent folding of the Chauga River Formation (Fig. 3).

Strike-slip faulting spatially separates the two structural styles (Fig. 4). Regardless of subdomain, phyllonites throughout the Chauga River Formation are deformed by right-lateral, S- C' shear bands (Fig. 5).

The Rosman fault also bounds the northern subdomain and marks the structural limits of BZ. The fault juxtaposes Chauga River Formation metasiltstones and metagraywackes to the southeast against Tallulah Falls Formation rocks to the northwest. Structural style changes along strike from a high-angle fault with a multi-colored damage zone on its southeast side to a moderately southeast-dipping thrust with a multicolored damage zone in its hanging wall. In some exposures, high-angle faulting in the damage zone is carried in the thrust's hanging wall. Southeast-verging, recumbent, open to tight folds deform the Tallulah Falls Formation rocks juxtaposed to the Rosman fault. High-angle, right-lateral, strike-slip faults also deform the forelimbs of the larger, southeast-verging, Tallulah Falls Formation folds located immediately to the northwest (Fig. 6).

Figure 2. Imbricate thrust places Henderson Gneiss and the Eastatoee fault above it over Chauga River Formation. Hammer head marks thrust plane.

Two younger periods of faulting displace these earlier structural relationships. The first period produced north-northwest-verging thrusts that overprint BZ in different locations. This thrusting overprints the described structural styles in the two subdomains, locally carrying horse blocks of Chauga River Formation in its hanging walls and producing flattening in its footwalls (Fig. 7). The second period adds further structural complexity, as younger, northwest-striking, high-angle, oblique-slip faults juxtapose different structural levels along strike of BZ (Clendenin and Garihan, 2007a). In the field, these faults were referred to humorously as "no see 'em's" because of the abrupt changes in mappable units or unit dimensions that occur across them.

Figure 3. Asymmetric folds in Chauga River Formation metasiltstone. Pencil (15 cm) right center. View is to west.

Figure 4. North Boundary Fault. Henderson Gneiss (left) juxtaposed to Chauga River formation (right side). Hammer scale lies on the fault. View is to west.

POLYPHASE DEFORMATION

Many of the previous studies have focused primarily on determining the sense of movement on BZ (See Hatcher, 2001 and references therein). Observations by Clendenin and Garihan (2007b) show that overprinting relations affecting Chauga River Formation phyllonites at Tommys Knob, located immediately south-southeast of BZ, indicate left-lateral shear occurred prior to right-lateral shear and subsequent overprinting asymmetric north-west-verging folding. Identification of early left-lateral shear has been recognized for some time; Roper and Dunn (1970) published photomicrographs of garnet porphyroclasts showing an apparent syntectonic left-lateral sense of rotation. Bobyarchick and others (1988) also reported that some garnet porphyroclasts show left-lateral rotation in BZ and suggested that those garnets record an earlier shear sense than the later right-lateral shear bands. It should be noted that the preservation of older left-lateral fabrics may be the result of heterogeneous strain

Figure 5. S - C' fabric in Chauga River Formation. Dollar coin is scale. View to northeast.

Figure 6. Strike-slip faulting in forelimb of southeast-vergent back fold. Hammer marks high-angle, dextral fault at the red-brown clay gouge. Steeply dipping layers along the shore of Lake Jocassee at low water level. View to east.

that postdates peak metamorphic conditions (Passchier and Trouw, 1996).

In a regional study, Hibbard (2000) proposed that Late Ordovician-Early Silurian collision of the Carolina terrane was the result of left-lateral oblique docking influenced by its south to

Figure 7. Younger thrusting of Chauga River Formation over Tallulah Falls Formation. Thrusting flattens southeast-vergent folds. Jack Garihan acts as scale. View is to east.

north convergence. In the southern Appalachians, this event probably should be correlated with the Middle Ordovician Blountain orgeny, prior to the Taconic event *senso stricto* farther north (Shanmugam and Lash, 1982; Drake and others, 1989; Ettensohn, 1991). Hibbard (2000) further points out that Late Ordovician-Early Silurian thrusts have yet to be identified in the southern Appalachians. However, overprinting by subsequent events may mask older events. Clendenin and Garihan (2004) described field evidence of polyphase deformation in the Inner Piedmont and correlated that deformation with different tectonic events. The deformation at Tommys Knob and older petrographic evidence (Roper and Dunn, 1970; Bobyarchick and others, 1988) show that an early left-lateral event occurred prior to right-lateral movement.

Bobyarchick and others (1988) proposed a convincing model that the right-lateral shear is related to the Alleghanian orogeny. Brown (2004), however, points out that assumptions concerning contemporaneous deformation across the entire width of a shear zone may not be valid in orogenic belts. Furthermore, few arguments can be offered that diachronous deformation in the Inner Piedmont does not imply polyphase deformation. It is possible that part, if not all, of the right-lateral ductile deformation actually may have been the result of the older Acadian orogeny (Ferrill and Thomas, 1988; Hatcher, 2001; Clendenin and Garihan, 2008).

BOUNDARY CONDITIONS

The BZ originally formed in a strongly anistotropic mechanical stratigraphy (Hatcher, 2001). It is uncertain whether this stratigraphy was able to buttress westward advancing thrusts sheets as Hatcher (2001) has suggested, but he described what may have localized deformation in BZ. He also pointed out that mesofabrics indicate wrench simple shear and pure shear in the *xy* plane of the strain ellipse and that Tikoff and Tessier (1994) would interpret this deformation as strain partitioning of contractional and strike-slip components in an obliquely converging strain field.

Clendenin and Garihan (2007b) utilized this oblique transpressive deformation explanation for BZ rather than a buttressing interpretation. Mapping in the Jocassee area shows that southeast-verging backfolding occurs adjacent to the Rosman fault along the northern boundary of BZ (Fig. 6). Clendenin and Garihan (2008) interpreted this backfold as a preexisting boundary condition that acted as a major structural anisotropy localizing BZ.

Backfolds are common in many collisional orogens and accretionary wedges and may form early, throughout the tectonic history of the orogen, or as late-orogenic features (Vogl, 2002). In the western Alps, initiation of backthrusting and backfolding are interpreted as largely contemporaneous with major nappe transport toward the foreland (Ring and Merle, 1992). Analogue modeling by McClay and Whitehouse (2004) shows that retrovergent movement is initiated when foreland-directed movement encounters a ramp with an angle of 35^{o}. The passage over a ramp or progressive formation of a duplex impedes foreland-directed displacement and results in the hinterland moving toward the foreland faster than displacement can be passed to the front of the thrust belt (J. Oldow, personal communication, 2004).

Hatcher and others (1989) proposed that interaction of foreland-directed thrust movement with foot wall rocks in the Appalachian hinterland initiated duplex development and transmitted retrovergent movement back into the hanging wall, resulting in folding of the thrust sheet. Hinterland movement implies foreland-directed movement was impeded. Severe space problems caused by large strain incompatibilities of duplex development are relieved by hinterland movement and deformation (Ave Lallemant and Oldow, 1998).

STRAIN PARTITIONING

Strain partitioning has been proposed to be controlled by lithosphere boundary conditions, by weak preexisting heterogeneities, or by the rheology of the orogenic wedge (Tavernelli and others, 2004, and references therein). Regional stress fields also may produce structural anisotropies in the deforming rock sequence that may influence rheology during subsequent or progressive deformation (Jones and others, 2004). Strain partitioning results in response to such pre-existing, or deformation-induced, structural anisotropies (Jones and Tanner, 1995) and is produced by the mechanical difficulty of superimposing oblique transpressive strain onto structure anisotropies that may not be suitably aligned (Jones and others, 2004). When oblique transpressive strain is superimposed onto such structural anisotropies, a spatial separation of bulk strain produces separate strike-slip-dominated and contractional-dominated structural subdomains (Tavarnelli and others, 2004, and references therein).

Backfolding is interpreted here as having resulted from thrust sheet movement being impeded during the Middle Ordovician Blountain orogeny. If this is true, the backfolding represented a preexisting structural anisotropy that influenced subsequent overprinting deformation. Oblique transpressive shortening was produced initially by Acadian deformation (Ferrill and Thomas, 1988); the orientation of such shortening has a tendency to be spatially partitioned into different subdomains (Jones and others, 1997).

DEFORMATION SEQUENCE

Observations in the Jocassee area show that little evidence of strike-slip movement is discernible and that the bulk of the deformation appears to have resulted from contractional strain. However, the presence of C'-shear bands provide insight into the strike-slip component (Figure 5). Clendenin and Garihan (2007b) interpreted the shear bands to be the initial products of unconfined Acadian transpression and dextral movement. When anisotropic rocks undergo oblique transpressive strain in the lower crust and to avoid strain incompatibilities, the component of simple shear may be partitioned between gliding along the anisotropy planes and development of C'-shears (Girard, 1993). The C'-shear planes form at an acute angle to the anisotropy plane and the bulk oblique transpressive strain (Girard, 1993). Shear zones also have a tendency to localize simple shear (Jiang and others, 2001); under transpression, shear zones further decease in width, localizing deformation (Lin and others, 1999).

Simple shear strain commonly is partitioned into narrow, zone-parallel structures where strike-slip might be poorly exposed and easily overlooked (Jones and others, 2004). The high-angle, right-lateral faults in the forelimbs of southeast-verging Tallulah Falls folds (Figure 6) and the subdomain-dividing strike-slip fault clearly satisfy descriptions of localized deformation and of spatial partitioning of simple shear strain (Figure 4; Lin and others, 1999; Jones and others, 2004). The presence of the right-lateral strike-slip faults in Salem and Reid quadrangles indicates that the simple-shear component was progressively partitioned into those discrete narrow zones.

During the early stages of deformation, the instantaneous strain axes would have been oriented consistent with strike-slip movement, but finite strain records an increased pure shear component as a result of the nonplane strain aspect of transpression (Tikoff and Teyssier, 1994). Under progressive strike-slip-dominated transpression, strain partitioning produced more widely dispersed contractional structures that began to form after strike-slip became localized in high-strain, easy slip zones. These contractional structures formed in the two subdomains. Imbricate thrusting in the southern subdomain resulted from the presence of less competent, easy slip horizons in the Henderson Gneiss; whereas, folding in the northern subdomain was controlled by thickness, competency, and sedimentary anisotropy of the Chauga River Formation metasiltstone and metagraywacke units (cf. Tavernelli and others, 2004).

Younger, overprinting thrusts are interpreted to be a result of significant Alleghanian overprinting deformation (Figure 7). During the main phase of that orogeny, Laurentia and Gondwana rotated toward each other, with rotation producing head-on collision (Hatcher, 2001). The resulting stress field would have been controlled by the angle of oblique convergence (α). Head-on collision probably was somewhere between $20^o<\alpha<90^o$ and produced pure shear-dominated transpression (cf. Tikoff and Teyssier, 1994). The resulting transpressive shortening would have had instantaneous strain values consistent with folding and thrust deformation, while being ineffective at producing strike-slip movement (cf. Tikoff and Teyssier, 1994). The moderately southeast-dipping thrust along the northwest-side of the Rosman fault, that separates a multicolored damage zone in its hanging wall from the Tallulah Falls Formation, is interpreted to be one of these overprinting thrusts (Figure 7).

On the basis of conventional wisdom, the younger, northwest-striking, oblique-slip faults are considered to be Mesozoic in age. It should be noted, however, that Cenozoic stress fields, e.g. collision of Cuba with the Bahamas, also could have induced brittle faulting. Regardless of age, younger northeast- and northwest-striking oblique-slip faults have been mapped throughout the Jocassee-Mountain Bridge area of the South Carolina Inner Piedmont (Garihan and others, 2009). Garihan (in press) offers detailed descriptions of this faulting in volume 48 of *South Carolina Geology*.

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ULTRAMAFIC ROCKS OF THE SOUTHERN APPALACHIANS

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ABSTRACT

Isolated bodies of metaultramafic rocks occur in both the Blue Ridge and Piedmont geologic provinces. Those in the Blue Ridge are dominantly olivine-rich with subordinate amounts of orthopyroxene, and have bulk compositions that range from dunite to harzburgite. Those in the Piedmont tend to be schistose rocks consisting mostly of hydrous mafic minerals (e.g., chlorite and actinolite) and have bulk compositions that correspond to olivine-rich gabbro. Regional metamorphism of Blue Ridge ultramafic rocks has effected recrystallization of primary olivine and pyroxenes and, where accompanied by hydration, growth of chlorite, calcic amphibole and other secondary hydrous magnesian silicates. Peak metamorphic conditions ranged from granulite facies in several Blue Ridge bodies (Cartoogechaye terrane) to upper amphibolite facies (sillimanite grade) in Tugaloo terrane and Piedmont bodies. The rocks were subjected to one or more retrograde metamorphic events, as evidenced by features such as tremolite or actinolite overgrowths on earlier aluminous calcic amphibole, talc replacement of orthopyroxene, and late-stage serpentinization. An origin as dismembered fragments torn from oceanic ophiolite is generally accepted for the Blue Ridge metaultramafic bodies, but such an origin is more speculative for the Piedmont metaultramafic schists.

INTRODUCTION

Metamorphosed ultramafic rocks are a minor but important constituent of the southern Appalachians. They occur as small, isolated bodies within the Blue Ridge and, to a lesser extent, Piedmont geologic provinces. Because of their small size and often fragmented nature, as well as their complicated metamorphic history – the result of having been subjected to Taconic, Acadian and Alleghanian regional metamorphism – the origin of these metaultramafic rocks is incompletely understood. The Blue Ridge metaultramafic bodies are generally considered to represent fragments of dismembered ophiolites (Williams and Talkington, 1977: McSween and Hatcher, 1985; Swanson and others, 2005). Identifiying the protoliths of the Piedmont metaultramafics is more problematic, but several workers (e.g., Horton and others, 1985; Conley, 1987) have suggested they also may be dismembered ophiolite fragments.

A prominent feature of the southern Appalachian metaultramafic rocks is that before or during their regional metamorphism water was introduced, so that the bodies became variably hydrated (Swanson, 2001). In those portions of the bodies that remained mostly anhydrous, the original (primary) minerals – mainly Mg-rich olivine and Cr-Al spinel - recrystallized some during metamorphism, but otherwise the rocks retained the mineralogy inherited from the protolith. Where water-rich fluids interacted with the ultramafic protoliths, metamorphic reactions produced a number of hydrous magnesian silicates (chlorite, amphibole group minerals, talc, serpentine). The occurrence of these secondary minerals is dependent on the P-T conditions of metamorphism, and hence is very useful for constraining the physical conditions of metamorphism (Trommsdorff and Evans, 1974; Evans, 1977; Raymond and Abbott, 1997). This has been a major goal of many recent studies of southern Appalachian metaultramafic rocks (McElhaney and McSween, 1983; Tenthorey and others, 1996; Swanson, 2001; Warner, 2001; Warner and Hepler, 2005; Warner and Swanson, 2010).

In this paper I will focus on a half dozen or so metaultramafic bodies in the Blue Ridge and Piedmont geologic provinces that I have investigated in the past few decades (Fig. 1). Blue Ridge metaultramafic bodies include the Buck Creek metadunite in Clay County and the Webster-Addie ultramafic complex in Jackson County of western North Carolina, the two largest metaultramafic bodies in the southern Appalachian Blue Ridge, plus the Dark Ridge metaultramafic body, also in Jackson County, and a smaller metaultramafic body in Transylvania County, North Carolina for which I propose the name Bohaynee. The first three occur in the Cartoogechaye terrane, while the Bohaynee metaultramafic body is in the Tugaloo terrane (Swanson and others, 2005). From the Piedmont of South Carolina there are three small metaultramafic bodies – near Clemson in Pickens County and near Seneca and Walhalla in Oconee County. Much of the variety in bulk composition and mineralogy that characterizes southern Appalachian metaultramafic rocks is displayed in the aforementioned bodies, and the contrasting nature of Blue Ridge versus Piedmont metaultramafic bodies will become evident.

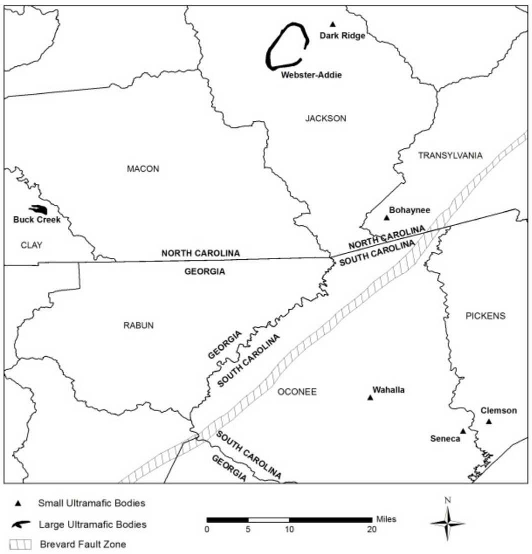

Figure 1. Map of western North and South Carolina showing location of metaultramafic bodies discussed in this paper. Also shown is the Brevard Zone, which marks the boundary between the Blue Ridge province (to the northwest) and the Piedmont province (southeastern side).

ROCK TYPES DEFINED

To avoid any possible confusion, it seems advisable at the outset to clarify the rock nomenclature used in this paper. Ultramafic rocks by definition are igneous rocks that contain 90% or more mafic minerals (usually olivine and pyroxenes), therefore little or no feldspar. They are phaneritic (coarse-grained), cumulate rocks. The IUGS classification of ultramafic rocks (see Fig. 2) is referenced to the ternary diagram olivine (Ol) – orthopyroxene (Opx) – clinopyroxene (Cpx). Note that peridotites are ultramafic rocks containing 40% or more olivine, whereas ultramafic rocks containing less than 40% olivine are pyroxenites.

With respect to their occurrence in the southern Appalachians, dunites are most common. Harzburgites are present in a number of bodies; pyroxenites are rare, and rocks with abundant calcic pyroxene (clinopyroxenite, websterite, and olivine websterite) are restricted to the Webster-Addie ultramafic complex. Where metamorphism of the ultramafic rocks largely involved recrystallization, thus producing metamorphic rocks that retain their parent igneous mineralogy, the igneous classification scheme is used in their naming but is prefixed by "meta" (hence, metadunite or metaharzburgite or metawebsterite, and so forth). If, however, metamorphism resulted in widespread crystallization of hydrous magnesian silicates, often accompanied by development of an obvious metamorphic texture, then a metamorphic rock name is assigned (e.g., chlorite-actinolite-olivine schist).

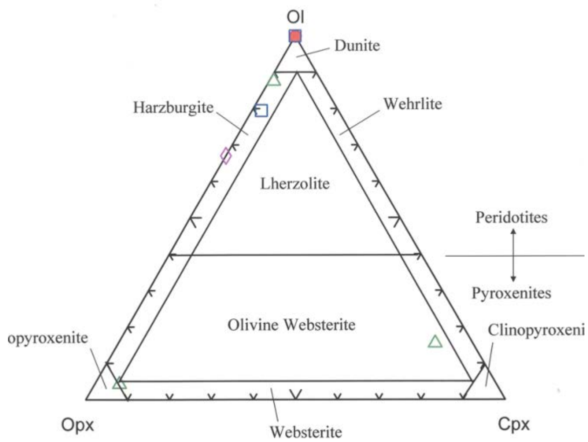

Figure 2. Olivine (Ol) – orthopyroxene (Opx) – clinopyroxene (Cpx) diagram used to classify ultramafic igneous rocks. Fields for the various ultramafic rock types (dunite, harzburgite, websterite, etc.) are as defined by Streckheisen (1973). Plotted on this diagram are CIPW normative mineralogies calculated from the average bulk rock compositions (Table 1) for Blue Ridge metaultramafic bodies: Buck Creek (solid red circle); Webster-Addie (open green triangles); Dark Ridge (open blue squares); and Bohaynee (open purple diamond).

DESCRIPTION OF METAULTRAMAFIC BODIES

Blue Ridge

Buck Creek consists largely of metadunite but also contains lenses of metatroctolite (metamorphosed olivine-plagioclase cumulate) and associated corundum-bearing edenite amphibolites (Hadley, 1949). The body is surrounded by amphibolites belonging to the Chunky Gal Mountain mafic complex (McElhaney and McSween, 1983). Most metadunite was partially hydrated and is characterized by the metamorphic assemblage olivine + chromite + chlorite $\pm$ calcic amphibole (Warner, 2001). Modal olivine is 90% or more in many samples, but some (more hydrated) samples contain less than 80% olivine; the latter often contain abundant (up to 22%) chlorite (Warner, 2001). About half of the metadunite samples studied by Warner (2001) contain calcic amphibole. A notable feature of the Buck Creek metadunite is the almost complete absence of pyroxene (Kuntz, 1964; Warner, 2001).

The Webster-Addie ultramafic complex consists of a discontinuous sheet of metaultramafic rocks that has been folded into a dome shape (Madison, 1968; Quinn, 1991). Metadunite is the principal lithology, together with subordinate metaharzburgite, but, unique to the southern Appalachians, pyroxene-rich rocks (metawebsterite, metaclinopyroxenite, metaorthopyroxenite) are locally abundant as layers and lenses ranging in thickness from a few millimeters to tens of meters (Warner and Swanson, 2010). Olivine + chromite + calcic amphibole $\pm$ orthopyroxene is the peak prograde assemblage in the olivine-rich rocks at Webster-Addie; many of the metadunites were subsequently moderately to extensively serpentinized in consequence of hydration accompanying retrograde metamorphism. Pyroxene-rich rocks typically contain the metamorphic assemblage clinopyroxene + orthopyroxene + olivine + calcic amphibole + Al-rich spinel (Warner and Swanson, 2010). Usually, one of the pyroxenes predominates, giving rise to two-pyroxene rocks that are either orthopyroxene-rich or clinopyroxene-rich; a few pyroxenites contain only a single pyroxene.

The Dark Ridge metaultramafic body is less than 10 km from the ring-like Webster-Addie complex and, though much smaller in size, is still one of the larger bodies in the Blue Ridge. It lacks the compositional variability of the Webster-Addie body, being composed of metadunite, serpentinized in part, and olivine-rich metaharzburgite. The highest grade assemblage is olivine + chromite + chlorite + calcic amphibole $\pm$ orthopyroxene (Warner and Hepler, 2005). Much of the orthopyroxene was later replaced by talc, with the result that about half of the samples of metaharzburgite contain $\geq$ 10% talc. Calcic amphibole (both tremolitic hornblende with 4-7 wt% Al_2O_3 and nearly pure tremolite) is common in the Dark Ridge rocks, and is particularly abundant (up to 15%) in metaharzburgite (Warner and Hepler, 2005).

Pratt and Lewis (1905) identified more than a dozen peridotite bodies in the vicinity of Sapphire, North Carolina, near the border between Jackson and Transylvania counties. Most of the peridotite bodies are associated with corundum deposits, and many were at one time worked for corundum. Commercial deposits of anthophyllite asbestos occur as well (Conrad and others, 1963). The Bohaynee metaultramafic body is located in Transylvania County (Fig. 1). It outcrops along the old Bohaynee road about four miles south of Sapphire, close to the corundum-bearing Grimshawe's Mine. Pratt and Lewis (1905) described this particular body as "a mass of dunite 150 feet wide" and noted that it bears needles of "colorless amphibole". Field and petrographic study confirm this description: the rocks are olivine-rich and contain abundant (average: ~17%) amphibole plus lesser talc and chlorite. Both anthophyllite and calcic amphibole (anthophyllite > calcic amphibole) are present, often as elongate needles; this appears to be a common association in the Sapphire area metaultramafic bodies (Pratt and Lewis, 1905). Some of the anthophyllite is partially replaced by talc. Here, the assemblage olivine + chromite + chlorite + anthophophyllite + calcic amphibole represents the highest grade of metamorphism.

