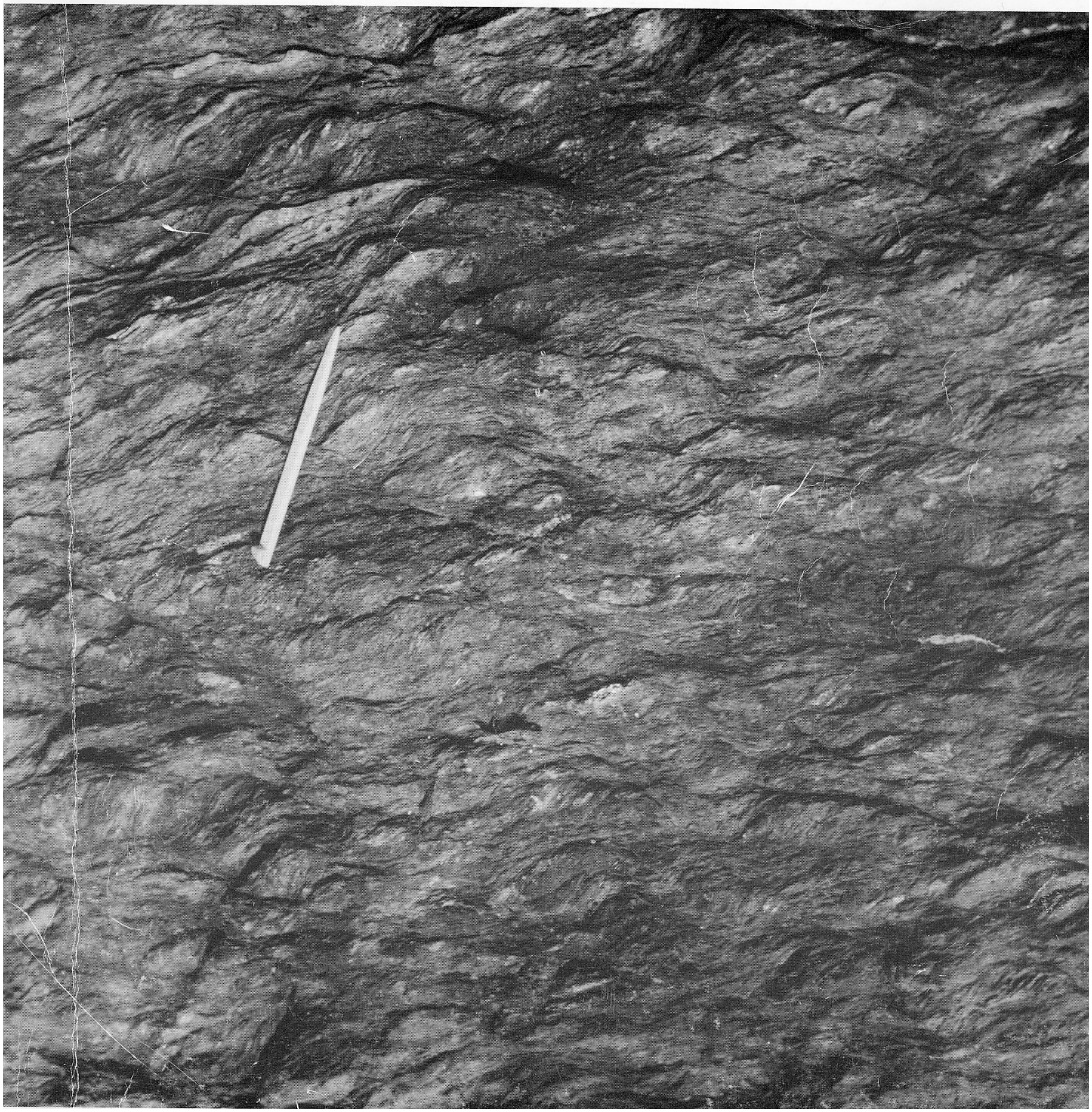
SOUTH CAROLINA GEOLOGY

VOLUMES 37 & 38 S.C. DEPARTMENT OF NATURAL RESOURCES 1995



SPECIAL ISSUE

Devoted to the 1995 Field Trip of the Carolina Geological Society

CAROLINA GEOLOGICAL SOCIETY 1995 OFFICERS

Acknowledgements. Many individuals have helped in the preparations for the 1995 Carolina Geological Society Annual Meeting, Field Trip and Guidebook. I would especially like to recognize the contributors to volume 38 of South Carolina Geology, bound with this field guide. The reviewers for volume 38 completed their reviews quickly and thoroughly. They were Bill Domoracki, Ron Fodor, Wright Horton, Harmon Maher, Butch Maybin, Clark Niewendorp, Bill Pirkle, Van Price, Scott Samson, Don Secor, John Shervais, and Scott Vetter. Harmon Maher, Tom Creech, and John Harper assisted in the initial preparation of the Road Log. Marie Shervais prepared the page setups and final copy. Duncan Heron and Bill Clendenin were supportive through the entire process. Terry and Edward Dennis sacrificed considerable time this summer as these materials were assenbled, and I am grateful for their forbearance. Finally, thanks to the 1995 CGS trip participants for their ongoing support and participation in our society. See you on the outcrop.
Allen Dennis

Cover photo; Well developed composite planar fabric in button schist of the ca. 275 Irmo shear zone indicates dextral shear. Normal slip crenulations consistently offset pre-existing, penetrative foliation surfaces to the right. 5 cm toothpick points approximately north on pavement surface. Outcrop is located off Forest Service Road 643A in Clarks Hill (SC-GA) 7.5' quadrangle.

SOUTH CAROLINA GEOLOGY

VOLUME 37 **1995**

FIELD TRIP GUIDE FOR THE

1995 CAROLINA GEOLOGICAL SOCIETY ANNUAL MEETING:

GEOLOGY OF THE WESTERN PART OF THE CAROLINA TERRANE IN NORTHWESTERN SOUTH CAROLINA

SOUTH CAROLINA GEOLOGY

VOLUME 38 **1995**

PAPERS RELATED TO THE THEME OF THE 1995 CAROLINA GEOLOGICAL SOCIETY ANNUAL MEETING:

GEOLOGY OF THE WESTERN PART OF THE CAROLINA TERRANE

ALLEN J. DENNIS, EDITOR

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 1-21

GEOLOGY OF THE WESTERN PART OF THE CAROLINA TERRANE IN NORTHWESTERN SOUTH CAROLINA: 1995 CAROLINA GEOLOGICAL SOCIETY FIELD TRIP

ALLEN J. DENNIS[1]
Department of Biology and Geology, University of South Carolina-Aiken, Aiken, SC 29801-6309
J. ROBERT BUTLER[2]
Department of Geology, University of North Carolina, Chapel Hill, NC 27599
JOHN M. GARIHAN, WILLIAM A. RANSON, KENNETH A. SARGENT[3]
Department of Earth and Environmental Sciences, Furman University, Greenville, SC 29613

1.Stops 1-2, 4-8, 10-12.
2.Stops 3-4.
3.Stop 9.

SATURDAY ROAD LOG

Begins at intersection of Main and Pine, downtown Spartanburg. Travel south and east on US 176. Go 7.7 (7.7) miles and turn left onto Quarry Road. Go 1.0 miles (8.7) and turn left into **STOP 1** (Vulcan Materials Pacolet Quarry).

Turn right out of quarry and go 1.0 (9.7) miles to US 176. Turn left onto US 176. Go 8.1 (17.8) miles and turn left onto Forest St. (S-44-12). At 0.8 (18.6) mile continue/bear right on Forest St. At 0.3 (18.9) mile, turn right on SC 9. At 1.1 (20.0) miles continue straight on SC 9. At 7.6 (27.6) miles turn right onto Hyder Road. Continue down 0.5 (28.1) mile to end of road. Park and walk west about 100 m into old quarry **STOP 2** (Hyder Bald Rock Quarry).

Drive 0.4 (28.5) back out and turn right onto SC 9. Cross Broad River at 5.8 (34.3) miles. Turn right onto Chester bypass at 14.0 (48.3) miles. At 3.7 (52.0) miles, turn right and rejoin SC 9. Turn left onto Meador St (S-12-74) at 3.6 (55.6) miles, and at 0.1 (55.7) mile park left off into grassy field. Walk down to rail siding: **STOP 3** (Chester metagabbro).

Return to SC 9 0.1 (55.8) and turn right onto it. At 3.5 (59.3) miles turn left onto 72/121/9 bypass. At 3.0 (62.3) miles turn left onto 72/121. At 1.4 (63.7) miles, Chester State Park. At 9.4 (73.1) miles turn right (S-12-25) for Woods Ferry Recreation Area. At 5.6 (78.7) miles turn left onto road to Woods Ferry Rec. Area. At 0.2 (78.9) mile, Fire Tower, Leeds Hunt Camp on left. At 1.1 (80.0) miles turn left onto Forest Rd 304. At 0.5 (80.5) miles bear right and continue 1.0 (81.5) mile to Neal Shoals, park. **STOP 4** (Charlotte Belt intrusive complex).

Return to S-12-25 (2.8/84.3) miles. Turn right onto S-12-25 and after 5.6 (89.9) miles, turn right onto 121/72. At 5.1 (95.0) miles, bear right on 215. At 8.7 (113.7) miles, bear left on 215. At 3.0 (116.7) miles, bear left, continue on 215. At 3.1 (119.8) miles, turn left. At 3.4 (123.2) miles, bear right on S-44-23 Mudbridge Road. At 6.1 (129.3) miles, turn right on S-44-12. At 0.5 (129.8) mile, turn left onto Lancaster Road. Stop at Log House at 0.4 mile (130.2). Follow track behind house to **STOP 5** (McClure Creek mafic metavolcanic rocks intruded by foliated biotite porphyry granodiorite).

Return to S-44-12 (0.4/130.6 miles). Turn left and park 0.4 (131.0) mile at gate on left for McClure Creek Hunt Club. Walk down track and turn right at second deer stand and follow hill down to creek: **STOP 6** (Undeformed, unmetamorphosed diorite containing foliated xenoliths and equant mafic enclaves).

Continue straight on S-44-12 and turn right onto S-44-12 at 0.7 (131.7) miles, crossing Fairforest Creek. At 0.2 (131.9) mile park at McClure Creek Hunt Club gate: **STOP 7** (Mean Crossroads metadiorite-diorite gneiss).

Turn around and follow S-44-12, turning left after crossing Fairforest Creek and continuing to follow S-44-12, past Lancaster and Mudbridge Roads, to its intersection with 215 (3.8/135.7 miles). Turn left on 215 and continue for 2.8 (138.5) miles to S-44-25. At 1.1 (139.6) miles, turn left on S-44-33; at 1.9 (141.5) miles turn right onto S-44-210. At 0.7 (142.2) miles, begins abundant gabbro outcrop, and at 0.3 (142.5) miles felsic intrusive rocks. **STOP 8**: Buffalo gabbro and associated felsic rocks.

Return to intersection with 215 (4.0/146.5), and turn left. Follow 215 to 56 at Pauline, and continue on 56 to Spartanburg, Routes 9 and 176.

END OF SATURDAY ROAD LOG.

SUNDAY ROAD LOG.

Sunday Road Log begins Exit 44 (SC 49) on I-26 south of Spartanburg.

Follow SC 49 south and west to Laurens (6.4 miles to I-385 intersection). At 2.6 (9.0) miles turn left onto US 221. At 1.5 (10.5) miles turn right onto US 76.

The following three sentences trace the 76 bypass around Laurens to where SC 252 separates from US 76 west of Laurens. Bear right at 0.8 (11.3) mile, and turn left at 0.2 (11.5).

Turn right at 1.2 (12.7) miles, and left onto SC 252 at 1.4 (14.1) miles. At 9.4 (23.5) miles, turn left onto Poplar Springs Road (S-30-64). At 1.2 (24.7) miles turn left onto Gilbert Road. Continue 0.95 (25.7) miles to the end of the gravel road. Park in the yard of the log home of Gerald and Diane Mitchell, and walk downhill about 300 m south of the house. **STOP 9**: Masters Kiln and marbles.

Retrace route back to SC 49 - I-26 intersection (25.7/51.4 miles). Continue on SC 49 3.1 (54.5) miles to Cross Anchor. Turn right at Cross Anchor onto SC 56. At 1.8 (56.3) miles bear right onto Horseshoe Falls Road. At 1.4 (57.7) miles cross bridge over Cedar Shoals Creek and 0.3 (58.0) miles park for **STOP 10**: Inner Piedmont gneisses at Cedar Shoals. Retrace route to SC 56 and continue north (1.7/59.7 miles). At 5.0 (64.7) miles turn right onto Blackstock Road (S-42-115, Woodsmen Sportsmen Club sign). At 0.8 (65.5) mile, just past bridge over Hackers Creek, pull off at gate on left hand side of road, and hike about 300 m northeast to **STOP 11**: Hackers Creek folded mylonite.

Return to SC 56 and turn right (0.8/66.3 miles). At 1.7 (68.0) miles fork right onto S-42-511 (Shealton Road), and right onto Toal Road at 0.3 (68.3) miles. Park either at bridge (0.5/68.5 miles) or at gate near Westvaco property line (0.3 mile past bridge/68.8). Stay on Westvaco property and proceed south to **STOP 12**: metavolcanic rock outcrops on Dutchman Creek.

Return to SC 56 (not bearing left onto Shealton Road, but continuing straight on Toal), and turn right, proceeding north to Spartanburg and SC 9.

END OF TRIP

STOP 1: VULCAN MATERIALS PACOLET GRANITE QUARRY

LOCATION

The quarry is located off US 176, west of Pacolet, South Carolina. (Fig. 1, Pacolet quadrangle)

DESCRIPTION

The Pacolet granite ranges from porphyritic to equigranular in texture. The Vulcan Materials quarry offers examples of both (potassium feldspar) porphyritic and equigranular phases of the granite. This quarry shows very clearly diking and discrete faulting in the granite that would be obscure in small Piedmont bedrock exposures. The dikes comprise both fine-grained leucogranite or alaskite and quartz-potassium feldspar-biotite pegmatites. Mutual cross-cutting relations between both types of dikes suggests that both types of dikes are related to the intrusion of the Pacolet granite and that the pegmatites are not a distinct different event. The significance of this observation will be discussed below. An approximately east-west striking fault zone dipping about 50° south, and east-west striking vein arrays may be observed at the south end of the active workings (Fig. 2). These vein arrays seem to have a consistent geometry: veins dipping about 50° north are several times thicker (ca. 1 m) than those that dip about 20° south (10's of cm thick). The kinematic significance of this geometry is not clear. It probably does not have its origin in rotated tension gashes (Hudleston, 1989), which would indicate top-to-the-north, because there appear to be only two dominant orientations, rather than a continuous range of orientations. The simplest explanation may be that these vein arrays represent a conjugate set related to the stresses at the time of emplacement of the Pacolet granite. David Cosh the quarry foreman suggested that the frequency of veining or diking may increase with depth.

Mittwede and Fullagar (1987) reported an whole rock Rb-Sr isochron for the Pacolet granite of 383±5 Ma based on 8 points, a biotite mineral age of 292 Ma, and a initial $^{87}Sr/^{86}Sr$ ratio of 0.7046±2. No more than 1.5 km to the west of the quarry, and 100's of m from the western edge of the pluton, the central Piedmont suture separating Inner Piedmont from the Carolina terrane rocks is exposed. Quartz-potassium feldspar-muscovite (rather than biotite) pegmatites are typically observed near the trace of the central Piedmont suture in the three quadrangles south of here (Glenn Springs, Cross Anchor, Philson Crossroads; Dennis, 1991). Only on the northern margin of the pluton are rocks of the Pacolet granite interpreted by Mittwede (1989) to be sheared; this fabric is thought to be an extension of Alleghanian strike-slip motion on the Kings Mountain shear zone (Horton, 1981). Foliation attitudes in rocks adjacent to the pluton parallel the pluton margin, and typically dip 50-70° to the southeast. Dennis (1991, 1995) presents form surface maps that show that the regional metamorphic fabric predates the central Piedmont suture and that this fault crosscuts the foliation. The purpose of this discussion and this stop is to bring together data that bear on the relative timing of motion on the central Piedmont suture versus the date of the intrusion of Pacolet granite. Did the Pacolet granite predate or postdate motion on the central Piedmont suture? If the central Piedmont suture dips at ca. 25°, the projected depth to contact with where the central Piedmont suture would be about 700 m beneath the quarry floor. Is the pluton decapitated or does the pluton postdate this fault? Dennis (1995) and Dennis and Shervais (1992) argue that the sequence of events was metamorphic fabric development in Carolina terrane rocks (ca. 570-538 Ma, Dennis and Wright, 1993), ductile motion on central Piedmont suture, intrusion of post-metamorphic granites and gabbros (ca. 383±5 Ma, e.g. Mittwede and Fullagar), west-vergent folding of foliation surfaces and retrograde strike-slip shearing on northeast-striking segments of the central Piedmont suture (Alleghanian, 300-280 Ma).

Most of the Pacolet granite outcrops in the Pacolet and Pacolet Mills quadrangles, however, to the south in the northern part of the Glenn Springs quad, a megacrystic por-

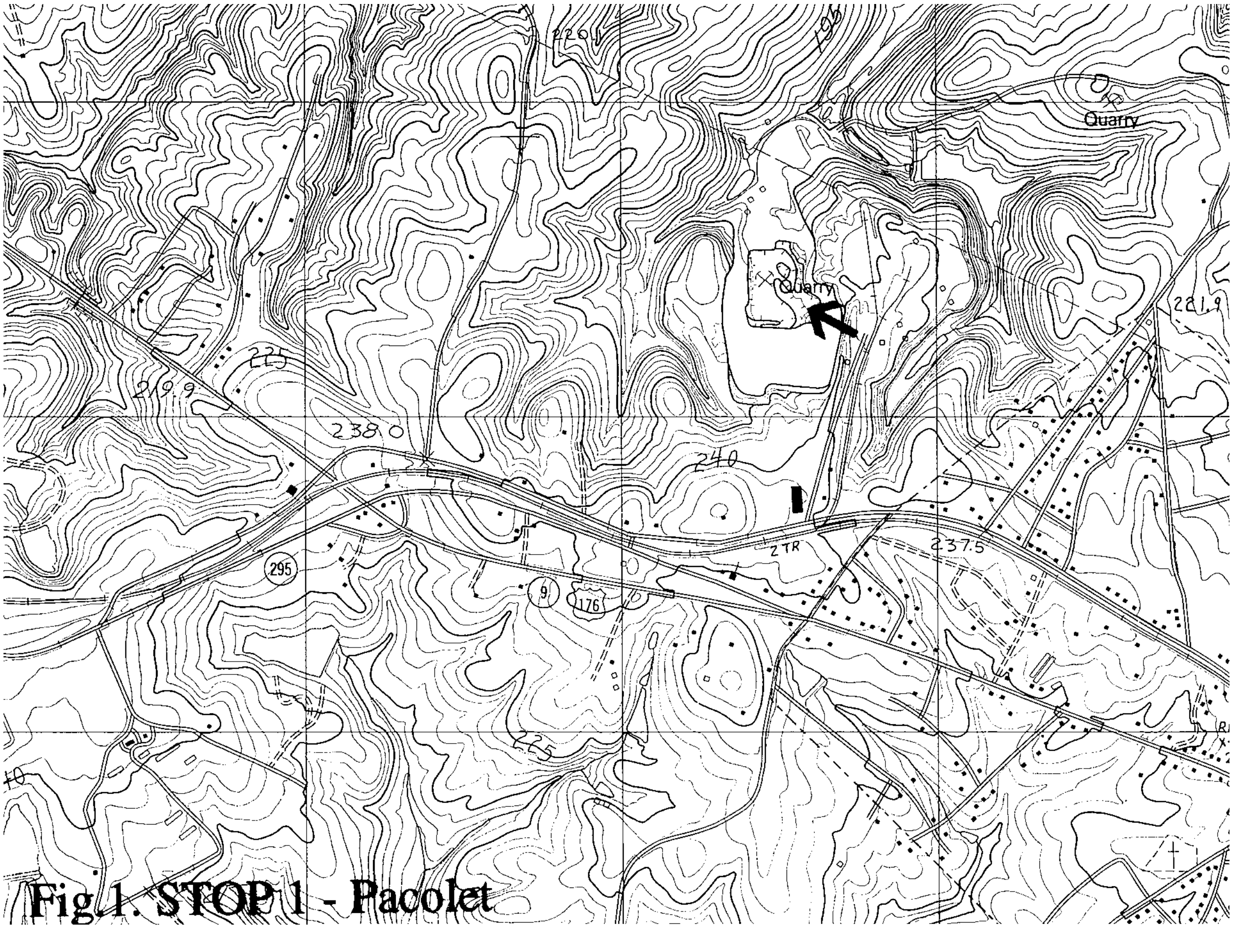


Fig. 1. STOP 1 - Pacolet

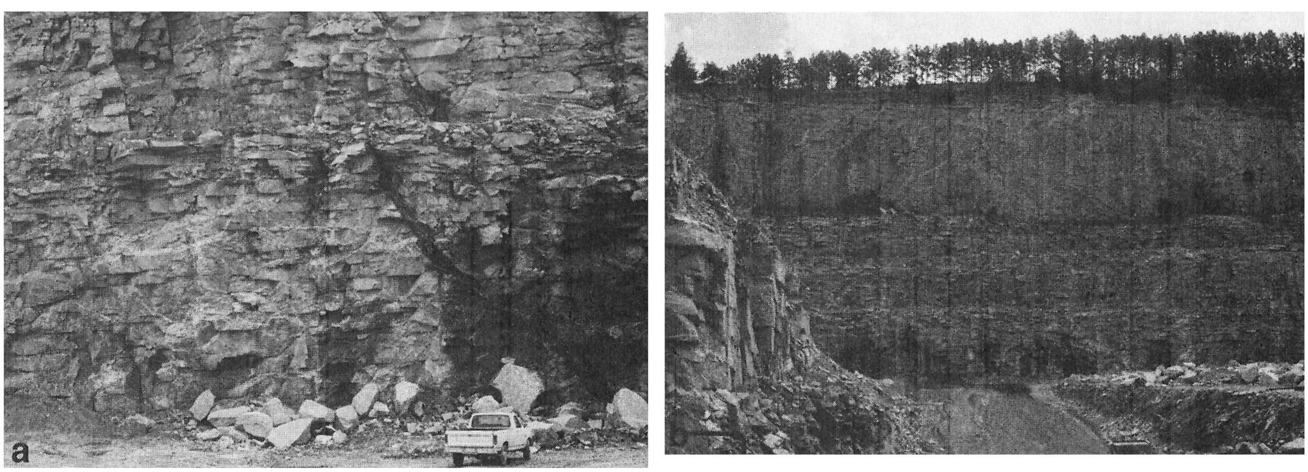


Fig 2. a. View east at south end of Pacolet quarry showing fault dipping 50-60° south, steeply north dipping veins, and shallowly south dipping, thinner veins. b. View east at the north end of the quarry. Veins dipping 45° north are ca. 1 m thick. Veins dipping 20° south are 10's of cm thick. Exposed face is slightly less than 100 m high.

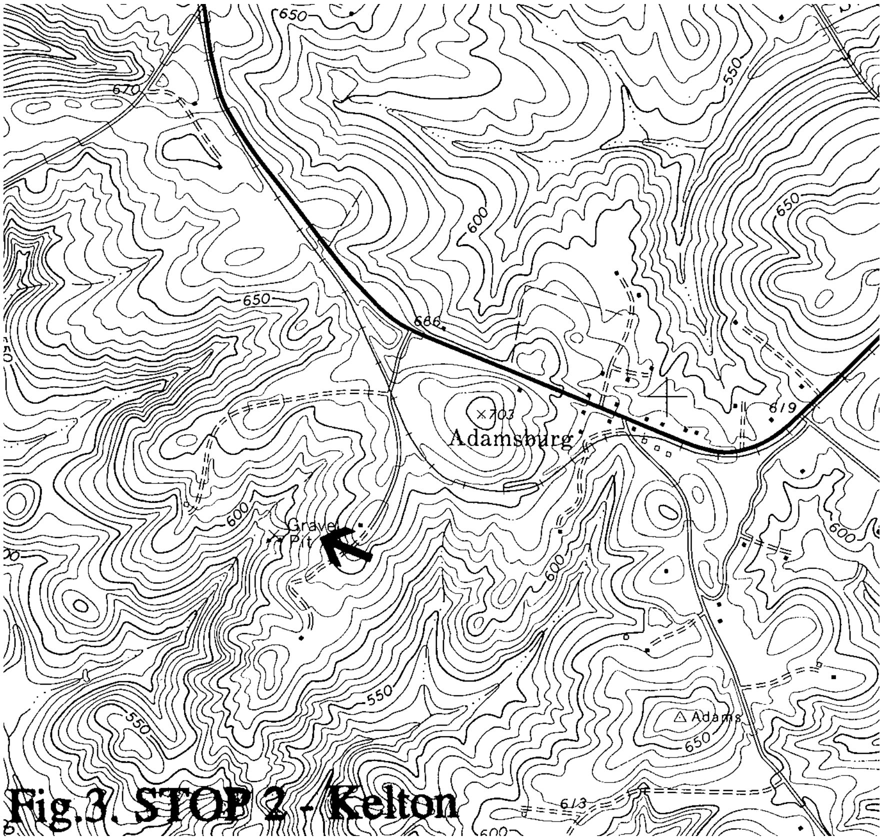


Fig.3. STOP 2 - Kelton

Fig 4. View into the Hyder Bald Rock quarry.

phyry was mapped by Dennis (1989) in erosional windows through the aluminous schists of the Battleground Formation. That megacrystic porphyry is interpreted to be a phase of the Pacolet granite and not a tectonic window through the Carolina terrane into the Inner Piedmont (Dennis, 1989). The contact is interpreted to be intrusive; fault rocks are not recognized.

STOP 2: HYDER FARM BALD ROCK GRANITE QUARRY

LOCATION

The "quarry" is located in a pasture approximately 300 m southwest of the house at the end of Hyder Road, off SC Highway 9. Hyder Road is 0.8 mile west of the intersection of SC 9 with S-42-57. (Fig. 3, Kelton quadrangle)

DESCRIPTION

This abandoned quarry (Fig. 4) illustrates the salient features of the Bald Rock granite: its megacrystic texture, the strong alignment of phenocrysts, and the parallel alignment of mafic enclaves. The megacrystic granite here is coarse-grained. The most common mafic phase here is biotite, hornblende may also be found. The orientation of megacrysts and mafic enclaves here is about north-south. Wagener (1977) reports that this quarry provided crushed stone for the interstate highway system.

Dennis and Wright (1993, 1995) have dated the Bald Rock granite by the U-Pb zircon method. Three fractions of zircon yielded an upper intercept at 323±3 Ma interpreted to be a crystallization age. Their sample came from this location. Dallmeyer and others (1986, p. 1331) report an 1985 personal communication from P.D. Fullagar that the Rb-Sr age of biotite from the Bald Rock pluton is ca. 290 Ma (cf. 292 Ma biotite age of Pacolet granite). Speer and others (1986) reported mineral chemistry for biotite, amphibole and pyroxene from the Bald Rock granite, and compared their results to mineral chemistry of known Carboniferous plutons of the eastern Piedmont. Vhynal and McSween (1990) used the Al-in-hornblende (7 grains) barometer to estimate a crystallization pressure for the Bald Rock at 4.8±0.5 kbar or 18.5±2km. Vhynal and McSween (1990) prepared pressure estimates for 14 Carboniferous plutons from both the eastern Piedmont (Carolina slate belt: 10.8-11.6 km depth of emplacement) and central Piedmont (14.2-19.3 km depth of emplacement) and documented the Alleghanian-regional scale warping of isotherms suggested by regional reconnaissance $^{40}Ar/^{39}Ar$ ages and other mineral ages and proposed by Dallmeyer and others (1986) and Secor and others (1986).

Speer and others (1986) and van Gelder and McSween (1981) present maps of the megacryst and mafic enclave fabric of the Bald Rock pluton. Generally the magmatic foliation is broadly concentric with the pluton margins, but tapered mafic enclaves define an asymmetric, counterclockwise pattern that Speer and others (1986) suggested was a consequence of either irregularities in the magma chamber or emplacement in a left-lateral fault zone. Based on contrasts in metamorphic grade and structural style east and west of the pluton (that will be observed later on this trip), it appears that the Bald Rock did intrude an existing fault zone, however, it has been difficult to evaluate the hypothesis of left-lateral shear along this zone in early Alleghanian time.

This is not the first Carolina Geological Society field trip to visit this site. In 1973 the 34th annual meeting based in Pageland and led by H.D. Wagener and D.E. Howell led a trip titled "Granitic Plutons of the central and eastern Piedmont of South Carolina." This was their stop 10.

The Bald Rock granite has a historical tie. The Union Jail on West Main Street was designed and construction supervised by South Carolina architect Robert Mills (1781-1855) over the period 1822-1823. The original design called for brick construction, however after a problem with the quality of the brick was recognized, Mills ordered the brick torn down, and after learning of the existence of a nearby granite quarry (Humphries quarry west of town, as described by Sloan, 1908 and Wagener, 1977), elected to complete the outside walls with Bald Rock granite. Among Mills' many later accomplishments were the US Treasury Building (1836, completed in 1842), Old Patent Office (now part of the Smithsonian Institution), and the Washington Monument (1836, completed 1884). The Union Jail is still in use and is the oldest functioning jail in the state and the oldest intact public building in the county (Charles, 1987).

STOP 3: CHARLOTTE BELT METAGABBRO AND GABBRO, ALONG RAILROAD SPUR JUST NORTH OF SC HIGHWAY 9 IN EASTERN CHESTER COUNTY, SOUTH CAROLINA.

LOCATION

The outcrops are along a railroad spur to the PPG Chester Plant, just north of SC-9 and just west of S-12-74, east of Chester. Park along S-12-74 and walk west to the railroad cuts. (Fig. 5, Chester Quadrangle)

Description

The rocks exposed in the banks exposed of the railroad cut are mainly dark-colored, medium grained metagabbro that is the most extensive rock type in the York-Chester mafic complex. Nearly everywhere the metagabbro is deeply weathered and forms low, flat, thickly vegetated topography. This is the best accessible exposure found in the region so far. The metagabbro is generally massive, but locally it is strongly deformed and has a tectonic foliation. There are shear zones of chlorite-rich schist, retrograded from the metagabbro. The metagabbro has some inclusions of mafic and possibly ultramafic rocks, and it is cut by several mafic dikes

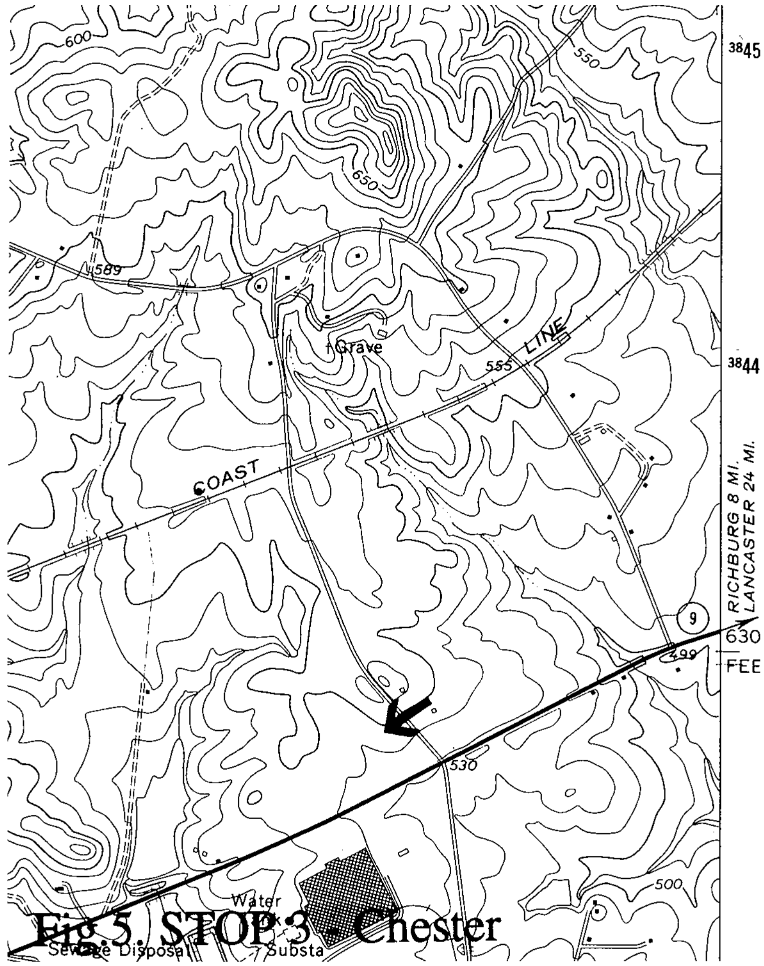


Fig.5. STOP 3 - Chester

and a number of pegmatite and granite dikes. In thin sections the massive rocks have relict igneous hypautomorphic-granular texture, strongly modified by replacement of original minerals by fine-grained, greenschist facies minerals such as actinolite, chlorite, epidote and albite. The texture, chemical composition, and relict crystals of hornblende, pyroxene, and calcic plagioclase indicate that the rocks was originally hornblende gabbro or gabbro-norite. Regional metamorphism here was under greenschist facies conditions, in contrast with regional amphibolite facies conditions in most of the Charlotte belt.

Near the southern end of the railroad cuts and about 80 meters north of SC-9, there are several low exposures of residual boulders of unmetamorphosed olivine gabbro. The gabbro is very different from rocks farther north in the outcrop, although there are no clear differences in soil and saprolite in between that would define a contact. The gabbro is similar to rocks that make up the Chester gabbro pluton, about 1.4 km to the west along SC-9. The gabbro is medium-grained and composed of plagioclase, olivine, augite, hypersthene, hornblende, and opaque minerals, with small amounts of biotite and spinel. This occurrence of gabbro is interpreted to be a dike or a small plug related to the Chester pluton, but it could be part of a larger body underlying the covered area south of the outcrop. These outcrops illustrate the difficulties of mapping gabbro versus metagabbro.

STOP 4: CHARLOTTE BELT INTRUSIVE COMPLEX AT NEAL SHOALS DAM, ON THE BROAD RIVER IN WESTERN CHESTER COUNTY (FIG. 6, LEEDS QUADRANGLE)

LOCATION

The outcrops are just below the eastern abutment of Neal Shoals Dam on the Broad River, at the end of National Forest Road 304, Sumter National Forest. The Neal Shoals Dam is owned by South Carolina Electric and Gas Company.

DESCRIPTION

Below the dam, there are excellent outcrops of fresh rock and saprock swept clean by periodic overflow. The main outcrop area is about 100m long by about 60 m wide. The rocks range in composition from felsic to mafic. The oldest rocks are inclusions of hornblende gneiss, amphibolite

Fig.6. STOP 4 - Leeds

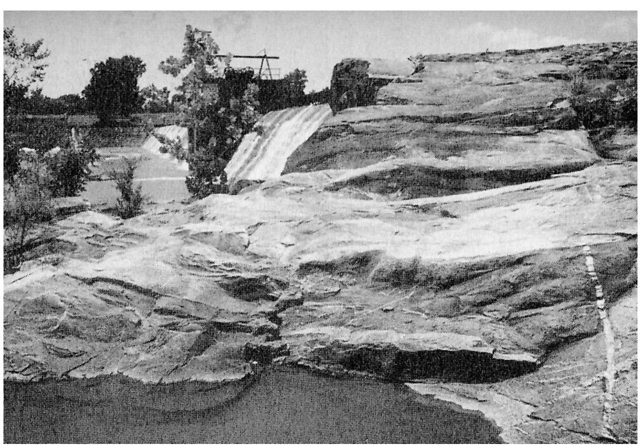


Fig. 7. View northwest across Stop 4, Neal Shoals

and metagabbro in granite and diorite. Various granitoid rocks make up the majority of the exposure. At least two types of mafic dikes and numerous pegmatite dikes crosscut the older units. Some rocks have a well developed tectonic foliation, but others are essentially undeformed. Where foliation and layering are developed they typically strike north-northeast and dip steeply east-southeast, approximately parallel to the regional trend. The outcrops here show many features typical of the Charlotte belt intrusive complexes in this region, but elsewhere they are mostly exposed piecemeal in small saprolitic outcrops. Here they are well displayed in one small area.

For convenience in pointing out the features, the exposure is divided into three parts, northern, central and southern, but they are all interpreted to be aspects of a single intrusive complex. The northern part (Fig. 7) is mostly foliated biotite granite with numerous inclusions of mafic rocks, all of which are cut by pegmatite dikes. The mafic inclusions are mostly amphibolite and hornblende gneiss that are typically elongate and oriented parallel to the regional trend. Some inclusions have wispy and stringy ends, suggesting partial assimilation and mixing with the granite magma.

The central part (Fig. 7) of the outcrop is mostly a variety of mafic rocks with some granite, cut by a mafic dike and numerous pegmatite dikes. The largest mafic body is a fine-grained biotite amphibolite with porphyroblasts of hornblende and relict (?) phenocrysts of plagioclase. The mafic dike is about one meter thick and has strong ductile deformation along its contacts. Rotation of the foliation and layering in the adjacent granite and amphibolite indicate that the block north of the dike moved relatively eastward. The dike is a metagabbro, with mineral assemblages indicative of amphibolite facies metamorphism.

The southern part of the outcrop is mainly strongly foliated coarse-grained granite, with some mafic inclusions, that is cut by a fine-grained, foliated mafic dike and many pegmatite dikes. In the steep bank on the eastern side of the outcrop, colluvium as much a two meters thick unconformably overlies saprolite of the intrusive complex.

The rocks here are interpreted to have been emplaced during a single protracted sequence of magmatic events. The

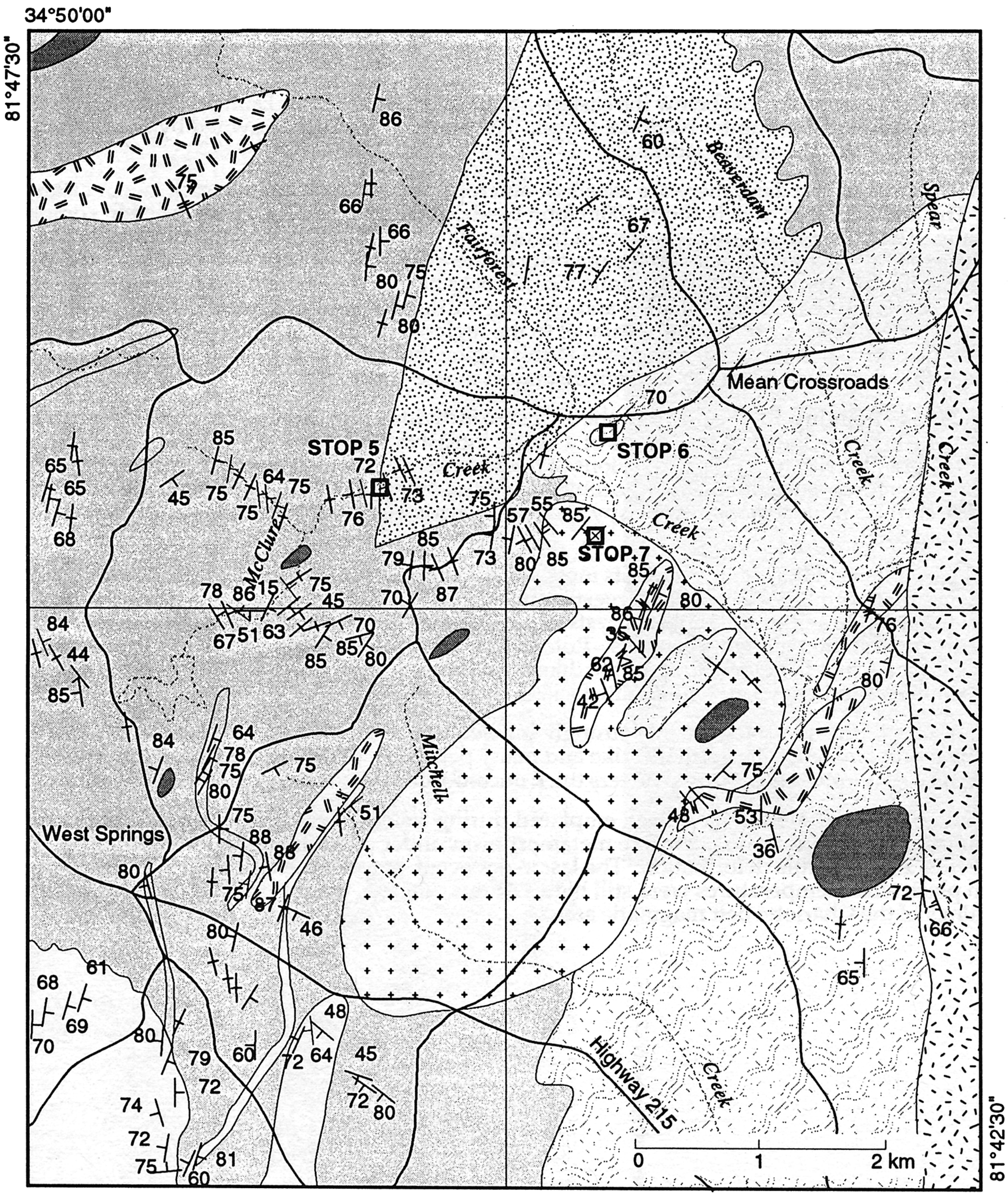


Fig. 8. Geologic map of a portion of the Glenn Springs and Jonesville quadrangles, showing the location of Stops 5, 6, 7. Light grey - mafic metavolcanic rocks; outlined areas within light grey - quartz sericite schist or silicification; no pattern - felsic metavolcanic rocks; dark grey - metapyroxenite-hornblendite; double bar random pattern - metagabbro; rippled gneiss pattern - Mean Crossroads metadiorite-diorite gneiss; random dot pattern - foliated biotite porphyry granodiorite; aligned crosses - undeformed, unmetamorphosed diorite; single bar random pattern - Bald Rock granite. Adapted from Dennis and Wright (1996).

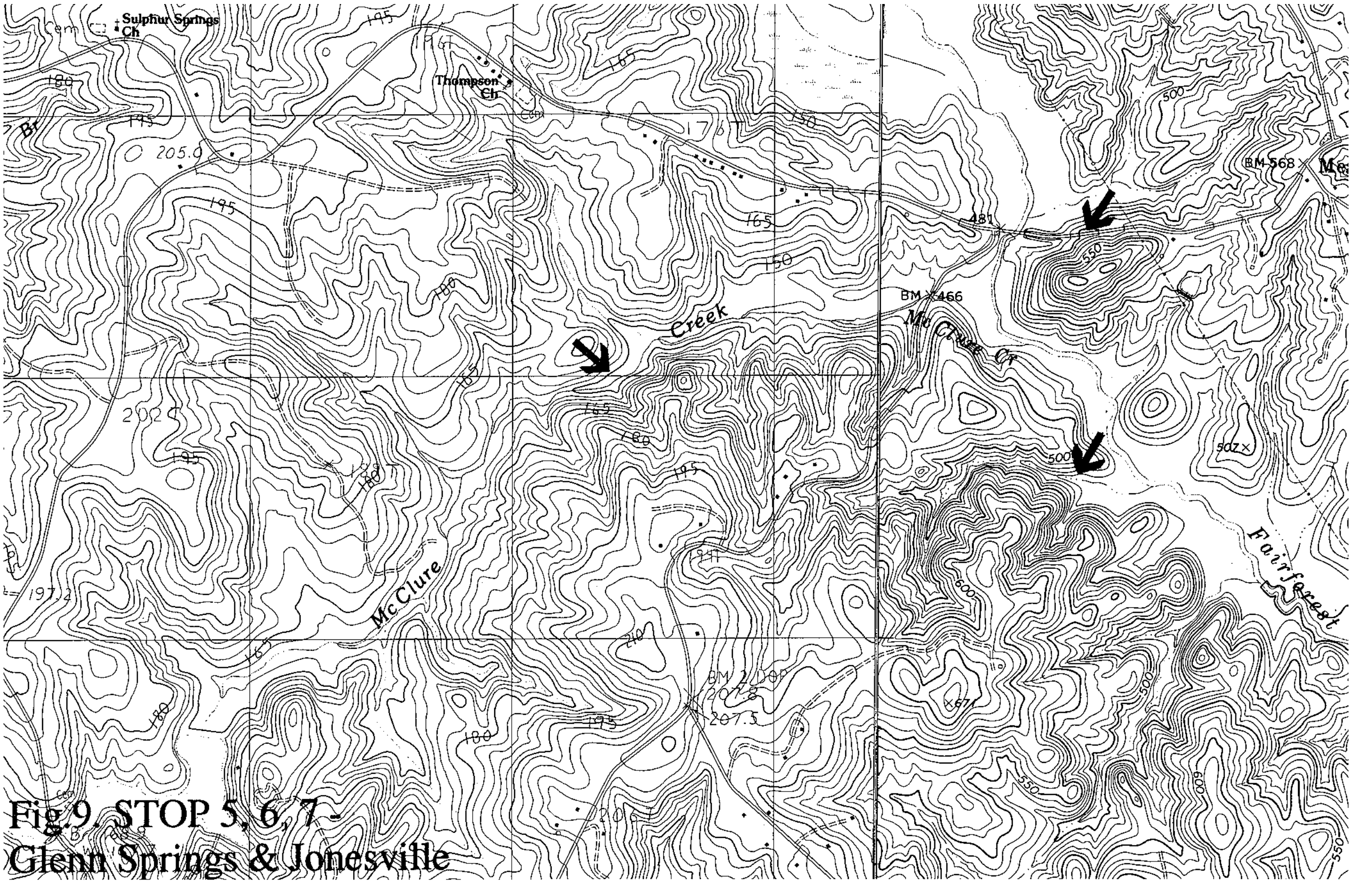


Fig.9. STOP 5, 6, 7 - Glenn Springs & Jonesville

mineral assemblages indicate pervasive metamorphism under amphibolite facies conditions. There is considerable evidence for ductile deformation. The last major event, emplacement of the swarm of pegmatites must have taken place while temperatures were still high. At this outcrop, we are probably looking at the midcrustal underpinnings of the Charlotte belt magmatic arc.

The next three field trip stops are very close together (Fig. 8), and illustrate the coeval magmatism, deformation, and metamorphism that distinguished the Carolina terrane in the latest Precambrian through early Cambrian (Dennis and Wright, 1993, 1996). All the events recorded here occurred on the fringes of Gondwana. Dennis and Shervais (1995) and Dennis (1995) discuss these events in the context of a tectonic model presented by Nance and Murphy (1994).

STOP 5: MAFIC METAVOLCANIC ROCKS OF CAROLINA TERRANE INTRUDED BY FOLIATED BIOTITE PORPHYRY GRANODIORITE, MCCLURE CREEK

LOCATION

The outcrops are located on McClure Creek approximately 200 m northwest of (behind) log home on Lancaster Road. Lancaster Road is off S-42-12, 0.5 mile north of the intersection of S-42-12 with S-42-23. (Fig. 9, Glenn Springs quadrangle)

DESCRIPTION

Here are observed mafic to intermediate metavolcanic rocks that are intruded by a biotite porphyry granodiorite. Volcanic rocks show porphyritic and amygdaloidal textures, and appear highly strained (Fig. 10). The contact with the granodiorite is gently dipping and near the water level in McClure Creek. The granodiorite is characterized by biotite clots that define a crude lineation and have dimensions approximately 2 cm x 1 cm x 2 mm. The granodiorite has a strong, almost gneissic fabric that parallels that in the mafic metavolcanic rock. Petrographic examination indicates that this is a composite planar fabric (so-called “S-C”) and that the granodiorite (and its country rock) have been ductilely sheared (Fig. 11). It is suggested here that the granodiorite is intruded into a locally significant dextral shear zone (of late Precambrian-early Cambrian age) based on the asymmetric tear-drop shape of the pluton and the sudden “hard-right” turn (at the map scale) of the foliation as it enters the pluton.

Foliations strike northerly to north and slightly west. Dips are steep (>70°) and to the west. This is typical for rocks of the Carolina terrane in this area. The thin foliation

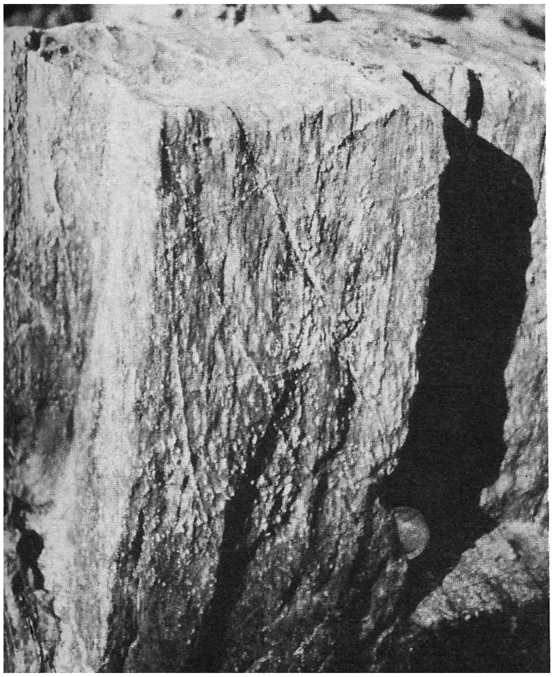


Fig. 10. Amygdaloidal greenstone on McClure Creek, Stop 5. Note subvertical foliation.

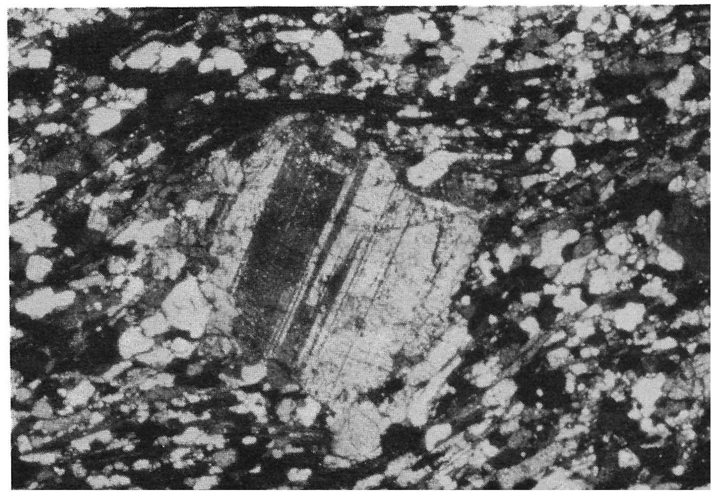


Fig. 11. Photomicrograph of foliated biotite porphyry granodiorite, Stop 5. Note rounded plagioclase porphyryclast wrapped in biotite. Aggregates of biotite flakes elsewhere in this pluton define a composite planar fabric that is subvertical in orientation. Field of view approximately 25 mm.

or cleavage observed mesoscopically on weathered rock surfaces is also typical. In thin section or on some fresh surfaces in hand specimen, it may be seen that the mafic metavolcanic rocks have been completely recrystallized with the growth of relatively coarse, idioblastic amphiboles, and fine-grained, equant, polygonal grains making up the felsic phases. The origin of this recrystallization is obscure.

Dennis and Shervais (1995) present geochemistry for an amphibolite at this site (their "McClure Porphyry") that is an andesite. Dennis and Shervais (1995) report an ankaramite

Fig. 12. Foliated xenolith in undeformed, unmetamorphosed diorite, Stop 6. Foliation orientation is at a high angle to the contact, and is consistent with orientations of foliation outside the pluton.

Fig. 13. Equant mafic enclave within undeformed, unmetamorphosed diorite, Stop 6.

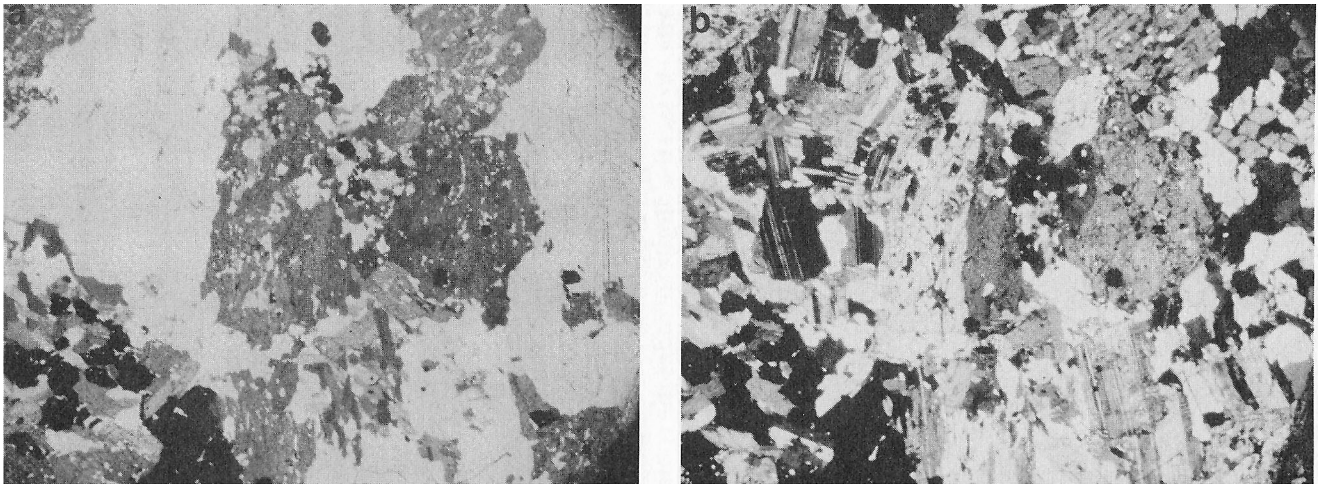


Fig. 14. Photomicrograph of undeformed, unmetamorphosed diorite, showing good igneous texture and mineralogy, Stop 6. Field of view approximately 25 mm

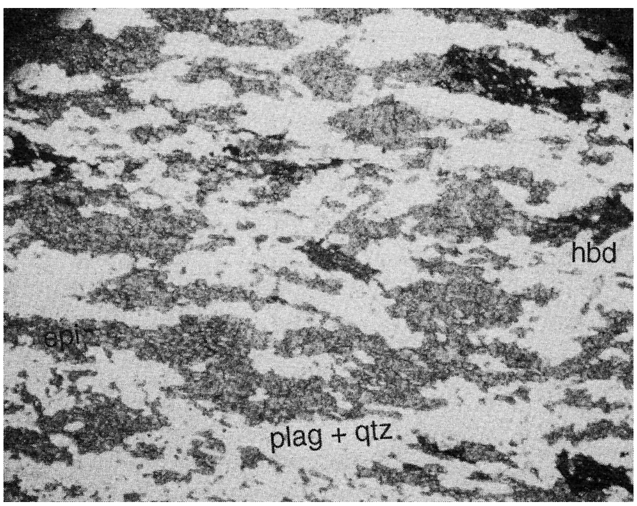


Fig. 15. Photomicrograph of gneissic metadiorite of Mean Crossroads complex, Stop 7. Whether samples contain a good metamorphic fabric or not, all samples show the ubiquitous development of epidote at the expense of plagioclase. The contact between this pluton and mafic metavolcanic rocks observed at Stop 5 is cut by the undeformed, unmetamorphosed pluton observed at Stop 6.

tuff (their 1512) upstream (south) of this site on McClure Creek. The area south of this stop to West Springs is a historic locus of gold exploration in this part of South Carolina as discussed by LaPoint (1995) in this volume. In this area it is not unusual to find mafic and ultramafic dikes cross-cutting the quartz-sericite alteration zones that are frequently an gold exploration target. This indicates that the alteration was broadly coeval with ongoing mafic and ultramafic volcanism accompanying arc-rifting as described by Dennis and Shervais (1991).

Dennis and Wright (1993, 1996) analyzed two fractions of zircon by the U-Pb method from the foliated biotite porphyry granodiorite at this stop. They interpret the upper intercept at 571±16 Ma as a crystallization age. To the south of this area in the Cross Anchor quad, Dennis and Wright (1993, 1996) dated another foliated diorite that also intrudes mafic metavolcanic rocks (at Stop 12). Four size fractions of zircon including an air-abraded fraction dated by U-Pb yield an upper intercept interpreted as a crystallization age at 579±4 Ma. Thus at least in these two areas, mafic metavolcanic rocks predate ca. 570-580 Ma, and the observed metamorphic fabric postdates ca. 570 Ma.