Piedmont

Isolated metaultramafic bodies are irregularly distributed throughout the Appalachian Piedmont (Larrabee, 1966; Misra and Keller, 1978). Three such bodies occurring in the Inner Piedmont belt of northwestern South Carolina are the subject of this section: they outcrop near Clemson, Seneca, and Walhalla, respectively (Fig. 1). Bryan and Griffin (1981) described the field relationships and provided preliminary mineralogic characterizations of these small metaultramafic bodies, while results of more detailed mineralogic and geochemical study were reported for the Clemson and Seneca bodies by Warner and others (1986) and for the Walhalla metaultramafic by Warner and others (1989). All three are remarkably similar in their field appearance – they are dark gray-green and have a schistose texture – and in their mineralogy – they are chlorite-rich with abundant amphibole laths and variable amounts of olivine. Modal abundances of chlorite and amphibole are very similar in the three metaultramafic schist bodies: amphibole (includes both calcic amphibole and anthophyllite) is slightly more abundant in the Clemson metaultramafic schists whereas chlorite is more abundant in the Walhalla metaultramafic schists; the Seneca body has roughly equal amounts of chlorite and amphibole. The peak prograde metamorphic assemblage is chlorite + calcic amphibole + anthophyllite + olivine. Locally, anthophyllite is replaced by talc and chlorite is replaced by serpentine; extensive serpentinization was noted only in several samples from the Seneca metaultramafic body (Warner and others, 1986).

BULK ROCK COMPOSITIONS

Table 1 summarizes the whole-rock geochemistry of the Blue Ridge and Piedmont metaultramafic rocks. With the exception of a single analysis of metaorthopyroxenite from the Webster-Addie ultramafic complex (column 3), each column represents an average of multiple whole-rock analyses previously reported for Buck Creek (Warner, 2001); Webster-Addie (Warner and Swanson, 2010); Dark Ridge (Warner and Hepler, 2005); Clemson and Seneca (Warner and others, 1986); and Walhalla (Warner and others, 1989) metaultramafic rocks. Data for the Bohaynee metaultramafic body (column 7) have heretofore not been published.

CIPW norms were calculated for each of the averaged analyses given in Table 1. All of the Blue Ridge metaultramafics contain more than 90% normative olivine plus pyroxene (diopside + hypersthene), so their normative mineralogy can properly be plotted (Fig. 2) on the IUGS classification diagram for ultramafic rocks (Streckheisen, 1973). Norms for the Piedmont metaultramafic schists have only 72-76% olivine plus pyroxene, and contain between 17 and 20% plagioclase. Hence, although their modal mineralogy (Warner and others, 1986; 1989) is clearly ultramafic, these rocks normatively are not truly ultramafic.

Consideration of the bulk rock compositions in Table 1, together with the resultant CIPW norms, lead to several interesting observations. Comparison of the metadunite analyses (columns 1, 2 and 5) reveals that the Buck Creek metadunite contains higher CaO and Al_2O_3; this is consistent with the presence of comagmatic metatroctolite lenses in this body (Tenthorey and others, 1996). Also, the norm for Buck Creek metadunite contains only 0.11% pyroxene (diopside), which accounts for the conspicuous lack of pyroxene noted by Kuntz (1964) and Warner (2001). In contrast, the CIPW norm for Webster-Addie metadunite contains nearly 12% pyroxene (mostly hypersthene) and plots as an olivine-rich harzburgite (Fig. 2). This is in keeping with the occurrence of pyroxene-rich rocks in the Webster-Addie ultramafic complex. The Dark Ridge metadunite, like Buck Creek, plots at the olivine apex in Figure 2, while average metaharzburgite from Dark Ridge has more normative pyroxene (~ 19%) than Webster-Addie metadunite. Averaged together, metadunite and metaharzburgite from Dark Ridge is compositionally very similar to the olivine-rich rocks at nearby Webster-Addie. The normative mineralogy for the Bohaynee metaultramafic body plots in the harzburgite field, too, but is noticeably more pyroxene-rich and olivine-poor (Fig. 2). A distinctive feature of the Bohaynee norm is that it contains a small amount of corundum – as noted in the preceding section, this body and many others in the Sapphire area are associated with corundum deposits (Pratt and Lewis, 1905).

The three Piedmont metaultramafic bodies (Clemson; Seneca; Walhalla) are broadly similar in bulk composition (Table 1). Their CIPW norms contain < 90% mafic minerals, so in terms of normative mineralogy they are not ultramafic rocks and thus are not plotted in Figure 2. Instead, a diagram suitable for gabbroic rocks is used (Fig. 3). Normative olivine, pyroxene, and plagioclase range from 46-55%, 16-27%, and 17-20%, respectively, placing these rocks in the olivine gabbro field. Hypersthene (opx) predominates over diopside (cpx) in the norms for all three bodies.

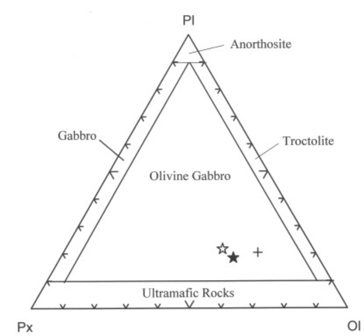

Figure 3. Plagioclase (Pl) – pyroxene (Px) – olivine (Ol) diagram used to classify gabbroic rocks. Fields for the various rock types are as defined by Streckheisen (1973). Plotted on this diagram are CIPW normative mineralogies calculated from the average bulk rock compositions (Table 1) for Piedmont metaultramafic schist bodies: Clemson (open star); Seneca (filled star); and Walhalla (plus symbol).

MINERAL CHEMISTRY AND PETROGRAPHY

Olivine is by far the most abundant mineral in the Blue Ridge metaultramafic bodies. Only in a few extensively serpentinized samples or the pyroxene-rich rocks at Webster-Addie does olivine constitute less than 50% of the modal mineralogy. Olivine occurs both as large, strained porphyroclasts and as smaller recrystallized grains often with granoblastic polygonal texture (Fig. 4A, B). There is no discernible difference in composition based on crystal habit: indeed, olivine shows very little variation in composition within a given body, being uniformly Mg-rich: olivine compositions are Fo_{90-92} in metadunite/metaharzburgite from Webster-Addie (Warner and Swanson, 2010), Dark Ridge (Warner and Hepler, 2005) and Bohaynee (this study), and about 2 mol% less magnesian (Fo_{88-90}) in Buck Creek metadunites (Warner, 2001). The slightly more Fe-rich nature of olivine in the Buck Creek metadunites is wholly consistent with that body's higher bulk rock

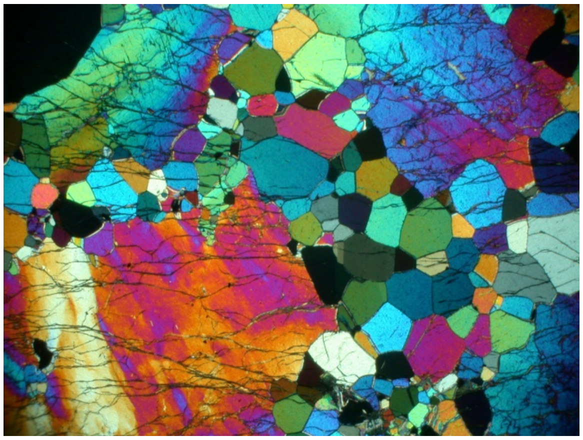

Figure 4A. Photomicrographs (X nicols) illustrating mineralogy and textures displayed in various metaultramafic rocks. A) Metadunite (Dark Ridge) with large, strained olivine porphyroclasts (undulatory extinction) separated by finer-grained recrystallized olivine with granoblastic polygonal texture.

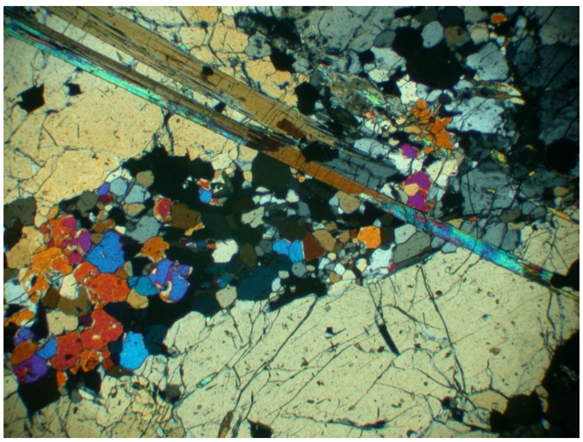

Figure 4B. Metaharzburgite (Bohaynee) with olivine porphyroclasts (Ol) separated by recrystallized finer-grained olivine and penetrated by needles of anthophyllite amphibole (Am); note partial replacement of anthophyllite by talc (T).

FeO (Table 1). Cpx-rich rocks in the Webster-Addie ultramafic complex show more variability in olivine composition and are notably more Fe-rich (Fo_{71-83}), however (Warner and Swanson, 2010).

In the Piedmont metaultramafic schist bodies olivine is less abundant than either chlorite or amphibole. Olivine in these rocks is a secondary mineral of metamorphic origin (Warner and others, 1986). It typically occurs as large, irregular, poikiloblastic porphyroblasts with numerous inclusions of chlorite and amphibole (Fig. 4C). Some polygonization of olivine was reported in all three bodies (Warner and others, 1986; 1989). Olivine compositions are comparable to those in Cpx-rich Webster-Addie rocks, ranging from Fo_{70} to Fo_{85}; they are thus more Fe-rich than in olivine-rich rocks in the Blue Ridge, a direct consequence of higher FeO and lower MgO bulk rock compositions in the Clemson, Seneca, and Walhalla metaultramafic schists as compared to the Blue Ridge metadunites and metaharzburgites (Table 1).

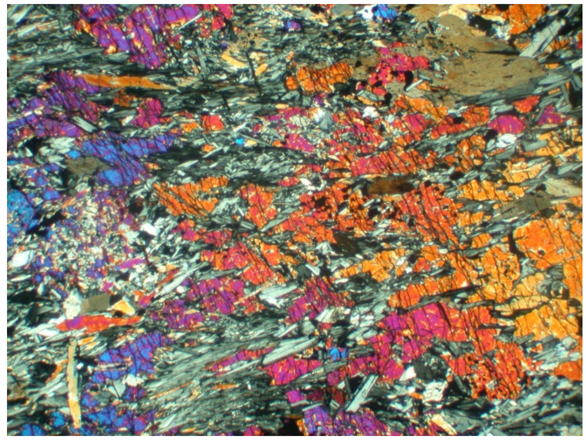

Figure 4C. Chlorite-actinolite-olivine schist (Clemson) with poikiloblastic olivine porphyroblast (a single crystal is shown) containing inclusions of chlorite, actinolite and opaque oxides.

Orthopyroxene in olivine-rich rocks primarily occurs as scattered porphyroclasts (Figure 4D). It is the dominant mineral in metaorthopyroxenite lenses and boudins at Webster-Addie, where it occurs as strained porphyroclasts; in Cpx-rich rocks from Webster-Addie orthopyroxene and clinopyroxene are intergrown in fine-grained masses that grade to coarser, porphyroclastic-textured areas (Warner and Swanson, 2010). Like olivine, orthopyroxene (and clinopyroxene) show little compositional variation and are very magnesian: Opx Mg# are comparable to olivine Fo, while Cpx Mg# are 3-7 mol% more Mg-rich (Warner and Swanson, 2010).

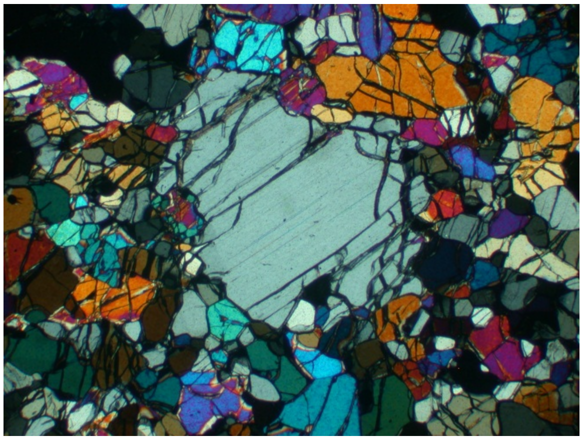

Figure 4D. Metaharzburgite (Webster-Addie) with orthopyroxene (Opx) porphyroclast surrounded by a matrix of subequant olivine crystals. Long dimension of field of view is ~6 mm in A) and D) and ~ 3 mm in B) and C).

Chromite is an important accessory mineral in the Blue Ridge metaultramafic rocks, typically comprising 1-2% of the mineral mode. Concentrations of chromite locally occur (e.g., in the Dark Ridge and Webster-Addie metaultramafic bodies), resulting in lenticular chromite deposits that in the past were mined for chromite (Hunter and others, 1942). Chromite exhibits considerable variety in texture, ranging from euhedral crystals included within olivine to irregular, poikiloblastic or "lattice" (Lipin, 1984) crystals surrounded by an aggregate of chlorite laths that separate chromite from olivine (Warner, 2001; Warner and Hepler, 2005). The latter are especially common in more hydrated metaultramafic rocks. Chromite exhibits much more extensive compositional variation than is shown by associated silicates: chromite inclusions in olivine tend to be Al-rich, whereas chromites enclosed by masses of chlorite are Cr-rich (Warner, 2001). In addition, some chromites are zoned, having cores richer in Al and rims richer in Cr.

Chromite is not present in the Piedmont metaultramafic schists. Instead, the Clemson and Seneca bodies contain 2-5% Cr-bearing magnetite (Warner and others, 1986). Minor ilmenite is also present. The Walhalla metaultramafic body lacks magnetite altogether; it has ilmenite (1-2%) as the sole oxide mineral (Warner and others, 1989).

Of the hydrous silicates occurring as secondary minerals in the metaultramafic rocks, amphiboles show the greatest variability in composition. In the Cartoogechaye terrane metaultramafic bodies (Buck Creek, Webster-Addie, Dark Ridge) all the amphibole is calcic. Microprobe analyses reveal two different populations of calcic amphibole: an Al-rich calcic amphibole (edenite) and tremolite (Warner, 2001; Warner and Swanson, 2010); where intergrown, tremolite invariably rims edenite cores (Fig. 5A). The Bohaynee metaultramafic body (Tugaloo terrane) contains primarily low-Ca amphibole (anthophyllite) and lesser calcic amphibole. Microprobe analyses (Table 2) reveal that the calcic amphibole is in part tremolitic hornblende containing up to 7.5 wt% Al_2O_3, and in part nearly pure tremolite.

As noted previously, amphibole is very abundant in the Piedmont chlorite-actinolite-olivine schists; amphibole and chlorite occur in subequal amounts and together make up 75-80% of the mineral mode. Both calcic amphibole and anthophyllite are present, but here calcic amphibole far exceeds anthophyllite (in keeping with the high bulk rock CaO in these rocks (columns 8-10, Table 1)). Microprobe analyses (Table 2) show that the calcic amphibole includes Al-poor actinolite and an aluminous calcic amphibole containing more than 5 wt% Al_2O_3. Thus, a common feature of both Blue Ridge and Piedmont metaultramafic rocks is that, where present, calcic amphibole manifests two distinctly different compositions: an earlier Al-rich amphibole (edenite or tremolitic hornblende) and a later (retrograde) Al-poor amphibole (tremolite or actinolite).

METAMORPHISM

The metamorphic history of metaultramafic bodies in the southern Blue Ridge has been the subject of several recent investigations (Tenthorey and others, 1996; Raymond and Abbott, 1997; Swanson, 2001: Warner, 2001; Warner and Swanson, 2010). Most have concluded that the ultramafic rocks record a history of a peak prograde metamorphic event (Taconic orogeny?) followed by one or more retrograde metamorphic events that were accompanied by increasing hydration. The latter may correlate with a specific orogeny (e.g., Acadian and/or Alleghanian) or reflect monotonic cooling from the peak Taconic metamorphism (Raymond and Abbott, 1997).

Table 3 lists the peak prograde metamorphic assemblages in olivine-rich rocks from the various Blue Ridge metaultramafic bodies discussed in this review. Chlorite plus calcic amphibole stably coexist in metaultramafic rocks to temperatures of at least 740ºC, and likely as high as 800ºC (Bucher and Frey, 1994). The general absence of chlorite in the Webster-Addie metadunites and metaharzburgites suggests that peak metamorphic temperatures in this body may have exceeded 800 ºC. The Cpx-rich rocks at Webster-Addie are characterized by the assemblage Cpx + Opx + olivine + calcic amphibole (edenite) + Al-rich spinel (Warner and Swanson,

Table 1. Whole-rock chemical analyses of selected southern Appalachian metaultramafic rocks

	1	2	3	4	5	6	7	8	9	10
SiO_2 (wt %)	39.9	41.6	55.7	51.4	40.2	43.1	44.5	42.5	42.1	39.5
TiO_2	0.13	BDL	0.03	0.06	BDL	BDL	0.02	0.31	0.28	0.37
Al_2O_3	0.90	0.37	1.23	2.27	0.29	1.22	1.07	6.9	5.8	6.5
Cr_2O_3	0.62	0.57	0.50	0.43	0.44	0.38	0.75	0.15	0.21	0.42
FeO	10.7	7.9	6.1	4.8	7.8	7.9	8.5	12.1	13.7	12.9
MgO	45.4	45.8	32.9	20.7	49.0	43.1	41.7	27.8	29.5	30.2
MnO	0.18	0.11	0.13	0.10	0.10	0.11	0.14	0.22	0.24	NA
NiO	0.29	0.32	0.10	0.04	0.37	0.31	0.25	NA	NA	NA
CaO	1.29	0.46	2.06	18.5	0.20	1.11	0.31	5.8	4.4	4.0
Na_2O	0.11	0.02	0.06	0.24	0.03	0.09	0.04	0.29	0.29	0.12
LOI	NA	2.0	0.3	1.3	0.7	1.85	1.75	4.1	4.3	5.7
Total	99.52	99.15	99.11	99.84	99.13	99.17	99.03	100.17	100.82	99.71
Mg#	88.3	91.2	90.6	88.5	91.8	90.7	89.8	80.4	79.3	80.7

BDL = below detection limit NA = not analyzed Mg# = Mg/(Mg+Fe)

Columns: 1 – average, 5 metadunite analyses (Buck Creek); 2 – average, 4 metadunite analyses (Webster-Addie); 3 – metaorthopyroxenite analysis (Webster-Addie); 4 – average, 4 metawebsterite/ metaclinopyroxenite analyses (Webster-Addie); 5 – average, 2 metadunite analyses (Dark Ridge); 6 – average, 4 metaharzburgite analyses (Dark Ridge); 7 – average, 2 metaharzburgite analyses (Bohaynee); 8 – average, 3 metaultramafic schist analyses (Clemson); 9 – average, 2 metaultramafic schist analyses (Seneca); 10 – average, 3 metaultramafic schist analyses (Walhalla).

Table 2. Amphibole Compositions in Bohaynee and Clemson Metaultramafic Bodies

	1	2	3	4	5	6
SiO_2 (wt %)	60.8	58.4	50.3	57.2	57.6	52.6
TiO_2	BDL	BDL	0.33	0.06	0.06	0.27
Al_2O_3	0.07	0.22	7.5	0.24	0.55	5.3
Cr_2O_3	BDL	BDL	0.47	0.09	0.04	0.14
FeO	6.9	1.4	2.9	12.3	4.3	5.1
MgO	29.7	25.1	21.8	25.9	23.4	20.7
MnO	0.20	BDL	BDL	0.65	0.11	0.28
CaO	0.55	12.8	12.6	0.95	12.5	11.9
Na_2O	BDL	0.14	1.61	0.07	0.09	1.01
Total	98.22	98.06	97.51	97.46	98.65	97.27
Ca	1.2	26.2	27.9	2.0	25.9	26.7
Mg	87.4	71.6	67.1	77.4	67.1	64.4
Fe	11.4	2.2	5.0	20.6	6.9	8.9

BDL = below detection limit

Columns: 1-3, anthophyllite, tremolite, and tremolitic hornblende, respectively, Bohaynee metaultramafic body; 4-6, anthophyllite, actinolite and aluminous calcic amphibole, respectively, Clemson metaultramafic body.

Table 3. Peak Prograde Mineral Assemblages in Olivine-rich Blue Ridge Metaultramafic Rocks

Metaultramafic Body	Metamorphic Assemblage
Webster-Addie	olivine + chromite + calcic amphibole[1] $\pm$ orthopyroxene
Buck Creek	olivine + chromite + chlorite $\pm$ calcic amphibole[1]
Dark Ridge	olivine + chromite + chlorite + calcic amphibole[2] $\pm$ orthopyroxene
Bohaynee	olivine + chromite + chlorite + anthophyllite + calcic amphibole[2]

[1]edenite [2]tremolitic hornblende

Sources of data: Webster-Addie, Warner and Swanson (2010); Buck Creek, Warner (2001); Dark Ridge, (Warner and Hepler, 2005); Bohaynee, this paper.

2010). This assemblage is characteristic of the amphibolite to granulite facies transition and, according to Figure 5.4 of Bucher and Frey (1994), is stable between temperatures just under 800 ºC to approximately 835 ºC. Application of the two-pyroxene geothermometer (Wells, 1977) to coexisting Cpx and Opx in the Webster-Addie metaultramafic rocks yields temperatures ranging from 798 ºC to 833 ºC (Warner and Swanson, 2010). The total absence of anthophyllite in the associated olivine-rich rocks indicates that pressure during metamorphism of the Webster-Addie rocks probably was at least 11 kb, the pressure that marks the upper limit for the coexistence of anthophyllite + olivine (Evans and Guggenheim, 1988). Thus, peak metamorphic conditions of 795-835 ºC at pressures at or just above 11 kb are inferred for the Webster-Addie metaultramafic complex (Warner and Swanson, 2010).

The remaining Blue Ridge metaultramafic bodies are characterized by the presence of chlorite, so peak metamorphic temperatures were somewhat lower (i.e., below 800 ºC). The Buck Creek and Dark Ridge bodies have similar metamorphic assemblages (Table 3) and differ only in that (1) orthopyroxene is present in Dark Ridge metaharzburgites, but Buck

Creek metadunites are devoid of Opx, and (2) calcic amphibole is more aluminous (edenite with > 10 wt% Al_2O_3) in the Buck Creek samples compared to tremolitic hornblende with 4-7 wt% Al_2O_3 at Dark Ridge. The absence of orthopyroxene in Buck Creek metadunite may just be a bulk composition effect, as the CIPW norm lacks opx (hypersthene). Calcic amphibole becomes increasingly aluminous (and sodic) at higher temperatures (Bucher and Frey, 1994), so the more Al-rich composition of Buck Creek calcic amphibole presumably indicates prograde metamorphism at a somewhat higher temperature (close to 800 ºC?) than was the case at Dark Ridge. This is consistent with two-pyroxene temperatures (770-810ºC) derived from two-pyroxene/spinel coronas in associated Buck Creek metatroctolites (Warner, 2001). The absence of anthophyllite in olivine-rich rocks at Buck Creek and at Dark Ridge suggests that pressure during prograde metamorphism was at or slightly above 11 kb in both these bodies, as inferred also for the Webster-Addie metaultramafic complex.

The Cartoogechaye terrane metaultramafic bodies discussed above are located in an area of granulite facies metamorphism that represents the thermal axis of Paleozoic metamorphism in the southern Appalachians (Absher and McSween, 1985). The Bohaynee metaultramafic body in the Tugaloo terrane was metamorphosed at a lower grade as indicated by the presence of anthophyllite (Table 3). Anthophyllite plus olivine coexist over a narrow temperature interval with an upper limit near 700 ºC (Bucher and Frey, 1994). Pressure also must have been lower (i.e., less than 11 kb).