STOP 6: UNDEFORMED, UNMETAMORPHOSED DIORITE

LOCATION

The outcrops are located on the unnamed tributary to Fairforest Creek south of McClure Creek. Park at the gate on S-42-12 located 0.4 miles north of the intersection of Lancaster Road and S-42-12. Walk east along the track and turn right (south, downhill) at the second deerstand down to the creek. (Fig. 9, Jonesville quad)

DESCRIPTION

In a traverse of several hundred meters along this tributary, it is possible to see mafic metavolcanic rocks intruded by an undeformed, unmetamorphosed diorite. In fact the diorite intrudes the contact between mafic metavolcanic rocks and diorite gneiss (Stop 7). The diorite contains foliated xenoliths of mafic metavolcanic rocks (Fig. 12) and mappable blocks of metagabbro and diorite gneiss (Fig. 8) of the Mean Crossroads complex. The orientation of the metamorphic fabric in these xenoliths and blocks is consistent with the orientation in the country rock and at a high angle to the intrusive contact. The diorite gneiss at this location also contains equant (spherical?) mafic enclaves (Fig. 13). Petrographic examination of the undeformed diorite shows igneous textures and mineralogy is preserved (Fig. 14). Every indication is that this rock is a post-metamorphic pluton.

Dennis and Wright (1993, 1996) dated three size fractions of zircon from the diorite at this site by the U-Pb method and interpreted the resulting upper intercept at 535±4 Ma as a crystallization age. Comparing this age with that reported by Dennis and Wright (1993, 1996) for Mean Crossroads metadiorite-diorite gneiss, one concludes that the metamorphic fabric observed in these rocks of the Charlotte belt must be older than 535±4 Ma. The Acado-Baltic fossils from the Carolina slate belt reported by Samson and others (1990) are middle Cambrian in age. Thus, we conclude that the metamorphic fabric observed here did not form as a consequence of collision of the Carolina arc with Laurentia, but must record events on the fringes of Gondwana (Dennis and Wright, 1995). Jim Hibbard and Scott Samson (1995) have correlated this deformation with the Virgilina orogeny of Glover and Sinha (1973).

STOP 7: MEAN CROSSROADS METADIORITE/ DIORITE GNEISS

LOCATION

: The outcrops are located on dirt tracks leading north and west around the prominent hill located 0.2 mile west of the S-42-12 bridge over Fairforest Creek. (Fig. 9, Jonesville quadrangle)

DESCRIPTION

Loose boulders and cobbles of metadiorite and diorite gneiss of the Mean Crossroads complex (Dennis and Shervais, 1991) litter the slopes of this prominent hill. Some samples show little fabric at all with randomly oriented coarse hornblende needles, others have a mylonitic foliation. What is common to all samples is the ubiquitous development of epidote at the expense of plagioclase (Fig. 15). This is interpreted to indicate intrusion of the Mean Crossroads diorite relatively late in the late Precambrian-early Cambrian orogenic event, when rather than a zone of broad, distributed strain, deformation was restricted to narrow bands irregularly distributed through a pluton that was intruded into a semicontinuously deforming zone.

Dennis and Wright (1993, 1996) dated four size fractions of zircon from this site by the U-Pb method. The data plot in a highly linear array with an upper intercept at 538±5 Ma, interpreted to be the crystallization age of the diorite and the age of the Mean Crossroads complex.

The Mean Crossroads complex was identified by Dennis (1988) and described by Dennis and Shervais (1991, 1995). The Mean Crossroads complex is zoned intrusive complex that has a hornblendite-clinopyroxenite core, surrounded by varieties of gabbro, and mantled by a thick rind of diorite. This entire package was metamorphosed at greenschist to lower amphibolite facies. It is believed that at least some of the mafic metavolcanic rocks in this area were derived from the Mean Crossroads complex because ankaramite and ultramafic dikes crosscut the plutonic rocks. Dennis (1988) and Dennis and Shervais (1991, 1992, 1995) argue that the Mean Crossroads complex, Wildcat Branch complex, the Hammett Grove Meta-Igneous Suite, York-Chester mafic-ultramafic complex, Davie County Complex (NC), Latimer (SC)-Nancy Hart (GA) complex, and Berner mafic complex represent loci of arc-rifting along the western edge of the Carolina arc while the arc was in a periGondwanide position. Probably the Caswell County complex described by Wilkins and others (1995) also belongs in this group. This arc-rifting occurred in the western Carolina terrane at the same time or slightly younger than eruption of Persimmon Fork Formation, Lincolnton metadacite, Uwharrie Formation, ca. 550 Ma (Dennis, 1995; Dennis and Shervais, 1995).

STOP 8: BUFFALO GABBRO/SYENITE CONTACT

LOCATION

The outcrops are located on S-42-210, 0.7 mile south of the intersection with S-42-33. (Fig. 16, Cross Anchor quadrangle)

DESCRIPTION

These road cuts and boulders in the adjacent woods show the Buffalo gabbro and the associated felsic rocks mapped on its south margin, and the contact between these two rock types (Medlin, 1966; Medlin and others, 1972). The gabbro here is medium to coarse-grained and black in color. In fact, the mafic rocks of the Buffalo gabbro grade in no apparently systematic way from gabbro to norite (Medlin and others, 1972). Medlin and others (1972) report modal percentages of olivine from 0-20.9% (norites) and 0-23% (gabbros); orthopyroxene from 12-42.2% (norites) and 0.6-21.9% (gabbros); and clinopyroxene from 7.2-36.3% (norites) and 7.8-58% (gabbros). Medlin and others (1972) report 8 olivine, 3 orthopyroxene, and 6 clinopyroxene mineral analyses: olivines range from Fo_{68}-$Fo_{80.6}$; orthopyroxenes from En_{75}-En_{78}; and, clinopyroxenes from $Wo_{41.5}$-$En_{44.5}$ to $Wo_{44}En_{41}$.

The felsic rocks are bluish-grey with bluish potassium feldspar phenocrysts. Medlin (1966) terms these rocks "biotite quartz monzonite," and Willis (1984) calls them "syenodiorite." Two modal analyses (Medlin and others, 1972) plotted on the 1976 IUGS classification scheme (Streckeisen, 1976) yield points in the quartz monzonite (QAP -> 14-43-43) and quartz syenite (9-62-29) fields Medlin and others (1972) did not think that there was a necessarily a petrogenetic or magmatic relation between the felsic and mafic rocks, but without explicitly establishing the rela-

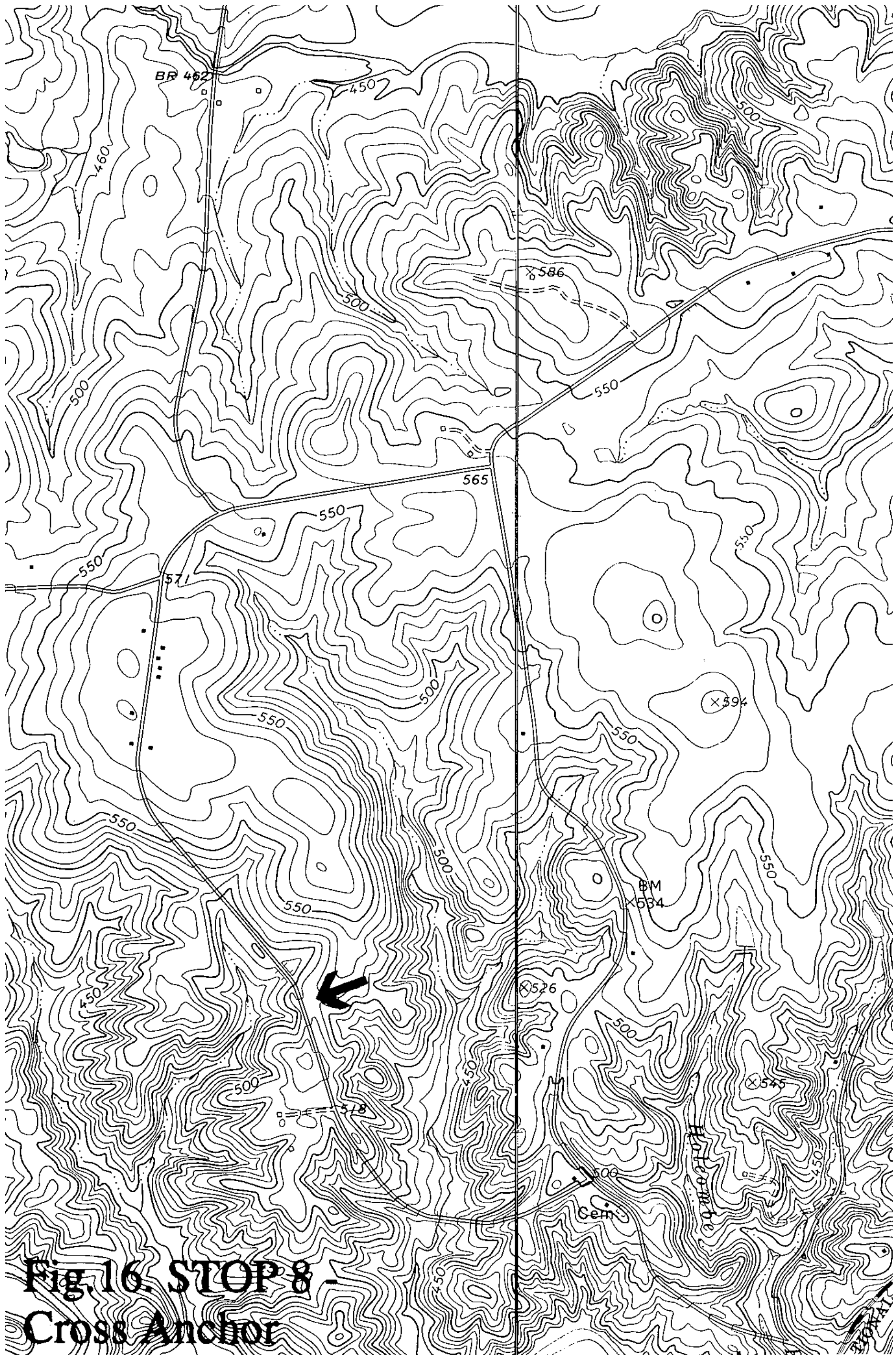


Fig. 16. STOP 8 - Cross Anchor

tion, Willis (1984) and Dennis (1991) did.

Several leucocratic dikes may be observed in the weathered residuum in the gully. Medlin and others (1972) note that the aplite to pegmatite veins and dikes cut across both gabbro and felsic rocks.

Medlin and others (1972) compare the Buffalo gabbro with mineralogic data from the other known post-metamorphic gabbros. They stress the differences between Buffalo and Mt. Carmel and Concord. Medlin and others (1972) note that Concord and Mt. Carmel show alkaline affinities, and the Buffalo gabbro either calc-alkalic or tholeiitic affinities.

Based on gross chemical similarities between the post-metamorphic gabbros, their linear arrangement just southeast of the central Piedmont suture, the ca. 400 Ma age of the array, strongly positive e_{Nd} (ca. +4) for the array, the association of an alkalic group of granites (Salisbury-Southmont group) of the same age with low initial Sr ratios (.7023-.7046) in the same structural position as the gabbros, as well as the pattern of mineral ages in the Inner Piedmont (younging to the east towards the central Piedmont suture), the problem of apparently coeval metamorphism in the Inner Piedmont and Carolina terrane with "cold" rocks in the hanging wall, Dennis (1991) offered the hypothesis that the central Piedmont suture formed (or was reactivated) as a Siluro-Devonian normal fault following crustal thickening accompanying the accretion of Carolina to Laurentia. Data to test this hypothesis, including U-Pb ages of monazite and construction of P-T-t curves are being collected.

SUNDAY

STOP 9: MASTERS' KILN MARBLE

LOCATION

Masters' Kiln is located off the end of Gilbert Road, off Poplar Springs Road (S-30-64) southeast of SC 252. (Fig. 17, Ware Shoals East quadrangle)

Masters' kiln lies hidden about 0.2 mi downhill from the house along an azimuth direction S5°W. A path through the thick brush will be marked. The kiln site comprises less than an acre and now lies in ruin. Although largely overgrown, this site is being preserved by the owner. **Do not collect samples from the kiln or building. Samples may be taken from the loose material at the site or judiciously sampled from the quarry walls.**

DESCRIPTION

This stop is divided into several parts: the remains of the kilns, a building foundation with partially standing walls, and the overgrown pit. Mineral collecting from scattered float in the pit is good and permitted. *Please do not remove stone from the kilns or building!* Further discussion of this site and other central Piedmont kilns is found in Garihan and others (1995).

Building foundation

For safety, please stay out of the building. Mortar for blocks in the walls, now crumbling, was made from quarry materials. The northwest-facing (back) wall remains standing because it is supported by two cedars. Interestingly, the walls contain some of the best remaining mineralogic speci-

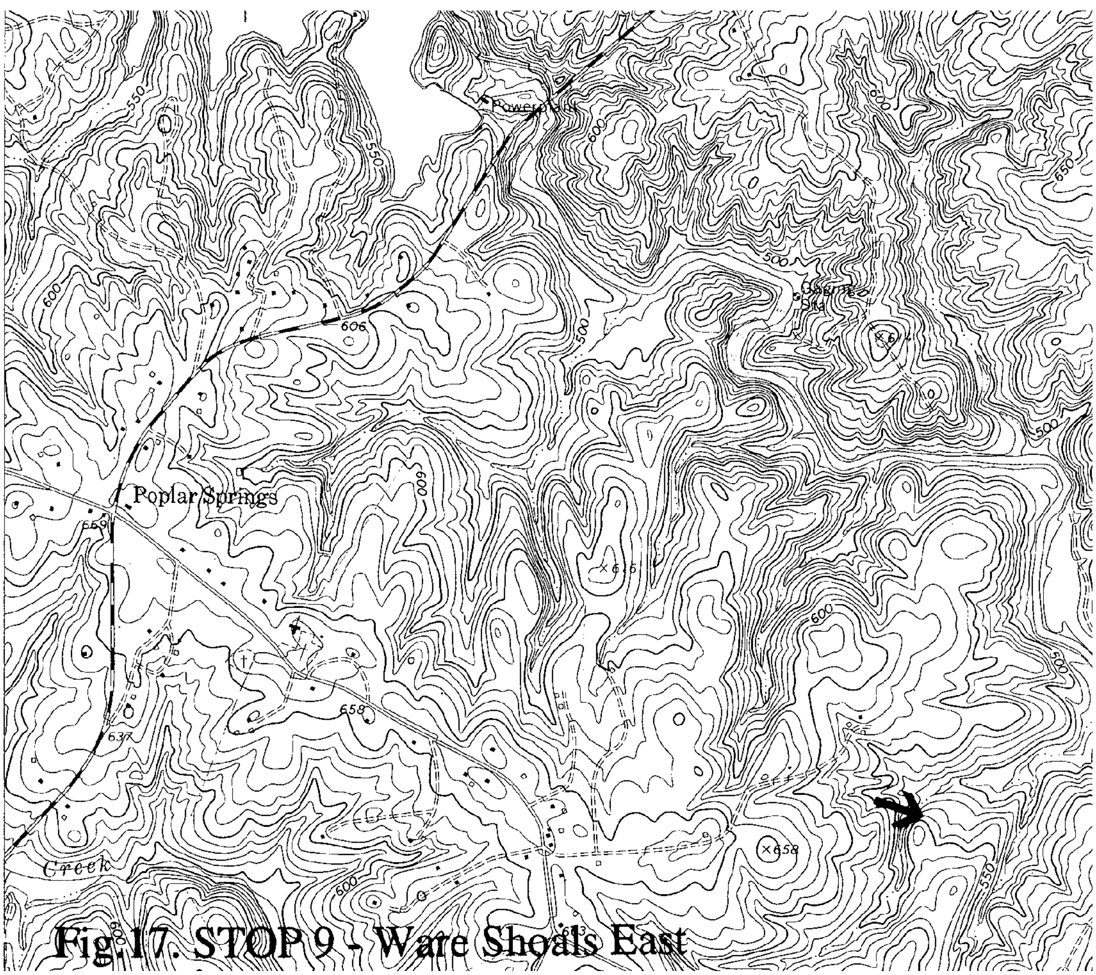


Fig.17. STOP 9 - Ware Shoals East

mens on the site, produced by metamorphism at the granite-marble contact: for example, 1) conspicuous purple scapolite (2 ft to the right of the left-hand cedar and 2 ft above the ground); and 2) coarse, idioblastic actinolite in a gray-purple calcite matrix (left of the right-hand cedar and 4 ft above the ground). Elsewhere, numerous blocks display the texture of the biotite granite, locally porphyritic, which is well foliated and compositionally layered near the marble contact.

On the northeast-facing wall (near the corner and 4 ft above the ground) one can see a block with boudinaged, dark green, calc-silicate layers; extensional space between the boudins has been filled with coarse calcite and/or wollastonite (?).

Boulders

Several 1-3 ft boulders with interesting textures and mineralogy (green quartz, actinolite, scapolite, and wollastonite(?)) lie on the pit floor approximately 100 feet from the building (S10°W). The following contact metamorphic mineralogical zonation can be demonstrated: foliated granite — scapolite (1-3 in wide) — calc-silicate rock (4-6 in wide) — fine-grained dolomitic marble.

One block contains a fine- to medium-grained, brown-black, biotite-amphibole gneiss, probably xenolithic country rock to the granitic intrusion. Several out of place boulders across the small creek display an unusual brecciated texture, with veins of calcite-wollastonite(?) filling between displaced, angular fragments of green calc-silicate rock; purple scapolite lies adjacent to the breccia at the granite contact.

Southeast pit face

The 10 ft high, southeast face of the pit shows in place, finely-bedded, manganese oxide stained, phlogopite-bearing dolomitic marble oriented N40°E, 32°SE. It lies beneath a resistant, sill-like, foliated granite and aplite. Marble is coarsely recrystallized below the igneous contact. A discordant granite pegmatite dike (9 in wide) truncates the sill and relict bedding in the marble. There is little obvious contact metamorphic affect other than minor actinolite along the dike walls. It is interesting to speculate whether quarrying operations mined completely through the entire thickness of the marble, which is unknown but probably less than 20 ft.

Upper pit

To the west of the southeast pit face in a higher cut a 12 ft ledge of granite and pegmatite overlies less resistant, locally solutioned, coarse marble. The contact here is distinctly undulating and sharp, and most contact mineralogy has been removed by collectors. A 20 ft cave existed along this contact in past years, but the entrance is now covered.

STOP 10: CEDAR SHOALS GNEISS OF THE INNER PIEDMONT

LOCATION

The outcrops are located on Cedar Shoals Creek near where it meets the Enoree River 0.1 mile past the Horseshoe Falls bridge over Cedar Shoals Creek. Horseshoe Falls Road intersects SC 56 1.0 mile north of the bridge over the Enoree River. These outcrops are owned by the South Carolina State Park System. (Fig. 18, Philson Crossroads quadrangle)

DESCRIPTION

These outcrops are the type locality for the Cedar Shoals gneiss of Horkowitz (1984). The Cedar Shoals gneiss comprises quartzo-feldspathic biotite paragneiss and felsic orthogneiss (Horkowitz, 1984). Metamorphic minerals present include sillimanite, muscovite, and garnet. Amphibolite boudins and pods are recognized in the Cedar Shoals gneiss, as well as dismembered metaplutonic rocks with compositions from tonalite to gabbro, and pegmatitic and aplitic dikes. These outcrops are comparable to Inner Piedmont outcrops along the central Piedmont suture on Fairforest Creek in the Glenn Springs quad described by Dennis (1988, stop 9, p. 245).

The slabby appearance, northeasterly strikes, gentle dips (typically 20-40°) to the southeast observed here are typical of the easternmost Inner Piedmont in northwestern South Carolina. Some small folds may be observed the axes of which plunge to the south at 15-20°. These parallel asymmetric, northwest-vergent mesoscopic folds, mineral lineations, and intersection lineations in the Carolina terrane (Dennis, 1988, 1995). Because foliations are folded without interruption across the central Piedmont suture (i.e. formlines are continuous across the terrane boundary) defining great circles with poles that also plunge 15-20° to the south (Dennis, 1988, 1995), and the lineation is a fabric element with a consistent geometry on either side of the terrane boundary, these folds are interpreted to postdate major motion on the central Piedmont suture and be Alleghanian in age.

From this location, Dallmeyer and others (1986) report a $^{40}Ar/^{39}Ar$ plateau age for biotite at 259±5 Ma (their sample 47). This sample and two other Inner Piedmont biotite plateaux from northwest of here in the Enoree quad (their samples 48 and 49) with ages of 272±5 and 271±5 Ma led these authors to conclude that the Inner Piedmont in this area cooled through 300°C ca. 260-270 Ma.

Horkowitz (1984) interpreted that the protoliths of the Cedar Shoals gneiss included graywacke, arenaceous sediments and siliceous/felsic volcanic rocks based on five petrographic modal analyses and plotting his modal data on a QFM diagram.

Structurally these rocks at Cedar Shoals are separated from the central Piedmont suture (as mapped by Horkowitz, 1984) and beneath a 3 km width of biotite gneiss that also

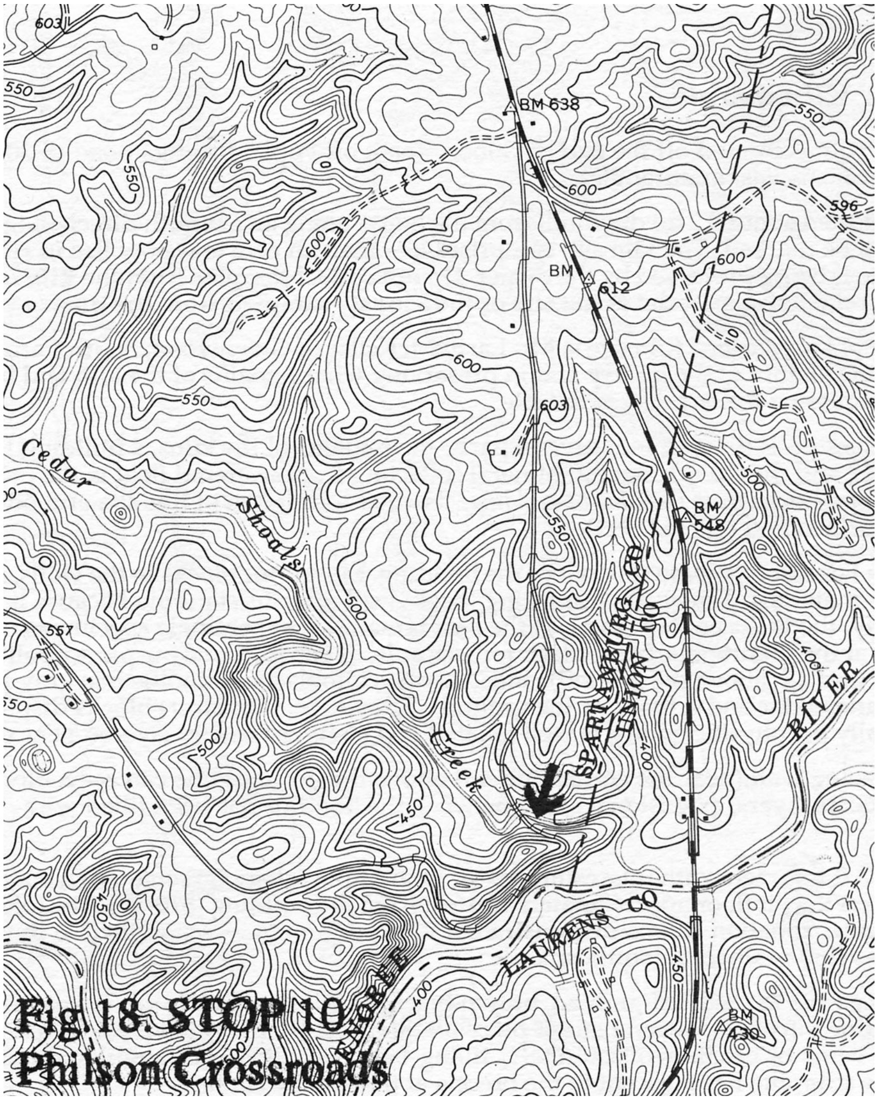


Fig. 18. STOP 10
Philson Crossroads

includes marbles, calc-silicates, sillimanite-muscovite schist, and garnet-quartzites (Horkowitz, 1984). Horkowitz' (1984) lithologic descriptions for this biotite gneiss unit are reminiscent of the southernmost exposures of Battleground Formation in the Glenn Springs and Pacolet quads (Dennis, 1988, especially p. 231, 246; 1989; Mittwede, 1988, especially p. 253-256). Horkowitz' (1984) biotite gneiss unit may be primarily highly altered metavolcanic rocks of the Carolina terrane and lie **east** of the central Piedmont suture. If this correlation is true, then the central Piedmont suture lies less than 1 km (across strike) southeast of this site.

STOP 11: SLICE OF TIGHTLY FOLDED MYLONITE OF CENTRAL PIEDMONT SUTURE ALONG HACKERS CREEK

LOCATION

The outcrops are located on Hackers Creek. Park at the gate just past the S-42-115 bridge over Hacker Branch, 0.9 mile from SC 56. S-42-115 is 4.0 miles north of the Enoree River Bridge on SC 56. Walk northeast approximately 500 m to the first outcrops on the creek. (Fig. 19, Cross Anchor Quadrangle)

DESCRIPTION

This spectacular series of outcrops was first recognized and described by Willis (1984, p. 49) and later by Dennis (1991). Quartzo-feldspathic and darker grey garnetiferous mylonites are complexly interleaved and cut by folded pegmatites at this location. Willis (1984) interpreted these rocks as prograde mylonites, recrystallized and equilibrated at sillimanite zone conditions. They are not annealed because the quartz in them does not make equant, polygonal grains, but instead the quartz forms large, elongate grains with little or no subgrain development. Both quartzofeldspathic and darker grey rocks contain garnet, and the garnets in the darker grey rocks are up to 3 cm in diameter. In the darker

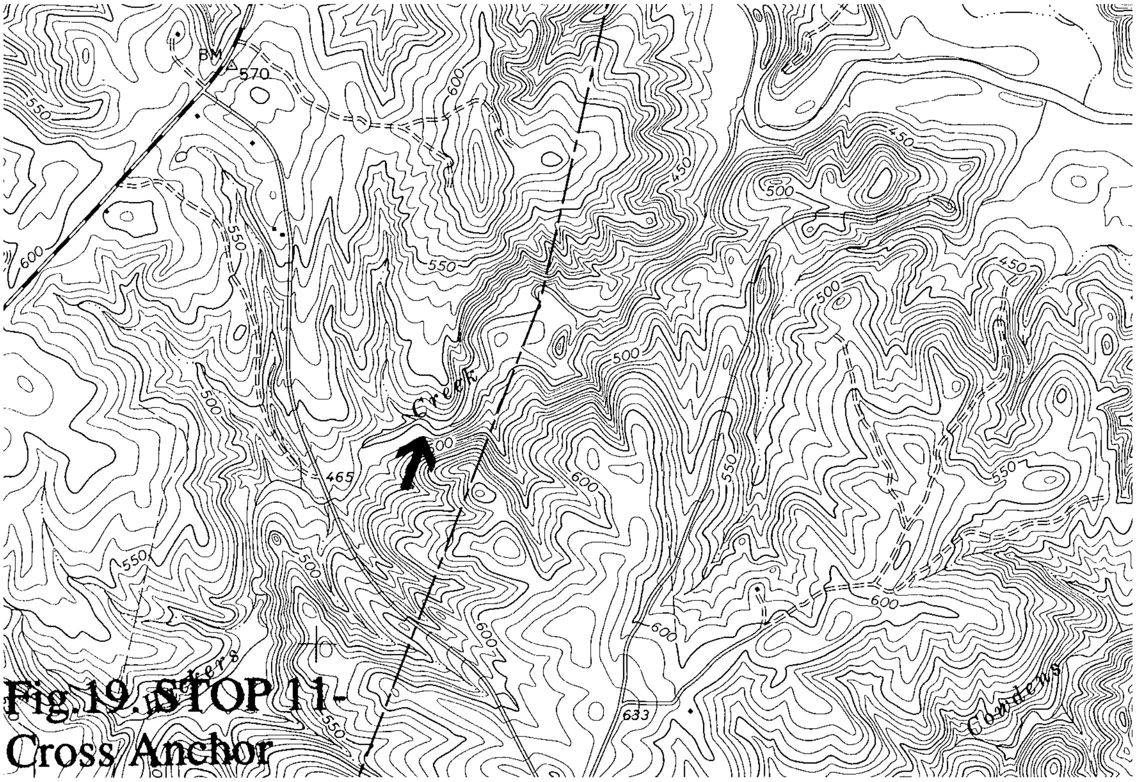


Fig. 20. Pavement surface showing large garnets enclosed in K-feldspar ± plagioclase within the darker grey mylonite of Hackers Creek at Stop 11. Hammer handle is 66 cm.

grey rocks, the mode of occurrence of the garnets is unusual. The garnets are often observed in the middle of highly altered aggregates of plagioclase ± K-feldspar (Fig. 20). The feldspars are recognized on the basis of twinning. The feldspars appear to have high relief because of the extensive development of sillimanite ± white mica along cleavage planes. The feldspars are typically the same size or slightly larger than the garnets they enclose. Some garnets appear to show two phases of growth with irregular fragments of garnet contained within larger well-formed crystals. Garnets are fractured and filled with retrograde chlorite; chlorite also rims grains. Mafic minerals, primarily micas, are much less common away from the garnets. Perhaps the darker grey rocks are paragneisses, it is difficult to say on the basis of their mineralogy or texture.