The Piedmont metaultramafic bodies (Clemson, Seneca, Walhalla) are characterized by the prograde assemblage chlorite + calcic amphibole + olivine + anthophyllite $\pm$ Cr-bearing magnetite. This is similar to the Bohaynee assemblage (except that Cr-bearing magnetite is present instead of chromite), despite the considerable differences in modal abundances – olivine is subordinate to both chlorite and calcic amphibole in the Piedmont metaultramafic schists – and bulk rock compositions (Table 1). Hence, peak temperature during prograde metamorphism is inferred to have been between 670ºC and 700ºC. Recent mapping and petrologic analysis of rocks in the Clemson Experimental Forest (in which the Clemson metaultramafic body is located) has confirmed the presence of sillimanite-bearing gneisses in the area as well as the occurrence of migmatite. This association suggests metamorphism occurred at a temperature of 650-700ºC (thus reinforcing the temperature estimate obtained from the metaultramafic rocks), and it constrains pressure to between 3 and 7 kb.

Evidence for retrograde metamorphism is widespread in the Blue Ridge as well as Piedmont metaultramafic rocks. At least four products of retrograde metamorphism have been identified: (1) tremolite (or actinolite) overgrowths on aluminous calcic amphibole (Fig. 5A); (2) talc replacement of orthopyroxene porphyroblasts (Fig. 5B) or of anthophyllite needles (Fig. 4B); (3) serpentine replacement of olivine along cleavage planes (Fig. 5C); and (4) pseudomorphous replacement of chlorite laths by serpentine (Fig. 5D). Formation of talc and tremolite probably occurred at temperatures between 570-670 ºC, while growth of serpentine took place at lower (< 570 ºC) temperatures (Warner and Hepler, 2005). As stated earlier, it is not clear whether these retrograde reactions reflect a single cooling event or multiple episodes of metamorphism.

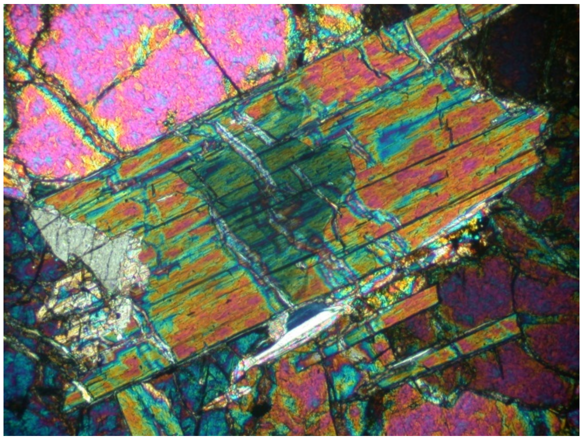

Figure 5A. Photomicrographs (X nicols) illustrating retrograde metamorphic reactions observed in the metaultramafic rocks. A) Edenite (Ed) – at partial extinction – overgrown and replaced by tremolite (Tr) in Buck Creek metadunite; inset at lower right is a backscattered electron image from same rock showing euhedral calcic amphibole – lighter-colored portion of crystal is edenite, while darker area mantling edenite is tremolite.

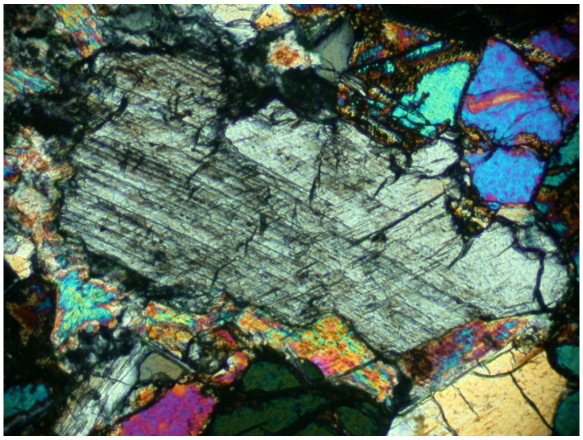

Figure 5B. Talc (T) replacing orthopyroxene (Opx) in Dark Ridge metaharzburgite.

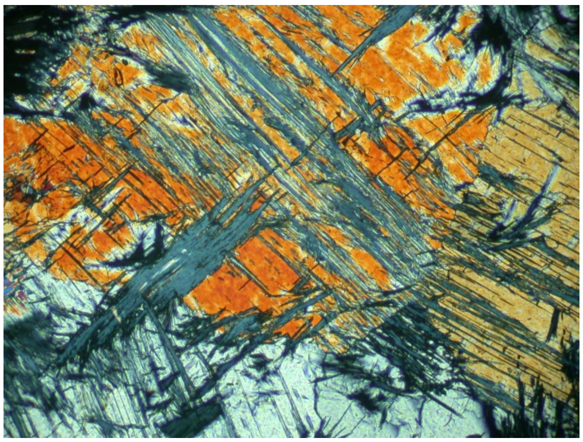

Figure 5C. Serpentinized metadunite (Dark Ridge) in which olivine (Ol) has been extensively replaced by serpentine (Srp) along cleavage planes.

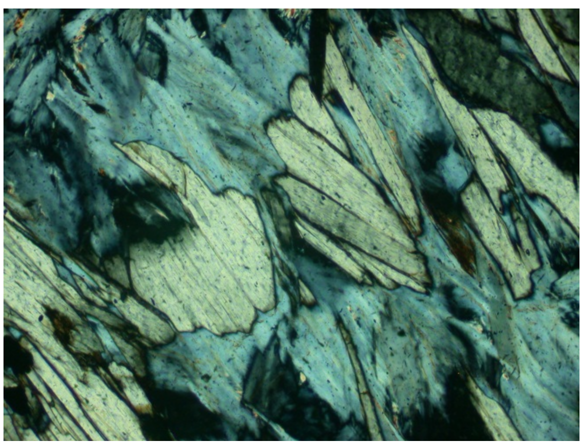

Figure 5D. Laths of chlorite (Chl) surrounded and partially replaced by serpentine (Srp), Seneca chlorite-actinolite-olivine schist. Long dimension of field of view is ~1 mm in each photomicrograph.

NATURE OF PROTOLITHS

The many small mafic-ultramafic bodies in the southern Appalachian Blue Ridge are thought to be dismembered parts of ophiolite sequences (Williams and Talkington, 1977). An ophiolite is a distinctive assemblage of mafic to ultramafic rocks that is interpreted to be a section of oceanic crust and the underlying upper mantle that has been emplaced onto the continental margin. According to Coleman (1977) the basal (= uppermost mantle) part of an ophiolite sequence consists of metamorphic peridotite in which harzburgite and dunite are the dominant rock types, although lherzolite subtypes also occur. Overlying this is a cumulate complex (= bottom of oceanic crust) in which cumulate peridotite grades upward into layered gabbros. In this context, the Dark Ridge and Bohaynee metaultramafic bodies, consisting of metaharzburgite and metadunite, equate with basal metamorphic peridotite. The interlayering of metadunite and metatroctolite found at Buck Creek may reflect derivation from the transition zone between ultramafic and gabbroic parts of an ophiolite cumulate complex (Warner, 2001). The Webster-Addie ultramafic complex with its locally abundant Cpx-rich rocks is inferred to be derived in part from basal metamorphic peridotite (metadunites and metaharzburgites) and in part from the overlying ultramafic cumulate complex (Warner and Swanson, 2010). In all cases the Blue Ridge metaultramafic bodies represent only portions of an entire ophiolite sequence, having been disrupted during their emplacement into the southern Appalachians.

The Piedmont metaultramafic bodies have several characteristics that make their origin more elusive. For one, they retain no primary igneous minerals – the olivine that is present is wholly secondary (Fig. 4C). Second, their bulk compositions are considerably different (Table 1). Also, they lack an association with mafic rocks that could correspond to the mafic dike swarms and mafic volcanics that overlie ophiolitic ultramafic cumulates (Coleman, 1977). Thus, Williams and Talkington (1977) hypothesize that the Piedmont occurrences may represent metamorphosed small intrusions rather than oceanic ophiolites. Nevertheless, Warner and others (1986) pointed out that plagioclase-bearing cumulate rocks from ophiolite sequences provide reasonable compositional analogs. In particular, average compositions reported by Coleman (1977) for feldspar dunite cumulates from the Bay of Islands, Newfoundland ophiolite and for cumulate gabbros from the Semail, Oman ophiolite were found to closely match the Piedmont metaultramafic schist bulk rock compositions. Also, Warner and others (1989) showed that the average compositions of the

Piedmont metaultramafic schist bodies fall within the compositional field for ophiolite ultramafic cumulate rocks in various plots utilized by Coleman (1977). Rocks very similar in composition from the Virginia Piedmont were reported by Conley (1987) and interpreted by him to be derived from an ophiolite sequence. So an origin for the Piedmont bodies as dismembered fragments torn from an ophiolite sequence is certainly possible.

ACKNOWLEDGEMENTS

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PHYSICAL EVIDENCE OF STREAM CAPTURE AS DRIVER OF ACTIVE LANDWARD RETREAT OF THE BLUE RIDGE ESCARPMENT

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INTRODUCTION

The Blue Ridge Escarpment (BRE), a 500-800m (locally 1 km or greater) topographic escarpment separating the Blue Ridge Plateau and Piedmont physiographic provinces, is one of the most striking elements of the southern Appalachian landscape (Fig. 1). Unlike most of the rugged topography of the southern Appalachians, the Escarpment does not coincide with outcrop of resistant lithologies and trends sub-parallel to the prevailing structural and lithologic grain. Along much of its length, the crest of the BRE coincides with the Eastern Continental Divide, which separates streams of the elevated Blue Ridge Plateau, which drain to the Gulf of Mexico, from Atlantic slope streams of the Escarpment face and Piedmont (Hayes and Campbell, 1894; Davis, 1903; Wright, 1927; Dietrich, 1957; Hack, 1973) (Fig. 1). The Blue Ridge Escarpment has been compared to the "great escarpments" of other passive margins, such as southeastern Australia, South Africa, and Madagascar, which also coincide with major drainage divides, but the relationship between the drainage divide and escarpment evolution in all of these settings has remained poorly understood. Understanding of the evolution of these features has been hampered by the tectonic quiescence of their host passive margins, which generally lack sub-aerial depocenters or datable Cenozoic volcanic material, which might provide insight into the mechanism and pace of escarpment evolution.

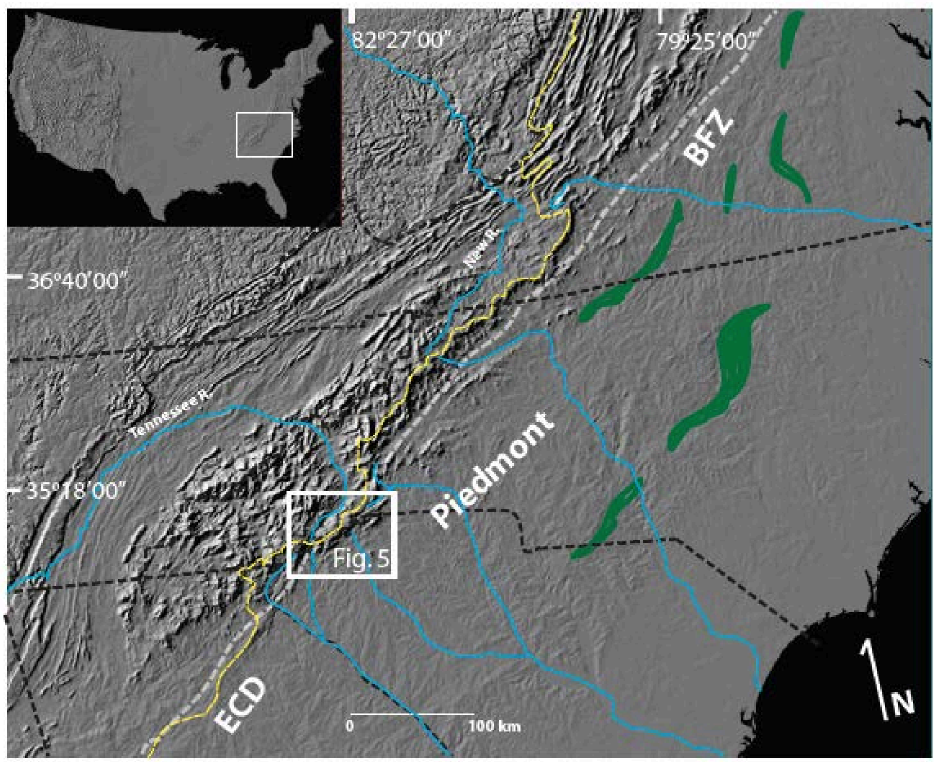

Figure 1. DEM topography of the southern Appalachians. Eastern Continental Divide (ECD) generally coincides with the crest of the Blue Ridge Escarpment. Green areas indicate outcrop of Mesozoic basin fill. DEM source USGS Map I-2206.

Passive margin escarpments are generally regarded as landward-retreating erosional features resulting from rift-flank uplift along nascent ocean basins (Ollier, 1984; Kooi and Beaumont, 1994; Gallagher and Brown, 1997). Opening of a new ocean basin provides a new, proximal base level to the rift flanks, driving accelerated erosion within the new seaward drainage basin (Ollier, 1984; ten Brink and Stern, 1992; Young and McDougall, 1993; Tucker and Slingerland, 1994; Seidl and others, 1996). While this accelerated seaward denudation is accepted to be the major driver of passive margin escarpment evolution, the mechanism through which it proceeds to control escarpment evolution has remained controversial. Some studies have suggested that passive margin escarpments are gradually excavated along a fixed inland drainage divide, which forms at the time of rifting (arch-type escarpments of Matmon and others, 2002; van der Beek and Braun, 1999) (Fig. 2). Others have suggested that a drainage divide forms at the initial rift shoulder, and the divide and escarpment experience landward retreat in parallel following rifting (shoulder-type of Matmon and others, 2002; King, 1962; Gunnell and Harbor, 2008; Gunnell and Harbor, 2010) (Fig. 2). These models have proven difficult to evaluate, as both result in a "wave" of landward exhumation and a pulse of post-rift sedimentation into the new ocean basin as topography adjusts to the presence of the post-rift base level (Spotila and others, 2004). Numerical models have fit present-day passive margin escarpments to both mechanisms as well (van der Beek and Braun, 1999; van der Beek and others, 2002), and the dominance of denudation in the passive margin setting has been assumed to have destroyed any surficial evidence which might shed light on the mechanism of escarpment development.

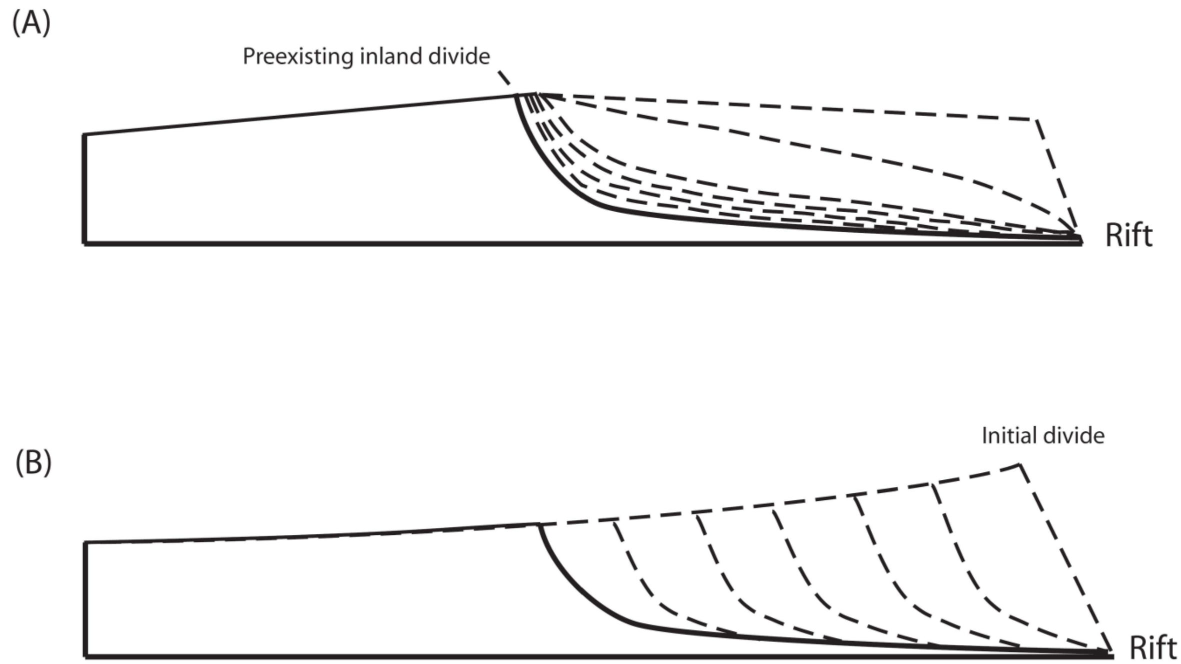

Figure 2. Two popular models of passive margin escarpment evolution. A) Fixed divide model, where an inland drainage divide forms during rifting and the escarpment is excavated seaward of the divide. B) Retreating divide and escarpment model, where a drainage divide forms at the rift shoulder and retreats landward along with the escarpment by focused erosion on the seaward flank of the divide. Both models produce a comparable exhumation signature. After Prince and others (2010).

The predominately shoulder-type BRE has remained a focus of study due to its exceptionally rugged topography and the age of the North American passive margin. The timing of Atlantic opening allows the possibility that the BRE is a very mature feature, and its persistent ruggedness suggests is may still be actively evolving some ~200 Ma after Atlantic Ocean opening (Pique and Laville, 1995; McHone, 1996). While most streams descending the BRE have their headwaters at the escarpment crest, the BRE is locally embayed by steep-walled gorges cut by streams which follow low-gradient courses across the elevated Blue Ridge Plateau before dropping across major knickpoints in the escarpment zone to the Piedmont, and, ultimately, the Atlantic Ocean (selected examples in Fig. 3).

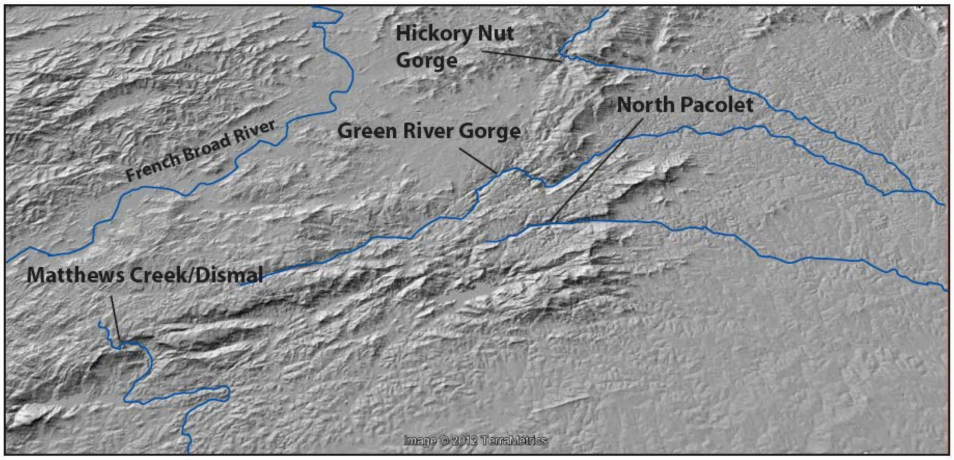

Figure 3. North-oriented inclined "horizon" view of the Blue Ridge Escarpment with selected gorges labeled. These gorges carry streams which flow across the Plateau along low-gradient courses before dropping over major knickpoints to the Piedmont.

In other settings, such streams have been regarded as the last seaward drainages to adjust to the fixed inland divide which formed at the time of rifting, with knickpoint migration proceeding very slowly as the divide is approached (Weissel and Seidl, 1998; Fleming and others, 1999; Heimsath and others, 2000; Matmon and others, 2002; Persano and others, 2002). Numerous workers have cited isostatic rebound related to thickened Appalachian crust or flexural response to offshore sediment loading as drivers of BRE-zone uplift, steepening streams to drive gorge development and BRE evolution (Wright, 1927; Pratt and others, 1988; Battiau-Queney, 1989; Hubbard and others, 1991; Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 2000). Other models have suggested these streams have been captured from the landward drainage basin into the younger Atlantic basin, with the subsequent rapid incision driving parallel retreat of the BRE and divide (Harbor and Gunnell, 2007; Gunnell and Harbor, 2008, Gunnell and Harbor, 2010). Attempts to prove both of these models have, however, been rooted in models and theoretical topographic interpretation, with little or no supporting physical evidence.

The earliest studies of passive margin escarpment evolution focused heavily on stream capture as the origin of these large streams whose morphologies were consistent with the landward drainage basin before they crossed the escarpment. Field work sought to identify underfed, landward-draining streams with headwaters truncated at the divide, along with stranded alluvium atop the divide, as evidence of drainage rearrangement. Taylor (1911) reported underfed valleys and stranded alluvium at the crest of the southeastern Australia escarpment, and Johnson (1907) described alluvium on the crest of the Chattahoochee-Chattooga divide as indicator of recent Chattooga capture and associated divide retreat and development of the Tallulah and Chattooga gorges. Neither of these studies offered clear descriptions of gravel locations, precluding subsequent study. Wright (1927) and Dietrich (1957) described rounded boulders along the BRE in Virginia, regarding them as evidence that divide and BRE had retreated landward due to stream capture and truncated formerly more extensive landward drainages. Despite this tantalizing physical evidence of capture events, increased acceptance of the dynamic equilibrium model (Hack, 1960) suggested preservation of capture-related gravels was unlikely. Additionally, numerical models and cosmogenic radionuclide studies of the BRE and other passive margin escarpments suggested the features were probably relatively stable, leading to widespread abandonment of the parallel escarpment-divide retreat model by the 1990s and 2000s (Fleming and others, 1999; Bierman and Caffee, 2001, Sullivan and others, 2007).

Spotila and others (2004) re-evaluated the parallel retreat model with apatite thermochronometry and morphologic studies of drainage networks and ruggedness atop the Blue Ridge Plateau and neighboring Piedmont. This study revealed deeper exhumation seaward of the BRE in Virginia, which, combined with differences between drainage patterns on the Blue Ridge Plateau and Piedmont, was viewed as evidence of landward retreat of the BRE and divide by stream capture. Gunnell and Harbor (2010) focused on intersecting, erodible structural elements (faults and joints) as drivers of such stream captures and associated "butte detachment", offering an explanation of the mountain outliers and transitional topography separated from the Blue Ridge Plateau by deep gorges. This study suggested that the BRE experiences "piecemeal," basin-by-basin retreat, fundamentally driven by the erosional adjustment of captured Blue Ridge Plateau streams to their new immediate base level on the Piedmont. The structurally-assisted "piecemeal" capture model was confirmed by the work of Prince and others (2010, 2011), which used stream valley morphology to identify beheaded streams hosting deposits of fluvial gravels atop the Eastern Continental Divide at the crest of the BRE (Fig. 4). Gravel deposits were found to occur near gorges where major streams exit the Blue Ridge Plateau from western North Carolina into Virginia, indicating that gorge development is the transient erosional response following capture of the streams from their landward courses into the Atlantic basin

(Prince and others, 2010). Additional gravels on the BRE crest away from any active gorges suggested complete erosional adjustment of captured basins which formerly extended 10s of kilometers seaward of the present-day BRE (Prince and others, 2010).