The orientation of mylonitic foliation here ranges from 125 80 (S, right hand rule) 100 45, 304 60, 320 45; with southwesterly dips common to the southern end of the outcrop and northeasterly dips common to the northern exposures. These are not orientations one typically associates with the central Piedmont suture, and they speak to the folding of the fault (where it has not been reactivated by Alleghanian strike slip motion, e.g. Kings Mountain shear zone) along the 50 km length of the central Piedmont suture between Spartanburg and Clinton in general (Dennis, 1991), and the fact that this is a fault-bounded slice in particular. At the northernmost exposures of the mylonite, the creek takes a hard left (northwest) bend, and highly fractured (brecciated?) rock is observed. Dennis (1991) interpreted that most of the mylonitic rocks along this segment of the central Piedmont suture had been removed by excision at higher structural levels. The generally non-cylindrical folding of mylonitic fabric is observed at outcrop and greater scales. Because these rocks are fault-bounded and folded at several scales it is difficult to make a convincing argument about the original orientation and/or asymmetry of fabric elements. The complex folding and refolding of mylonitic layering at this location defies conventional kinematic analysis ("shear-sense", e.g., Simpson and Schmid, 1983). This aspect of these rocks is frustrating for workers studying the history of ductile motion along the central Piedmont suture.

Mineral separates have been prepared from darker grey gneiss (monazite) and folded pegmatites (zircon) from this site, and U-Pb analyses are forthcoming from the laboratories of J.E. Wright, Rice University.

Nearby is the site of a significant revolutionary war battle. This outcrop is about a mile west-southwest of the Blackstock battlefield, where action took place 20 November 1780. The much better known Battle of Kings Mountain took place six weeks prior on 7 October 1780. The following account is Lumpkin's (1981, p. 268) summary of the battle (which is also treated in an entire chapter in his book):

"Banastre Tarleton, pursuing the retreating Thomas Sumter [retreating from Fishdam Ford on the Broad River], pushed forward with his calvary and mounted infantry, leaving his slower infantry and artillery to follow at their best speed. Sumter meanwhile had determined to make a stand at the farm of William Blackstock overlooking the Tyger River. Tarleton with an inferior force [270] frontally attacked [900-1,000] strongly posted Americans and was beaten back with heavy casualties [92 killed, 100 wounded]. The Americans lost only 3 killed and 4 wounded but among the latter was Thomas Sumter. Colonel John Twiggs of Georgia assumed command of the Americans and retreated that night with his little army across the Tyger leaving the field to Tarleton, who claimed victory."

"The battle of Cowpens, where Tarleton was to experience his greatest defeat, occurred less than two months later on 17 January 1781. The importance of the battle of Blackstock's therefore lay in the fact that the dreaded "Bloody" Tarleton had been fought and checked by American militia, a fact that was to influence markedly the future course of the war in the South. Thomas Sumter survived his serious wound and took the field again in a few months." (p. 115)

STOP 12: MAFIC METAVOLCANIC ROCKS EXPOSED ALONG DUTCHMANS CREEK

LOCATION

The outcrops are located on Dutchmans Creek. Access is via S-42-511 (a/k/a S-44-68), and entrance can be gained at the Bridge over the Creek or at gates 0.1 or 1.0 miles from the intersection with SC 56. (Fig. 21, Cross Anchor quadrangle)

DESCRIPTION

: A good section of mafic metavolcanic rocks is exposed in this reach of Dutchman Creek. These rocks are thought to be typical, if very well exposed, examples of the mafic metavolcanic rocks that are representative of the Carolina terrane in this area. They are comparable to the McClure Creek section discussed above at Stop 5, even to the extent of being intruded by a foliated 579±4 Ma granodiorite (Dennis and Wright, 1993, 1995). The metabasalts here are well foliated, and many contain a strong lineation. These rocks are cut by leucocratic granitic to pegmatite dikes that are clearly unfoliated and undeformed, and cut across the metamorphic fabric (Fig. 22; Dennis, 1995). At this location we are less than 3 km from the surface trace of the central Piedmont suture to the west, and less than 1 km from felsic intrusive rocks associated with the Buffalo gabbro to the east and southeast.

Foliation dips in this area are moderately steep, in the range of 45-55° to the south or southeast. Mineral lineations plunge 35° to 45° within a few degrees of 180. This is comparable to lineations discussed above in the stop 10 description, and the regional pattern of lineations in this segment of the central Piedmont suture (Dennis, 1995) that are subparal-

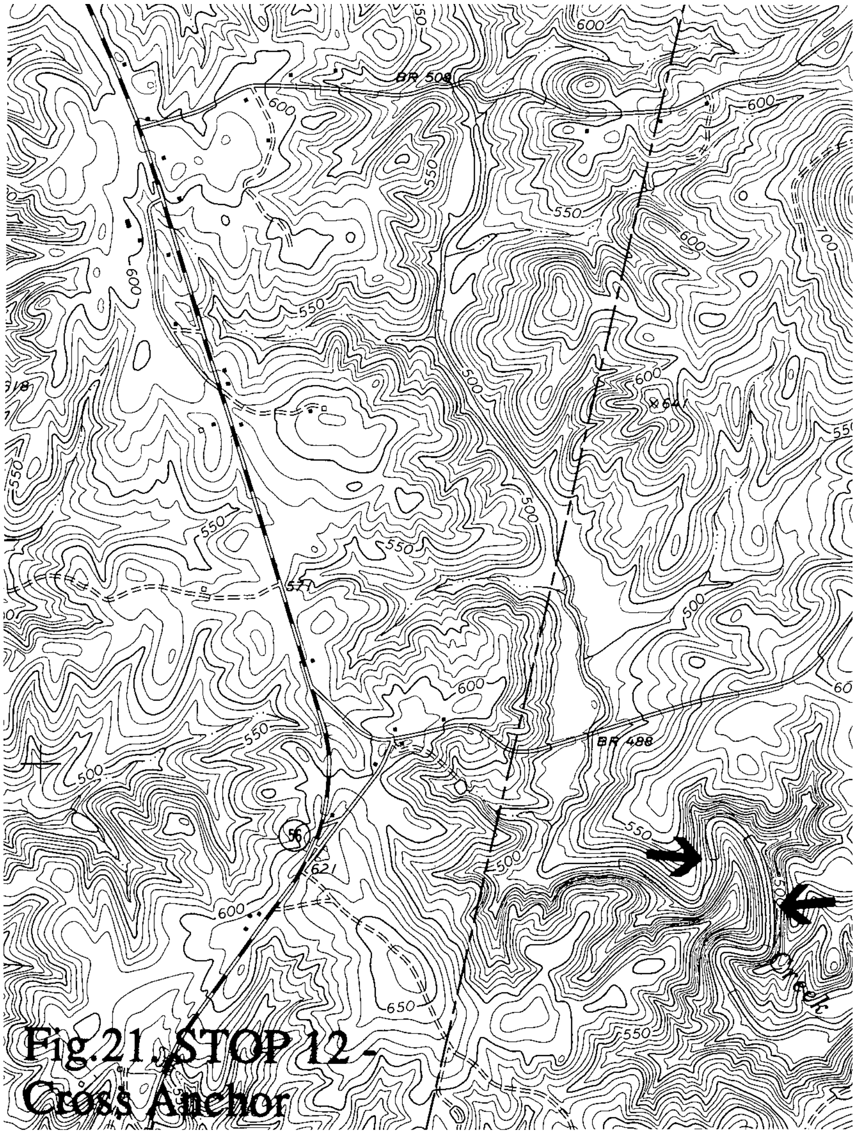


Fig.21, STOP 12 - Cross Anchor

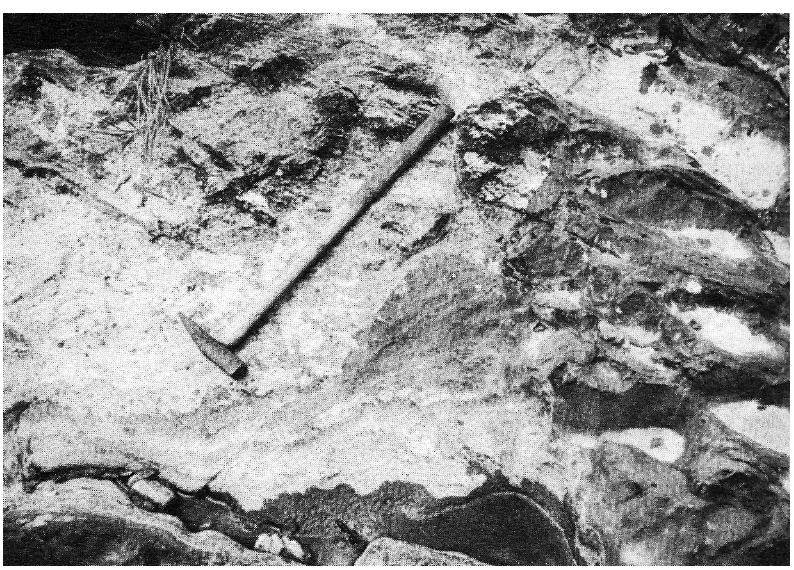


Fig. 22. Mafic metavolcanic rocks cut at a high angle by undeformed granitic dike, parallel to hammer, Dutchman Creek, Stop 12. Note the very sharp, angular contact. Sand and pollen fill in small depressions in the mafic metavolcanic rock. Dike is interpreted to be related to intrusion of the Buffalo gabbro, less than 1 km to the west. Hammer handle is 66 cm.

lel to the pole to a great circle of poles to folded foliations, and are interpreted to represent west-vergent folding of Alleghanian age.

Dennis and Shervais (1995) report whole-rock major and trace element geochemistry from this series of outcrops (their samples 2472, 2473a, b, 2474a, b). Dennis and Shervais interpreted the protoliths of the rocks they analyzed from this location to be high-Mg basalts (hornblende and augite porphyries), basaltic andesites, and basalt.

Dallmeyer and others (1986) report a 40Ar/39Ar biotite plateau age at 289±5 Ma from this site (their sample 45). This mineral age is consistent with a hornblende plateau age of 302±6 Ma (sample 46B) reported by Dallmeyer and others (1986) 3 km north-northwest of here also on Dutchman Creek (S- - 91 bridge, the same site where the 579±4 Ma foliated diorite (Dennis and Wright, 1993, 1996) was collected). Their sample 46A, also from that site, was a biotite plateau at 313 Ma, older than that of the hornblende ands interpreted by these authors as evidence of extraneous argon contamination. Dallmeyer and others (1986) note that variations in the ^{40}Ar/^{39}Ar plateau ages they report for Inner Piedmont - Kings Mountain belt - Charlotte belt samples are "not clearly related to any belt boundary, . . . and are tentatively interpreted to indicate faulting or northwestward tilting of isothermal surfaces between ca. 275 and 300 Ma." Based on the stops presented on this trip, it is suggested that uplift related to northwest-vergent folding accompanied by minor Alleghanian-age faulting in this segment of the central Piedmont suture is responsible for the observed variation.

It is thought that the undeformed felsic dikes here are related to the Buffalo gabbro, and are equivalent to those observed at Stop 8. If the Buffalo gabbro belongs indeed to the Siluro-Devonian array of gabbros, and these dikes are related to the late stages of its intrusion, then it can be said that there has been very little penetrative deformation in the subsequent period. This observation and the proximity to the central Piedmont suture was another line of evidence that led Dennis (1995) to conclude that the primary, significant motion on the central Piedmont suture predates ca. 400 Ma (see also Stop 1). Thus, his interpretation is that significant motion on the central Piedmont suture in this area postdates foliation formation (ca. 535 Ma) and predates intrusion of post-metamorphic rocks ca. 400-380 Ma. Where the strike of this fault is oriented northeast-southwest, to the north and to the south (Kings Mountain shear zone and Middleton-Lowndesville zone respectively), it is reactivated as an Alleghanian, retrograde strike-slip shear zone, but in this area Alleghanian effects are less dramatic. The advantage is that we have a better opportunity to see what this boundary looked like prior to the strong Alleghanian overprint observed in areas to the north and south.

REFERENCES CITED

Charles, A.D., 1987, Narrative history of Union County, South Carolina, Spartanburg: Reprint Company, 512 p.

Dallmeyer, R.D., Wright, J.E., Secor, D.T. and Snoke, A.W. , 1986, Character of the Alleghanian orogeny in the southern Appalachians. Part II. Geochronological constraints on the tectonothermal evolution of the eastern Piedmont in South Carolina: Geological Society of America Bulletin, v. 97, p. 1329-1344.

Dennis, A.J., 1988, Preliminary geology of the Glenn Springs-Jonesville area and tectonic model with road log, in Secor, D.T., ed., Southeastern Geological Excursions: Columbia, SC: South Carolina Geological Survey, p. 226-249.

Dennis, A.J., 1989, Tectonogenesis of an accreted terrane: The Carolina arc in the Paleozoic: [Ph.D. thesis]: Columbia, University of South Carolina, 139 p.

Dennis, A.J., 1991, Is the central Piedmont suture a low-angle normal fault?: Geology, v. 19, p. 1081-1084.

Dennis, A.J., 1995, The Carolina terrane in northwestern South Carolina: Relative timing of events and recent tectonic models, in Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., New Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, in press.

Dennis, A.J. and Shervais, J.W., 1991, Evidence for arc rifting along the Carolina terrane boundary in northwestern South Carolina: Geology, v. 19, p. 226-229.

Dennis, A.J. and Shervais, J.W., 1992, Reply: Geology, v. 20, p. 473-475.

Dennis, A.J. and Shervais, J.W., 1995, The Carolina terrane in northwestern South Carolina: Insights into the development of an evolving island arc, in Nance, R.D. and Thompson, M.D., eds., Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic: Geological Society of America Special Paper 304, in press.

Dennis, A.J. and Wright, J.E., 1993, New Late Precambrian-Cambrian U-Pb zircon ages for zoned intrusives in the western Carolina terrane, Spartanburg and Union Counties, South Carolina [abstract]: Geological Society of America Abstracts with Programs, v. 25, p. 12.

Dennis, A.J. and Wright, J.E., 1995, Mississippian (ca. 326-323 Ma) U-Pb crystallization ages for two granitoids in Spartanburg and Union Counties, South Carolina: South Carolina Geology, v. 38, in press.

Dennis, A.J. and Wright, J.E., 1996, The Carolina terrane in northwestern South Carolina, USA: Age of deformation and metamorphism in an exotic arc: Tectonics, accepted pending revision.

Garihan, J.M., Ranson, W.A., Sargent, K.A., and Niewendorp, C.A., 1995, Geology of Masters' Kiln and history of the marble occurrences in Laurens and Union Counties, South Carolina: South Carolina Geology, v. 38, in press.

Glover, L., III and Sinha, A.K., 1973, The Virgilina deformation, a Late Precambrian to Early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina: American Journal of Science, v. 273, p. 234-251.

Hibbard, J. and Samson, S.D., 1995, Orogenesis unrelated to Iapetan cycle in the Southern Appalachians, in Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., New Perspectives in the Appalachian-Caledonian Orogen: Geological Association of Canada Special Paper 41, in press.

Horkowitz, J.P., 1984, Geology of the Philson Crossroads 7.5' quadrangle, South Carolina -- Nature of the boundary separating the Inner Piedmont from the Carolina-Avalon terrane in central northwestern South Carolina [M.S. thesis]: Columbia, University of South Carolina, 100 p.

Horton, J.W., Jr., 1981, Shear zones between the Inner Piedmont and Kings Mountain belts in the Carolinas: Geology, v. 9, p. 28-33.

Hudleston, P.J. , 1989, The association of folds and veins in shear zones: Journal of Structural Geology, v. 11, p. 949-957.

LaPoint, D., 1995, Gold Deposits of the West Springs area: South Carolina Geology, v. 38, in press.

Lumpkin, H., 1981, From Savannah to Yorktown: The American revolution in the South, New York: Paragon House Publishers, 332 p.

Medlin, J.H., 1966, Geologic map of the Buffalo pluton, Union County, South Carolina: OFR-10: Columbia, SC, South Carolina Geological Survey.

Medlin, J.H., Thornton, C.P. and Gold, D.P., 1972, Petrology of the mafic igneous complexes in the southeastern U.S. Piedmont: II. The Buffalo mafic igneous complex, Union County, South Carolina: Southeastern Geology, v. 14., p. 73-106.

Mittwede, S.K., 1988, Road log for stops in the Ora, Pacolet and Pacolet Mills quadrangles, in Secor, D.T., ed., Southeastern Geological Excursions: Columbia, SC: South Carolina Geological Survey, p 250-265.

Mittwede, S.K., 1989, Geologic maps of the Pacolet and Pacolet Mills 7.5' quadrangles, South Carolina: OFR-64: Columbia, SC, South Carolina Geological Survey.

Mittwede, S.K. and Fullagar, P.D., 1987, Petrology and geochemistry of the Pacolet monzogranite in northwestern South Carolina: Petrogenetic implications [abstract]: Geological Society of America Abstracts with Programs, v. 18, p. 118.

Nance, R.D. and Murphy, J.B., 1994, Contrasting basement isotopic signatures and the palinspastic restoration of peripheral orogens: Example from the neoproterozoic Avalonian-Cadomian belt: Geology, v. 22, p. 617-620.

Samson, S.L., Palmer, A.R., Robison, R.A., and Secor, D.T., Jr., 1990, Biogeographical significance of Cambrian trilobites from the Carolina slate belt: Geological Society of America Bulletin, v. 102, p. 1459-1470.

Secor, D.T., Snoke, A.W., Dallmeyer, R.D., 1986, Character of the Alleghanian orogeny in the southern Appalachians. Part III. Regional Tectonic Relations: Geological Society of America Bulletin, v. 97, p. 1345-1353.

Sloan, E., 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geological Survey Bulletin 2, 505 p.

Speer, J. A., Brauer, S.V.G., and McSween, H.Y., Jr., 1986, The Bald Rock granitic pluton, South Carolina: Petrography and internal fabric: South Carolina Geology, v. 30, 1-17.

Streckeisen, A.L., 1976, To each plutonic rock its proper name: Earth Science Reviews, v. 12, 1-34.

van Gelder, S.M. and McSween, H.Y., Jr., 1981, Intrusion of the Bald Rock batholith into the Kings Mountain belt and Charlotte belt rocks, South Carolina, in Horton, J.W., Jr., Butler, J.R., and Milton, D.M., eds., Geological investigations of the Kings Mountain belt and adjacent areas in the Carolinas: Carolina Geological Society Guidebook: Columbia, South Carolina Geological Survey, p. 147-154.

Vyhnal, C.R. and McSween, H.Y., Jr., 1990, Constraints on Alleghanian vertical displacements in the southern Appalachian Piedmont, based on aluminum-in-hornblende barometer: Geology, v. 18, p. 938-941.

Wagener, H.D., 1977, The granitic stone resources of South Carolina: Mineral Resources Series 5: Columbia, South Carolina Geological Survey, 65 p.

Wagener, H.D. and Howell, D.E., 1973, Granitic plutons of the central and eastern Piedmont of South Carolina: Carolina Geological Society Guidebook: Columbia, South Carolina Geological Survey, 25 p.

Wilkins, J.K., Shell, G.S., and Hibbard, J.P., 1995, Geologic contrasts across the central Piedmont suture in north-central North Carolina: South Carolina Geology, v. 38, in press.

Willis, J. , 1984, Geology of the Cross anchor area: The boundary between the Carolina terrane and the Inner Piedmont in northwestern South Carolina [M.S. thesis]: Columbia, University of South Carolina, p. 61.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 25-32

GEOLOGIC CONTRASTS ACROSS THE CENTRAL PIEDMONT SUTURE IN NORTH – CENTRAL NORTH CAROLINA

James K. Wilkins, Glenn S. Shell, and James P. Hibbard
Department of Marine, Earth and Atmospheric Sciences
N.C. State University
Raleigh, NC 27695

INTRODUCTION

The central Piedmont suture (CPS) marks the boundary between two distinct tectonostratigraphic packages in the southern Appalachians, the Piedmont zone and the Carolina zone (Figure 1, Hatcher and Zeitz, 1980; for zonation terminology, see Hibbard and Samson, 1995). This first-order boundary is recognized along much of its length in Georgia to South Carolina by the transition from high grade schists and gneisses with gently dipping foliations in the Piedmont zone (primarily the Inner Piedmont in this region) into lower grade, late Precambrian-Cambrian metaigneous and metasedimentary rocks with steeply dipping foliations in the Carolina zone (primarily the Carolina slate belt and the Charlotte belt). Accompanying this transition is a change in the geophysical signature within each belt (Hatcher and Zietz, 1980). In particular, magnetic signatures in the Piedmont zone are characterized by low frequency patterns relative to higher frequency patterns within the Carolina zone. Similar contrasts in lithologies, structural style, and geophysical signature have recently been recognized across a shear zone separating high grade gneisses from the Carolina zone of north-central North Carolina. These findings have led to a proposal that this boundary represents the northern extension of the CPS (Hibbard, 1993).

In many areas the CPS has been affected by later deformation, the effects of which vary quite dramatically. For example, in north-central South Carolina the CPS is deformed into upright, tight folds (Hatcher and others, 1988; Dennis, 1991). Elsewhere the CPS has been overprinted by Alleghanian dextral shear zones (Hooper and Hacher, 1989;

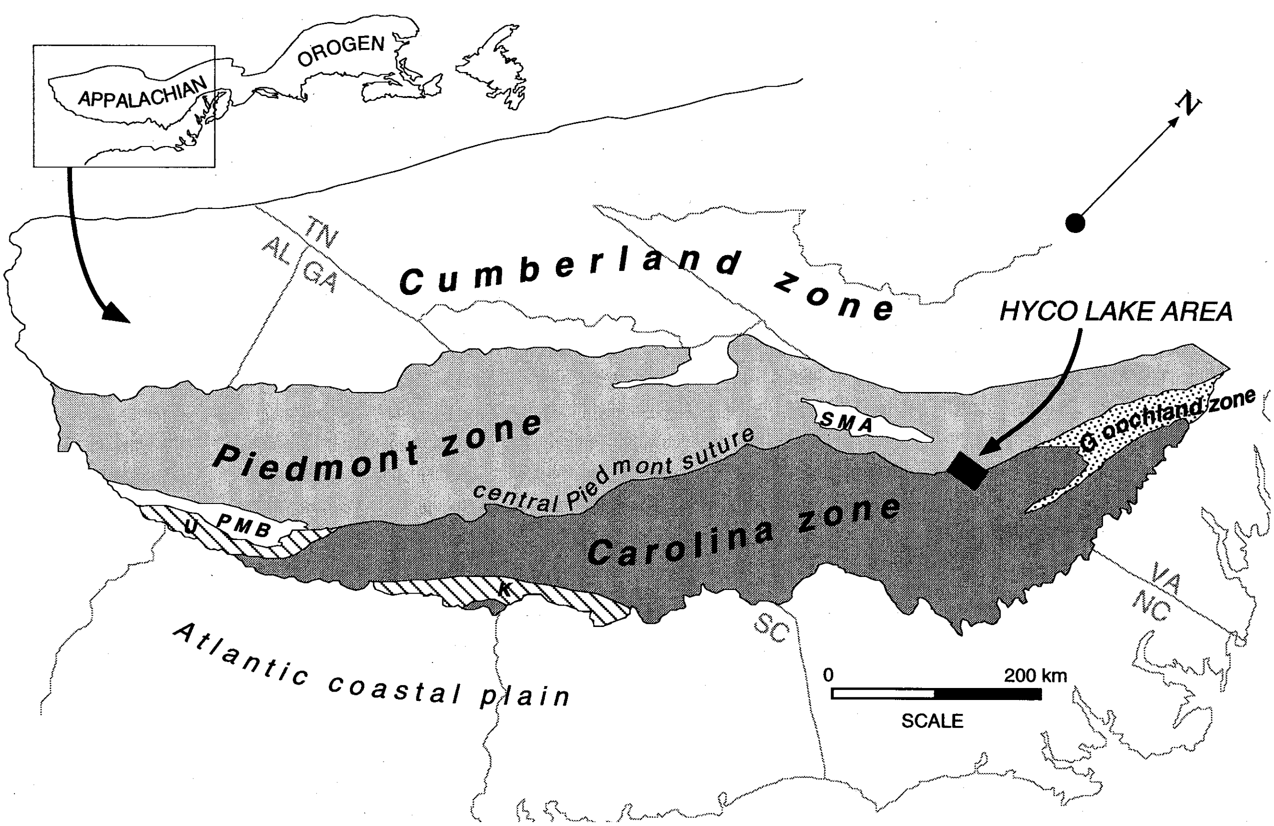


Figure 1. Regional map of the four tectonostratigraphic zones of the southern Appalachians, the black box denotes the study area; K= Kiokee belt, PMB = Pine Mtn. Elt, SMA = Sauratown Mtns. Anticlinorium's, U = Uchee belt (after Hibbard and Samson, 1995).

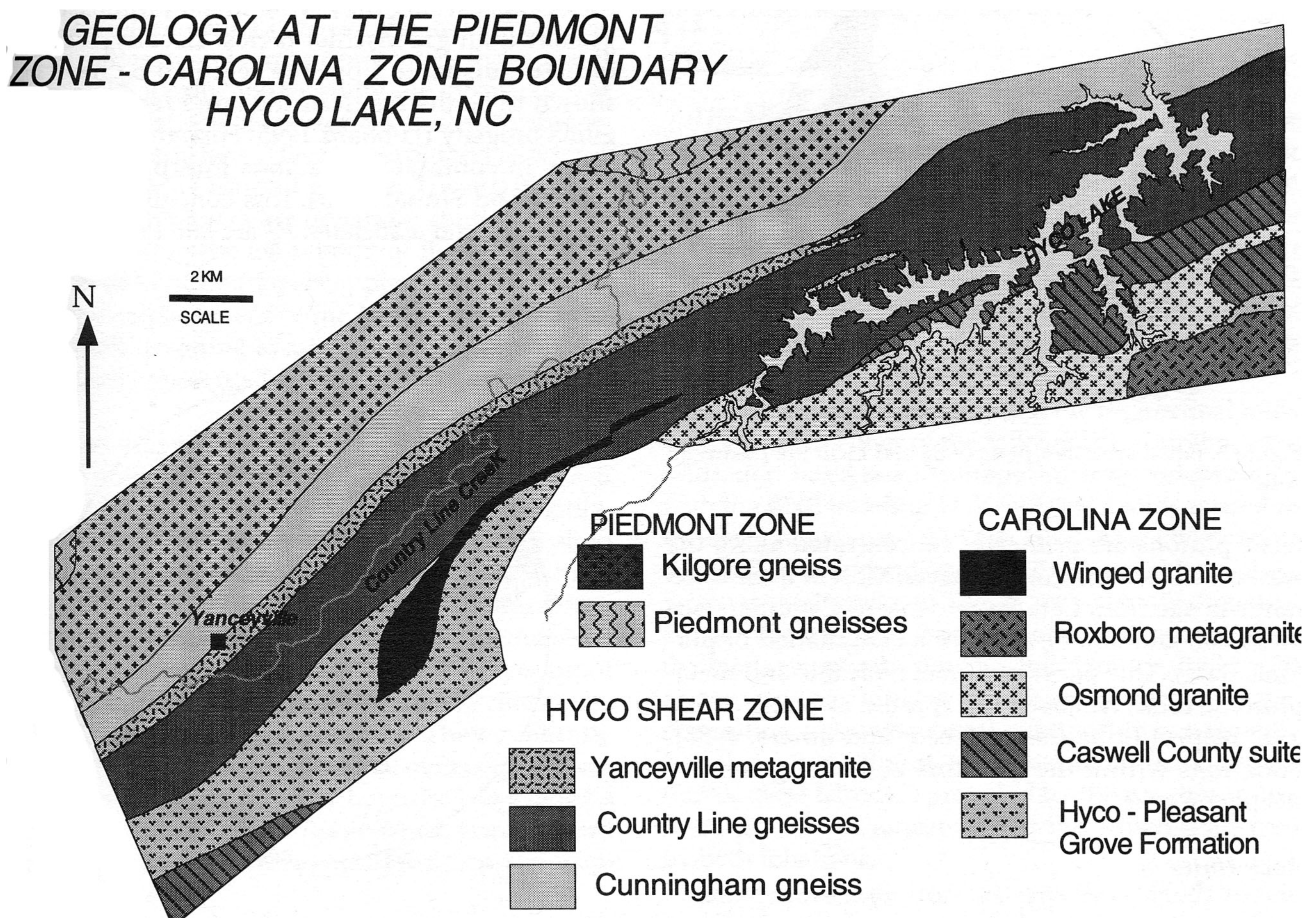


Figure 2. Geologic map of the CPS in north-central North Carolina

Horton, 1981). In north-central North Carolina the CPS has also been significantly affected by late deformation. This deformation is focused along the Alleghanian Hyco shear zone (HSZ) which records dextral shearing with a component of normal down to the south southeast motion (Hibbard, 1991; Shell and Hibbard, 1993); Wilkins and others, 1994). A clear understanding of the kinematics and timing of the events overprinting the CPS is vital if we are to unravel the history of this significant boundary. The purpose of this paper is to present the findings of our recent work along the CPS in north-central North Carolina and to briefly compare this segment with those found elsewhere.

GEOLOGIC SETTING

The location of our present study area straddles the Piedmont zone-Carolina zone boundary from just west of Yanceyville, NC to Virgilina, VA (Figure 2). This discussion focuses on the North Carolinian portions of the boundary, a region approximately 22 km wide and 40 km long. Our work includes detailed mapping within the 4-6 km wide HSZ and within the Piedmont and Carolina zones to the north and south of the HSZ.

PIEDMONT ZONE OF NORTH-CENTRAL NORTH CAROLINA

Rocks of this region have historically been characterized as a package of subhorizontal interlayered high-grade gneisses and schists (Tobisch and Glover, 1971; Baird, 1991; Butler and Secor, 1991). Tobisch and Glover (1971) interpreted the major structure of the area as being a west-verging regional scale nappe. They also recognized that these gneisses achieved peak metamorphism at upper amphibolite facies.

Rock Units

The Piedmont zone in our area is comprised of an interlayered mixture of highly deformed biotite gneisses, garnet + sillimanite schists, felsic orthogneisses, amphibolites, and minor calc-silicate gneisses bearing little resemblance to the Carolina zone rocks to the southeast (see Figure 2). We have divided this region into four informally named units including the layered gneiss, the Milton gneiss, the Conally Church gneiss, and the Kilgore gneiss. The structurally highest unit recognized at this time, the layered gneiss, consists of interlayered biotite + garnet gneisses and garnet + sillimanite schists, with minor amphibolites and calc-silicate gneisses. The abundance of metapelites and minor interlayered calc-silicates implies a sedimentary component for the protolith of the layered gneiss. The Milton gneiss structurally underlies the layered gneiss. This unit is distinct with the common occurrence of large quartzo-feldspathic porphyroclasts (up to 20 cm in diameter) in a biotite rich, gneissic matrix. At this time the origin of the Milton gneiss is uncertain, but it could be a highly deformed migmatitic version of the layered gneiss. The Conally Church granitic orthogneiss forms the core of the Milton antiform. These gneisses are interpreted to be younger than the layered gneiss since discordant intrusions resembling the Conally Church gneiss locally cross-cut the compositional layering of the layered gneiss. These same intrusions are in turn overprinted by main foliation (though not as penetratively) in the layered gneiss which suggests that these intrusive rocks predate or were injected coeval to the main fabric forming event. The Conally Church gneiss has been interpreted by some workers as being part of the intrusive Shelton formation (Tobisch and Glover, 1971). A megacrystic granitic orthogneiss, the Kilgore gneiss, intrudes the southern edge of the Piedmont zone. Dikes of the Kilgore gneiss locally cross-cut the layered gneiss.

Table 1. Fabric Terminology by Zone

Carolina Zone
S_C – Virgilina(?)-related axial planar foliation
F_C - Virgilina(?)-related fold axes
Hyco Shear Zone
S_H – Main HSZ foliation
S_{HL} – Gently-dipping HSZ foliation
F_{HL}, F_H – Fold axes in the HSZLH – HSZ mineral/stretching lineations
Piedmont Zone
S_P – Layer-parallel foliation, main foliation
S_{PL} – Gently-dipping foliation overprinting S_P
L_P – Mineral/stretching lineations

Structure/Metamorphism

The most conspicuous structural element of these gneisses is a layer-parallel, gently dipping foliation, S_P, which primarily affects the layered gneiss, the Milton gneiss, and the Conally Church gneiss (Figure 3, see table 1 for a description of our structural terminology). Abundant asymmetric folds, winged porphyroclasts, S-C fabrics, and stretching lineations, L_P, associated with S_P suggests that this fabric is a product of ductile shearing with an east-over-west sense of shear (Figure 3). The metamorphism associated with this deformation appears to have been upper amphibolite facies. This main schistosity, S_P, has been deformed into

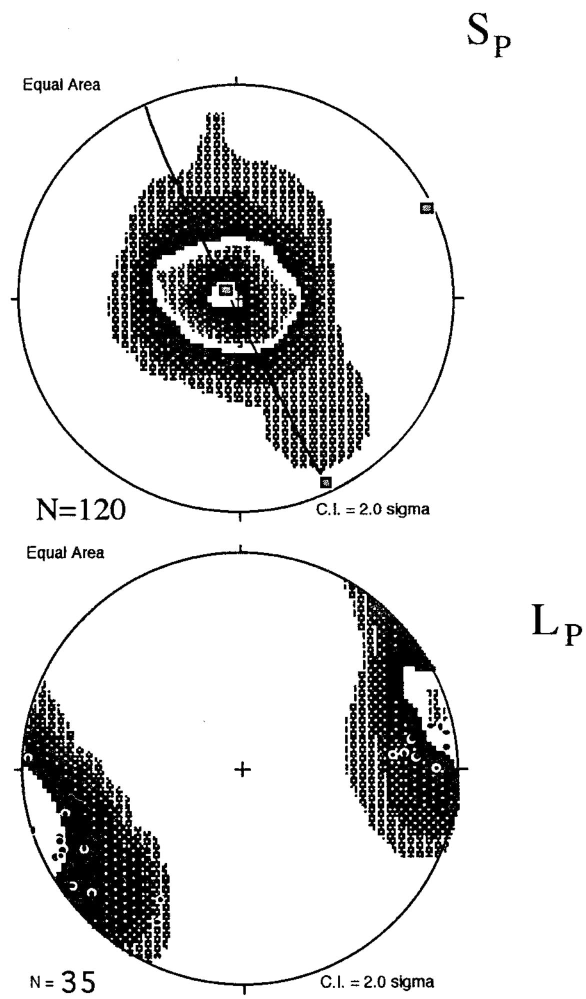


Figure 3. Equal area stereo plots of S_P and L_P in the Pied mont zone.

an ENE trending open upright antiform. It is possible that S_P is correlative with the foliation folded by Piedmont zone nappes to the north of our study area.

Overprinting S_P is a later subhorizontal fabric, S_{PL}, that is axial planar to recumbent folds with E-W trending axes. This foliation primarily affects the Kilgore gneiss on the southern edge of the Piedmont zone here, although it locally affects the layered gneiss and the Milton gneiss. Locally these folds are asymmetric, with an extensional, Carolina zone down and to the south, sense of motion. Near the HSZ, S_{PL} is rotated clockwise into concordance with the zone, suggesting that it pre-dates the shear zone.

CAROLINA ZONE OF NORTH-CENTRAL NORTH CAROLINA

The Carolina zone is a lower greenschist to amphibolite facies sequence of felsic and mafic volcanics and metasedimentary rocks intruded by felsic to mafic plutonic rocks of various ages. The mafic and felsic plutons are primarily concentrated along the western edge of the Carolina zone. Most of these rocks range in age from Late Proterozoic to Cambrian (see McSween and others, 1991 for a compilation of plutonic data). This package of metavolcanic and metaplutonic rocks has been interpreted as being exotic with respect to Laurentia (Secor and others, 1983). Foliations within the Carolina zone are generally steeply dipping.

Rock Units

Rocks of this zone comprise the southern portion of our study area (see Figure 2). Here, these rocks are predominantly comprised of steeply dipping low-grade felsic and mafic volcanics and a variety of meta-plutonic bodies. The oldest unit in the area, the Pleasant Grove formation, comprises interlayered fine-grained felsic tuffs and fine-grained mafic volcanics that is likely correlative with the ca. 620 Ma Hyco formation (Glover and Sinha, 1973). A suite of metamorphosed gabbros, diorites and pyroxenites that we term the Caswell County mafic-ultramafic suite intrudes the Pleasant Grove formation. Following the emplacement of the Caswell County mafic-ultramafic suite, the Osmond granite intruded these rocks. A U/Pb zircon age date of ca. 615 Ma has been obtained from the Osmond granite (Wortman and others, 1995).

Structure/Metamorphism

All of the Carolina zone units in our area were deformed by upright folds, F_C, with a well developed axial planar cleavage, S_C (Figure 4, see table 1 for terminology description). Mineral assemblages in these rocks suggest that they

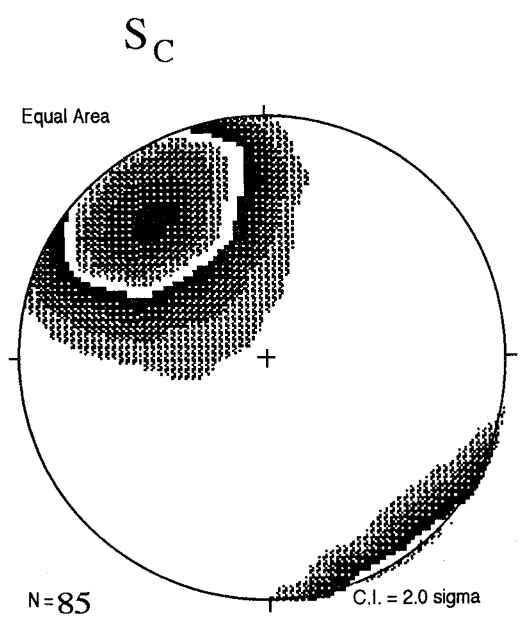


Figure 4. Equal area stereo plot of S_C in the Carolina zone.

were metamorphosed at no greater than greenschist facies. Locally, foliations indistinguishable from the regional S_C have been shown to be the result of the late Precambrian Virgilina orogeny (Hibbard, 1995; Hibbard and Samson, 1995). In contrast to previous interpretations (e.g. Glover and Sinha, 1973), it is conceivable that the regional S_C and associated F_C are late Precambrian. In the southern portions of our field area, S_C and F_C trend approximately N20°E. Along the northern edge of the Carolina zone in our area, effects of the HSZ become much more pronounced and most earlier structures are completely transposed into concordance with the ENE trending shear zone fabrics.

HYCO SHEAR ZONE

Rock Units

Rocks affected by the HSZ can be divided into four ENE to NE trending lithologic packages including the Country Line gneiss, the Yanceyville gneiss, he Cunningham gneiss, and the Winged granite (Figure 2). The most extensive of these units is the Country Line gneiss. This unit is an interlayered assemblage of mafic gneisses, amphibolites, felsic gneisses and subordinate semipelitic schists. They have been metamorphosed to approximately low to mid-amphibolite facies. The interlayering between the mafic and felsic gneisses varies in scale from centimeters to meters. It appears to be locally enhanced b the intrusion of at least two generations of concordant to slightly discordant granitic intrusions. The earliest of these is related to the ca. 615 Ma Osmond granite. These 0.05 to 30 meter thick interlayers are generally confined to the region adjacent to the main body of the granite. The second set of felsic interlayers are generally confined to the region adjacent to the main body of the granite. The second set of felsic interlayers appears to have accompanied the emplacement of the Yanceyville gneiss. A suite of NNE-trending syn-late tectonic granite pegmatite dikes cross-cuts layering in the Country Line gneiss.

The pre- to syn-tectonic Yanceyville gneiss lies along the northern edge of the Country Line gneiss. It is a medium- to coarse-grained, equigranular, biotite-muscovite granitic orthogneiss which forms an elongate tabular body. Cross-cutting relationships between the Yanceyville gneiss and the surrounding gneisses have locally been observed, but in general it appears to have intruded parallel to the layering of those adjacent gneisses. Sills of the Yanceyville gneiss can be found in adjacent gneisses. They generally increase in thickness from 0.05 to 20 meters with proximity to the main body. The orthogneiss has yielded an U/Pb zircon age of 335±2 Ma age which is interpreted to represent a crystallization age (Wortman and Samson, 1994).

The Cunningham gneiss lies to the north of the Yanceyville gneiss. The Cunningham gneiss is an interlayered package of highly deformed medium- to coarse-grained

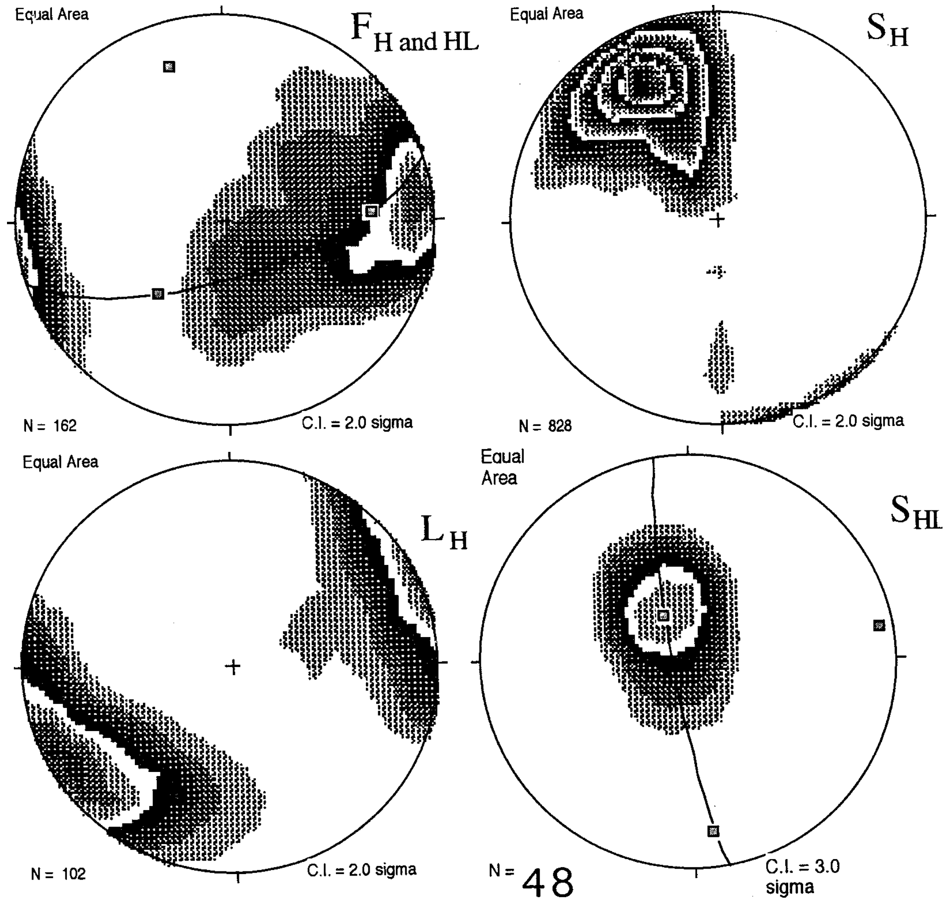


Figure 5. Equal area stereo plots of S_H, F_H, and H_L, L_H and S_{HL} in the Hyco Shear zone.

metagranite, biotite gneiss, amphibolite, and metadiorite. Along much of its northern border, the Cunningham gneiss is cross-cut by dikes and sills of the Kilgore gneiss. The metamorphism affecting this unit is difficult to discern due to its composition, but it appears to be in the amphibolite facies. The late syn-tectonic suite of NNE-trending granite pegmatites that intrudes the Country Line gneiss also intrudes the Cunningham gneiss.

Between Yanceyville and Hyco Lake another granitic body intrudes into the HSZ. This stock, the Winged granite, is a coarse grained biotite-muscovite granite which has a shape resembling a large dextrally deformed winged porphyroclast. The northern tail of the Winged granite forms a continuous tabular body which extends for several kilometers. The age of the Winged granite is uncertain, but the kinematics inferred from its shape and apparent partitioning of deformation into an outer highly deformed rim cored by a lesser to undeformed interior suggests a syntectonic, Alleghanian age, for this body.

Structure

The HSZ is highly deformed ductile shear zone involving multiple generations of structures. The most striking feature of the HSZ units is the gneissic layering which is overprinted by an ENE to NE striking layer parallel foliation, S_H, that is axial planar to isoclinal folds, F_H (Figure 5, see table 1 for a terminology description). The foliation dips up to 75° SE near the Carolina zone and decreases to 35° SE near the Piedmont zone.

Our observations suggest that the F_H isoclinal folds may represent either of the following 1) Carolina zone folds that have been transposed into concordance with the ENE trending HSZ and/or 2) folds related to the early development of the HSZ. Also observed in the HSZ is a second, gently-dipping, fabric, S_{HL}, which is axial planar to a set of recumbent tight to isoclinal folds, F_{HL}. S_{HL} has been observed overprinting the more steeply-dipping S_H foliation locally as well as being overprinted in turn by S_H at other locales suggesting a close temporal relationship between the foliations. A maximum age constraint for the formation of these fabrics is provided by the pre- to syn-tectonic ca. 335 Ma Yanceyville gneiss which is affected by both foliations.

Shear sense indicators are well developed, widely distributed, and are associated with both S_H and S_{HL}. With S_H, indicators include S-C fabrics, winged porphyroclasts, shear bands, asymmetric folds and well developed ENE to NE trending subhorizontal mineral and stretching lineations (Figure 5). These indicators yield a dextral-oblique sense of motion with a lesser component of normal motion (Hibbard, 1991: Sheil and Hibbard, 1993: Wilkins and others, 1994). This interpretation is supported by the clockwise rotation of S_C into concordance with the HSZ. The rotation of S_C also implies that some HSZ fabrics may be pre-Alleghanian and possible composite in nature.

S_{HL} also bears a suite of shear sense indicators such as asymmetric folds, S-C fabric, and shear bands which all suggest a dominantly extensional sense of motion, Carolina zone down and to the SSE, with a minor component of dextral transcurrent motion. The S-C fabric is found primarily within a select group of semipelite lenses. These observations in conjunction with the apparent inter-relation of SH and SHL have led to our proposal that the HSZ records a significant amount of post ca. 335 Ma dextral transtensional motion (Hibbard, 1993; Wilkins and others, 1994).

DISCUSSION

Our work has identified several distinct fabric forming events across the CPS in north-central North Carolina, the most recent being the complex Alleghanian motion along the HSZ. In the Piedmont zone rocks of the Milton area, at least two deformation events have affected rocks in this region. The earliest of these seems to involve an east over west ductile shearing event of uncertain age. A later deformation, which formed S_{PL}, is the youngest foliation forming event we have recognized in the Piedmont zone. It pre-dates the HSZ to some extent because the structures related to this event are affected by the Alleghanian HSZ motion, but it could also be an early Alleghanian phase of deformation prior to initiation of the main dextral transtensional motion.

In the Carolina zone of north-central North Carolina, our field studies have identified many features common to the Carolina zone elsewhere along its western boundary with the CPS. The steep regional foliation and upright folds in this area, potentially of late Precambrian age (Virgilina orogeny) mimic similarly oriented structures on the Carolina zone side of the CPS elsewhere in the southern Appalachians. In addition, the age constraints for the formation of the Virgilina structures in this area are very similar to those reported for a Late Proterozoic deformation in north-central South Carolina (Dennis, 1994). Structural correlation between the two areas lends support to the regional extent of the Virgilina event as proposed by Harris and Glover (1988) and Dennis (1994). Also, the abundance of intrusive mafic and ultramafic bodies in our area, the Caswell County mafic-ultramafic suite (Eades, 1988), coincides with similar reports of mafic bodies being concentrated along the CPS in the western Carolina zone, for example: the Berner mafic complex, GA (Hatcher and Hooper, 1989), the Davie County complex, NC (Butler, 1989), the Blue Branch group, SC (Butler, 1989), the Latimer complex, SC (Butler, 1989), the Means Crossroads complex, SC and the Wildcat Branch complex, SC (Dennis, 1991).

In our study area, the HSZ seems to primarily affect Carolina zone rocks and is dominated by Alleghanian (post ca. 335 Ma here) structures related to dextral transtension. These structures appear to overprint most if not all pre-Alleghanian structures to the immediate north and south. This late deformation also appears to have completely wiped out any recognizable structural evidence of the original relation between the Carolina zone and the Piedmont zone. As a result, our proposed location for the CPS relies heavily on lithologic and isotopic evidence.

The transtensional kinematics of the HSZ may be the result of this section being along a right jog in the CPS. In the Hyco Lake area, the HSZ is trending ENE, whereas to the immediate north and south, NNE to NE trends are more common. This orientation of the Hyco Lake segment requires that a component of extension accompany the dextral motion resulting from the migration of the Carolina zone to the SW relative to the Piedmont zone (Wilkins and others, 1994). An extensional component of motion also helps explain the apparent jump in metamorphic grade seen across the HSZ near Hyco Lake. However, north of the Hyco Lake area, where the HSZ trends more northeasterly, similar jumps in metamorphic grade across the HSZ also demand some form of extensional motion. It is possible that this boundary was subjected to a pre-Alleghanian phase of extension as suggested by Dennis (1991) or that it may be an early Alleghanian phase of extension similar to that proposed for the Modoc zone of South Carolina (Secor and others, 1994). Field work in progress along that section of the CPS will hopefully shed some light on this problem.Gneisses in the southern half of the HSZ, mainly of the Country Line gneiss, resemble Carolina zone rocks to the south. South of Yanceyville, NC, these gneisses strongly resemble metavolcanic rocks of the Pleasant Grove formation to the south. Around Hyco Lake, NC these gneisses mainly resemble the dominantly metaplutonic bodies of the Osmond granite, the Caswell County mafic-ultramafic suite with local occurrences of rocks similar to the Pleasant grove formation. This correlation is supported by two observations: 1) south of Hyco Lake, Carolina zone rocks are rotated from their NNE trend into concordance with the HSZ fabrics and 1) eNd values of Country Line gneisses are very similar to those of the Carolina zone (Wortman and others, in press). This correlation suggests that most of the older rocks within the Country Line Creek gneiss are Late Proterozoic in age. Rocks of the Cunningham gneiss show no clear lithologic or isotopic signature that would allow for correlation with either the Carolina zone or the Piedmont zone. As a result we propose that the CPS must lie within the Cunningham gneiss.

SUMMARY

Our work in the Hyco Lake area has led to the recognition of a distinct contrast in lithologies, metamorphism and deformation style across the CPS, similar to differences historically associated with this boundary elsewhere in the southern Appalachians. These differences are expressed as low grade metaigneous rocks with steep foliations and upright folds in the Carolina zone juxtaposed against high grade gneisses and schists with gently dipping foliations and recumbent folds within the Piedmont zone. This transition is overprinted by the HSZ which records a post ca. 335 Ma dextral transtensional motion.

ACKNOWLEDGMENTS

We thank S. Samson and G. Wortman for providing isotopic data. Field work was supported by grant no. EAR-9219979 from the National Science Foundation to J.P. Hibbard, and a grant from the North Carolina Geological Survey and the Geological Society of America to G.S. Shell. We also thank Allen Dennis for his invitation to contribute to this volume and for providing a forum to summarize our preliminary results and interpretations.

REFERENCES

Baird, R., 1991, Stratigraphy of the northern Charlotte metamorphic belt; application to the Charlotte belt/Milton belt problem: Southeastern Geology, v. 32, p. 61-82.

Butler, J.R., 1989, Review and classification of ultramafic bodies in the Piedmont of the Carolinas, in Mittewede, S.K., and Stoddard, E.F. (eds.), Ultramafic Rocks of the Appalachian Piedmont: Geological Society of America Special Paper 231, p. 19-31.

Butler, J.R., and Secor, D.T., 1991, The Central Piedmont, in Horton, J.W., Jr. and Zullo, V.A. (eds.), Geology of the Carolinas, Carolina Geological Society 50th Anniversary Volume: Knoxville, Tennessee, University of Tennessee Press, p. 59-78.

Dennis, A.J. 1991, Is the central Piedmont suture a low angle normal fault?, Geology, v. 19, p. 1081-1084.

Dennis, A.J., Wright, J.E., and Secor, D.T., 1994, Late Precambrian-early Cambrian orogeny in the South Carolina Piedmont, New Perspectives in the Appalachian-Caledonian Orogen: Abstracts with programs, Geological Society of Canada, Nuna Conference, Grand Falls, NFLD, p. 10.

Eades, J.D., 1988, Mafic and ultramafic rocks of he northwestern Carolina slate belt, North Carolina Piedmont: Evidence for epidote-amphibolite facies metamorphism of an island arc related intrusive suite, B.S. thesis, Guilford College, Greensboro, NC, 13 p.

Glover, L., III, and Sinha, A.K., 1973, The Virgilina deformation, a late Precambrian to early Cambrian(?) orogenic event in the central Piedmont of Virginia and North Carolina: American Journal of Science, v. 273-A, p. 234-251.

Harris, C.W., and Glover, L., III, 1988, The regional extent of the Virgilina deformation: implications for stratigraphic correlation in the Carolina terrane, Geological Society of America Bulletin, v. 100, p. 200-217.

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

Hatcher, R.D., Jr. and Zietz, 1980, Tectonic implications of regional aeromagnetic and gravity data from the southern Appalachians, in Wones, D.R. (ed.), The Caledonides in the U.S.A.: Blacksburg, Virginia Polytechnical Institute and State University Department of Geological Sciences Memoir 2, p. 235-244.

Hatcher, R.D., Jr., Hooper, R.J., Heyn, T., McConnell, K.I., and Costello, J.O., 1988, Geometric and time relationships between thrusts in the crystalline southern Appalachians, in Mitra, G., and Wojtal, S. (eds.), Geometry and mechanisms of Appalachian thrusting with special reference to the Appalachians: Geological Society of America Special Paper 222, p. 185-196.

.Hatcher, R.D., Jr., Hooper, R.J., 1989, The origin of ultramafic rocks from the Berner mafic complex, central Georgia, in Ultramafic Rocks of the Appalachian Piedmont: Geological Society of America Special Paper 231, p. 19-31

Hibbard, J.P., 1991, The Carolina slate belt – Milton belt contact in north-central North Carolina, Geological Society of America Abstracts with Programs, v. 23, p. 44.

Hibbard, J.P., 1993, The Milton belt – Carolina slate belt boundary: The northern extension of the central Piedmont suture?, in Hatcher, R.D., Jr., and Davis, T.L. (eds.), Studies of Inner Piedmont geology with a focus on the Columbus Promontory: Carolina Geological Society field trip guidebook, p. 85-89.