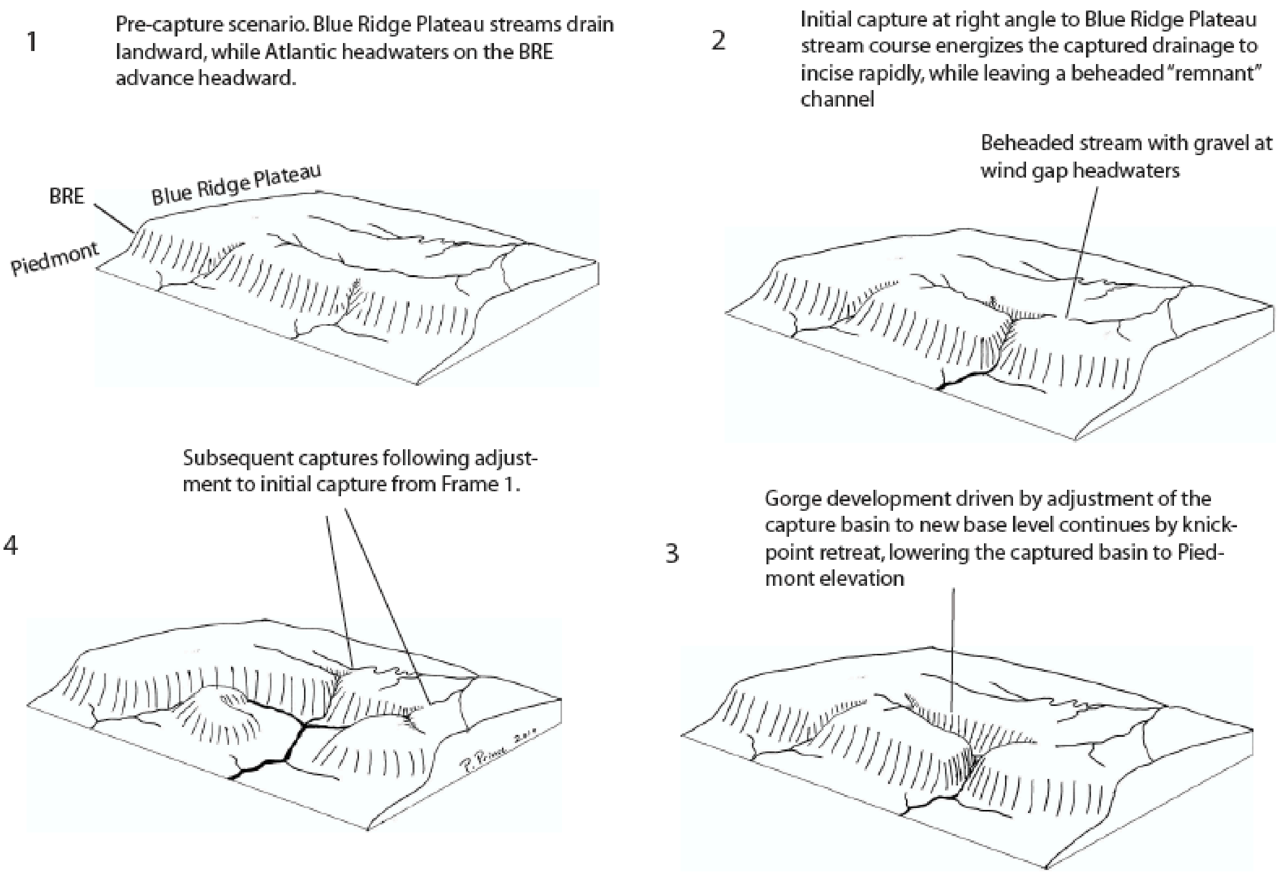

Figure 4. Cartoon illustration of the "piecemeal" escarpment retreat model driven by episodic stream capture. Gravel deposits atop the Eastern Continental Divide at the BRE crest in western North Carolina (Prince and others, 2010) confirm the validity of this model.

In western North Carolina, the French Broad River basin has lost considerable drainage area to stream capture and associated erosional retreat of the BRE (Fig. 5). Two recent captures from the French Broad system, which produced the Jocassee Gorges topography and the Green River gorge, were identified through channel morphology and relict gravel deposits by Prince and others (2010). The beheaded streams left by these captures exhibit typical underfed channel morphology, with unusually low headwaters gradients and broad, flat-bottomed alluvial valleys opening into wind gaps at the crest of the BRE. These wind gaps contain mature fluvial gravel, dominated by well-rounded vein quartz clasts, whose shapes suggest many 10s of kilometers of transport (Cailleux, 1947; Sadler and Reeder, 1983) (Fig. 6). The morphological characteristics of these streams, along with their relict gravel deposits, are detailed below.

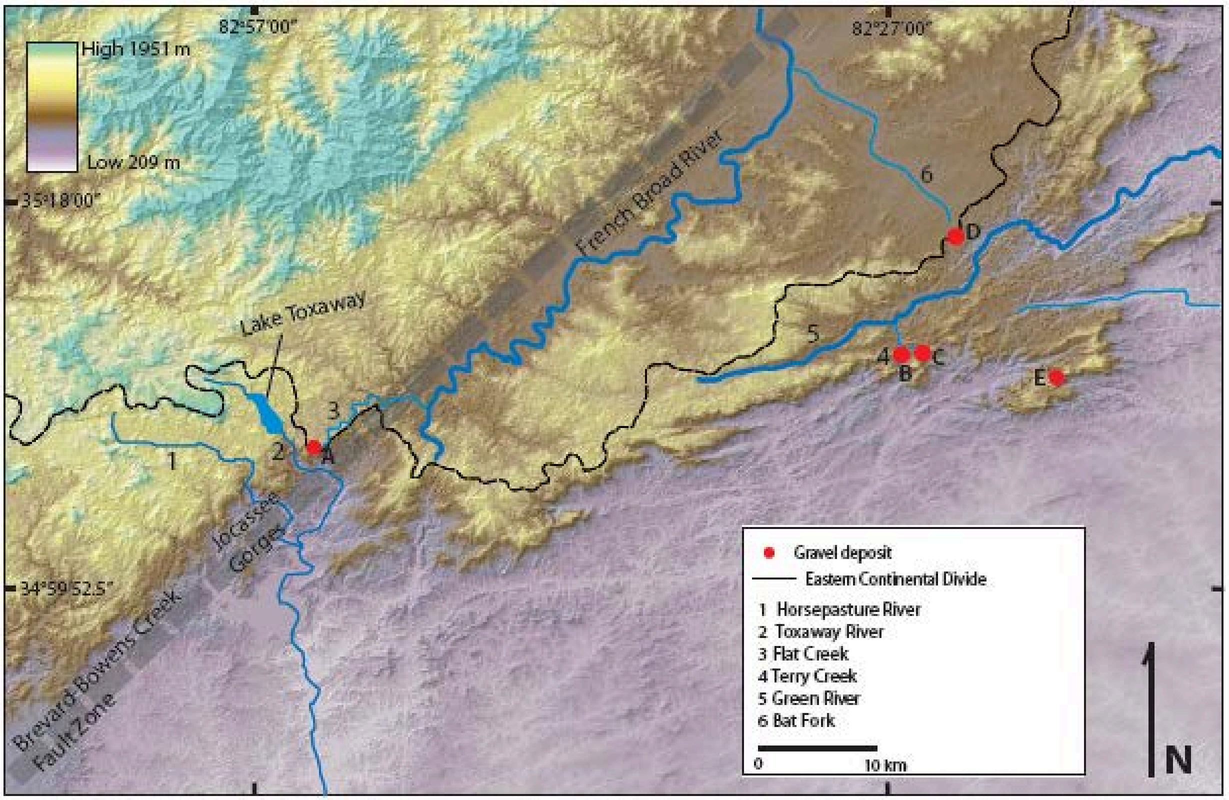

Figure 5. Color-coded DEM with hillshade topography showing gravel deposits related to capture of French Broad River headwaters in western North Carolina. Regional setting of this map is shown in Figure 1. DEM source: www.seamless.usgs.gov.

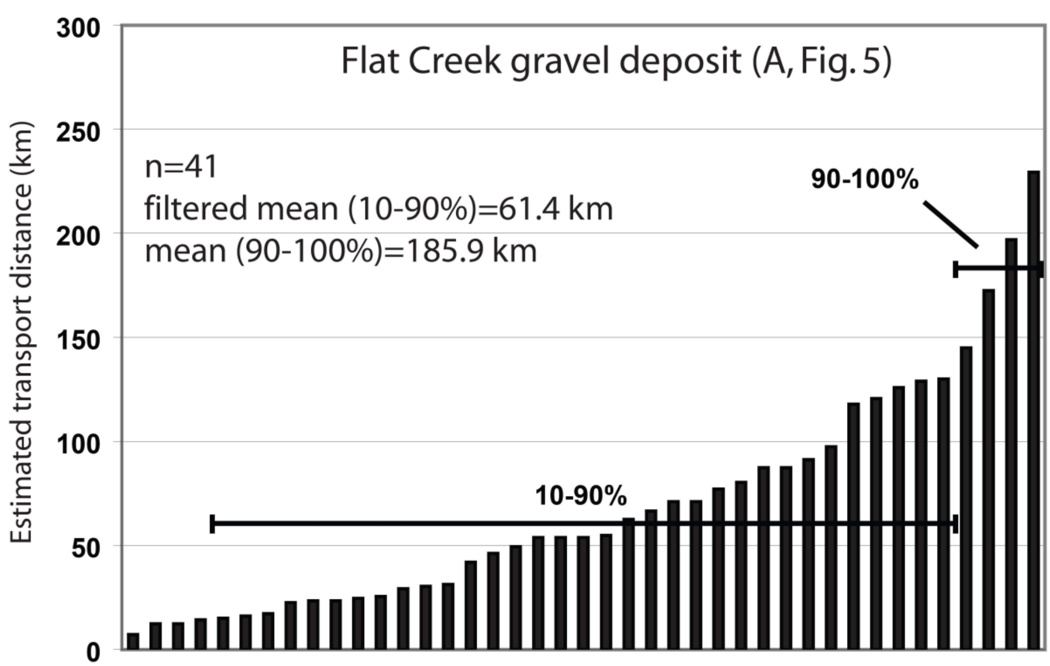

Figure 6. Estimated fluvial transport distances of vein quartz cobbles from the Flat Creek gravel deposit (A, Figure 5). Estimates are based on the methods of Cailleux (1947) and Sadler and Reeder (1983). From Prince and others (2010).

FLAT CREEK VALLEY GRAVEL DEPOSIT

The south fork of Flat Creek (French Broad River tributary) rises in a wind gap 2.7 kilometers southeast of the Lake Toxaway dam (Figs. 5, 7). At its headwaters, the Flat Creek valley is very broad and gives the appearance of a "bottomland" encountered further downstream along the main stem of the French Broad River. The low-gradient topography of Flat Creek valley stands in sharp contrast to the neighboring BRE. Flat Creek exhibits a linear longitudinal profile from its headwaters for ~2.5 km, before it steepens and drops to the present-day West Fork of the French Broad River. Field inspection of Flat Creek valley reveals an unusual white quartz sand soil filled with very well-rounded vein quartz river cobbles. Roundness of these cobbles suggests many 10s of kilometers of transport (Cailleux, 1947; Sadler and Reeder, 1983). Weathering of the cobbles is not advanced, and some contain chalky feldspar crystals that are apparent in hand specimen. Clast density is variable within the deposit, but the soil is locally clast-supported. Clast size is variable, but rounding is very advanced at all sizes, including pea gravel. Local residents are well-aware of the presence of river cobbles inconsistent with the size of Flat Creek, as they are somewhat of an impediment to cultivation of the soil.

Figure 7. Selected photographs of gravel deposits from Figure 5. A) White sand matrix and vein quartz cobbles in gravel deposit A, Figure 5. B) View south across gravel deposit A, Figure 5. Eastern Continental Divides trends across the hill in the distance before crossing the valley floor northwest of the photo. C) Selected well-rounded vein quartz cobbles and pebbles from gravel deposit A, Figure 5. D) Outcrop of fluvially-rounded small boulder, gravel deposit C, Figure 5. E) Outcrop of gravel deposit B, Figure 5, showing reddish clay matrix and quartz cobbles. F) Selected rounded to well-rounded cobbles and small boulders from gravel deposits B and C, Figure 5.

The Flat Creek area is cut by numerous lineaments with northeast-southwest trend (orogenic strike) and northwest-southeast trend (joints of uncertain age and origin). These lineaments intersect at near 90 degree angles, allowing a small amount of headward erosion to lead to capture of a very large drainage area. The size and roundness of cobbles in the Flat Creek Valley suggest that it the remnant of the capture of a stream larger than the modern Toxaway River headwaters. Simultaneous plotting of several Jocassee Gorges rivers reveals that the elevation and gradient of the Horsepasture River is most reasonably projected beyond the entry into its modern gorge and into the Flat Creek headwaters (Fig. 8). The Whitewater and Thompson Rivers were probably tributaries to the Horsepasture, and may have been captured off of the Blue Ridge Plateau before the Horsepasture when the Plateau extended at least as far as the present location of the Jocassee Dam. This profile projection indicates the volume of Blue Ridge Plateau already dissected and lowered by the transient erosional response following capture. Ultimately, the entire Keowee headwaters will be eroded to match Piedmont elevation, removing a substantial area of Blue Ridge Plateau.

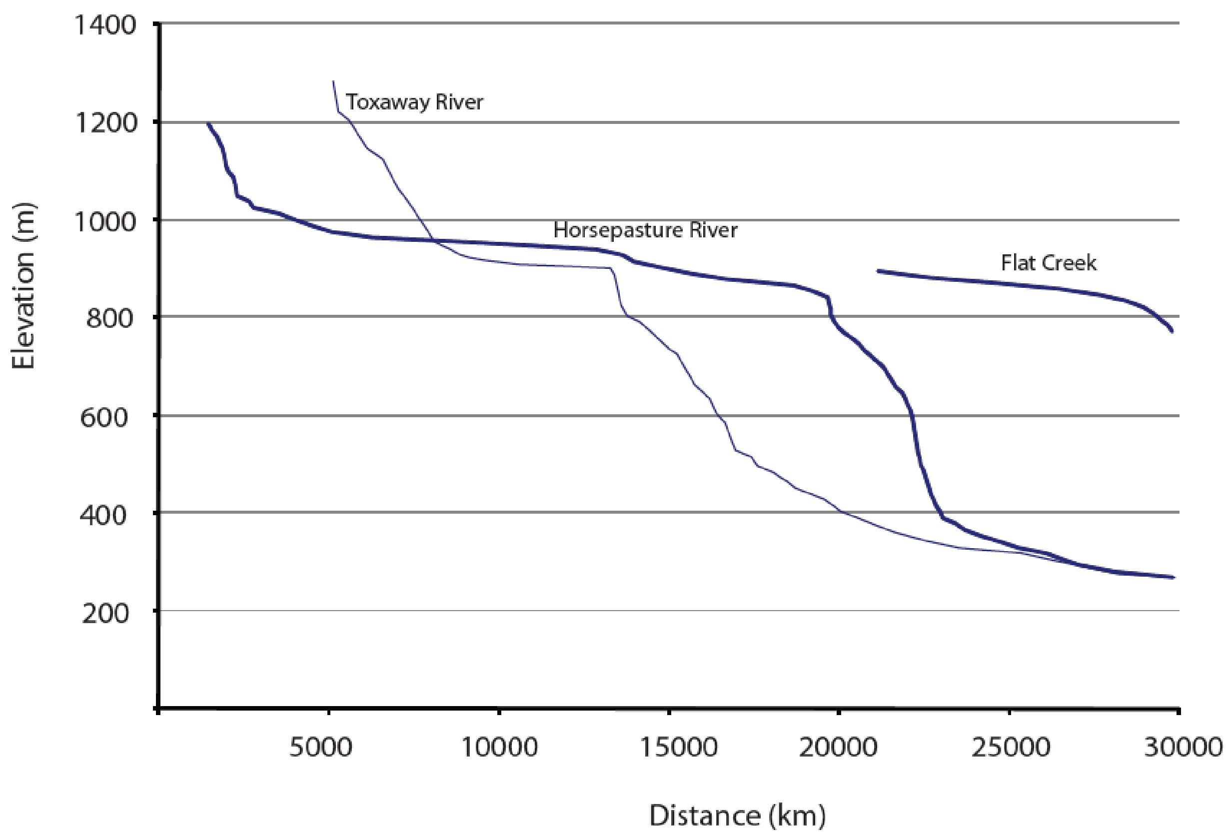

Figure 8. Longitudinal profiles of the Horsepasture and Toxaway Rivers and Flat Creek (Figure 5).

GRAVEL DEPOSITS IN THE VICINITY OF THE GREEN RIVER GORGE

Numerous deposits of rounded fluvial gravel occur at the BRE crest in the vicinity of the Green River gorge south of Hendersonville, North Carolina. South of the gorge, a large "butte" of Blue Ridge Plateau topography now draining entirely to the Green River (Atlantic basin) hosts several gravel deposits in wind gaps at the crest of the BRE (Figs. 5, 7). This "butte" is yet to be reached by knickpoints migrating up Green River tributaries, and maintains the elevation and morphology of the local landward-draining portions of the Blue Ridge Plateau. The gravel deposits along the margins of the butte are unrelated to the most recent capture of the Green River itself, and suggest capture and complete dissection of the basins of former French Broad River tributaries. These gravels are dominated by well-rounded vein quartz cobbles and small boulders set within a red clay matrix. Gravels are associated with broad, aggraded valleys, low gradient stream headwaters, and linear stream profiles, consistent with loss of drainage area to capture. The best exposures can be found along Terry Creek and within the boundaries of a summer camp facility at the headwaters of Terry Creek.

An additional gravel deposit can be found atop the Eastern Continental Divide at the northern margin of the Green River gorge where Upland Road crosses Interstate 26. Interstate 26 enters the French Broad River basin here through a very broad wind gap. The drainage divide itself appears to have no topographic expression, suggesting recent beheading of the remnant French Broad tributary (Bat Fork) and no subsequent adjustment of the stream valley to reduced discharge (Fig. 9). The gravel deposit has been heavily disturbed by construction, but well-rounded vein quartz cobbles can still be found on undeveloped land immediately east of the Interstate. The cobbles are set in a light-colored sandy clay matrix, but whether this matrix is of depositional origin or relates to weathering of the local quartz-rich bedrock is unclear. The elevation of this gravel deposit is consistent with the elevation of the Terry Creek gravels, indicating the likelihood of all the gravels representing the former valley elevation of a stream network following a low-gradient course to the French Broad River. As with the Flat Creek deposit, these gravels represent transient "relict" topography which will ultimately be dissected and lowered to Piedmont elevation by continued headward retreat of knickpoints.

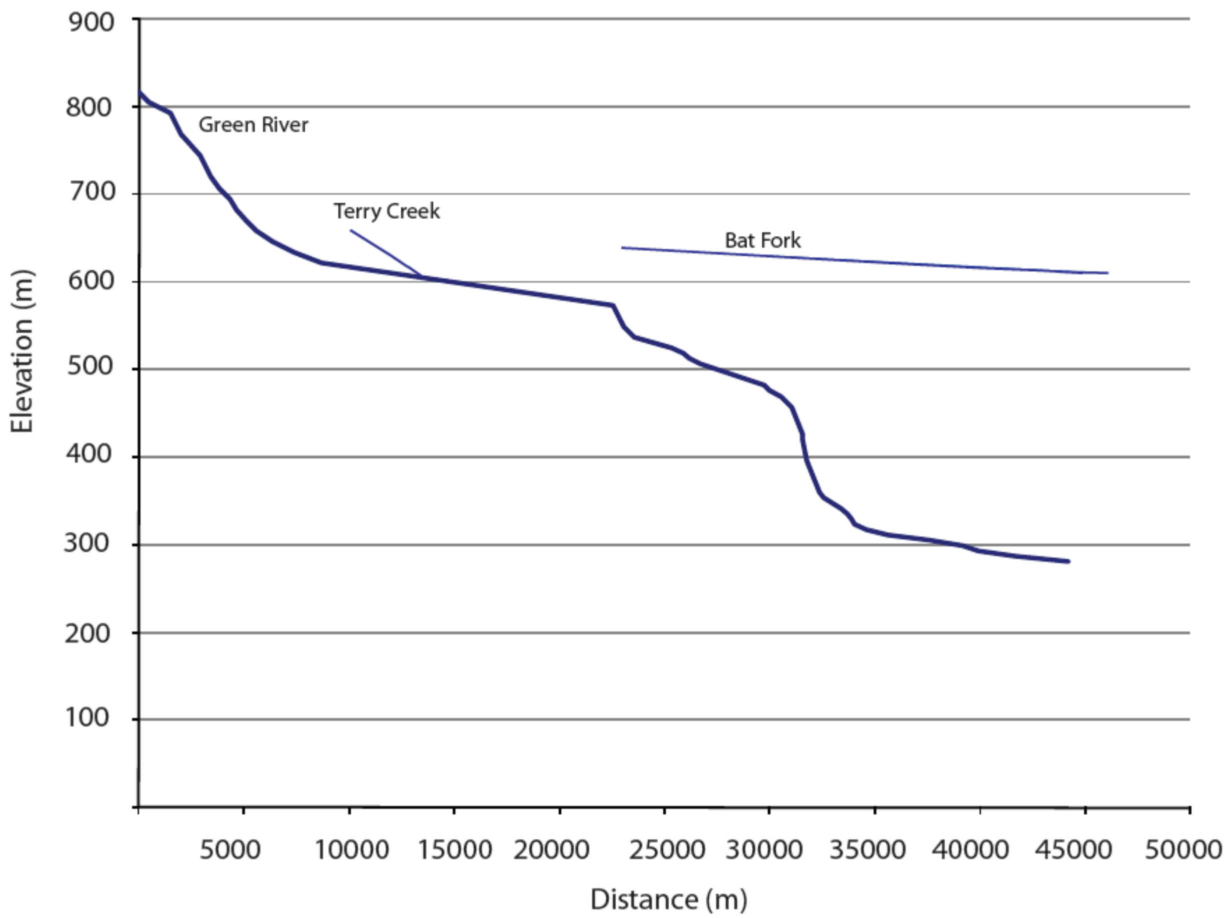

Figure 9. Longitudinal profiles of the Green River, Terry Creek, and Bat Fork (Figure 5).

DISCUSSION

Fluvial gravels preserved along the crest of the BRE in western North Carolina confirm the role of stream capture as the major driver of BRE evolution during the Cenozoic. Complete dissection of the Keowee and Green River headwaters will lead to the local expansion of the Piedmont surface at the expense of the Blue Ridge Plateau, producing local retreat of several kilometers of BRE. While gravels have yet to confirm the capture origin of other gorges such as The Dismal Gorge of Matthews Creek, Hickory Nut Gorge of the Rocky Broad River and the North Pacolet gorge (Figure 3), the characteristics of these streams are consistent with the Jocassee Gorges and Green River gorge and likely reflect a similar capture history. Large detached buttes in western North Carolina, such as the Brushy Mountains and South Mountains, may represent the final stages of adjustment to large captures of the Catawba and Yadkin River systems from the Blue Ridge Plateau into the Atlantic basin. Even if these basins are not the result of capture, continued adjustment in documented captures will drive the Piedmont (Atlantic) base level further into the Blue Ridge Plateau to accomplish further captures. Incision in captured basins is driven by gravitational potential energy of Plateau streams being tapped by Atlantic headwaters, and as long as elevation contrast exists across the BRE, the energetic driver for capture and BRE retreat will be preserved. Prince and others (2011) described the Blue Ridge Plateau as an "energy reservoir," which stores relict topographic potential energy to drive rapid fluvial incision long after the end of Appalachian orogenesis.