Hibbard, J.P., 1995, The Virgilina orogeny in the Carolina terrane, Geological Society of America Abstracts with Programs, v. 27, p.62.

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

Hooper, R.J., and Hatcher, R.D., Jr., 1989, The geology of the east end of the Pine Mountain window and adjacent Piedmont, central Georgia: Atlanta, Georgia Geologic Survey, 37 p.

Horton, J.W., Jr., 1981, Shear zone between the Inner Piedmont and Kings Mountain belts in the Carolinas: Geology, v. 9, p. 28-33.

McSween, H.Y., Speer, J.A., and Fullager, P.D., 1991, Plutonic rocks, in Horton, J.W., Jr. and Zullo, V.A. (eds.), Geology of the Carolinas, Carolina Geological Society 50th Anniversary Volume: Knoxville, Tennessee, University of Tennessee Press, p. 109-126.

Secor, D.T., Jr., Samson, S.L., Snok, A.W., and Palmer, A.R., 1983, Confirmation of the Carolina slate belt as an exotic terrane: Science, v. 221, p. 649-651.

Secor, D.T., Jr., Pray, J.R., West, T.E., and Maher, H.D., Jr., 1994, Character of the Alleghanian orogeny in the hinterland of the southern Appalachians: Kinematics and tectonic models: Geological Society of America Abstracts with Programs, v. 26, p. 61.

Shell, G.S., and Hibbard, J.P., 1993, Nature of the Carolina slate belt- Milton belt boundary in north-central North Carolina: Geological Society of America Abstracts with Programs, v. 25,

p. 69.

Tobisch, O.T., and Glover, L., III, 1971, Nappe formation in the southern Appalachian Piedmont: Geological Society of America Bulletin, v. 82, p. 2209-2230.

Wilkins, J.K., Shell, G.S., and Hibbard, J.P., 1994, Lithologic-structural transition across the Milton belt-Carolina slate belt boundary, Hyco Lake area, NC: Geological Society of America Abstracts with Programs, v. 26, p. 69.

Wortman, G.L., Samson, S.D., and Hibbard, J.P., in press, Discrimination of the Milton belt and the Carolina terrane in the southern Appalachians: a Nd isotopic approach, Journal of Geology, v. 103.

Wortman, G.L., Samson, S.D., and Hibbard, J.P., 1995, U-Pb zircon geochronology of the Milton and Carolina slate belts, southern Appalachians, Geological Society of America Abstracts with Programs, v. 27, p. 98.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 33-41

GOLD DEPOSITS OF THE WEST SPRINGS AREA, UNION COUNTY, SOUTH CAROLINA

DENNIS J. LAPOINT
Appalachian Resources
P.O. Box 3810
Chapel Hill, NC 27515

INTRODUCTION

Five historic gold mines are reported in the literature for the West Springs area of the Glen Springs and Cross Anchor 7.5 minute quadrangles in Union county South Carolina (Figures 1 and 2). There are no reports of production and no detailed maps or descriptions of the extent of the workings. A rough estimate, based on the extent of the visible workings at the Ophir and West mines and on historic descriptions, is that the district has produced between 30,000 and 50,000 ounces of gold, primarily prior to the Civil War and in the 1890s.

These mines were first described by Tuomey in 1848 as the Fair Forest mines. The name was from the major drainage of the region. Tuomey (1848) does not indicate when gold was first discovered, but mining was well established by the time of his visit in 1844. Lieber, in his 1858 Survey of South Carolina, included the mines in the Union district, which also included deposits to the northeast in the Smyrna district of York County. At the time of his examination, none of the West Springs mines were active. Sloan's (1908) Catalog of the Mineral Localities of South Carolina presents the best geologic description of the deposits and includes some assay data. At the time of his work, the Ophir or Thompson mine was the only mine active. Other geologists have redescribed earlier descriptions (McCauley and Butler, 1966: Maybin, SC Geological Survey files) or have given information based on their own brief visits (Becker, 1895; Graton, 1906). In part, the lack of detailed information on the deposits is due to poor access to the old, abandoned workings and to the non-existence of mining records.

A brief flurry of modern exploration occurred from 1982 (when U.S. Borax drilled the Ophir mine) to 1985 (when FMC and Kennecott drilled the Ophir and West mines respectively, and American Copper Nickel Corporation (ACNC) and Boise Cascade were carrying out a joint venture in regional exploration). Partial results from these programs are available in the South Carolina Geological Survey files (Table I and Figure 3). The data are incomplete in that drill core is available for only two of the three known drilling programs (FMC and U.S. Borax). Furthermore, the logs are only brief summary logs or field logs, and assay data are for gold only. Moreover, the assay data for gold is provided only for U.S. Borax drilling while FMC provided no drill core or assay data. Further research is required to better describe these deposits and their genesis. When compared to other exploration targets that and to production mines, the West Springs area merits further exploration.

Table 1. Drill hole summary for Ophir mine, Union County, South Carolina

DRILL HOLE (Company)	DEPTH (feet)	MINERALIZED INTERVAL (feet)	INTERCEPT (feet)	GRADE (oz/ton)	LITHOLOGIES
GSU-4D1 (US Borax)	307	141-145 195-210	5 15	0.014 0.046	Muscovite quartz schist
GSU-4D2	405	213-251 (226-228)	38 (2)	0.044 0.420	Muscovite quartz schist
GSU-4D3	304	145-160 175-194	14 19	0.018 0.037	Musc-biot-qtz schist; qtz blebs Marble: 190-194 ft
OP 85-1 (FMC)	400	170-245 (185-205) 335-390	75 (20) 35	0.018 0.045 0.014	Microcline-biotite-musc-quartz schist; up to 6% pyrite; w/quartz-rich layers
OP 85-2	350	None reported			Pyrite muscovite qtz schist
OP 85-3	500	110-165	55	0.033	Biot-musc-qtz schist
OP 85-4	400	None reported			Amphibolites
OP 85-5	400	None reported			Mica qtz schist and amph.
OP 85-6	500	135-150 175-215 (175-190)	15 40 (15)	0.017 0.082 0.187	Biot-quartzite w/ molybdenite and microcline-biot-musc-qtz schist; up to 6% pyrite
OP 85-7	500	295-325 (300-315)	30 15	0.012 0.024	Microcline-biot-musc-qtz schist; qtz veins; mafic dike

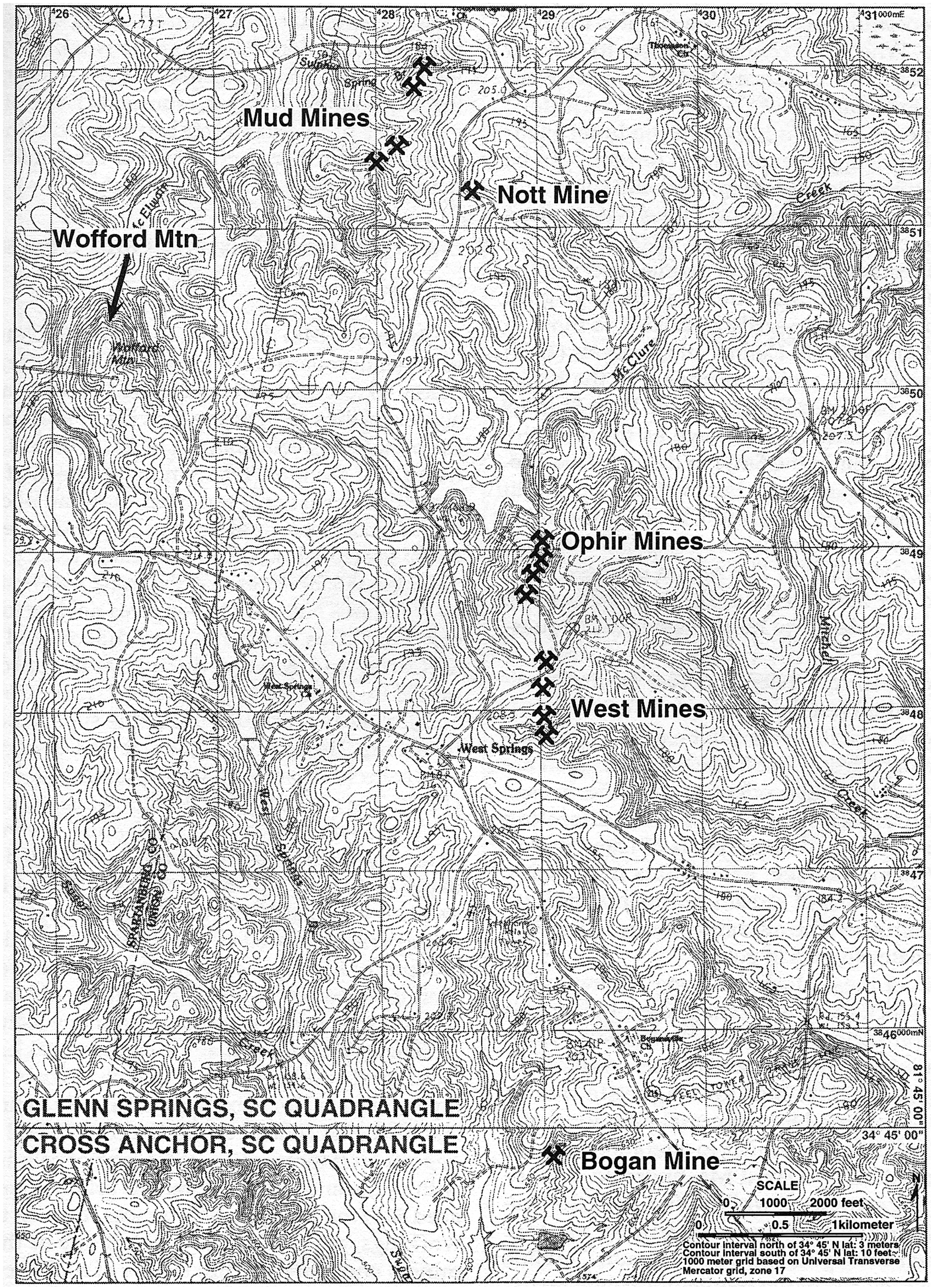


Figure 1. Location of historic gold mines in the West Springs region, Union county, SC.

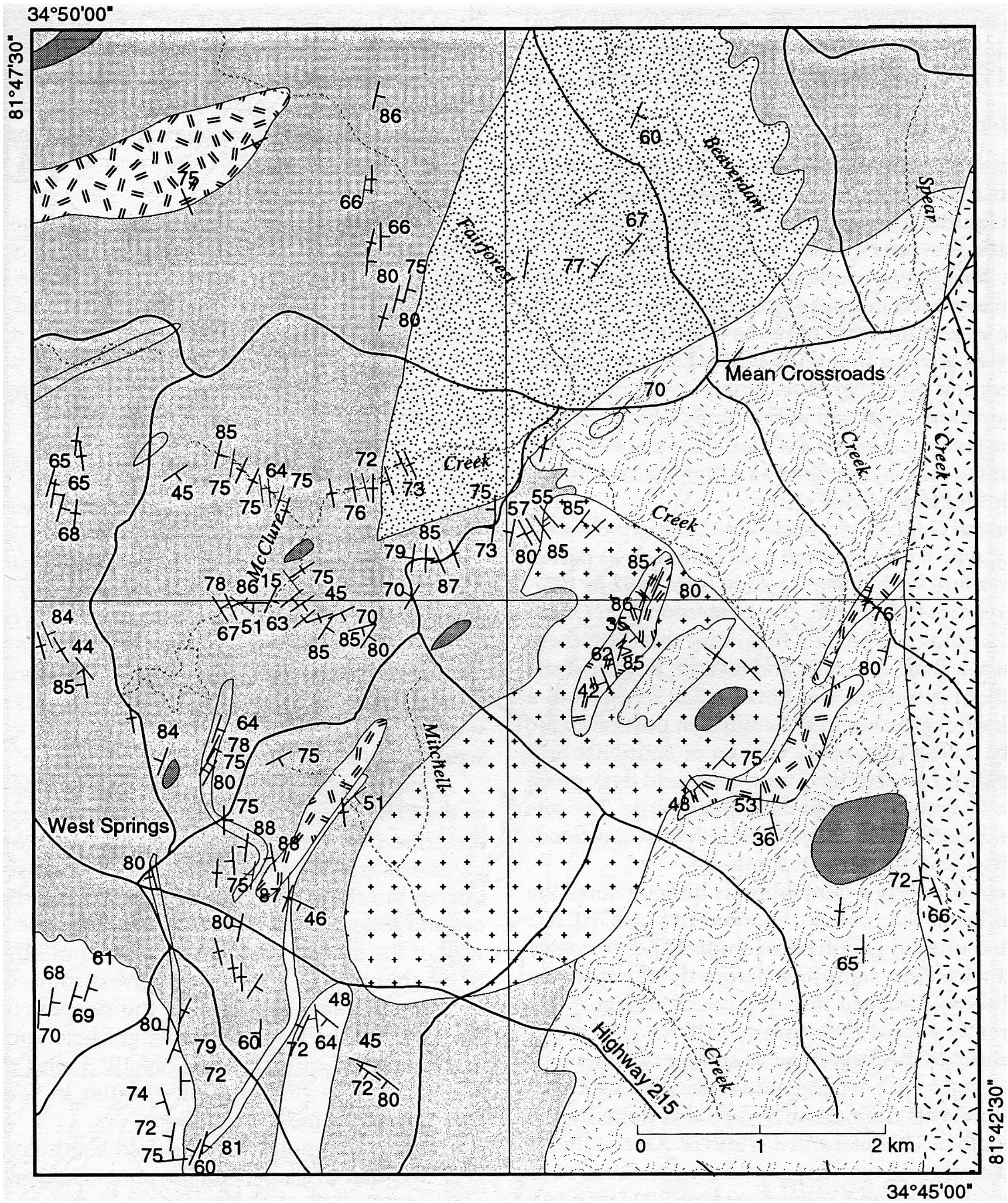


Figure 2. Geology of the West Springs area from Dennis and Wright (1995); Light grey – mafic metavolcanic rocks; outlined areas within light grey – quartz sericite schist or silicification; no pattern – felsic metavolcanic rocks; dark grey – metapyroxenite-hornblendite; double bar random pattern – metagabbros; rippled gneiss pattern – Mean Crossroads metadiorite-diorite gneiss; random dot pattern – foliated biotite porphyry granodiorite; aligned crosses – undeformed, unmetamorphosed diorite; single bar random pattern – Bald Rock granite.

GEOLOGIC SETTING

Dennis (1989) mapped the Glenn Springs 7.5 minute quadrangle on which most of the mines occur (Figure 2). The gold occurs in quartz veins or in very schistose pyritic quartz sericite schists within a package of mafic volcanic rocks and associated intrusives. Iron formations and quartz-rich exhalative rocks are found along strike of some of these sericitic rocks, such as at Wofford Mountain (Figure 1). Dennis and Shervais (1995) place these mafic rocks in what they describe as the northwestern Carolina terrane, and they interpret that the mafic volcanism and intrusions represent rifting of a pre-existing volcanic arc. Deep-seated fracturing is proposed so that highly magnesian magmas were able to ascend to high crystal levels without appreciable fractionation. This geologic setting, especially with deep fracture systems and mafic magmas, is a permissive environment for major gold deposits.

Maybin and Niewendorp (1993) present evidence that the West Springs area is part of what they describe as the central Piedmont allochthon, an Alleghanian age thrust. The allochthon is considered to be a suspect terrain of unknown affinities. If this is an allochthon, it still does not change the chemistry of the rocks, the tectonic model developed by Dennis and Shervais (1995) based on rock geochemistry and lithologic association, or the gold potential of the West Springs area. What does change is where to look for similar deposits. For instance Maybin and Niewendorp (1993) find similar rocks, which host the historic Saluda copper mine, in a klippe in the Inner Piedmont, and they suggest exploration for gold can be extended to this region (Maybin, personal communication, 1995). Some gold deposits of the West Springs area are also copper-rich (Tuomey, 1848). However, the central Piedmont allochthon overlies rocks of the Kings Mountain belt, and the West Springs gold deposits would not necessarily be related to those in the Kings Mountain belt. Dennis and Shervais (1995) extend the western Carolina terrane into the Kings Mountain belt (see their Figure 2). The West Springs deposits are the same general age as those in the Kings Mountain belt in the Smyrna district (Late Precambrian to Early Cambrian), but the gold deposits in the Smyrna district of York and Cherokee Counties are associated with more felsic volcanic and intrusive rocks (Butler, 1966; 1980). The region between West Springs and the Smyrna gold districts needs to be mapped in more detail to help answer these questions.

Dennis and Shervais (1995) note that the mafic volcanic rocks of the West Springs area are cut by corridors of quartz-sericite schist that can be traced for kilometers along strike. These zones of alteration are the focus of historic gold production. Metamorphosed mafic and ultramafic dikes crosscut the alteration zones and indicate that alteration is of Late Precambrian-Early Cambrian age. ACNC data from heavy mineral concentrates of stream sediments indicate that other quartz-sericite alteration zones in the area are also anomalously rich in gold.

The origin of these alteration zones is unclear, in part due to a lack of detailed mapping of the zones and alteration facies. Dennis and Shervais (1995) briefly describe andesitic pyroclastic rocks that can be traced into sillimanite-sulfide-magnetite-quartz schists. This suggests hydrothermal alteration of a volcanic protolith and is similar to alteration noted at Parsons Mountain by David Mashburn in unpublished mapping completed while a student at the University of Georgia. However, examining the core available from the Ophir mine at the South Carolina Geological Survey, the pyrite-biotite-muscovite-quartz alteration appears to represent a zone of intense shearing. Rock fabrics suggest mylonitic textures; quartz veins and sericite layers appear to have been intensely folded and disrupted. The shearing may be a later event that was focused along a pre-existing zone of alteration. Petrographic work and detailed logging of the core is needed to help answer some of these questions. The core represents some of the best examples of unweathered bedrock from the region and merits further study, both for academic and economic reasons.

DESCRIPTIONS OF HISTORIC GOLD DEPOSITS

Nott Mine

Toumey (1848) describes the Nott (or Nott's) mine as an enormous and irregular vein of quartz, in some places 40 feet thick, which crosses the slates at a small angle and dips 45°. During his visit in 1844 the shaft at the back of this vein was at a depth of 90 feet. Toumey noted that the most ferruginous portions of the vein were the richest and reported that one pocket contained $3000 worth of gold in approximately half a ton of ore (roughly 300 ounces/ton).

Lieber (1858) states that the mine was first worked by Adolphus Nott, M.D., but gives no date for discovery. He states the mine was discovered by Jno. McCarter and worked during its best productive period by an Englishman, Blondel. Later Gov. Means and Col. Peay worked it under the supervision of Mr. Johnstone. The records of the size and character of the vein collected by Johnstone are summarized in Lieber (1958). The strike is N7°E with an eastern dip. The vein was worked for 400 feet before the vein split. Only one split was auriferous and it died out at a depth of 40 feet. The main vein was 5 to 14 feet wide and was terminated at a depth of 105 feet by a dioritic dike. Pyrite appeared below the depth of oxidation at a depth of 85 feet. Early operations were regular in their distribution of shafts and levels, but later work was more random and obliterated many features.

Sloan (1908) noted that the country rock consists of biotite and hornblende slates which strike N 10°E and dip southeast. He refers to an obscurely defined igneous intrusion central to mineralization and calls the deposit an impregnation consisting of cellular quartz with pyrite and chalcopyrite. The cellular quartz averaged $15/ton (roughly 0.75 ounces/ton). In the lower workings, at the 130 foot level of one of the shafts, miners encountered thin sheets of native copper in what is described as quartz hornblende schist. The Nott mine represents a pyrite-chalcopyrite quartz vein that is cut off at a depth of 105 feet. Although impressive in size in Toumey's time, it appears that there is little exploration potential, and McCauley and Butler (1966) report minor production during the 1930's. I know of no recent exploration of this deposit.

Mud (Harmon) Mine

Tuomey's (1848) description of the Harmon mine suggests that it was richer in copper than any other mine in South Carolina at that time. He reported vast quantities of copper sulfate leaching from the copper pyrites. This led to problems in gold recovery since the mercury used in gold recovery also extracts copper. The vein at the Mud mine, as described by Lieber (1958), was about a foot wide with a selvage of sericitic alteration on either side. Sloan (1908) noted the vein was poorly exposed at the time of his examination; one sample assayed $27/ton (1.35 ounces/ton). The country rock is described as a highly altered mass of biotite and hornblende slates.

American Copper and Nickel (ACNC) explored the property, which they referred to as Union-A, as part of a joint venture with Boise Cascade from 1982 to 1987. ACNC reports (Dial, 1986, company report on Union A in SC Geological Survey files) that there are three major pits, a shaft, a trench, and an adit. Rocks consist primarily of actinolite and hornblende schists and a granodiorite intrusion in the southeast portion of the property. In the pits, rocks consist of actinolite and hornblende schists cut by quartz veins and dark green siliceous layers with pyrite and chalcopyrite. The pits follow a general trend of N25°E with foliation trending N15°E and dipping 60° southeast.

Current property examination is difficult since the tract has been clear cut and planted in pines. ACNC conducted ground geophysical studies and extensive soil and rock chip sampling before deciding not to drill. Three of thirteen heavy mineral concentrates were greater than 1,000 ppm gold from drainages both internal to the property and adjacent to the property. A soil grid with 400 feet line spacing and 100 foot sample intervals defined an anomalous zone over a strike length of 1000 feet and a width of 300 feet that is centered on the old workings. Values range from 10 to 780 ppb gold. A second anomalous area 900 feet north of the Mud mine covered an area 1,600 by 1,600 feet. Gold values were in the range of 10 to 550 ppb gold. Eight of eleven rock chips were anomalous (<10 ppb to 350 ppb gold) with a high value of 7.72 ppm gold (0.23 ounces/ton) from the mine workings. Copper analyses were not reported. Geophysics consisted of two lines of Induced Polarization (IP) and magnetics; the results are not available. A decision was made to drop the property without any trenching or drilling near the end of the ACNC exploration effort in the southeast. The property was later leased by Boise Cascade to USMX who sold the lease to Cominco in 1990. No reports of further work have been released.

Bogan Mine

The Bogan mine is the southern extension of the alteration seen at the Ophir and West mines according to Sloan (1908). Tuomey (1848) implies the sericitic alteration appears to be feathering out and is more intrastratified with hornblende schist and dikes. By the time of Lieber's examination (1858) the workings were in a sad state and only a little placer operation was present.

OPHIR (FAIR FOREST; THOMPSON) AND WEST MINES

The Ophir and West mines are part of the same trend of alteration and mineralization (Figure 3). These two mines are by far the most extensive workings in the West Springs area and are among the largest in South Carolina. Many early reports compare these mines to the Haile mine both in terms of the occurrence of the ore within slates rather than discrete quartz veins and in terms of the large size of the workings (Lieber, 1858). Even today, the extent of workings is impressive.

At the time of Tuomey's (1848) visit in 1844, mining at the Fair Forest (Ophir) mines and West mine was described as most deplorable. The ore was easily extracted from the soft sericitic ore and associated quartz, but the workings extended along strike of the ore and followed the dip of the ore. Thus the hanging wall of the mine would fall in, and would then have to be abandoned. In 1844, the West mine was at a depth of 115 feet, which was the deepest in South Carolina. At the West mine, the gold-rich portion of the slates and quartz strikes N10°E and dips 70° southeast. The richest ore, whether in sericite or quartz, was the most ferruginous.

Lieber (1858) notes that the gold bearing veins are very irregular in shape, and the miners had great difficulty in following the same vein down plunge with a new shaft. At times they might encounter new veins in the shaft. The irregular nature of the veins led to the use of the term shoot for the rich ore. From one such shoot Mr. Thompson took $6,000 dollars in 1847 ($115,000 at today's prices). At the Thompson mine (Ophir), a mafic dike cuts off the veins, although some veins appear to have continued into the dike. The mineralization could not be followed below the dike.

The strike of the slates at the Thompson mine was reported by Lieber as N7°E with a 45° westerly dip. Note the change in dip from the West mine.

At the time of Becker's (1895) visit, the Thompson mine was being worked on a small scale using the Dahlonega method of combined hydraulic mining and milling. Graton (1906) estimated in 1895 that production by this method produced $100,000 worth of gold (5000 ounces – two million dollars at today's gold prices). At the time of Graton's visit, the mine was filled with water and was inac-

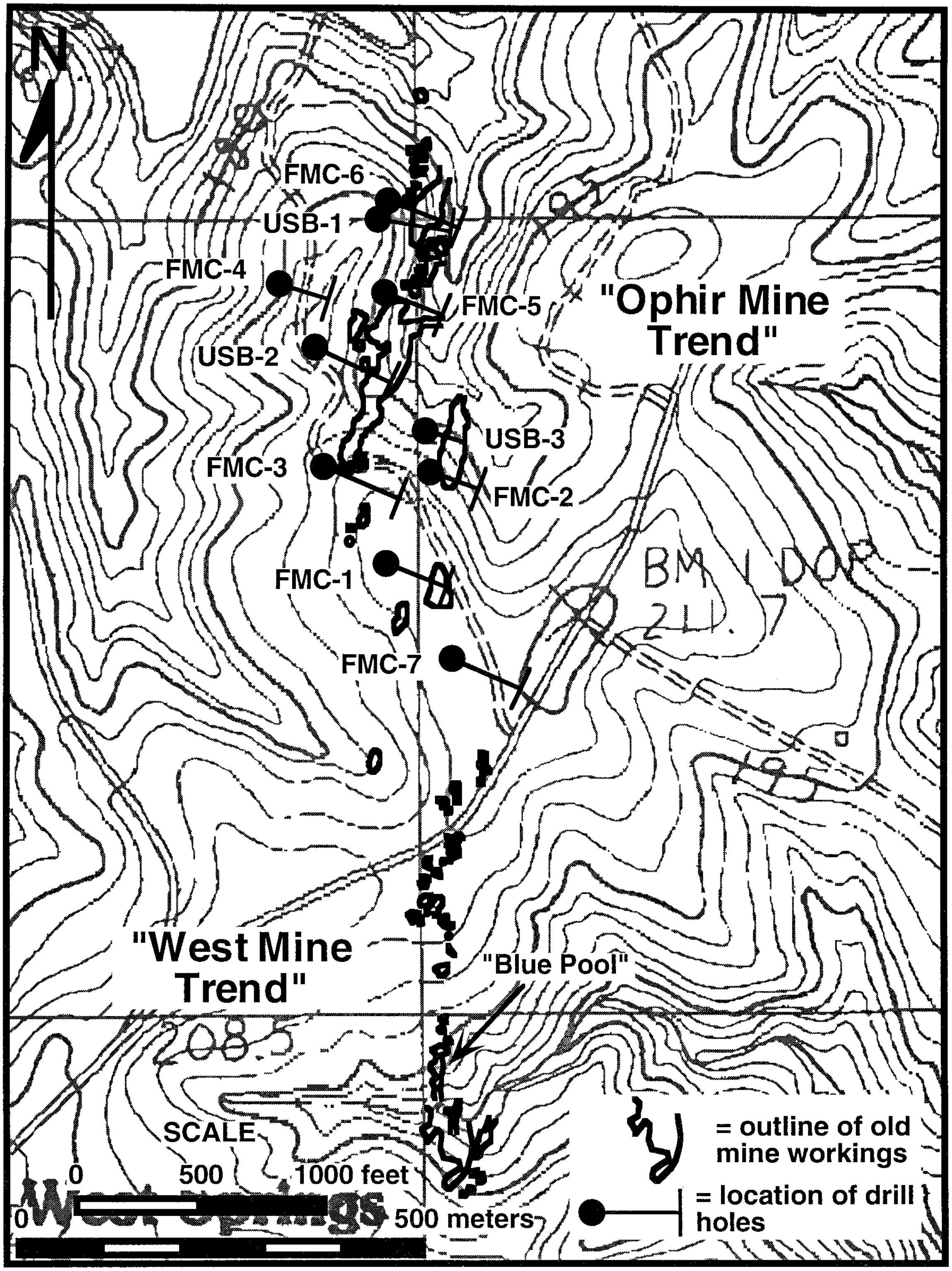


Figure 3. Location of old mine workings at the Ophir and West mines and exploration drilling at the Ophir mine.

cessible. It was owned by Ophir Gold Mining Company of Indianapolis, IN, and was leased to Mr. M.C. Mayes. The workings at the Thompson mine during the time of Graton's visit were described as a vertical shaft 165 feet deep, an incline to the same depth, and n open cut about 100 feet long where hydraulic mining took place. There was a 20 stamp mill with two Wilfley concentrators on site.