While the fluvial gravels and stream metrics of beheaded streams reveal the capture mechanism, little is known about the timing of capture or the rate of knickpoint retreat and topographic adjustment following capture. Knickpoint retreat and gorge advancement in captured streams certainly outpaces lowering of the surrounding Blue Ridge Plateau, as indicated by preservation of the gravel deposits at the BRE crest. Few constraints on denudation rates of the Plateau surface exist, but rates of <10 m/Myr have been indicated by cosmogenic radionuclide studies (Sullivan and others, 2007) as well as apatite thermochronometry (Spotila and others, 2004). If these rates are accurate and the gravel deposits were not exceedingly (10s of meters) thick, gorge advancement must outpace lowering of the surrounding upland by orders of magnitude. Nott and others (1996) obtained km/Myr knickpoint retreat rates in rivers carving gorges into the southeastern Australia escarpment. These streams are of similar size to the Keowee headwaters and Green River, and flow across a similar substrate in a similar climatic setting. Evolution of the captured streams may have proceeded more rapidly during the Pleistocene, when vegetation and precipitation patterns were different and likely favored more rapid denudation. In any case, captured basins evolve more rapidly than the adjacent Blue Ridge Plateau to accomplish localized retreat of the Eastern Continental Divide and BRE. If this mechanism occurs along the entire BRE over the long term, kilometers of landward parallel retreat of the divide and BRE have likely occurred during the Cenozoic.

The tectonic origin of the BRE also remains uncertain. Gravel deposits and gorge development suggest 10s of kilometers of retreat are certainly possible within the Cenozoic, and this retreat distance can restore the BRE at least as far as the westernmost Mesozoic basins in southern Virginia (Fig. 1). Lack of preservation of such basins in southern North Carolina or South Carolina (landward of the Crowburg basin) makes the limit of major depocenter development during Atlantic opening less clear. The exhumation signature of BRE retreat identified by Spotila and others (2004) in Virginia did not preclude a very large retreat distance, but no exhumation data from the Piedmont further south also limits extrapolation of this data to the western North Carolina BRE. It therefore remains unclear whether the BRE has experienced self-similar retreat since its inception on a rift flank during Mesozoic Atlantic opening, or if BRE formation and retreat was initiated more recently by an unknown flexure and uplift. Improved understanding of post-Mesozoic tectonics in the southern Appalachians may offer insight into these questions in the future.

Whether or not stream capture and divide migration controls the evolution of other passive margin escarpments is also yet to be determined. Inverted dendritic drainage patterns along the southeastern Madagascar escarpment (Gunnell and Harbor, 2008) offer anecdotal evidence of capture events which will ultimately produce escarpment retreat, but no surficial deposits have been located to confirm the process. Gorges cut into the southeastern Australia escarpment, particularly the Shoalhaven gorge, display comparable topography to BRE gorges and also appear to be associated with barbed tributaries and beheaded channels, but no field work has sought to evaluate the capture model due to the acceptance of the arch-type model (Persano and others, 2002). Similar gorges embay the Drakensberg Escarpment of South Africa, but these features have also been attributed to ongoing adjustment towards a fixed inland drainage divide (Moore and Blenkinsop, 2006). Until extensive field work is conducted in these settings, whether or not stream capture is, in fact, a major driver of passive margin escarpment evolution worldwide will remain uncertain.

DIRECTION OF FUTURE RESEARCH

While considerable data regarding BRE evolution has been gathered in recent years, numerous questions remain regarding its tectonic significance and the pace of its evolution. Additional study of a number of aspects of the modern BRE topography, its associated ecosystems, and the detrital signature of its erosional retreat would greatly enhance understanding of the evolution of the BRE and, potentially, passive margin escarpments worldwide.

^{10}Be analysis of bedrock landforms and stream sediments

While ^{10}Be analysis has been applied to sediments in streams draining the BRE, results were fit to a steady-state model which disregarded the transient nature, and thus mixed erosional dynamics, of BRE streams. No study to date has attempted to constrain incision rates or knickpoint retreat rates within the gorge systems of transient BRE streams which are still actively adjusting following capture. Applying the methodology of Norton and others (2008) could potentially reveal incision rates within the rapidly evolving gorge systems, offering quantitative constraint on the pace at which the margin of the Blue Ridge Plateau is consumed following a capture event.

^{10}Be analysis of bedrock exposure age could also shed light on incision rates and rates of hillslope and cliff evolution following capture and incision. Hanging bedforms (flutes and potholes) are known to exist within the gorges of actively adjusting streams, and evaluating there subaerial exposure age in the context of their height above the active channel could be useful in determining incision, and thus adjustment, rates. While cliffs along the gorges are dominated by rockfall due to the intersection of joints and foliation, the rate at which rockfalls occur is unconstrained. Several exposure ages collected along extensive cliff faces could also offer some quantitative constraint on how dynamic these oversteepened slopes may actually be.

Genetic studies of aquatic organisms

Occurrence of fish species and other aquatic organisms endemic to landward drainages in the headwaters of Atlantic basin streams has long been viewed by biologists as the result of stream capture (c.f. Jenkins and others, 1971). The steepness of Atlantic slope headwaters flowing down the BRE would prevent aquatic organisms from travelling down one headwaters to an arterial drainage and then moving back upstream into an adjacent headwaters; species in these headwaters are therefore isolated once detached from the landward basin by capture. Some workers have suggested that comparing genetic mutations in the same species from landward and adjacent Atlantic streams could offer data on the timing of capture. This method would rely on the accuracy of mutation rate applied, but could offer some indication on the timing of captures which have produced a known topographic response.

Offshore sedimentary record

Pulses of erosion following capture events transport several cubic kilometers of rock as sediment to the continental margin. Rapid Miocene sedimentation in the Chesapeake area has been regarded as possible evidence of growth of the Potomac basin by capture, but no similar analyses have been conducted further south along the Atlantic margin. Large capture events might be visible as sediment pulses in the near-shore sedimentary record. Landward erosional retreat of the divide and BRE also connects an ever-changing array of sediment sources to the Atlantic basin over time. Identification of unique tracer minerals or zircons of a given age in offshore strata might indicate the time at which the Atlantic basin breached a particular zone of bedrock through stream capture and associated BRE retreat. The Savannah basin is an excellent candidate for this type of analysis, due to its short length, potentially recent growth from accretionary terranes into Laurentian units, and the lack of anecdotal evidence for alteration of its basin by post-BRE retreat captures within the Piedmont.

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Roadlog for Saturday, October 13, 2012

The purpose of the field trip is to describe and view exposures of lithologies in Pickens, Sunset, Eastatoe Gap, and Salem quadrangles in Pickens and Oconee counties, SC. We will transect parts of the Jocassee and Walhalla thrust sheets, looking at an ultramafic rock occurrence at Lake Keowee and metamorphic units within the old 'Chauga belt'. These units are, in order downsection, Table Rock gneiss, Poor Mountain Formation, Chauga River Formation, the Eastatoee ductile thrust separating the Walhalla and the underlying Jocassee thrust sheets, and the Henderson Gneiss. We will also visit an historic grist mill in Pickens County, with its rock exposures and unusual petroglyphs.

Depart from downtown Greenville, SC. Travel to Pickens, SC.

Total miles Increment mileage
0.0 *0.0* Roadlog begins at the intersection of US 178 and US 183 in Pickens, SC. Travel north on US 178.

2.6 *2.6* Turn west (left) onto Hagood Mill Road.

2.75 *0.15* **Stop 1 Hagood historic mill at Hagood Creek,** Pickens quadrangle.

(UTM: 342710 3866020)

Features of Interest: Historical site buildings, bedrock exposures, petroglyphs

Stop leaders: Ed Bolt, Bill Ranson, Jack Garihan

A Short History of the Hagood Mill Site

Built in 1826 and then rebuilt in 1845 by James Hagood, the Hagood Mill utilizes the waters of Hagood Creek (formerly Jennings Creek), a tributary of the Twelve Mile River, to turn its wooden water wheel. A dam on Hagood Creek was 1650 feet upstream of the mill, and from there water from the creek was diverted to the mill by an earthen headrace (ditch). Today water is pumped from the creek up to the headrace, the last 80 feet of which is made of wood. The wooden water wheel is 20 feet in diameter by 4 feet wide, and produces 22 horsepower (Figure 1-1).

Figure 1-1. Hagood Mill, water wheel, and flume along Hagood Creek.

Figure 1-2. Petroglyphs, SC Rock Arts Center at Hagood Mill site.

The wheel and mechanical components were rebuilt in the mid-1970s using as many original parts as possible. Restoration work continued in the mid-1980s, and again in the mid-1990s. The ring gear is 18 feet in diameter, and the two granite millstones weigh about 1600 pounds each. During most of its life, the Hagood Mill was a busy center of commerce. The *Products of Industry Census* records Hagood Mill as having produced 2,500 bushels of meal (140,000 pounds), and 200 bushels of flour (11,200 pounds) in the year 1870. In 1880, 120,000 pounds of meal and 20,000 pounds of flour were produced.

Almost without exception, the farmers that came to Hagood Mill were cotton farmers. They needed about five acres of corn to feed themselves and their animals, and then ten acres or more of cotton to sell for cash. In tribute to these farmers, the mill site obtained and operated an 1890 Daniel Pratt Cotton Engine. Along with the old gristmill, it is an exceptional piece of nineteenth century technology and was completely restored by a team of skilled volunteers. Before the cotton gin, it took one person eight hours to pick the seeds out of one pound of cotton; this machine can do a thousand pounds (or two) in an hour. Indeed, cotton farming was a way of life in this area, and there were many textile mills that dotted the Pickens County landscape, and textiles became its main industry for almost a century.

In 2003 Native American petroglyphs (rock carvings) were discovered on a large, thirty-foot long rock near the mill. The petroglyphs are difficult to see and easy to miss in the bright daylight, but when lit from the side after dark these ancient works of rock art stand out as if they were carved yesterday (Figure 1-2). The carvings were found by a member of a team working with archaeologist Tommy Charles as they were conducting a ten-year "SC Rock Art Survey" of the state for the South Carolina Institute of Archaeology and Anthropology. This survey documented over 300 petroglyph sites in the Upstate counties of Oconee, Pickens and Greenville. The seventeen human "stick men" on the Hagood Mill rock are thought to be between 1,000 and 2,000 years old. A 38' x 80' building (the "SC Rock Art Center") was recently constructed over the rock to protect the petroglyphs and to feature the photographic images of the survey and other related exhibits.

In 1972, Hagood Mill was added to the National Register of Historic Places. Hagood Mill is one of the oldest known gristmills in the state of South Carolina that still produces grain products, and the only mill in South Carolina that uses the original wheel components. On the third Saturday of each month, the millwright turns on a pump and the waters of Hagood Creek once again spill over the waterwheel. In addition to the mill, there is a heritage park that consists of a caretaker's cabin, gift shop, the Murphree-Hollingsworth Log Cabin (circa 1790) and the Hagood Family Cabin (circa 1825). Throughout the year, the mill is also the site of heritage-based music festivals, traditional mountain crafts, and living history presentations. Hagood Mill is an official site along the South Carolina National Heritage Corridor. The mill is open the third Saturday of each month from 10 AM – 4 PM, and is available for viewing every day of the year by appointment. To get to the mill from Pickens – take Highway 178 North for 3 miles to Hagood Mill Road, turn left onto Hagood Mill Road, and the mill is on the right. For more information and viewing appointments, contact Pickens County Museum, 307 Johnson Street, Pickens, SC 29671. (864) 898-5963, picmus@co.pickens.sc.us

(Extracted with permission from the Hagood Mill website and the Pickens County Museum website, with figures added).

Stop 1 is located along Hagood Creek in an erosional embayment of the Six Mile thrust sheet. Table Rock gneiss of the Walhalla fold-nappe (Figure 1-3) is exposed along the creek and behind the historic buildings (Figure 1-4). The rock is a fine crystalline biotite-hornblende-plagioclase-quartz gneiss (amphibolite) with accessory epidote in thin section. Sheared, medium- to coarse-crystalline hornblende-plagioclase gneiss with accessory rutile is interlayered locally with the gneiss. Small inclined to overturned folds are west-vergent.

Red-weathering hornblende metagabbro forms low exposures and boulders behind the log cabins. The presence of this rock suggests amphibolite layers in the Walhalla fold-nappe are derived by shearing of a gabbro protolith. Regionally there are both dikes and sills in the gneiss sequence. Folding post-dates the shearing.

The petroglyphs are showcased in the covered SC Rock Art Center. One can also see a well-developed isoclinal fold in the gneiss (Figure 1-5).

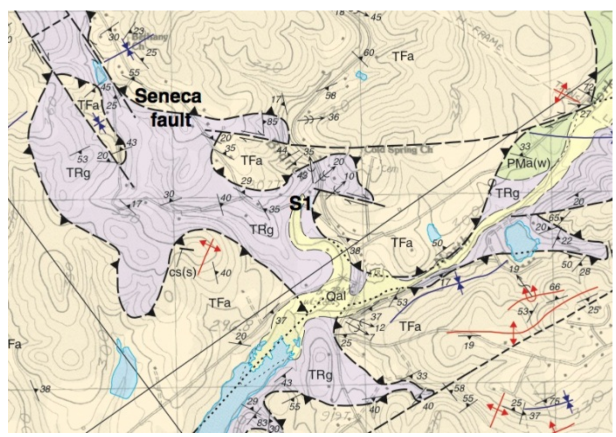

Figure 1-3. Portion of Pickens geologic map. S1- Stop 1. TRg- Table Rock gneiss; PMa(w)- Poor Mountain amphibolite; TFa- Tallulah Falls Formation; cs(s)- calc-silicate rock.

Figure 1-4. Ledge exposures of gneiss and amphibolite along Hagood Creek.

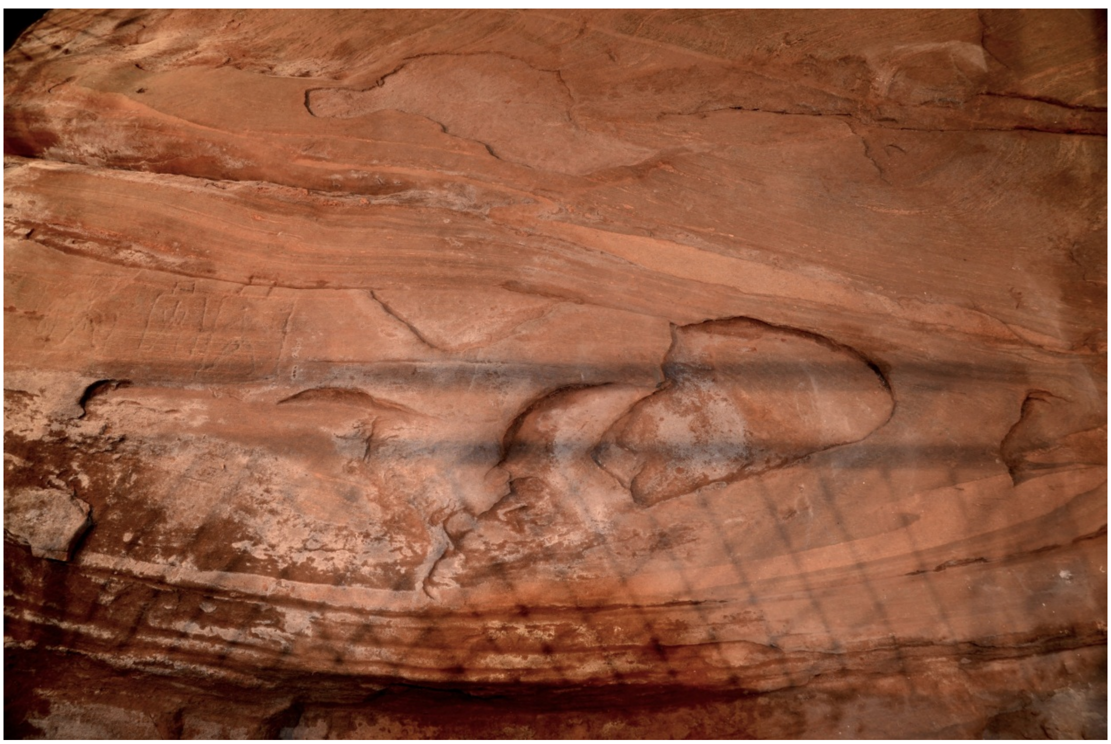

Figure 1-5. Isoclinal fold and petroglyphs, pavement in the SC Rock Arts Center.

Return to US 178, 0.15 miles. Travel north on US 178.

8.4 *5.5* Intersection of US 178 and SC 288. View ahead of Pinnacle Mountain beyond Holly Springs Church. Pinnacle is the highest peak entirely within South Carolina (elevation 3425 ft). A klippe of the Six Mile thrust sheet with the Seneca thrust at its base occurs at its summit. Rounded, exfoliated exposures of Table Rock gneiss are visible along Drawbar Cliff (Figure 2).

Figure 2. Holly Springs Church and Pinnacle Mountain, with Six Mile klippe at the highest peak. Balds are underlain by Table Rock gneiss. View north.

9.0 *0.6* Intersection of US 178 and SC 11. Turn west (left) onto SC 11.

11.5 *2.5* Post office Sunset, SC 29685

15.8 *4.3* Cross Lake Keowee on SC 11. Enter Oconee County.

16.2 *0.4* **Stop 2 Large exposure of Chauga River Formation,** Salem quadrangle.

(UTM: 325059 3865143)

Features of Interest: Chauga River Formation lithologies, S-C structures

The prominent iron- and manganese-stained exposure of Chauga River Formation rocks lies on the north side of Highway 11 along an uphill grade, west of the bridge over Lake Keowee (Figure 3-1). Structurally the locality lies within a belt of regional northeast-striking, northwest-vergent, overturned folds involving rocks of the Chauga River and Poor Mountain formations. In addition the rocks locally are complexly faulted. An array of northwest-striking faults terminates against two northeast-striking faults with right-lateral offsets, resembling a ladder-like pattern (Figure 3-2).

The Chauga River Formation rocks here include dark gray, fine-crystalline pelitic muscovite-biotite gneiss (also referred to as metasiltstone) and fine- to medium-crystalline mica button schist. “Siltier”, less micaceous layers are darker than more schistose ones. These textural variations at the scale of several centimeters are visible in Figure 3-2, with a ‘siltier’, more equigranular layer present above the scale. Continuous, thin felsic layers a few mm thick are isoclinally folded. Schistosity dips gently south toward the road and is a transposing foliation. Well-developed S-C structure in porphyroclastic muscovite schist (Figure 3-3) at the western end of the large exposure is consistent with regional southwest-directed shearing in these rocks (Hatcher and Merschat, 2006).

Figure 3-1. Stop 2. Exposure of Chauga River Formation, SC 11, Oconee County.

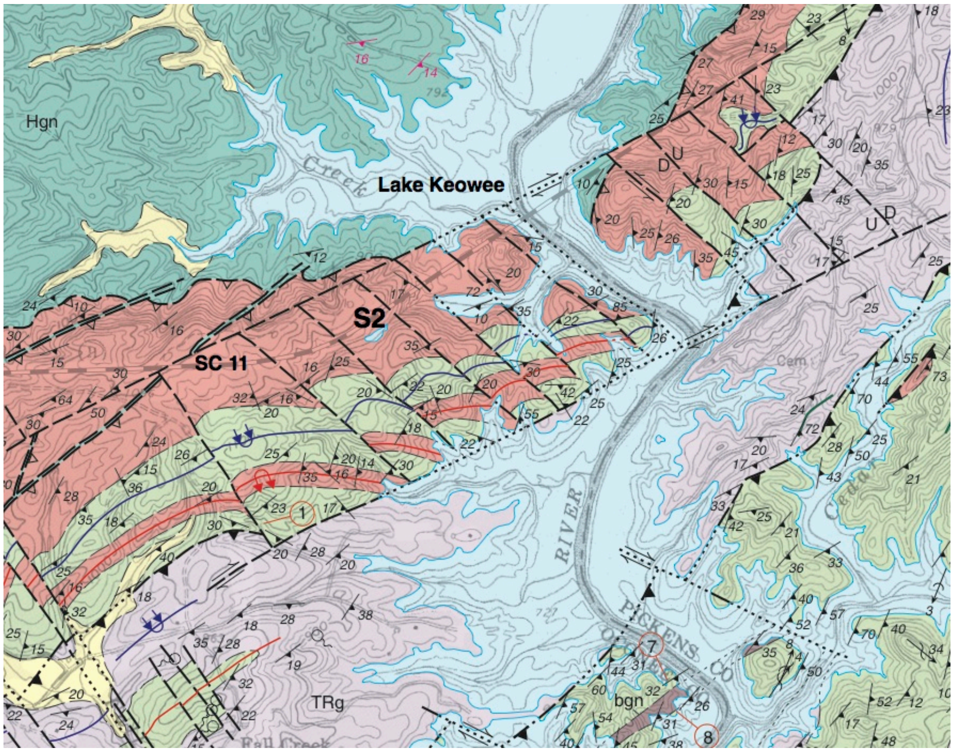

Figure 3-2. Stop 2. Geologic map of Stop 2 area, Salem quadrangle. S2- Stop 2 location. HGn- Henderson Gneiss; TRg- Table Rock gneiss; red- Chauga River Formation; green- Poor Mountain Formation. Open tooth thrust- Eastatoee fault. Blue line- trace of overturned synform; red line- trace of overturned antiform.

Figure 3-3. Stop 2. S-C structure developed in button schist and metasiltstone. Sense of S-C structure indicates generally westward shearing (to left). View to north.

16.8 0.6 Turn south (left) off SC 11 into the Keowee Falls South Cliffs Community. Prior permission is necessary to enter this property. Roadlog mileage does not include the distance from this turn off SC 11 to the ultramafic exposure and the return.

Stop 3 Salem ultramafic at Long Cove Trail, Keowee Falls South Cliffs Community. Salem quadrangle.

(UTM: 324997 3861063)

Features of Interest: mineralogy, chemistry of Inner Piedmont ultramafic rock

Stop leaders: Jay Bridgeman and Bill Ranson

Of interest at this stop are several exposures of ultramafic rock, containing dark green amphiboles in a chlorite matrix and kink folding of the schistosity. The rock is moderately to extensively weathered. This ultramafic body (see figures in paper of Bridgeman and Ranson, this volume) has a lenticular shape, with dimensions 0.7 km long by 0.1 km wide and a northeasterly trend on the geologic map of Salem quadrangle (Clendenin and Garihan, 2007). It is generally associated with Poor Mountain amphibolite. The exposures here are boulders and low, ledge-forming outcrops of chlorite-amphibole schist (Figure 4-1, A). Chlorite abundance ranges from approximately 25 to 45%, and amphibole is from 30 to 60% of the rock, as estimated from representative thin sections. A common accessory mineral is magnetite.

Textures range from a well foliated, well developed lepidioblastic schistosity to weakly schistose and felty. Where it can be measured, schistosity generally dips more steeply (65°-78°) than the foliation in surrounding rocks. Chlorite is highly magnesian with Mg numbers ranging from 0.72 to 0.89. Amphibole varieties based on electron microprobe analyses include tremolite, tremolitic hornblende, magnesio-hornblende, ferrian-magnesio-hornblende, and magnesio-cummingtonite. Relict olivine (Fo 77.71 to Fo 87.34) in amounts <10% was observed in two thin sections whereas relict orthopyroxene was observed in one thin section and constituted <10% of the sample (Bridgeman, 2012 and Bridgeman and Ranson, this volume).

Four whole rock chemical analyses of rocks from this location reveal a range in weight percent for SiO_2 from 37.08 to 42.50; for MgO from 20.76 to 27.68; for Al_2O_3 from 5.95 to 9.77; and for CaO from 4.42 to 7.15. Based on alumina content, the protolith for these rocks was likely a plagioclase lherzolite (Bridgeman, 2012 and Bridgeman and Ranson, this volume).

The Salem ultramafic, like others nearby in Sunset and Table Rock quadrangles, is partially surrounded by amphibolite. One boulder of micaceous rock displays chevron folding of schistosity, indicating participation in compressional deformation (Figure 4-1, B). As is common in the Inner Piedmont, the contacts with surrounding rocks are not exposed, and the nature of emplacement is uncertain. Based on our study, we suggest a model of emplacement for these rocks. It begins with a lherzolite or plagioclase-lherzolite protolith from a mantle derived, sub-oceanic crustal setting. The protolith underwent sea-floor hydrothermal metamorphism in which the olivine, pyroxene, and plagioclase (?) altered to chlorite and amphibole. The ultramafic body was then tectonically emplaced. These rocks then experienced amphibolite facies regional metamorphism, during which the chlorite remained stable because of its high Mg content. The amphiboles became more aluminous, eventually stabilizing as hornblende, although incompletely because of the presence of tremolite and cummingtonite.

A.

B.

Figure 4-1. Exposures of chlorite-amphibole schist as exposed in the Salem Quadrangle. A. Weathering rind on ultramafic boulder. Jay Bridgeman is scale. B. Ultramafic schist boulder with chevron folds.

16.8 *0.6* Resume mileage at the intersection of SC 11 and the Keowee Falls South Cliffs Community entrance.

Travel east on SC 11.

21.5 *4.7* **Stop 4 Long Shoals Wayside Park,** Sunset quadrangle.

(UTM: 330926 3868702)

Features of Interest: Lunch. Pavements of Table Rock gneiss, joints, potholes

Extensive pavement exposures of leucocratic, mylonitic Table Rock gneiss are present at Long Shoals Wayside Park along Little Eastatoe Creek, ~0.75 km northwest of Buzzard Roost Mountain. The small Park (Figure 5-1) is along Rt. 11 east of Lake Keowee. The fine-crystalline biotite quartzo-feldspathic gneiss has abundant compositional layers of coarse quartz-feldspar pegmatite lying parallel to gneissic foliation (Figure 5-2). Numerous interesting features are spectacularly exposed along the creek, including several sets of systematic joints and potholes (up to 3 ft across). Rounded bedrock exposures have been extensively polished, fluted, and grooved (Figure 5-3). Potholes appear to have formed along prominent joint directions by current scouring action along these planes of weakness in the rock (Figure 5-4). The systematic joint data collected from Long Shoals Wayside Park are shown in Figure 5-5. The dominant joint sets, in order of decreasing frequency, are N-N5°E, N45°-50°W and N10°-15°E.

Figure 5-1. Stop 4. South Carolina Forestry Commission sign, Long Shoals Wayside Park.

Figure 5-2. Stop 4. Table Rock gneiss and pegmatite.

Figure 5-3. Stop 4. Pits, flutes, and grooves on polished bedrock surfaces produced by abrasive current action during stream flow.

Figure 5-4. Stop 4. Potholes developed along joints.

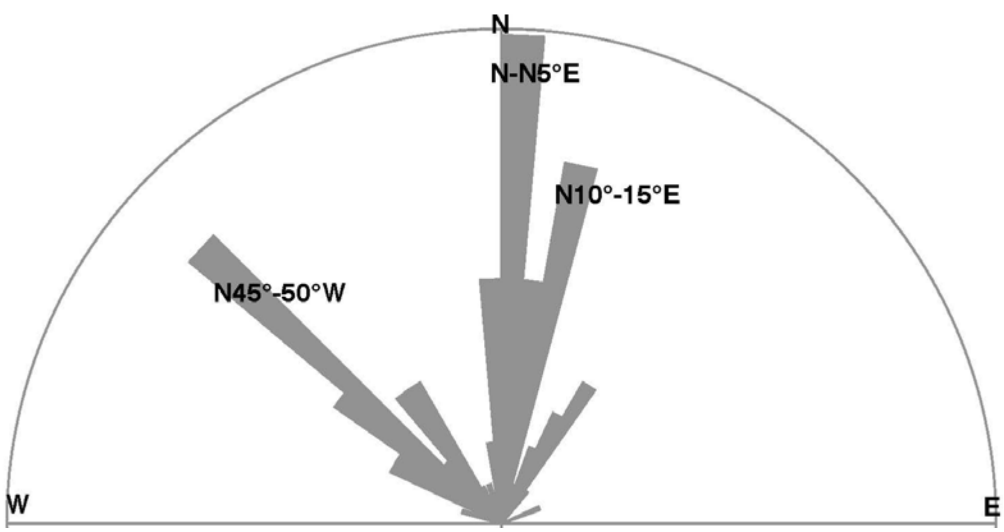

Figure 5-5. Stop 4. Rose diagram of joint strikes collected from Long Shoals Wayside Park. Outer semi-circle is 15% of all data (n=81). Three joint sets are present.

Continue east on SC 11.

22.6 *1.1* Intersection of SC 11 and Roy F. Jones Highway (SC39-143). Turn west (left) onto Roy F. Jones Highway. Near this intersection a granite marker commemorates Roy F. Jones as the first 50-year employee of the SC Highway Department. Except for the stop at Dug Mountain, all exposures described in the traverse below are located on the north (right) side of Roy F. Jones Highway. All are located in Sunset quadrangle except stop 10 (Figure 6).

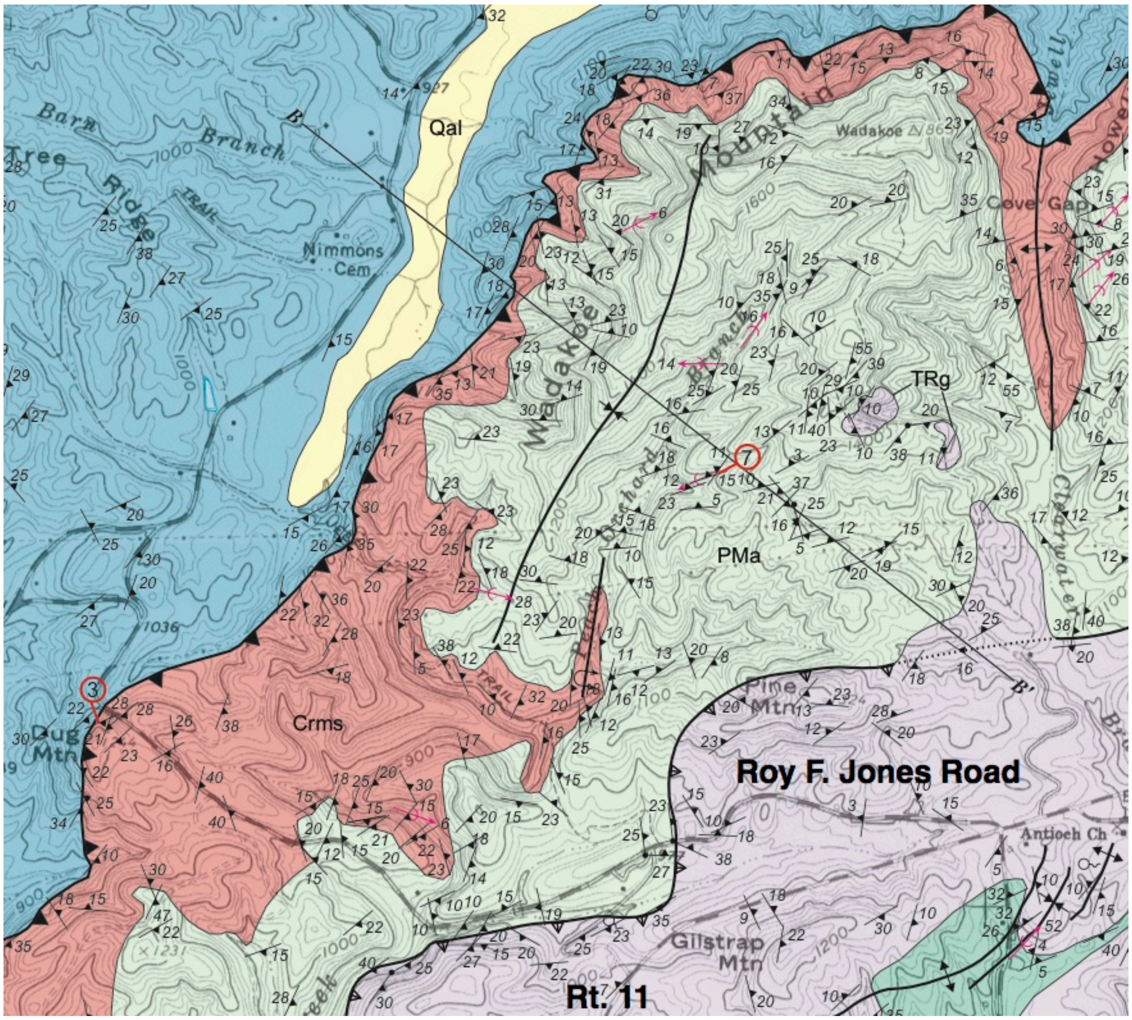

Figure 6. Geologic map of our traverse route along Roy F. Jones Highway, Sunset quadrangle. Units same as Figure 3-2 caption. Cross section B-B' is shown in Figure 10.

Our traverse this afternoon highlights the major lithologies of the old 'Chauga belt' along Roy F. Jones Highway, starting from its intersection with Rt. 11 (the Cherokee Foothills Parkway) and traveling west-northwest toward Dug Mountain. The transect begins in Table Rock gneiss (Middle Ordovician), which here is a structurally higher part of the metamorphic sequence in the Walhalla fold-nappe. We will pass successively through Poor Mountain Formation amphibolite, Chauga River Formation schist, and Henderson Gneiss, making several stops and walking along the road to observe the various lithologies and features. We will also observe the relationship between soil chemistry and associated plant communities. **For your safety please be aware of the road traffic.**

Regionally, the units in northwest Sunset quadrangle strike northerly and dip easterly, with variations due to polyphase folding. The units are not grossly overturned along our route, and we encounter a normal sequence top (at east end) to bottom (west end). The Eastatoee ductile thrust is exposed at Dug Mountain.

22.7 *0.1* Typical exposures of Table Rock gneiss on north side of road. Gray-tan, soft, sandy saprolite of biotite quartzo-feldsapthic gneiss.

(UTM: 332749 3870048)

23.2 *0.5* At road bend, exposures of reddish, iron-stained saprolite of Table Rock gneiss. Rock is a fine-crystalline, biotite quartzo-feldsapthic gneiss. Texture varies from a poorly layered, leucocratic rock with individual well aligned, fine biotite flakes to a gneiss with discontinuous, mm-scale biotite layers. As the contact with adjacent amphibolite is approached to the west, exposures of Table Rock gneiss acquire a red coloration.

(UTM: 331783 3870017)

23.3 *0.1* The first exposures of Poor Mountain Formation amphibolite occur near the Peach Orchard Angler Access trailhead road. (UTM: 331585 38699)

A thrust fault is present along this traverse between the Table Rock gneiss and underlying Poor Mountain Formation, although it is not exposed along Roy F. Jones Highway. The sinuous trace of the fault is relatively simple to map in the area where saprolitic quartzo-feldspathic gneiss lies adjacent to limonite-weathering amphibolite. This unnamed fault is interpreted as an out-of-the-core thrust resulting from localized strain during regional overturned, northwest-vergent folding.

23.4 *0.1* Red exposure of Poor Mountain Formation amphibolite. (UTM: 331515 3869917)

A striking feature is the orange-red coloration of weathered amphibolite, informally termed ‘ochre gneiss’. The rock is soft and saprolitic, forming some resistant, slabby ledges. Larger broken float blocks have cores of fresh, dark gray-black, fine-crystalline, thinly layered amphibolite with 0.2-0.5 cm limonitic weathering rinds. Foliation is broadly warped in the exposure. Minor gray-tan, fine-crystalline quartzite is present. About 1.5-2m of tan-white, fine-crystalline muscovite-quartz phyllonite with wavy schistosity is present at road level (Figure 7, left side) below ~2m of exposed amphibolite.

Figure 7. Red-weathering Poor Mountain Formation amphibolite and phyllonite. Note broad folding of amphibolite foliation. View to north.

23.7 *0.3* **Stop 5 Poor Mountain Formation amphibolite, east side of bridge over Eastatoe Creek.** Please do not hammer on this exposure. Be aware of traffic on this curve!

(UTM: 330822 386917)

Features of Interest: amphibolite, calc-silicate layers, incipient boudins, isoclinal folds, gash vein filling mineralogy

This interesting exposure of Poor Mountain amphibolite shows a variety of mineralogic and structural features, including calc-silicate layers, incipient boudinage, isoclinal folds of thin felsic layers, and filled gash veins (Figures 8-1, 8-2, and 8-3). Overall the surface of this exposure is discolored. It appears altered, presumably due to the chemical breakdown of pyrite in the rock by its interaction with water draining down the rock face. Thin, soft biotite-bearing amphibolite interlayers are differentially weathered compared to resistant amphibolite layers without mica. Foliation dips gently northeast.

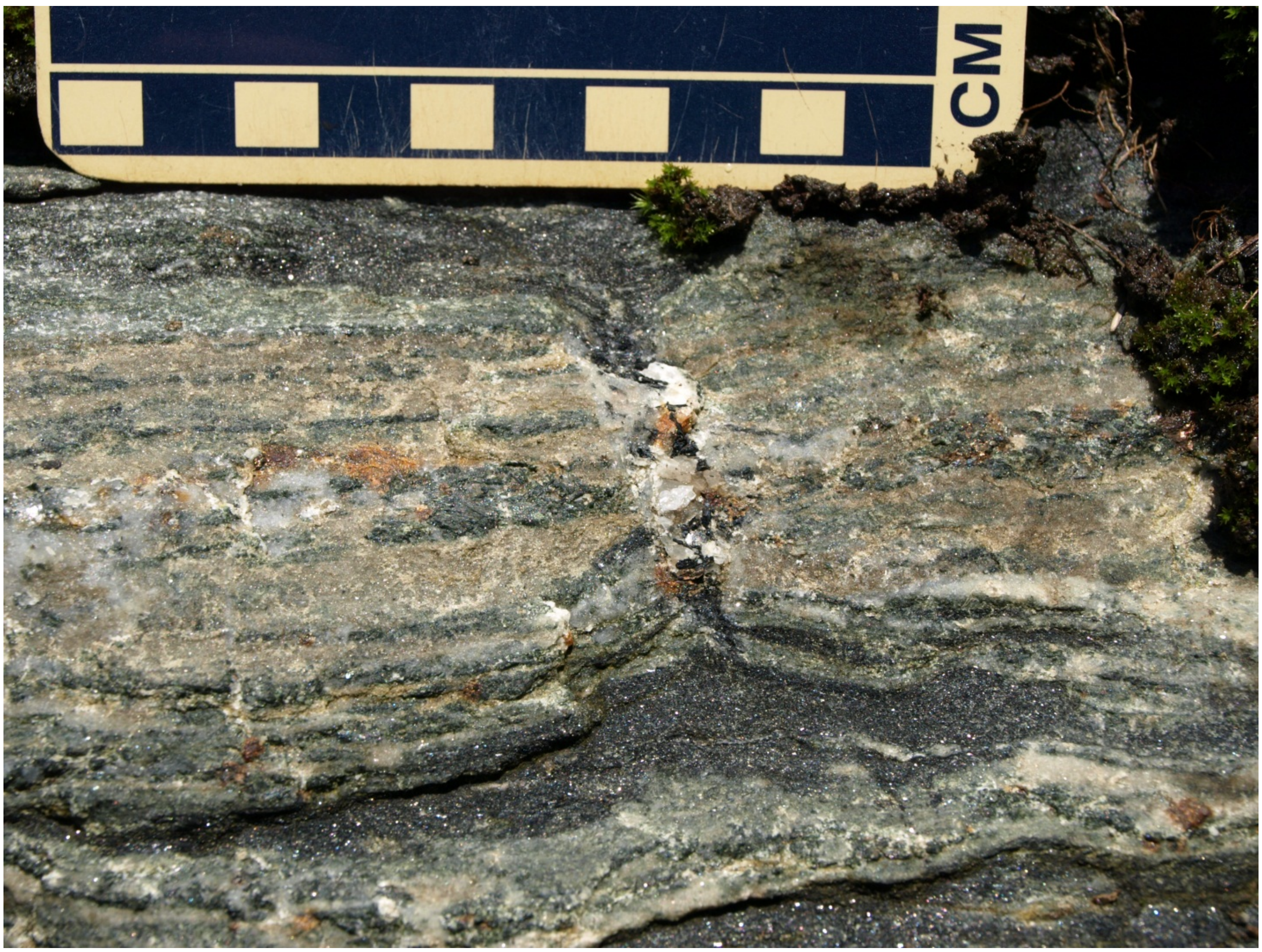

Figure 8-1. Stop 5. Incipient boudinage of calc-silicate layers in amphibolite.

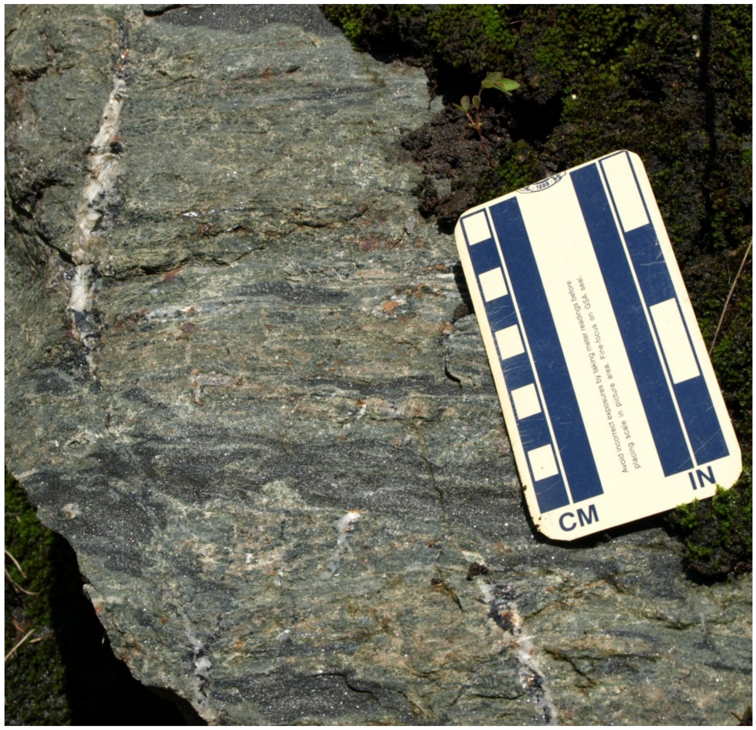

Figure 8-2. Stop 5. Gash vein in epidote amphibolite, filled with calc-silicates, quartz, calcite, and pyrite.

Figure 8-3. Stop 5. Small, near-recumbent isocline in amphibolite, outline by thin felsic layer. View to north.

A gray, fine-crystalline, schistose muscovite quartzite is present on the west side, at the base of the exposure. Above it, fresh amphibolite is black, fine-crystalline, and thinly layered with coarse-crystalline pods and layers along foliation. Thin interlayers (a few centimeters thick) in amphibolite are composed of green, fine-crystalline, granoblastic green epidote, quartz, and calc-silicate minerals (including garnet. clinoamphibole, and plagioclase). At the east end of the exposure, a 1m discordant pegmatite appears to have affected the foliation in adjacent amphibolite at its lower margin (drag during pegmatite emplacement?).

23.9 0.2 **Stop 6 Dug Mountain Anglers Access, Eastatoe Creek.** Poor Mountain Formation amphibolite is well exposed along the creek and on the hillslope across it to the east.

(UTM: 330754 3869824)

Feature of Interest: Discussion of connections among plant communities, substrate rock types, and soil chemistry

Stop leader: Tom Goforth. Crow Dog Native Ferns, Pickens, SC.

Geologic Connections with Native Plants

Botanists have long recognized the connection between plant occurrences and substrate geology. Typically either general site geology or regional geologic information is included in plant survey and other biological literature. Plants have adapted and are adapting to variable soil chemistry that is derived from substrate lithologies and/or sediments and aqueous solutions transported locally or from afar. Some plant species, called specialists, occur exclusively in habitats with soils derived from specific rock types. Non-specialist plants, called cosmopolitans, occur in habitats with different substrates. Where vigorous specialists are observed in a habitat, the substrate can be inferred as occurring directly below or close by. Infrequent and stunted plant species may be encountered within a substrate that does not readily support the specialists.

Along a transect where variable substrate lithologies exist, different plant specialists occur that reflect the different minerals and soils produced by the weathering of a particular rock type. Plant specialists and the soils in which they reside can be used as indicators of substrate when outcrops are few or absent. Lithologic contacts are sometimes slightly to moderately blurred by the effects of local topography, hydrology, sedimentation, or metasomatism in metamorphic terrain.

Bedrock mineralogy is the primary source of surface soil. The composition and characteristics of the soil directly influences the variety of organism and habitat composition. The Inner Piedmont of South Carolina is underlain by felsic, mafic, and intermediate metamorphic rocks composed chiefly of alumino-silicate minerals. Mineralogy of rock units varies primarily in metal content, and metals are key components in soil character development as well as plant community structure and vigor. The percentages of acidic (aluminum, hydrogen, sulfur, etc.) and alkaline (calcium, magnesium, and manganese, etc.) elements in minerals in these rocks vary and influence the characteristics of soils they produce and the availability of plant nutrients. In general, mafic rocks produce richer soils and higher plant diversity compared to felsic rocks. A knowledge of a relatively small number of plant species that are substrate specialists adds a valuable dimension to geologic mapping and other field studies.

24.1 0.2 Low ledges of Poor Mountain Formation amphibolite. Continue west, uphill.

(UTM: 330504 3869974)

24.2 0.1 **Stop 7 Pelitic mica gneiss (metasiltstone).**

(UTM: 330420 3869968)

Features of Interest: Rocks of the upper part of the Chauga River Formation

Several poor exposures occupy a position near the contact between Poor Mountain Formation rocks (downhill, stratigraphically above) and the Chauga River Formation (uphill, stratigraphically beneath the amphibolite). Bend in the road. On Roy F. Jones Highway, across from the AT&T underground cable station.

Outcrops and float of fine-crystalline pelitic muscovite-biotite gneiss (also termed mica metasiltstone or metagreywacke, to emphasize its low metamorphic grade). Mica is golden brown weathering. Also present in the ditch are float pieces of mica button schist. This is the Chauga River Formation.

Even at the scale of a thin section, more equigranular, fine-crystalline, biotite-quartz-plagioclase (‘siltier’) layers alternate with schistose biotite-muscovite-quartz-accessory epidote layers. In the latter, coarser muscovite and lesser fine biotite aggregates form tapered polycrystalline foliation fish with a consistent, sense of shear.

24.3 0.1 Pelitic mica gneiss (metasiltstone) and amphibolite.

(UTM: 330393 3869975)

Exposure of interlayered fine-crystalline mica metasiltstone and slabby, thinly layered amphibolite. More Chauga River Formation.

24.4 0.1 **Stop 8 Pull-off across from entrance to Eastatoe Park gated community**.

(UTM: 330109 3870137)

Feature of Interest: Chauga River Formation button schist

Several exposures of saprolitic Chauga River mica button schist on the south side of the road. Individual buttons are visible in reflected sunlight.

Half the group from this point will walk downhill to stop 7 and the other half will proceed uphill to stop 9. The groups will then switch. To reach stop 9, turn south (left) onto a logging road and climb uphill to a gravel road and the exposure.

Stop 9 Dug Mountain. Please do not dig in this soft exposure.