The ore bodies at the Thompson mine are described by Graton (1908) as three approximately parallel chutes which strike northerly, dip westerly and pitch southerly. The Pine Tree and Gully veins are 51 feet apart and both veins, plus the intervening auriferous slates, were worked through a long open cut 65 feet wide to a depth of 48 feet where the free milling ore was replaced by pyritic ore. A shaft was sunk to a depth of 149 feet in the hanging wall to intercept the Pine Tree vein at a depth of 130 feet. Cross cuts intercept the other veins, or chutes, as described by Sloan (1908). The Pine Tree vein is described as an ellipse in cross section with a major axis of 60 feet and a diameter of 7 feet. It strikes N10°E, dips 70° northwest, and pitches 43° southwest. The Gully and Possum Tree veins, or shoots, are said to be five feet and four feet thick, respectively, and the Possum Tree vein lies 99 feet east of the Gully vein. The West vein is a similar ore chute between two mafic dikes. It was worked from an open pit 105 feet long and a drift from the Byers shaft. Pyritic concentrates from the Thompson mine are reported as $80/ton (4 ounces/ton) by Sloan (1908) and $100 by Graton (1906).

There are no reports of production since Sloan's description in 1908. When examining the Ophir and West mines today, a line of open cuts, declines and shafts extends in a north-south orientation for at least 5000 feet, and perhaps farther, since some workings are now covered by a small private lake (Figure 3). Gold mineralization is associated with a zone of quartz-sericite alteration that is 300 to500 feet wide on the surface. This alteration can be traced for at least 12,000 feet and is up to 3000 feet wide (unpublished mapping by TexasGulf).

As mentioned earlier, two companies, U.S. Borax and FMC drilled the Ophir mine in 1982 and 1985, respectively. Ten holes were drilled with a total footage of 4066 feet (Figure 3). Their core and field or summary logs are stored at the South Carolina Geological Survey. FMC summarized assay data and Borax included assay sheets. The Borax program analyzed for gold by atomic absorption and not fire assay. Detection levels and accuracy at lower levels of gold is not as accurate as with fire assay techniques. Drill data are summarized in Table 1. Kennecott drilled the West mine, but data and core were not released.

Mineralization is within intensely deformed, biotite sericite quartz schist with variable amounts of fine- to medium-grained pyrite, up to 5 percent. Distorted laminations, layers, veins, and blebs of quartz are found in the biotite-sericite matrix. Often the rock appears laminated. My impression is that the quartz and laminated quartz-sericite layers have been intensely distorted by shearing. Small hook-shaped folds are noted in the quartz laminations and the blebs of quartz veins are very distorted. The deformation of the alteration suggests the alteration may predate shearing. This is also substantiated by the historic descriptions of the workings where the gold is described as occurring in shoots with a southwestern plunge. These shoots may represent tightly folded fold noses. If the shearing post-dates mineralization, what age is it, and how significant of a disruption is the shearing?

As noted in the literature and as shown in assay data and logs, ore is hosted in the pyritic biotite sericite quartz schists. Historically, where the rocks are more pyritic and siliceous, the gold grades were higher. The drilling is too incomplete to substantiate this.

U.S. Borax encountered gold in hole GSU-4D3 (Figure 3) in a sericitic limestone that was four feet thick. This was the only hole reported to encounter this lithology. Limestone is the main host rock for gold at the Kings Mountain mine in North Carolina (LaPoint, 1992). Because of acidic soils, carbonates are rarely reported in saprolite and may be leached to depths of several hundred feet. Other unique lithologies such as iron formation or alumino-silicate alteration were not described in drill logs.

Neither company presented any analytical data other than that for gold, however FMC reported visible molybdenite in hole OP85-1 at 390 feet and in hole OP85-6 at 135-138 feet. None of the early reference (Tuomey, 1848; Lieber, 1858; Sloan, 1908) cites the occurrence of copper from these two mines, in contrast to the Mud and Nott mines.

EXPLORATION POTENTIAL

Historic mining focused on the high grade ore shoots which are thin, small and discontinuous. It is unlikely that any of these individual ore shoots are now a viable mine. However, Sloan's (1908) description of the three veins at the Ophir mine and assay data from drilling by Borax and FMC show that a halo of lower gold values surrounds these shoots. Prior drilling focused on drilling for high grade ore shoots below the old workings, and it is not obvious that these exploration programs considered a bulk tonnage deposit. To do so would require more systematic testing with larger diameter core drilling or reverse circulation rotary drilling, recovering and assaying the saprolitic alteration, and gold analysis using fire assay with low detection levels. More complete geologic mapping of the extent of the alteration system, better understanding of the structural controls on mineralization, and geophysics, such as IP would also help to locate and define an economic deposit. The Ophir-West mine alteration system is large enough to contain bulk minable gold targets. The Ridgeway mine owned by Kennecott is economic because irregular high grade zones are mined in conjunction with the surrounding, more extensive low grade zones. As an example of new gold mines being put into production, a recent article in the Mining Record (June 7, 1995) discussed a mine being developed in Nevada with an average grade 0.0027 ounces per ton gold (900 ppb gold). The key is enough tonnage of ore at a low stripping ratio for bulk mining and extraction techniques.

COMPARISON WITH WESTERN SIERRA FOOTHILLS AND KLAMATH MOUNTAINS, CALIFORNIA

Dennis and Shervais (1995) cite the Klamath Mountains and the western Sierra Foothills of California as analogs to the tectonic setting for the northwestern Carolina Terrane. The Klamath Mountains are a well documented magmatic arc and accretionary wedge (Hacker and others, 1993). Both of these terranes are well known for their historic gold production (Clark, 1970; Hotz, 1971). Probably the best known district is the Mother Lode, a 120 mile-long system of linked en echelon gold-quartz veins and mineralized schist and mafic volcanic rocks. Other districts whose geologic descriptions are similar to West Springs include the Allegheny district in southwest Sierra County which is the most famous high grade gold district in California. The value of gold produced from this district is estimated at over $50 million with much of the production from small but spectacularly rich ore bodies. Gold quartz veins occur in amphibolites; the veins are characterized by their extreme richness, erratic distribution, and small size of ore shoots. The mafic volcanic rocks have been cut by many basic and ultrabasic intrusions. At the Angels Camp in the Mother Lode region, gold deposits occur in amphibolite and chlorite schist as massive quartz veins, zones of parallel quartz stringers, and bodies of mineralized schist and greenstone. Calcite, talc, ankerite, and sericite are common gangue minerals in the ore (Clark, 1970).

CONCLUSIONS

The major gold rush in the southeastern US predated the California Gold Rush of 1849 (Feiss, 1993). Early prospectors focused on mining coarse visible gold associated with quartz veins and free gold found in saprolite after oxidation of sulfides. As with other gold mines in the 1800's, the technology to recover gold from lower grade sulfidic ores did not exist. Since the California gold rush, most mining and exploration has been in the western part of the United States. There you can see rocks to sample, and mineral rights can be claimed by staking the land. There is no royalty on claims and no need to deal with individual landowners.

Now, new technology and gold prices allow for the recovery of gold from lower grade sulfidic ores, such as those at the Ridgeway mine. However, the level of exploration activity remains low in the southeast for a variety of reasons. First, the geology is still poorly understood with much of the area unmapped at the 1:24,000 scale. Secondly, the deposits are poorly understood and described. Exploration geologists from the western U.S. need to understand that the same geologic processes that formed gold deposits in the west occurred here. Finally, company management that are used to staking claims generally do not understand the methods for leasing land in the eastern U.S., and are wary of the permitting requirements for gold mines in the east.

The West Springs area is similar to other gold deposits in the east. When companies come into a new area and examine the old prospects, they may drill a few holes or complete some geochemistry and geophysics, then decide exploration is not warranted. The level of such activities is too little to adequately test the gold potential of the deposit. As can be documented at the Ridgeway and Haile gold mines, the key to exploration success is persistence and drilling in a systematic pattern. The gold deposits of the West Springs area may or may not be mined at some future date, but prospecting and drilling to date remain incomplete.

Metal deposits are excellent indicators of tectonic environments (Sawkins, 1990) and when mapping, geologists should pay attention to unusual rock types that may represent alteration, structure or exhalative units. Examples include iron formation, sericitic schists, aluminosilicates, garnetiferous beds, sulfidic units, etc. The type of metal deposits may provide further clues to understanding the tectonic setting of the rocks and providing key stratigraphic markers.

A number of core holes have been drilled in the southeast by mining companies, most of them in barren rock. When the project is completed, the companies need to dispose of the core. The South Carolina Geologic Survey has attempted to save and store as much core as there is room to store. Core is often the best example to fresh rock available for research and mapping in the southeast, but too little has been utilized by geologists in their research. Core is a valuable resource that can be used by all geologists, and state surveys should be encouraged to serve as depositories for core offered to them. Companies should be encouraged to donate core and associated data.

REFERENCES

Anonymous, 1995, Kinross Gold acquires 50% of Goldbanks Nevada Property; The Mining Record, June 7, 1995, p. 21.

Becker, G.F., 1895, Reconnaissance of the gold fields of the southern Appalachians: U.S. Geological Survey 16th Annual Report, v. 4, pt. 3, p. 251-319.

Butler, J.R., 1966, Geology and mineral resources of York County, South Carolina: South Carolina Geological Survey Bulletin No. 33, 65 p.

Clark, W.B., 1970, Gold Districts of California; California Division of Mines and Geology, Bull. 193, 186 p.

Dennis, A.J., 1989, Tectonogenesis of accreted terrane; The Carolina arc in the Paleozoic [Ph.D. thesis]: Columbia, University of South Carolina, 139 p.

Dennis, A.J., and Shervais, J.W. 1995, The Carolina terrane in northwestern South Carolina: insights into the development of an evolving island arc, in Nance, D., ed., Recent developments in Avalonian Tectonics: Geological Society of America Special paper 304, in press.

Dennis, A.J., and Wright, 1995, The Carolina terrane in northwestern South Carolina, USA: Age of deformation and metamorphism in an exotic arc: accepted pending revisions for Tectonics.

Feiss, P.G., 1993, Overview of nonfuel mineral resources in the southeastern U.S.: unpublished manuscript of talk presented at SE GSA in Tallahassee, Fl.

Graton, L.C., 1906, Reconnaissance of some gold and tin deposits of the southern Appalachians: U.S. Geological Survey Bulletin 293, 106 p.

Hacker, B.R., Ernst, W.G., and McWilliams, M.O., 1993, Genesis and evolution of a Permian-Jurassic magmatic arc/accretionary wedge, and reevaluation of terranes in the Central Klamath Mountains: Tectonics, v. 12, p. 387-409.

Hotz, P.E., 1971, Geology of the lode gold districts in the Klamath Mountains, California and Oregon: U.S. Geological Survey Bulletin 1290, 91 p.

LaPoint, D.J., 1992, Geologic setting of the Kings Mountain gold mine, Cleveland County, North Carolina, in Denisson, J.M. and Stewart, K.G., ed., Geologic field guides to North Carolina and vicinity: Chapel Hill, North Carolina, Department of Geology, University of North Carolina at Chapel Hill, Geologic Guidebook No. 1, p. 35-48.

Lieber, O.M., 1858, Report on the Survey of South Carolina, Second Annual Report to the General Assembly of South Carolina: Columbia, S.C., R.W. Gibbes, State printer, 145 p.

Maybin, A.H. III, undated manuscript in files of South Carolina Geological Survey listing gold occurrences in South Carolina.

Maybin, A.H. III and Niewendorp, C.A., 1993, The central Piedmont allochthon: Alleghanian terrane in the central Piedmont of South Carolina: south Carolina Geology, v. 36, p. 47-58.

McCauley, C.K. and Butler, J.R., 1966, Gold resources of South Carolina: S.C. Geological Survey Bulletin 32, 78 p.

Sawkins, F.J., 1990, Metal Deposits in Relation to Plate Tectonics, 2nd ed., New York, Springer-Verlag, 461 p.

Sloan, E., 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geological Survey Bulletin 2, reprinted 1979, 505 p.

Tuomey, M., 1848, Report on the Geology of South Carolina: Columbia, S.C., A.S. Johnston, State Printer, 349 p.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 43-47

MISSISSIPPIAN (CA. 326-323 MA) U-PB CRYSTALLIZATION FOR TWO GRANITOIDS IN SPARTANBURG AND UNION COUNTIES, SOUTH CAROLINA

Allen J. Dennis
Department of Biology and Geology
University of South Carolina-Aiken
Aiken SC 29801-6309

James E. Wright
Department of Geology and Geophysics
Rice University
Houston TX 77005

INTRODUCTION

Two granitoids were identified for U-Pb zircon dating in the course of detailed mapping in the Glenn Springs and Jonesville 7.5' quadrangles. This area is of interest because it contains the boundary between the Carolina terrane and Inner Piedmont. This boundary is hereafter referred to as the central Piedmont suture of Hatcher and Zietz, but is known in this area also as the Cross Anchor fault of Willis (1984). In the map area underlain by the Carolina terrane, mafic to intermediate volcanic and plutonic rocks metamorphosed to greenschist to lowermost amphibolite facies predominate (Dennis and Shervais, 1991, 1995). A companion investigation has outlined the age relations of these rocks, and concludes that magmatism was coeval with metamorphic fabric development in Late Precambrian through Early Cambrian time (Dennis and Wright, 1993, 1996). The Inner Piedmont is characterized in this area by a variety of ortho- and paragneisses that have generally low dips and are slabby in appearance. Several middle Paleozoic plutons also outcrop in this general area including the Pacolet granite (383±7 Ma, Rb-Sr whole-rock, Mittwede and Fullagar, 1987; Mittewede, 1989) and the undated Buffalo gabbro (Medlin and others, 1972). Structural analysis and an interpretation of the sequence of events that affected this area of the Piedmont are presented in Dennis (1995). Data in this contribution were collected from rocks of the Bald Rock granite and an unnamed granite that appears to cut the central Piedmont suture.

DESCRIPTION OF ROCK BODIES

Bald Rock Granite

The Bald Rock pluton is an elliptical granite body that covers all or parts of seven 7.5' quads and is centered on the Kelton 7.5' quad north of Union, South Carolina. On its western margin in the Jonesville quad, the pluton intrudes mafic metavolcanic rock, metadiorite and diorite gneiss. Foliation attitudes in Carolina terrane rocks adjacent to the pluton are subparallel to that contact. Mappable blocks of country rock (metagabbros and sillimanite schist of the Battleground Formation) are present within the pluton. To the east, in York and Chester Counties, intermediate-ultramafic volcanic and plutonic rocks also comprise the country rock, but the metamorphic grade is higher and the structural story appears more complex (e.g., Neal Shoals on the 1995 Carolina Geological Society field trip, Dennis and others, 1995).

The Bald Rock pluton is most easily identified as a coarse-grained megacrystic granite with potassium feldspar phenocrysts 5-7 cm in length. These megacrysts are typically highly aligned and concordant with elliptical xenoliths and/or mafic enclaves. Speer and others (1986) identify five facies within the Bald Rock pluton, and present a fabric map that shows the regional pattern defined by megacrysts and flattened mafic enclaves. McSween and others (1991) correctly anticipated a Carboniferous age for the Bald Rock pluton, based in part on a comparison of its mafic mineral chemistry with that of other Southern Appalachian Carboniferous plutons (Speer and others, 1986).

Weathered flat rock pavements are quite common in the area underlain by the pluton, but it is generally difficult to find large outcroppings of fresh rock. The sample dated here came from an inactive quarry located on the Hyder Farm in the Kelton quad identified in Wagener (his U2, 1977). This outcrop will be visited by the 1995 Carolina Geological Society Field Trip (Dennis and others, 1995). The latitude and longitude of the sample site are 34°47'15"N and 81°33'18"W.

Unnamed granite on Dutchman Creek, Glenn Springs quad.

This small (2 km diameter) foliated granitic body was mapped by Dennis (1989), and interpreted to cross cut the central Piedmont suture. This granitoid is mapped in contact with Inner Piedmont ortho- and paragneisses, including augen gneiss, sillimanite schist, and amphibolite to the southwest, and Carolina terrane to the east and north. To the east the granite is in contact with felsic metavolcanic rocks and to the north with mafic metavolcanic rocks. Dennis (1989) mapped a small ultramafic body near the southeastern margin of the pluton.

The rock contains a fabric that is defined by alignment

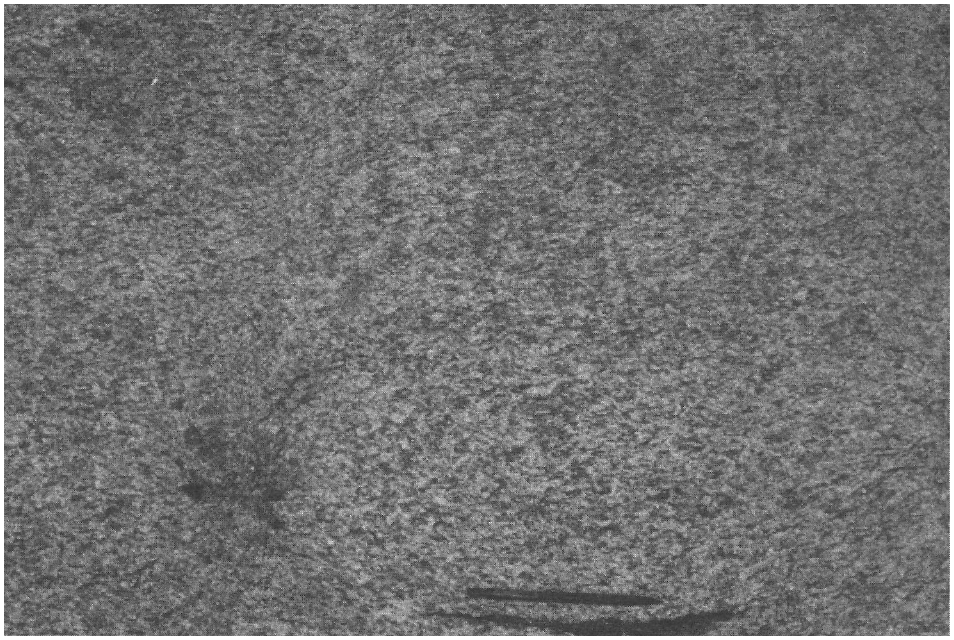


Figure 1. Pavement of unnamed granitoid (sample 1823) intruding the central Piedmont suture along Dutchman Creek, Glenn Springs 7.5' quadrangle, South Carolina. Pencil points north. Note schlieren and weak compositional layering oriented approximately N-S.

of microcline phenocrysts and crude compositional layering defined by feldspars and quartz and is parallel to biotite-rich schlieren in the rock (Figure 1). The strike of this fabric is oriented within 30° of north where it is observed, and is approximately subparallel to the trace of the central Piedmont suture in this area. Dips are consistently to the east and range from 30° to vertical. Locally a nearly strike-parallel lineation is apparent and plunges south. In the metavolcanic rocks a parallel lineation is observed, and in that rock is interpreted to be parallel to the regional fold axis. There is no consistent variation or difference between the orientation of the slaty cleavage in the metavolcanic rocks and the weak fabric in the granitoid.

The outcrop (1823) where the sample was collected is located in the southeastern corner of the Glenn Springs quad at the intersection of Dutchman Creek and Friendship Church Road (S-42-112), o.4 mile south of the intersection of S-42-112 with SC 56. The latitude and longitude of the sample site are 34°46'24"N and 81°51'03"W.

U-PB GEOCHRONOLOGY

Analytical Procedures

Analytical procedures were the same as those described by Wright and Fahan (1988) and Dilles and Wright (1988). Isotopic data were determined on a multicollector Finnegan Mat 262 mass spectrometer at Rice University. Total Pb blanks at Rice have ranged over the years from as little as 10 pg to as much as 100 pg. Concordia intercepts were calculated using the program of Ludwig (1984). Further details of analytical procedures and error analysis are contained in Table 1.

Analytical Results

As evident from the isotopic data all analyzed zircon fractions from each sample have lost moderate amounts of radiogenic lead, but $^{207}Pb^*/^{206}Pb^*$ dates agree within analytical error for the individual samples (Table 1). We interpret these results to indicate recent loss of radiogenic lead. In addition, there is no evidence of an older, premagmatic zircon component. On the Concordia diagram (Figure 2) sample AD-1823 (unnamed granite) gives an upper Concordia intercept age of 326±3 Ma and sample Hyder (Bald Rock granite) gives an upper Concordia intercept age of 323±3 Ma. The chords for each sample were force-fit through a lower Concordia intercept of 0± 10 Ma which is essentially averaging the $^{207}Pb^*/^{206}Pb^*$ dates while taking into consideration the error associated with each data point on the Concordia plot. This treatment is justified, in our opinion, due to the agreement of all $^{207}Pb^*/^{206}Pb^*$ dates for each respective sample, and necessary due to the lack of spread in $^{206}Pb^*/^{238}U^*$ for each respective sample.

INTERPRETATION

Results presented here confirm the inferences drawn by McSween and others (1991) that the Bald Rock is an

Table 1. Uranium-Lead Isotopic Dada

Sample #		Total U ppm	206Pb* ppm	Measured Ratios** 206Pb/204Pb	207Pb/206Pb	208Pb/206Pb	Atomic Ratios 206Pb*/238U	207Pb*/235U	207Pb*/206Pb*	Apparent Ages (Ma)§ 206Pb/238U	207Pb/235U	207Pb/206Pb
AD-1823	100-200	695	28.42	5076	0.05482	0.24089	0.04760	0.34741	0.05294	299.7	302.8	326+/-2
AD-1823	200-325	1031	53.40	9346	0.05411	0.18170	0.04863	0.35488	0.05293	306.1	308.4	326+/-2
AD-1823	-325	1078	55.70	8474	0.05426	0.18986	0.04817	0.35148	0.05292	303.3	305.8	325+/-2
Hyder	100-200	1107	57.98	7042	0.05456	0.16387	0.04982	0.36301	0.05284	313.4	314.5	322+/-2
Hyder	200-325	1035	56.96	2825	0.05764	0.19776	0.05063	0.36902	0.05286	318.4	318.9	323+/-2
Hyder	-325	1034	57.32	3448	0.05669	0.20800	0.05064	0.36904	0.05285	318.4	318.9	322+/-2

+200, 100-200, refer to size fractions in mesh

* Denotes radiogenic Pb, corrected for common Pb using the isotopic composition of 206Pb/204Pb=18.6 and 207Pb/204Pb=15.6. Sample dissolution and ion exchange chemistry modified from Krough (1973).

** Isotopic compositions corrected for mass fraction (0.11% per A.M.U.)

§ Ages calculated using the following constants: decay constant for 235U and 238U = 9.8485E-10 and 1.55125E-10yr-1 respectively; 238U/235U = 137.88.

Error analysis for individual zircon fractions follows Mattinson (1987). Concordia intercepts and errors calculated using program of Ludwig (1984).

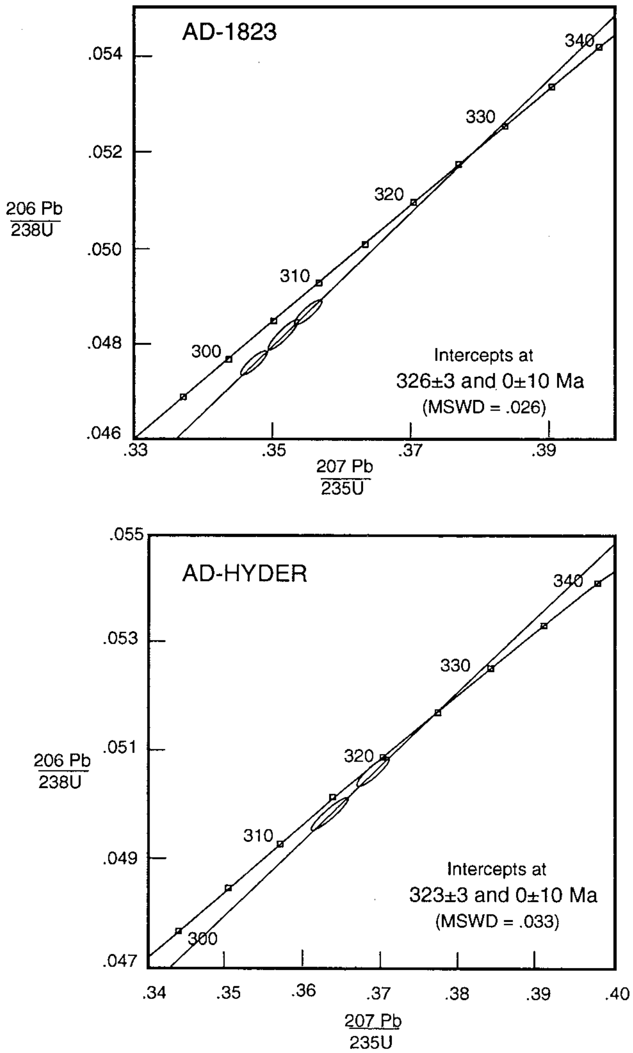


Figure 2. Concordia diagrams for unnamed granitoid (AD-1823) and Bald Rock granite (AD-HYDER)

Alleghanian granite and that the Bald Rock pluton belongs in the western group of Alleghanian granites (York-High Shoals-Churchland; e.g., Horton and others, 1987). A Late Paleozoic tectonothermal event has been identified in the central Piedmont on the basis of $^{40}Ar/^{39}Ar$ mineral ages (Dalmeyer and others, 1986; Horton and others, 1987).

The relationship between this event and plutonism in the central Piedmont is most clearly displayed in the vicinity of the High Shoals granite (Horton and others, 1987); elsewhere this relation is less clear. Intrusion of the Bald Rock and other Alleghanian plutons may be responsible for the "annealed" country rock fabric described by Dennis and Shervais (1991). It is suggested that the location of the Bald Rock may have been controlled by existing faults, especially given the contrast in grade and/or structural style between the country rock on the east and west sides of the pluton.

The unnamed granite is interpreted to cut the central Piedmont suture. Thus, the central Piedmont suture in this area is a pre-Alleghanian feature. The lineation, a magmatic to submagmatic fabric, and possible some penetrative, solid-state deformation are here interpreted to be related to northwest-vergent Alleghanian folding and what Dennis (1995) interprets to be no more than minor ductile motion along the 50 km N-S trending segment of he central Piedmont suture between Spartanburg and Clinton. The central Piedmont suture is interpreted to have controlled the location of the intrusion. Alternatively, the granitoid may be related to augen gneisses of the Inner Piedmont recognized 2 km southwest of this outcrop on Trail Branch. However, the existence of Carboniferous orthogneisses in the eastern part of the Inner Piedmont has not been documented.

Finally we note the lack of a xenocrystic zircon component or evidence of inheritance in these isotopic data. The origin of the southern Appalachian Alleghanian granites is a popular topic for speculation (e.g., Sacks and Secor, 1990; Speer and others, 1994). The data from these plutons does not indicate an origin in crustal anatexis or remobilization of Carolina terrane basement.

CONCLUSIONS

We have documented two Carboniferous plutons in the western Carolina terrane of northwestern South Carolina. Three size fractions of zircon from an unnamed granitoid that intrudes the central Piedmont suture in the Glenn Springs quadrangle yield an upper intercept at 326±3 Ma. Thus, in the Carolina terrane adjacent to the central Piedmont suture between Spartanburg and Union, three episodes of plutonism are identified. In the Late Precambrian-Early Cambrian (Mean Crossroads complex) ultramafic-intermediate composition intrusive rocks record the rifting of the Carolina arc at which time deep-seated faulting allowed highly magnesian magmas to ascend with little fractionation. In the Devonian the Pacolet granite and Buffalo gabbro intruded as parts of a linear, post-metamorphic array of gabbros and granitoids that is largely restricted to the area just south and east of the central Piedmont suture. In the Carboniferous the Bald Rock and unnamed granite are part of the well known group of granitic plutons that cover the entire age range of the Alleghanian orogeny mapped in the Carolina terrane and are related to that collision. The unnamed granite crosscuts the central Piedmont suture and provides an upper limit on timing of ductile motion on this fault.