(UTM: 329725 3870387)

Feature of Interest: Eastatoee fault

The Henderson Gneiss–Chauga River Formation contact is exposed in an embankment above a gravel road on the east side of Dug Mountain. This is the most easily accessible exposure of the ductile Eastatoee thrust contact along the traverse. Rocks here are saprolitic. Three meters below the contact, the Henderson Gneiss contains elliptical to rounded K-feldspar augen (maximum dimensions: 0.6 x 1.5 cm) in a fine-crystalline biotite gneiss ground mass. Upward toward the contact, Henderson Gneiss is a thinly layered, fine-crystalline, leucocratic biotite gneiss with <10% K-feldspar augen (~2 mm in maximum dimension). Different Chauga River Formation rocks are juxtaposed above the Henderson Gneiss. Interlayered brown, fine-crystalline mica schist and light gray micaceous metasiltstone (foliation N40°W, 30°NE) with pegmatite are preserved above the sharp contact with Henderson Gneiss (Figure 9).

Figure 9. Stop 9. Eastatoee fault at Dug Mountain. Contact is at the base of the saprolitic brown, fine-crystalline metasiltstone (Chauga River Formation), at the pencil. Below it is Henderson Gneiss with thin pegmatitic layers.

24.5 *0.1* Exposure of Chauga River Formation.

(UTM: 329913 3870325)

Saprolitic metasiltstone layers dip gently northeast. Mica buttons are weathering down the outcrop face.

24.6 *0.1* Entrance to small borrow pit and powerlines.

(UTM: 329783 3870402)

Henderson Gneiss is poorly exposed in the pit and in ruts in the access road. The rock is mylonitic with <10% small, lenticular augen. The rugged Jocassee Gorges Wilderness Area lies to the north of the powerlines. The Bad Creek pump storage dam is visible to the northwest on a clear day.

Continue downhill on Roy F. Jones Highway.

24.8 *0.2* Turn north (right) onto Granny Greer Road. Pass fire station.

25.0 *0.2* At T-intersection, turn east (right) onto Cleo Chapman Highway.

As we travel north-northeast up the scenic Eastatoe Valley, the rugged ridge to the east (right) is Wadakoe Mountain (elevation 1,865 ft) (Fig. 6). It is underlain by a thick section of Poor Mountain Formation amphibolite, with Chauga River Formation rocks and the sinuous trace of the Eastatoee fault further downslope. Amphibolite also underlies the area between Peach Orchard Branch and Winnie Branch. The exposure belt of folded amphibolite is ~1.6 km wide (Fig. 10). Petrography indicates that the rocks were metamorphosed to epidote amphibolite facies of metamorphism (Prince and Ranson, 2004).

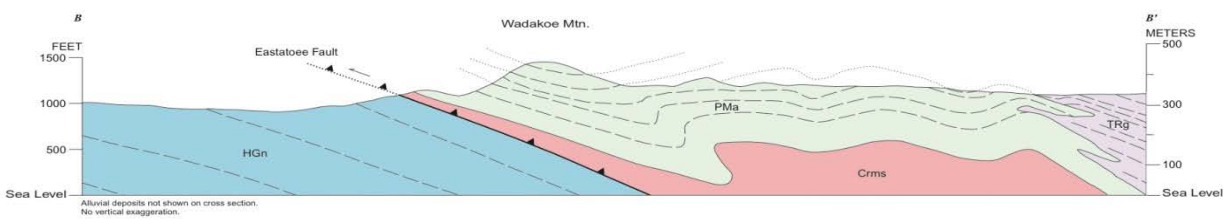

Figure 10. Cross section through Wadakoe Mountain and the region to southeast. Cross section location is on Figure 6. Units same as Figure 3-2 caption

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26.7 *1.7* Eastatoee Church.

The name for the Eastatoee fault was derived from several local features in the area, including this church and a rural road near Sunset, SC.

27.8 *1.1* Intersection of Cleo Chapman Highway and Eastatoee Community Road. Turn north (straight ahead) onto Eastatoee Community Road.

28.6 0.8 Turn east (right) onto Water Falls Road. Cross Eastatoe Creek. Continue to the parking area at the end of the road.

29.0 0.4 **Stop 10 Parking area for Twin Falls.** (Eastatoe Gap quadrangle)

Features of Interest: Spectacular falls, mylonitic Henderson Gneiss, jointing

We will hike or stroll up the old trail (about 15 minutes) to the Twin Falls overlook. Excellent exposures of variably mylonitic Henderson Gneiss with conspicuous feldspar augen are seen in the stream bed adjacent to the trail. A new trail has been cut from Cleo Chapman Highway that leads to the top of the falls. Take your camera.

This popular scenic falls lies on the Reedy Cove Creek branch of Eastatoe Creek. The latter is the major drainage in the Eastatoe Valley. Eastatoe Creek extends into North Carolina, draining southward off the Blue Ridge Front. Twin Falls is also known as Reedy Cove Falls. It is estimated to be about 75 feet high (Fig. 11-1). Participants must be careful of wet, slippery rock surfaces if they decide to climb down from the overlook onto the pavements. There one can observe a variety of features, including mylonitic Henderson Gneiss with S-C-C’ structure (Fig. 11-2) and triple joint intersections (Fig. 11-3).

Figure 11-1. Stop 10. Twin Falls in Henderson Gneiss, Eastatoe Creek.

Figure 11-2. Stop 10. Mylonitic Henderson Gneiss with S-C-C' structure. C surfaces are horizontal in this view; C' surfaces locally extend from upper left to lower right, with motion down and to the right (generally south). Water-covered exposure.

Figure 11-3. Stop 10. Intersection of three joints, Henderson Gneiss.

End of roadlog for Saturday October 13, 2012. Proceed to Pinnacle Pavilion in Table Rock State Park for supper and entertainment.

We hope you have enjoyed today's activities!

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Prince P. S., and Ranson, W. A., 2004, Geochemistry, petrography, and mineral chemistry of amphibolites from the Inner Piedmont of northwestern South Carolina: Abstracts with Programs, Geological Society of America, v. 36, n. 2, p. 103.

Road log for Sunday, 14 October 2012, Jones Gap State Park

Stop Leader: Suresh Muthukrishnan

The purpose of the Sunday field trip is to visit localities in Jones Gap State Park, looking at geomorphology, structure, and landslide activity along the foot of the Blue Ridge Front. The Middle Saluda River there is deeply incised into granitic gneisses, with ~2000 feet of local relief. Excellent exposures on steep slopes are available for study.

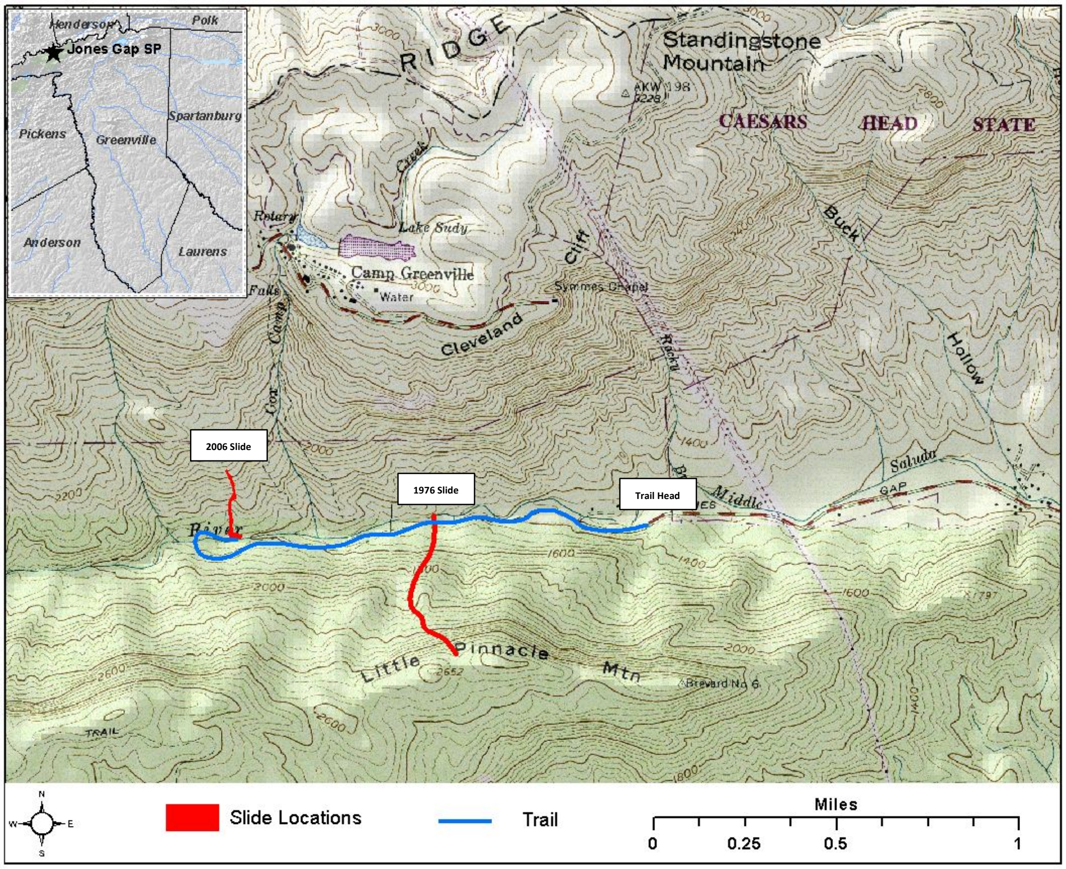

Figure 1: Location of Jones Gap State Park, Jones Gap Trail, and the two landslides to be visited during this trip (Cleveland and Standingstone Mountain quadrangles).

Features of Interest

Scenic landscape along base of Blue Ridge Front, fluvial and geomorphological features, landslides, optional hike to Falls Creek Falls. The Middle Saluda River that flows through the park provides scenic hiking and camping opportunities for visitors all through the year. This is one of the most popular destinations in the Upstate of South Carolina for visitors during the fall season. With limited parking available in the park, people often wait in line to get into the park.

Jones Gap Trail Information

After parking, we walk towards the park visitor center building and assemble outside for an overview of the activities. There is a restroom available near the park office but no facilities along the trail until we return. After briefing, we will start from the trail head and walk the Jones Gap Trail (blue trail). This trail is oriented east-west, and closely follows the Middle Saluda River (Fig. 1). We will make two main stops today to observe and discuss the mass wasting history of this area.

Total duration of this trip at the park is expected to be around 3 hours. This trail would be considered moderate with an elevation gain of 350 feet over 1.2 miles distance. Elevation at the trail head is 1350 feet. The trail can be wet and muddy along some parts. Wear appropriate shoes and dress.

Bring plenty of water; dress for the weather.

Directions to Jones Gap State Park from Downtown Hyatt Hotel

From Hyatt (220 North Main Street, Greenville, SC 29601), head north on N Main St toward College St then turn left onto College Street. Continue straight onto Buncombe Street (0.3 miles) then turn right onto US-276 N/Rutherford Street. Continue to follow US-276 N for about 30 mins (19 miles) then turn right onto County Rd 97/River Falls Rd (watch out for a local store, F-Mart at the turn). Continue to follow County Rd 97 for about 11 mins (6 miles) to Jones Gap State Park (303 Jones Gap Road, Marietta, SC 29661).

Jones Gap State Park Overview

Jones Gap State Park is located at the northern edge of Greenville County along the foot of the Blue Ridge Escarpment in the headwaters region of the Middle Saluda River (Cleveland and Standingstone Mountain quadrangles). The Middle Saluda River flows from west to east and is locally joint controlled. Majority of the rocks exposed here are Table Rock gneiss, with occasional outcrops of amphibolite and schist at higher elevations (Fig. 2). At the trail head, the elevation of the valley floor is about 1300 feet with the ridge tops to the north and south reaching 3000 feet above sea level. The valley width, from ridge top to ridge top, is about one mile. Jones Gap is part of the larger Mountain Bridge Wilderness Area, a designated conservation area prized for its biodiversity. Climatically, this area receives much higher precipitation (>75 in/year) than the adjacent piedmont region. Steep slopes, a relatively thin soil cover, a well-defined rock-soil boundary, and heavy rain fall seen here are the ingredients that have triggered mass wasting. Many large boulders seen all through the valley indicates the prolonged landslide history of the area. This field trip will focus on two of the landslides that occurred along Jones Gap Trail that are easily accessible to study.

Stereoplots of joint measurements from Jones Gap State Park shows three regional joint sets, representing NE, NW, and E-W joint directions (Fig. 3, left side). These multiple jointing strikes make for favorable conditions to break rocks into blocks and to facilitate rock slip, which has been observed at the initiation points of both the 1976 landslide and another landslide in the valley. In addition, the exfoliation surfaces (N=13) of balds along the steep valley walls are also favorable for landslides (Fig. 3, right side). Significantly, on the south-facing slope the exfoliation surfaces dip south into the valley, and on the north-facing slope they dip north into the valley. Therefore the attitudes of the steep systematic joints and the exfoliation surfaces together indicate there is a strong potential for future mass wasting activity utilizing these natural breakage systems.

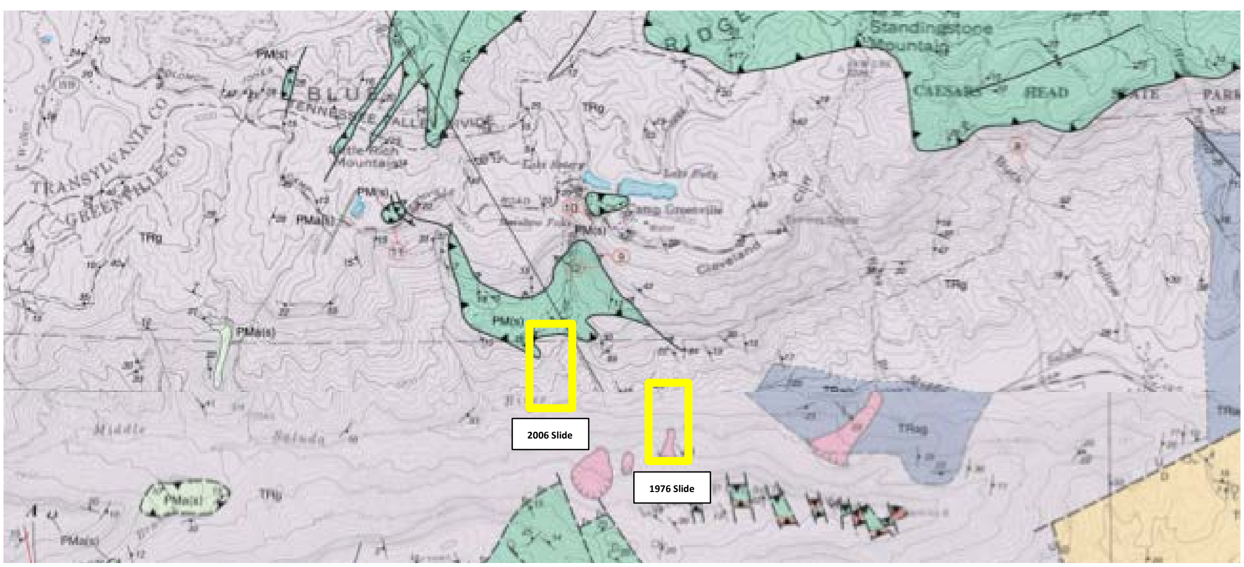

Figure 2: Geologic map of Jones Gap area. Dominant rock is Table Rock gneiss (purple shades) underlying the balds. Green is amphibolite and schist of the Six Mile thrust above the Seneca fault (solid saw tooth line). Boxes indicate the 1976 and 2006 landslides. Elsewhere Table Rock is thrust over Six Mile rocks. Several other landslides have been recognized on the north slope of Little Pinnacle Mountain south of the river (pink) (from Cleveland and Standingstone Mountain geologic maps).

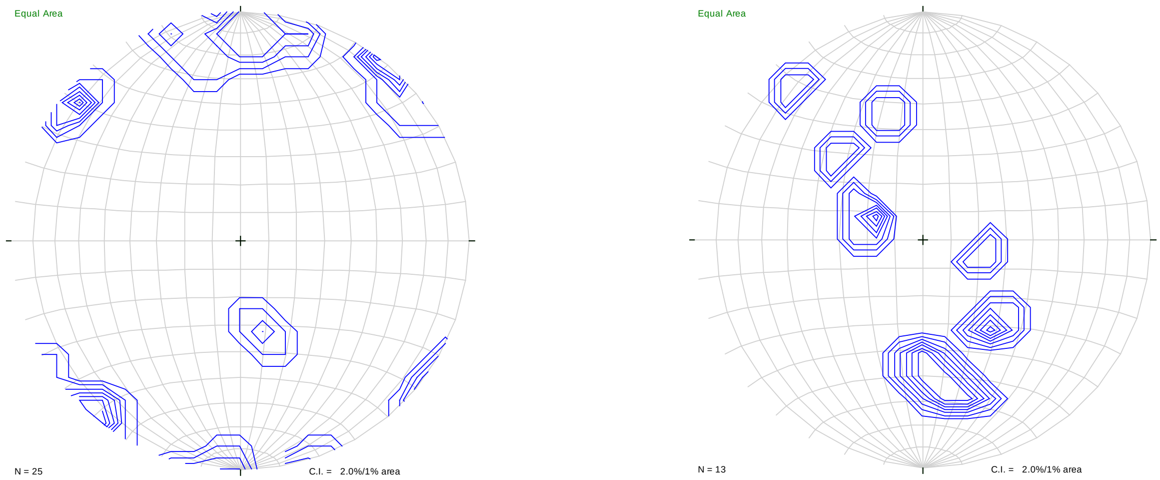

Figure 3: Contoured stereoplots of systematic joints (left). Exfoliation surfaces (right).

Stop 1: 1976 Debris Slide

Walk about 0.45 mile from the trail head. As we hike to this point, notice that trail elevation goes up slightly to the point where a perennial creek cuts across the trail and joins the Middle Saluda River (is the main stream here). The trail goes downhill past the creek. At this point, notice the terrain and the vegetation. Majority of the trees are much younger along the creek than in the surrounding area (Fig. 4 top). They are composed of early successional species such as tulip poplar and beech. The creek bed is mostly made of boulders and cobbles.

If time permits, we will follow the creek up the slope for five minutes. This will take us to the bottom of 1976 mass wasting site. A rocky surface with prominent exfoliation joints parallel to the surface is present (Fig. 4, bottom). The small creek cascades over the exposed Table Rock gneiss. The exact circumstances that lead to this landslide are not clear, but the exfoliation joints and east-west and north-south striking joints seem to have played a significant role in slope failure.

The landscape scar left by this event can be identified by the presence of immature canopy structure and some bald spots in the recent color aerial photo (Fig. 5) and as bright barren surface in the historic aerial photos from 1978 (Fig. 6, bottom). Historic aerial photo taken before 1976 landslide is presented for reference (Fig 6, top). The total length, as measured from the aerial photos, of this landslide from head to toe is about 0.55 mile. Tree core studies of the younger trees that have grown over the landslide debris field indicate the age of those trees is anywhere between 24 to 33 years. This implies that it takes at least 3 years or more for vegetation to get re-established on landslide debris field.

A less used, steep (unofficial) trail follows parallel to the slide on the northern flank all the way to the top. From here, we will walk back down to the main Jones Gap trail and continue west for another 0.5 mile.

Figure 4. Top: Young beech trees growing along the 1976 landslide debris path. Bottom: Exposed failure surface of 1976 landslide. Several sets of exfoliation joints, EW, and NE joints are visible. Both views to the south.

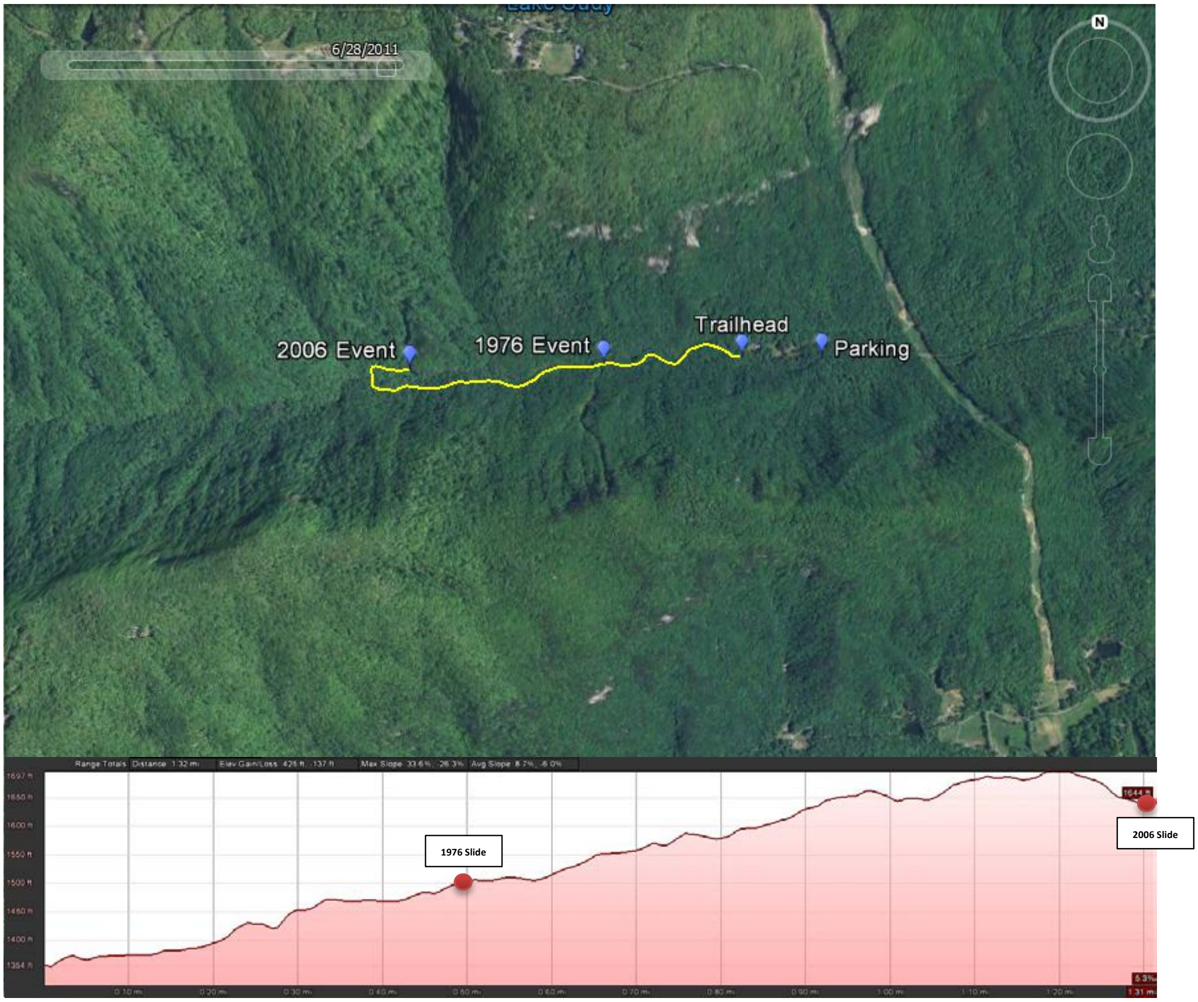

Figure 5: Aerial view of Jones Gap State Park area with locations of 1976 and 2006 landslides and elevation profile of the trail. (Image credit: Google Earth)

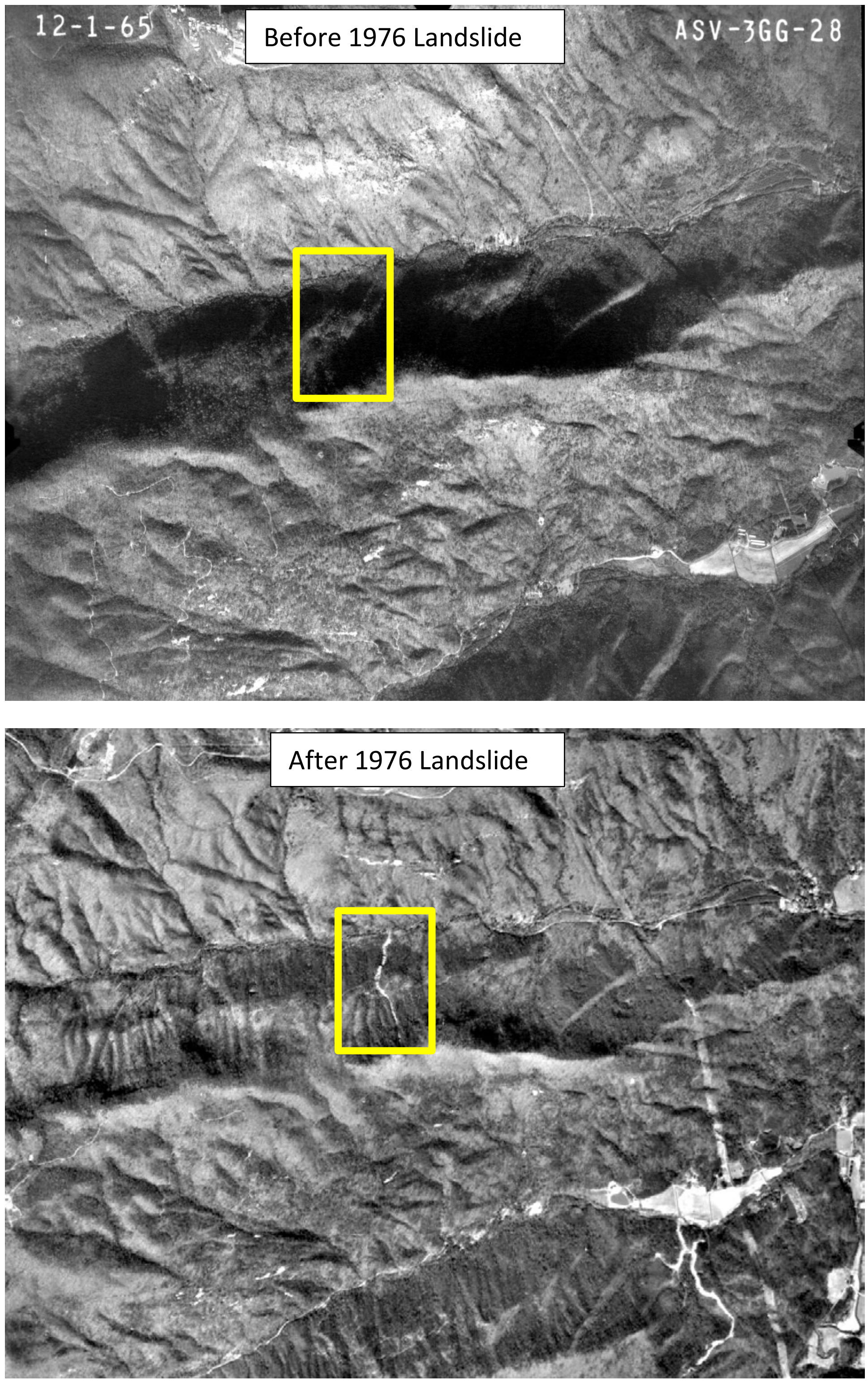

Figure 6. Top: 1965 B/W aerial photograph of Jones Gap State Park area before landslide occurrence. Bottom: 1978 B/W aerial photograph of the same area after landslide occurrence. (Image credit: University of South Carolina library)

Stop 2: 2006 Debris Slide

After crossing Middle Saluda River, head east for approximately 1/10th of a mile on an unused trail. Go through a field of thorny bushes to an open area. This marks the site of 2006 summer landslide.
In June 2006, between the 24th and 28th, the upstate area received nearly 10 inches of rainfall, triggering this landslide. The slide occurred as excessive rainfall saturated the soil, increasing the hydrostatic pressure in the soil and colluvial layers. This created buoyancy, lowering the shear strength of the mass above the impervious gneissic rock and leading to failure.

This mass-wasting event is classified as a debris slide, composed of colluvium made up of talus, sandy and silty sediment, and soil. The maximum boulder size observed is 15 ft long by 9 ft wide by 12 ft high. These large boulders commonly show freshly broken corners, attesting to their violent down-slope movement. Rock debris is primarily a medium-crystalline, well-foliated (commonly folded), and well-layered biotite-quartz-feldspar gneiss derived from the local bedrock, mapped as Table Rock gneiss (Garihan and Ranson, 2001, 2006; Garihan 2007). Lesser amounts of fine- to medium-crystalline amphibolite and medium-crystalline garnet-muscovite schist occur in the rock debris as well. Indeed, the top of the slide is proximal to a klippe of the Poor Mountain Formation according to the bedrock map of Garihan and Ranson (2006) (Fig. 2), although the narrow, uppermost scar exposed only Table Rock gneiss (Fig. 7, right). The Poor Mountain Formation in the region consists of amphibolite, garnet-muscovite schist, and quartzite.
This landslide is about 0.25 mi long and width varies from about 6 m at the top to as much as 25 m. The path of the slide closely follows an existing creek. Morphologically, the slide broadens with decreasing gradient as it reaches the valley floor and the Middle Saluda River. This destructive debris slide uprooted trees up to 14 in (36 cm) in diameter. Trees trunks have come to rest at the terminus of the slide and against dense rhododendron growth on a small island in the Middle Saluda River (Fig. 8, bottom).

Foliation in the Table Rock gneiss is variable, records at least two generations of folding, and bears no obvious relationship to the nature of failure surface in bedrock. More importantly exfoliation surfaces appear to be the surfaces along which water-saturated soil and colluvium moved downward.

Continue east along the trail back to the parking area (1 mile). Return to Greenville.

Figure 7. Left: 2006 debris slide, view from bottom of the slide looking north. Top of the slide is not visible in this photo. Right: Initial failure surface along exfoliation surface at the headwall of 2006 debris slide.

Figure 8. Top: Winter color aerial photograph taken before 2006 debris slide occurrence. Bottom: Aerial photograph taken after 2006 debris slide occurrence. (Photo credit: Greenville County GIS)

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Road log Sunday, for 14 October 2012 Chimneytop Gap traverse, Eastatoe Gap quadrangle.

Stop Leaders: Bill Ranson, Jack Garihan

Feature of Interest: Mylonitic Henderson Gneiss along the Foothills Trail

LOCATION: The stop is located along the Foothills trail between Chimneytop Gap and US 178, Laurel Valley SC.

DESCRIPTION

The traverse will follow the Foothills Trail southwest for approximately 2 mi (3.2 km). The Foothills Trail is a 76 mi (125 km) trail that follows along the Blue Ridge Front through northwestern South Carolina and adjacent North Carolina (Fig. 1). It runs from Table Rock State Park to the west to Oconee State Park. The middle section of the trail is remote and wanders just north of Lake Jocassee in state land designated as the Jocassee Gorges area. The trail at this point is about 2 km west-southwest of Sassafras Mountain (elevation 1084 m, 3554 ft), the highest point along the trail and indeed the highest point in South Carolina. The Foothills trail is marked with white blazes, but participants should be aware of several unmarked trails that branch off of the main, well-traveled trail.

The trail trends southwesterly for most of its length between here and the Laurel Valley parking area on US 178 (Fig. 2). There are, however, several notable switchbacks. The discussion below describes features of interest en route along the trail, with emphasis on two main exposures. These outcrops and other features of interest will be marked with orange flagging.

The trail begins by ascending moderately from Chimneytop Gap along the south side of the ridge. Just a few tens of meters up the trail, encounter saprolitic Henderson Gneiss with well-developed joints about 30 cm apart. The trail follows along the base of this Henderson Gneiss ledge. Pass occasional blocks of sheared granite pegmatite in the path before coming upon a 0.5 m ledge of pegmatite above the trail (orange flagging). The pegmatite has a slightly discordant contact with well-foliated Henderson Gneiss here. Just beyond these outcrops the trail begins to descend.

After the descent, the trail ascends again along a prominent exposure of Henderson Gneiss. At about 1 km, just before descending a stairway footbridge, note a joint-bound exposure with symmetrical cross-sections of augen perpendicular to the mineral lineation oriented 2°/N38°E (orange flagging). This stairway is the first of four footbridges, here crossing a deep ravine adjacent to prominent ledges of Henderson Gneiss.

Pass through open growths of rhododendron and laurel, eventually reaching a steep descent via wooden stairs at a switchback in the trail. The trail here descends along a curved (N55°-65°W) joint face bounding a ledge of sheared Henderson Gneiss (orange flagging). Descend into a more open valley with prominent outcrops of mylonitic Henderson Gneiss on the northwestern (right) side of the trail.

Stop 1. (UTM: 335556 3880513). Orange flagging will indicate an overhang beside the trail with features of particular interest. No hammers, please! At the overhang Henderson Gneiss displays mylonitic foliation (N32°E, 15°SE). Elongated pink K-feldspar ribbons are developed (Fig. 3) where viewed parallel to mineral lineation on the foliation. This well-developed mineral lineation is visible on the roof of the alcove and plunges 1°/ N15°E (Fig. 4). Examine blocks of gneiss that have fallen from the overhang. A view on a surface perpendicular to the lineation shows more ovoid, discrete augen, whereas parallel to lineation one sees continuous ribbons of K-feldspar with myrmekite margins.

Follow the trail as it continues into the flat bottom area, crossing a flowing stream on a wooden bridge. Quartz float is abundant along the trail as you pass through a more open, younger-growth woods. The trail continues southwest, traversing several spurs and intervening valleys and crossing two small footbridges before reaching a substantial cliff exposure on the north (right) side of the trail (orange flagging).

Stop 2. (UTM: 335063 3880256). The south-facing exposure is rounded by exfoliation, and large flat pieces of rock have moved down slope just below the path. Venture up to the overhang. Here is an excellent place to see fresh, gray Henderson Gneiss with mylonitic textures both parallel and perpendicular to nearly horizontal mineral lineation (plunges 1°/N40°E). Feldspar augen, generally <1 cm in size, have rounded gray cores with white rims. Note well-developed quartzo-feldspathic ribbons. Mesoscopic S and C surfaces are present. Winged augen and S-C structures indicate rock above C surfaces moved to the southwest; that is, sinistral motions in this view

(Fig. 5). Continuing to the east along the ledge, note aplitic veins 5-10 cm wide. A thin pegmatite lens with a thin lower margin of mylonite has been enveloped by a faintly-layered aplite lying parallel to foliation (Fig. 6). Later curved, spaced fractures cross cut contacts and foliation.

This outcrop is the last stop on our traverse. Continuing southwestward, the path descends across spurs, by intermittent ledges of Henderson Gneiss, and through drainages with several switchbacks. As US 178 is approached the trail gently ascends to a saddle before switching back to the north. Cross the stream on the last wooden bridge and head west a short distance to US 178. Stream-worn Henderson Gneiss exposures are beneath the highway bridge.

This creek continues southward and eventually spills over Twin Falls (Stop 10, Saturday roadlog). Return to Greenville.

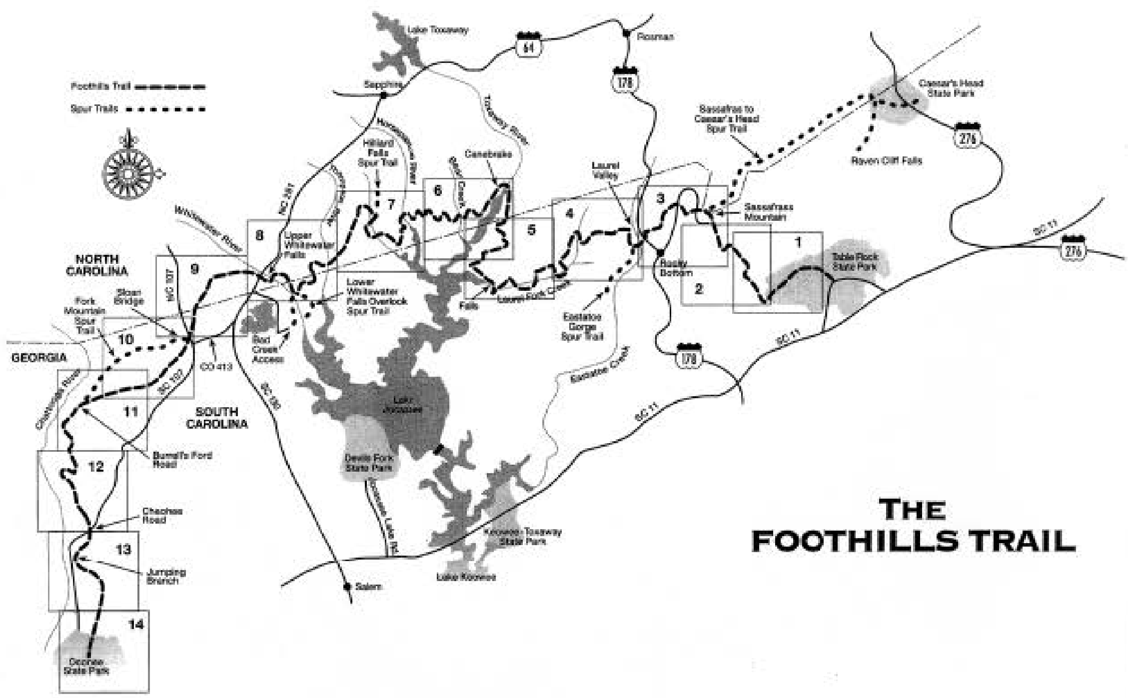


Figure 1. Map of the Foothills Trail. Taken with permission from a Guide to the Foothills Trail, 3rd Edition published by The Foothills Trail Conference, Inc., PO Box 3041, Greenville, SC 29602.

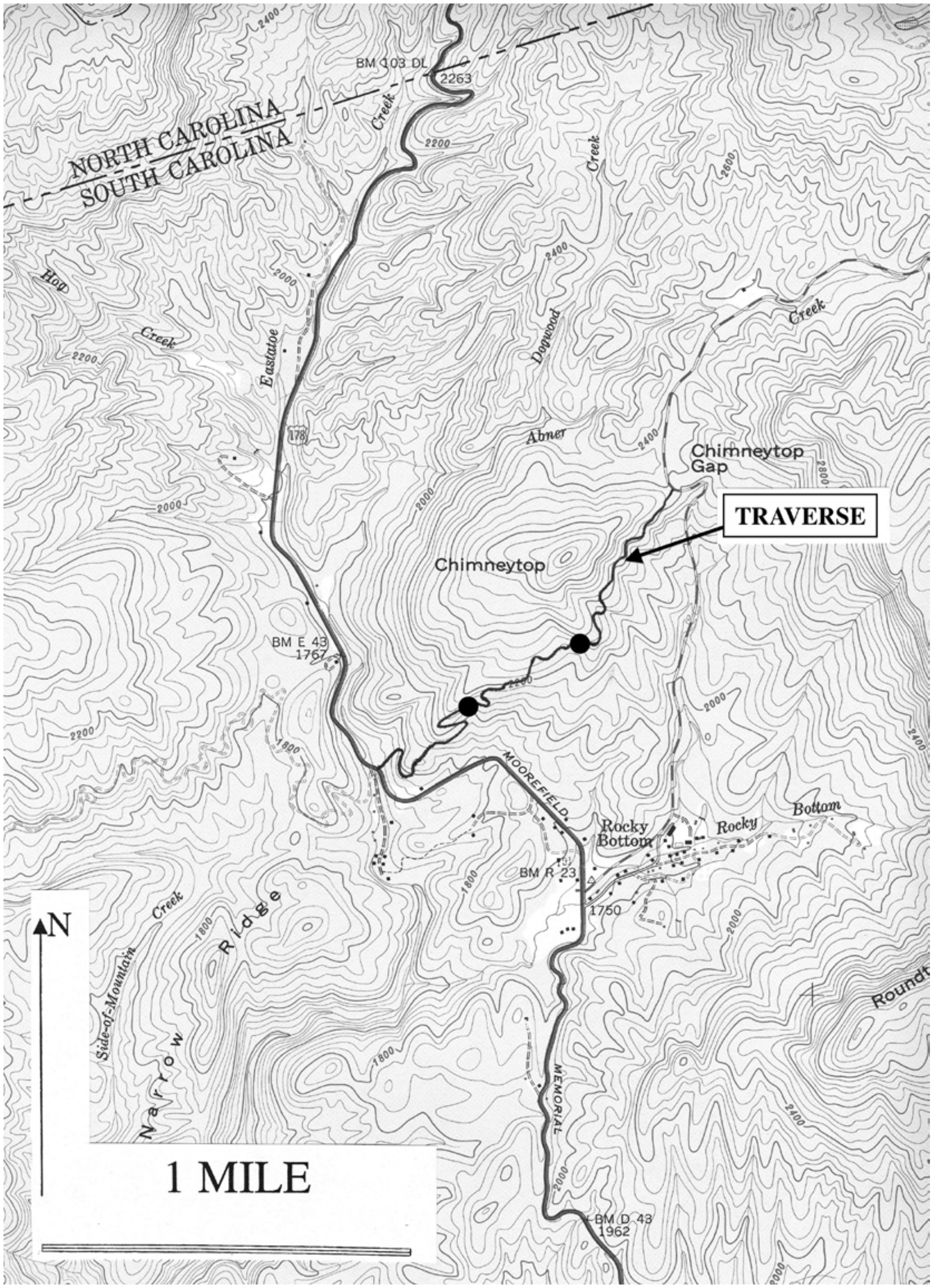


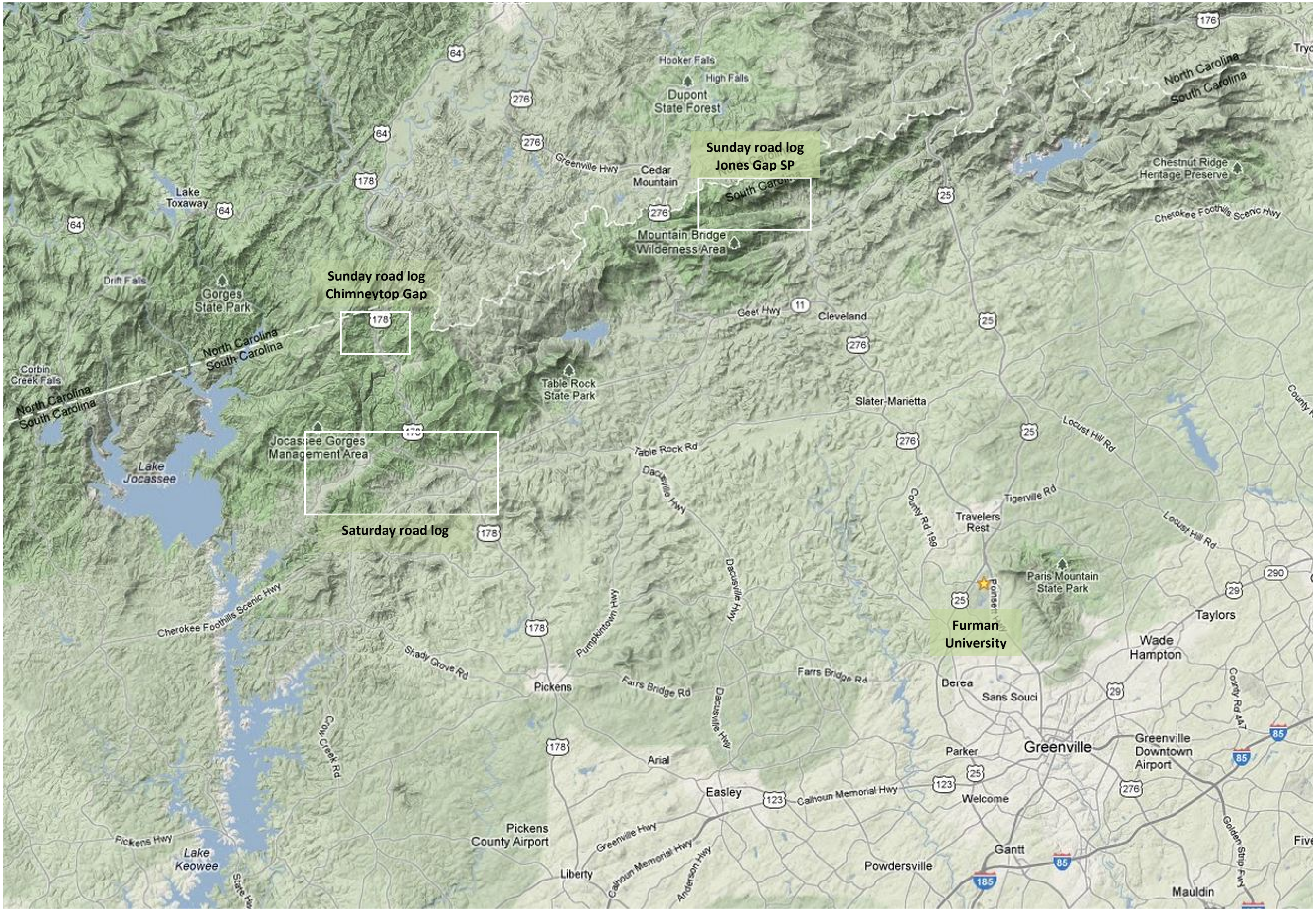
Figure 2. Location map of Chimneytop Gap traverse, near Rocky Bottom, SC. Eastatoe Gap quadrangle.

Figure 3. Stop 1. Pink K-feldspar ribbons with white myrmekite rims, viewed on a surface parallel to the mineral lineation. Lens cap 3.5 cm. Henderson Gneiss.

Figure 4. Stop 1. View up at the roof of the small alcove. Mineral lineation plunging 1°/N40°E is parallel to the edge of the cm scale (held vertically). Henderson Gneiss.

Figure 5. Stop 2. Asymmetric winged K-feldspar (sigma) strucures and quartz ribbons in mylonitic Henderson Gneiss (See the paper by Ranson, this volume). Shear sense indicators show the top of the near-horizontal C (shear) surfaces moved to the left (southwest). A few poorly-developed C’ surfaces in the exposure corroborate this regional shearing direction affecting these rocks.

Figure 6. Stop 2. Pegmatite, aplite, and fractures, east side of exposure of mylonitic Henderson Gneiss. Pen is 14.5 cm.


Sunday road log
Jones Gap SP
Sunday road log
Chimneytop Gap
Saturday road log
Furman
University
Hooker Falls
High Falls
Dupont
State Forest
Cedar
Mountain
Mountain Bridge
Wilderness Area
Lake
Toxaway
Drift Falls
Gorges
State Park
North Carolina
South Carolina
Corbin
Creek Falls
Lake
Jocassee
Jocassee Gorges
Management Area
Table Rock
State Park
Table Rock Rd
Geer Hwy
Cleveland
Slater-Marietta
Chestnut Ridge
Heritage Preserve
Cherokee Foothills Scenic Hwy
Locust Hill Rd
Tigerville Rd
Travelers
Rest
Paris Mountain
State Park
Taylors
Wade
Hampton
Greenville
Greenville
Downtown
Airport
Berea
Sans Souci
Parker
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Mauldin
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County Airport
Liberty
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Keowee
Pickens Hwy
Shady Grove Rd
Farrs Bridge Rd
Dacusville Hwy
Pumpkintown Hwy
Crow Creek Rd
Calhoun Memorial Hwy
Greenville Hwy
Anderson Hwy
Golden Strip Fwy
Greenville Hwy