ACKNOWLEDGEMENTS

Support for U-Pb geochronologic studies was provided by the South Carolina Universities Research and Education Foundation (Task 14) and NSF EAR 91-17915. thanks to John Shervais for his helpful review.

REFERENCES

Dallmeyer, R.D., Wright, J.E., Secor, D.T. and Snoke, A.W., 1986, Character of the Alleghanian orogeny in the southern Appalachians. Part II. Geochronological constraints on the tectonothermal evolution of the eastern Piedmont in South Carolina: Geological Society of America Bulletin, v. 97, p. 1329-1344.

Dennis, A.J., 1989, Tectonogenesis of an accreted terrane: The Carolina arc in the Paleozoic: [Ph.D. theses]: Columbia, University of South Carolina, 139 p.

Dennis, A.J., and Shervais, J.W, 1995, The Carolina terrane in northwestern South Carolina: Insights into the development of an evolving island arc, in Nance, R.D. and Thompson, M.D., eds., Avalonian and related peri-Gondwanan terranes of the Circum-North Atlantic: Geological Society of America Special Paper 304, in press.

Dennis, A.J., 1995, The Carolina terrane in northwestern South Carolina: Relative timing of events and recent tectonic models, in Hibbard, J.P., van Staal, C.R., and Cawood, P.A., eds., New Perspectives in the Appalachian-Caledonian Orogen: Geological Society of Canada Special Paper 41, in press.

Dennis, A.J., and Wright, J.E., 1993, New Late Precambrian-Cambrian U-Pb zircon ages for zoned intrusives in the western Carolina terrane, Spartanburg and Union Counties, South Carolina [abstract]: Geological Society of America Abstracts with Programs, v. 25, p. 12.

Dennis, A.J., Wright, J.E., 1996, The Carolina terrane in northwestern South Carolina, USA: Age of deformation and metamorphism in an exotic arc: Tectonics, accepted pending revision.

Dennis, A.J., Wright, J.E., 1988, The chronology of early Mesozoic arc magmatism in the Yerington district of western Nevada and its regional implications: Geological Society of America Bulletin, v. 100, p. 644-652.

Hatcher, R.D., Jr. and Zietz, I., 1980, Tectonic implications of regional aeromagnetic and gravity data from the southern Appalachians, in Wones, D.R., ed., The Caledonides in the U.S.A.: Virginia Polytechnic Institute, Department of Geological Sciences Special Publication 2, p. 235-244.

Horton, J.W., Jr., Sutter, J.F., Stern, T.W. and Milton, D.J., 1987, Alleghanian deformation, metamorphism and granite emplacement in the central Piedmont of the southern Appalachians: American Journal of Science, v. 287, p. 635-660.

Krogh, T.E., 1973, A low contamination method for hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica and Cosmochimica Acta, v. 37, p. 485-494.

Ludwig, K.R., 1984, Plotting and regression programs for isotope geochemists, for use with HP-86/87 microcomputers: U.S. Geological Survey Open File Report 83-849, 102 p.

Mattinson, J.M., 1987, U-Pb ages of zircon: A basic examination of error propagation: Chemical Geology (Isotope Geology Section), v. 66, p. 151-162.

McSween, H.Y., Speer, J.A. and Fullagar, P.D., 1991, Plutonic rocks, in J.W. Horton, Jr. and V.A. Zullo ed., The Geology of the Carolinas: Knoxville, University of Tennessee Press, p. 109-126.

Medlin, J.H., Thornton, C.P. and Gold, D.P., 1972, Petrology of the mafic igneous complexes in the southeastern U.S. Piedmont: II. The Buffalo mafic igneous complex, Union County, South Carolina: Southeastern Geology, v. 14., p. 73-106.

Mittewede, S.K., 1989, Geologic maps of the Pacolet and Pacolet Mills 7.5' quadrangles, South Carolina: OFR-64: Columbia, SC, South Carolina Geological Survey.

Mittewede, S.K., and Fullagar, P.D., 1987, Petrology and geochemistry of the Pacolet monzogranite in northwestern South Carolina: Petrogenetic implications [abstract]: Geological Society of America Abstracts with Programs, v. 18, p. 118.

Sacks, P.E. and Secor, D.T., Jr., 1990, Delamination in collisional orogens: Geology, v. 18, p. 999-1002.

Speer, J.A., Brauer, S.V.G., and McSween, H.Y., Jr., 1986, The Bald Rock granitic pluton, South Carolina: Petrography and internal fabric: South Carolina Geology, v. 30, 1-17.

Speer, J.A., McSween, H.Y. and Gates, A.E., 1994, Generation, segregation, ascent and emplacement of Alleghanian plutons in the southern Appalachians: Journal of Geology, v. 102, p. 249-267.

Wagener, H.D., 1977, The granitic stone resources of South Carolina: Mineral Resources Series 5: Columbia, South Carolina Geological Survey, 65 p.

Willis, J., 1984, Geology of the Cross anchor area: The boundary between the Carolina terrane and the Inner Piedmont in northwestern South Carolina [M.S. thesis]: Columbia, University of South Carolina, p. 61.

Wright, J.E. and Fahan, M.R., 1988, An expanded view of Jurassic orogenesis in the western United States Cordillera: Middle Jurassic (pre-Nevadan) regional metamorphism and thrust faulting within an active arc environment: Geological Society of America Bulletin, v. 100, p. 859-876.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 49-55

GEOLOGY OF MASTERS' KILN AND HISTORY OF THE MARBLE OCCURRENCES IN LAURENS AND UNION COUNTIES, SOUTH CAROLINA

John M. Garihan, William A. Ranson, and Kenneth A. Sargent
Department of Earth and Environmental Sciences
Furman University
Greenville, S.C.
Clark A. Niewendorp
South Carolina Geological Survey
Columbia, S.C.

INTRODUCTION

Masters' Kiln is one of the known historic kiln sites in the piedmont of South Carolina. This guidebook article is intended to give a brief historical background of the kiln sites in Laurens and Union Counties and then a descriptive overview of the geology of the Masters' kiln, which concludes with a brief petrography of the skarn developed along the contact between marble and country rock. The details of the metamorphic petrology must await further study. Figure 1 shows the location of the kilns, quarries, and marble locations described in this section.

HISTORY OF THE LIME KILNS OF LAURENS AND UNION COUNTIES

Lime was an important commodity in the early 1800's for use in both agriculture and the building trades. In agriculture, lime rendered "…stiff clay land more light and porous…" (Tuomey, 1844) and helped neutralize acidic soils. In the building trades, a mortar made from lime and sand was the most frequently used until the late nineteenth century. Marble was also quarried and used for building stones and for monuments.

The first reference found by the authors appears in the 1843 Report of the Commencement and Progress of the Agricultural Survey of South Carolina by Edmund Ruffin. Ruffin describes the occurrence of a "limestone" on the south fork of Raiburn's (sic) Creek on land owned by a J. Garlington and the erection of a kiln there during 1842-1843. In Sloan (1908), this kiln is referred to as Mahaffey's Kiln. Ruffin also reports the occurrence of a white to pale blue, crystalline marble in three outcroppings within a two mile extent stretching from the Reedy River to Walnut Creek, a major south tributary to the Reedy River. These outcroppings varied from 40 to 100 yards in outcrop extent and up to 10 feet in height. The northernmost end of this trend is the Masters' Kiln location. According to Ruffin, the discovery of this location occurred a few years earlier when a well was dug on an adjacent ridge and "limestone" was discovered at a depth of 64 feet. He does not mention whether a kiln was present by 1843.

The 1844 Report of the Geological and Agricultural Survey of the State of South Carolina by M. Tuomey describes the occurrence of a 15 by 20 foot thick bed of limestone with a N30E strike and SE40 dip outcropping along a tributary to the Saluda River one half mile south of Ware Mill (located at Ware Shoals). This outcropping later became the location of Raysor's Kiln but in 1844 no quarrying operations had been initiated. Tuomey also mentioned the occurrence on Reaburn's (sic) Creek and noted that it was being worked.

The 1848 Report on the Geology of South Carolina by M. Tuomey describes the occurrence of a 15 to 20 foot thick bed of limestone between beds of gneiss outcropping along the Saluda River south of Ware Mill and along an adjacent creek. Two other occurrences located approximately two miles to the northeast (probably those along Walnut Creek) were also mentioned. No quarrying operations were yet active at any of these locations. Tuomey describes the limestone as a "white crystalline rock… colored by streaks of chlorite, and groups of crystals of actinolite." Tuomey describes the Reaburn's (sic) Creek location in greater detail and includes a figure depicting the outcrop. He also discussed the kiln located there. The limestone is described as a blue limestone associated with soapstone and gneiss. The middle 10 feet of the bed was composed of "good limestone" but the material above and below was of poor quality. The kiln was described as being "unfavorable to the quality of lime produced, and to the economy of the operation." Tuomey also included a discourse on the burning of lime and the construction of kilns. A portion of this discussion is reproduced in Appendix A.

Raysor's Kiln commenced operations sometime during the interval between 1848 and 1860. the November 6, 1860 issue of the Laurensville Herald contains an advertisement by Raysor for the best "southern made lime" from his kiln at Arnold's Old Quarry at 30 to 34 cents a bushel depending on the number of bushels. The January 18, 1861 issue of the Herald contains a similar advertisement for lime from G. W. Sullivan's Kiln near Popular Springs. Around 1870, Sullivan's Kiln was acquired by Dr. Jake Masters and the kiln was renamed.

Additional references to these localities occur in the

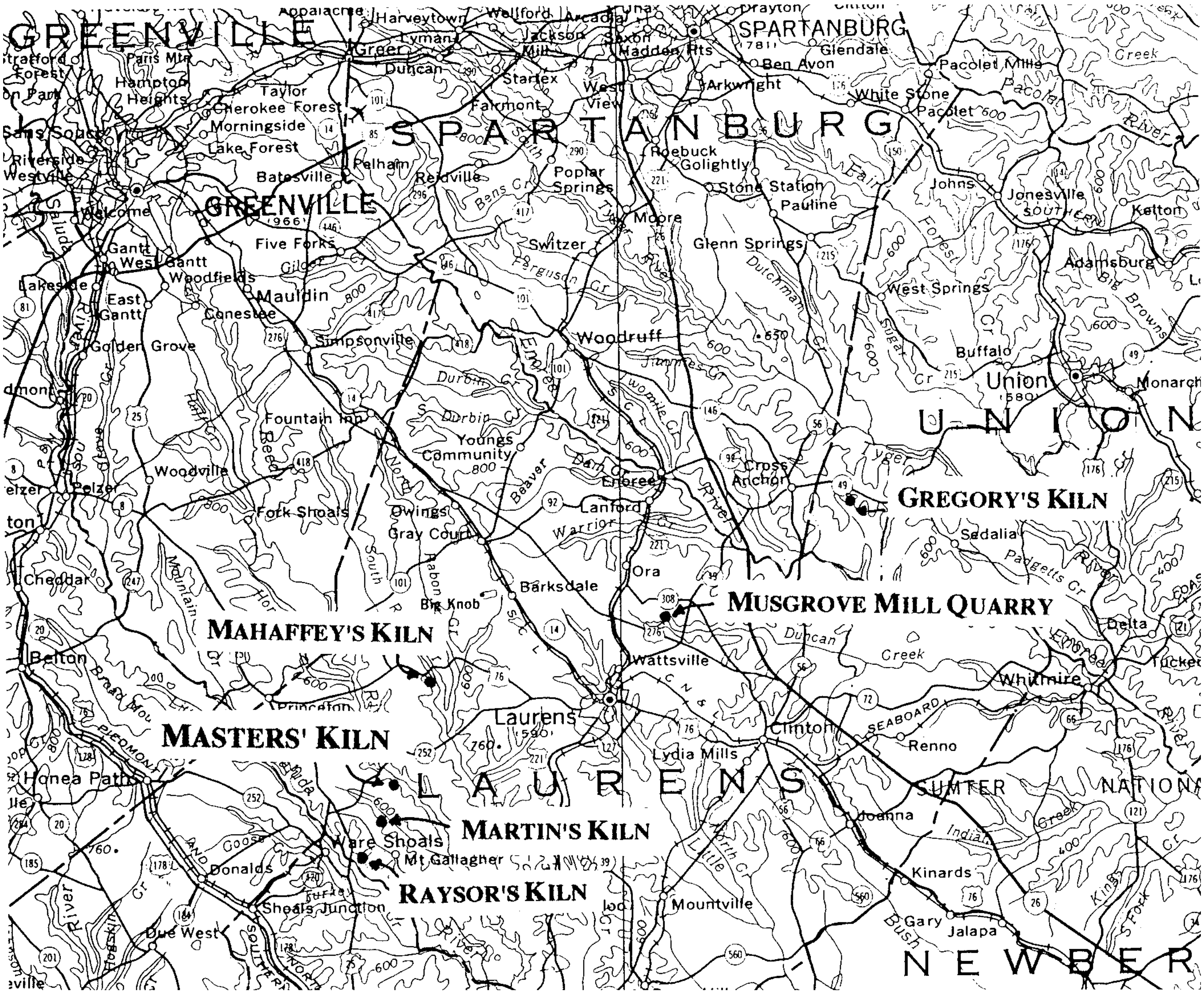


Figure 1. Location of kilns, quarries, and marble locations.

1908 Catalogue of Mineral Localities of South Carolina by Earle Sloan. A picture of the collapsed Masters' Kiln was used on the cover of the 1979 reprint of Sloan's Catalogue. Sloan described Raysor's Kiln, the Walnut Creek location, Master's (sic) Kiln, the Reaburn (sic) Creek location (Mahaffeys Kiln), and two new locations: the Gregory Quarry located in Union County about 20 miles to the northeast of Reaburn's Kiln; and the Musgrove Mill marble located approximately 10 miles to the northeast of Reaburn's Kiln. These new locations do not occur along strike with those in Laurens County. The Masters' Kiln location is described as "about eight feet of white, coarse-grained dolomitic limestone, in two adjacent layers… long quarried as a source of lime and also for marble for neighborhood monumental purposes." Sloan included chemical analyses from several limestone and marble occurrences in South Carolina. Chemical analyses of the marbles from Master's (sic), Gregory's, Mahaffey's, and Raysor's Quarries, excerpted from Sloan, 1908, pp. 257-259, are reproduced in Appendix B. While the quarry and kiln n Masters' land was active when Sloan visited in 1908, Twitchell (1911) does not mention it in his report.

James W. Clarke (1957) reported on the petrography and origin of the contact zone at Master's (sic) Kiln and noted scapolite, diopside, and actinolite as the primary minerals and a small amount of molybdenite. He concludes that the mineralization developed at the time of the intrusion of the granite.

David Snipes (1969) assigned the Master's (sic) Kiln occurrence to the Kings Mountain Belt and noted that the skarn consisted primarily of actinolite, diopside, and scapolite with minor amounts of talc, phlogopite, and other minerals.

Two of Don Secor's and Bob Hatcher's students worked on the Inner Piedmont-Carolina Terrane Boundary in the vicinity of the marble locations. John Horkowitz (1984) worked in the Philson Crossroad Quadrangle and John Willis (1984) in the Cross Anchor Quadrangle to the north. The Gregory Kiln and Quarry location lies along the boundary between these two quadrangles. Both workers assign the dolomitic marbles to the Inner Piedmont.

Clark Niewendorp (1993) visited Raysor's, Masters', and Mahaffey's Kilns and the kiln on Walnut Creek referenced by Ruffin (1843) and Tuomey (1848). This latter kiln Niewendorp named Martin's Kiln based on the proximity of a nearby road of the same name and references to the ownership of the land by an L. Martin found in Kyzer and Hellam (1883) and a J. Martin found in Sloan (1908). Exact locations to these kilns can be found in Niewendorp (1993).

The present owner of the Masters' Kiln site is Mr. Larry McKellar of Greenwood, South Carolina. Mr. McKeller is very interested in the history of the quarry and in preserving what remains of the kiln and building. He has graciously granted permission for our visit to the site.

DESCRIPTIONS OF THE LAURENS COUNTY KILNS

Garlington's/Mahaffey's Kiln

This kiln is now beneath the waters of Lake Rabon on the south side of the South Rabon Creek channel. In 1991, the temporary lowering of the water level in lake Rabon allowed one of the authors (Niewendorp) to visit the site. A circular area dug out of the hillside and a few stone blocks from the kiln wall were all that remained. Figure 2 is a picture of the site taken during that visit. Cobbles of blue-grey to yellow marble lay scattered around the site.

Figure 2

Martin's Kiln

Figure 3 is a picture of this kiln taken in 1991. Features to be noted are the closely fitted stone work and an air hole called the "eye of the kiln" which is located just below the entryway.

Figure 3

Raysor's Kiln

Figure 4 is a picture of this kiln taken in 1991. The back wall of the kiln is intact but blocks from the front and entryway have fallen down.

Figure 4

Masters' Kiln

It appears that lime was produced from two kilns arranged in a side by side fashion (see Appendix A). Having two kilns allowed constant operation, while one was burning the other could be unloaded and recharged. Fire brick lines the interior of both kilns. This lining protected the exterior granitic block walls from the intense heat. Nearby is the ruin of a small building which probably served as a warehouse for storing and selling of the lime (Figure 5). The building foundation is made of large marble blocks fit together without mortar. The walls on top of the foundation are made of cobble stones and lime sand mortar.

Figure 5

Petrography

Hand specimen and thin section petrography of Masters' Kiln samples reveal a series of interesting metamorphic zones at the contact between the country rock (granite or granitic gneiss) and the dolomitic marble. In hand specimens and in polished slabs of hand specimens the most commonly observed progression (shown in Fig. 6) is as follows:

1. leucocr5atic granite/granitic gneiss
2. massive, pale purple scapolite ± quartz
3. medium- to coarse-grained, dark green actinolite
4. fine-grained mixture of light green CaMg silicates
5. medium- to coarse-grained dolomitic marble.

Although these zones appear in this order repeatedly, the contacts between the various zones may be wavy or even convoluted, with some zones protruding or intruding into other zones (Fig. 6). In some instances the fine-grained mixture of light green CaMg silicates is sandwiched between *two* layers of the medium- to coarse-grained, dark green actinolite (Fig. 7). The medium- to coarse-grained dolomitic marble exhibits beautifully etched, slightly saddle-shaped, dolomite rhombs on weathered surfaces. Other metamorphic minerals less commonly observed in hand specimen include phlogopite and wollastonite(?).

Based only on hand specimens and limited study of thin sections, it is difficult to document metamorphic reactions that might have occurred to produce the observed zones or

Figure 6. Slabbed sample from Master's kiln site.

layers. In fact it is unclear whether they have resulted from contact metamorphic reactions between an impure dolomitic limestone and a granite of unknown age, size, and origin, or whether these zones are the product of metasomatism along a preexisting lithologic or tectonic contact between country rock gneiss and dolomitic marble during some stage of regional metamorphism. Clark (1957) concluded that the skarn resulted from the intrusion of the granite, whereas Snipes (1969) reported that the skarn resulted when metasomatic fluids encountered the dolomitic marble. The source of fluids which have played an important role in the production of the observed mineralogy is problematic, emanating from the country rock or the intrusion or perhaps both.Preliminary thin section petrography provides a more detailed look at the various zones described above from hand specimens. In thin section the granite, which may be distinctly foliated in the contact zone, consists of microcline, plagioclase, quartz, biotite, ± muscovite, ± hornblende. Adjacent to the granite is massive, coarse-grained scapolite exhibiting upper second and third order interference colors. For the scapolite, Clark (1957) reported N_o=1.585, which corresponds to Meionite$_{65}$. This is the variety of scapolite known as mizzonite, which is the most common calcic scapolite. Quartz occurs as interstitial grains among the coarse scapolite crystals. The next layer of coarse actinolite consists of elongated prisms of green pleochroic actinolite, some of which protrude into the scapolite layer. Among the prisms of coarse actinolite are less abundant coarse carbonate grains. Thin section petrography of the light green calcsilicate zone reveals it to be the

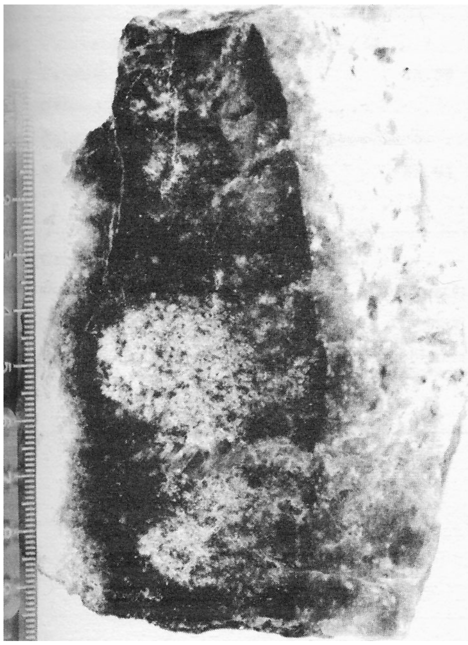


Figure 7. Slabbed sample from Master's Kiln site,

most complex. This layer consists of a fine-grained mixture of actinolite, diopside, and minor epidote and olivine. The olivine is optically negative with a 2V=85-80, indicating that it is approximately Fo_{100}. Anhedral, embayed forsterite in one instance forms the core of a larger actinolite crystal, suggesting that it may be reacting with a fluid phase to produce the amphibole.

APPENDIX A

Discourse on Lime Burning from Tuomey, 1848.

Limestone, marlstone, marl, and all the varieties of calcareous rocks, are made up of carbonate of lime, more or less mixed with impurities. 100 parts of pure carbonate of lime is composed, in round numbers, of 44 carbonic acid united to 56 of lime. The object of burning is to obtain the lime in its caustic state, that is, freed from the carbonic acid, which is driven off at a high temperature. The lime, in this state, combines rapidly with water, and falls to a fine powder, combines again with carbonic acid, and when mixed with sand, forms an artificial stone, or mortar.

The object of burning lime in agriculture, is to obtain it in a state that it may be spread upon the land without difficulty. Besides this, it acts with more energy on organic matter, produces all the effects of carbonate of lime in a shorter time, and, for this reason, requires greater caution it its application.

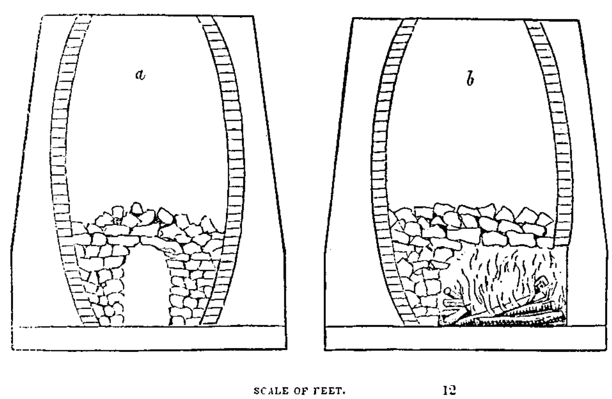
The weight is diminished by one half, by burning, at the same time that its bulk is doubled, if it be allowed to absorb moisture, or to slack, as it is technically called - two important facts connected with lime, where it has to be hauled to any considerable distance.

Notwithstanding that lime has been burned for a number of years, there is not one single well constructed lime kiln in the State. Those that are pretty well built are defective, particularly in the construction of the fire-places. They are either so small as to allow but little wood to be placed in them at a time, or so large as to admit a volume of cold air, (for there are no doors) that must carry off the heat that otherwise would be employed in the burning of lime. There is consequently a vast and unnecessary expenditure of time and fuel.

The simplest mode of burning lime is to pile up alternate layers of wood and limestone, the latter broken into fragments three or four inches in diameter; the outside of the pile is roughly plastered with clay, so as to stop up all the openings, excepting at the bottom, where holes are left sufficient for draft. Such a pile may be burned in the quarry, and would involve no carriage of the limestone, till it was burned. The plastering is important, especially in windy weather, and, at all times, a great saving of fuel.

Where lime is burned constantly, kilns of a permanent character are built, and the larger they are the less the cost of burning. The interior of the kiln must be of some substance that will stand the intense heat required. For this purpose the mica slates answer well, where the granular quartz rock cannot be procured. Fire clay is also abundant along the limestone range in York; and, whatever the material used for the lining, this will form the best mortar.

In selecting the site, of course convenient to the quarry will be a prime location, and if possible, a hill-side should be selected…. I have prepared some plans of kilns, from the most approved structures, of this sort, which are here presented.



APPENDIX B: FACSIMILE TABLE FROM SLOAN 1908

CRYSTALLINE AREA SERIES—ANALYSES OF LIMESTONES.

TABLE No. 3.

1	COUNTY	LAURENS	LAURENS	LAURENS	LAURENS	UNION
2	Locality	Masters Kiln	Mahaffey Kiln	Mahaffey Kiln	Raysors Kiln	5MW Cross K
3	Stream	Walnut Crk.	Reaburn Crk.	Reaburn Crk.	Saluda River	Frenchman Crk.
4	Owner (?)	J. Johnson	Mrs. S. B. Mahaffey	Mrs. S. B. Mahaffey	J. C. Raysor	Mr. Gregory
5	AREA	Santee	Santee	Santee	Santee	Santee
6	SURVEY No.	5189	5240(a)	5240(b)	5185	5675
7	ANALYSIS:					
8	Lime	35.61	29.43	30.46	45.80	39.18
9	Magnesia	17.30	18.34	19.20	5.86	14.74
10	Alumina	.24	...	...	1.23	.12
11	Ferric Oxide	.18	2.08	2.26	1.57	.28
12	Ferrous Oxide	.21	...	...	...	...
13	Titanic Oxide	.01	...	...	...	trace
14	Manganese Oxide (MnO)	trace	.17	.45	...	trace
15	Soda (Na_2O)	.02	...	...	...	.02
16	Potash (K_2O)	.05	...	...	...	.01
17	Carbonic Acid (CO_2)	44.80	43.23	44.71	38.80	44.40
18	Phosphoric Acid (P_2O_5)	trace	...	...	...	trace
19	Iron Sulphide	trace	...	...	...	trace
20	Sulphuric anhydride	...	...	...	...	...
21	Silica (and insoluble)	1.66	6.63	2.45	6.75	1.13
22	Ignition	.02	.09	.14	...	.12
23	Moisture (at 100°C)	.08	.07	.03	...	...
24	...	...	...	...	...	...
25	Total	100.18	100.04	99.70	100.01	100.00
26	EQUIVALENTS:					
27	Calcium Carbonate	63.56	52.46	54.39	81.77	69.93
28	Calcium Phosphate	...	...	...	...	...
29	Calcium Sulphate	...	...	...	...	...
30	Magnesium Carbonate	32.01	38.54	39.98	5.91	25.94
31	...	...	...	...	...	...
32	GEOLOGICAL HORIZON	...	...	...	...	...
33	PETROGRAPHIC ZONE	A-Y Cherokee(?)	A-Y Cherokee(?)	A-Y Cherokee	A-Y Cherokee (?)	A-Y Cherokee (?).
34	GEOGNOSTIC	Pit; 8 ft. marble interstrat. with hornblende and quartzose slates	Upper Strat.; 4 ft. gray limestone interstratified with hornblende and mica slates.	Lower Stratum; 9 ft. gray limestone interlam. with hornblende and mica slates.	Bed of branch; thickness indeterminable interstrat. with biotite and hornblende slates.	Ravine; 5 to 7 ft. marble interlam. with quartz and mica slates.

REFERENCES

Clark, J.W., 1957, Contact Metamorphism in Laurens County, South Carolina, South Carolina: South Carolina State Development Board Division of Geology, Mineral Industries Laboratory Monthly Bulletin, v. 1, no. 4, pp. 2-7.

Horkowitz, J.P., 1984, Geology of the Philson Crossroads 7.5; quadrangle, South Carolina – Nature of the boundary separating the Inner Piedmont from the Carolina-Avalon terrane in central northwestern South Carolina [M.S. thesis]: Columbia, University of South Carolina, 100 p.

Kyzer and Hellams, 1883, A Complete Map and Sketch of Laurens County, South Carolina: laurens County Library.

Niewendorp, Clark A., 1993, Bedrock Geology of the Ware Shoals East 7.5 minute Quadrangle: OFR-76: Columbia: South Carolina Geological Survey.

Ruffin, Edmund, 1843, Report of the Commencement and Progress of the Agricultural Survey of South Carolina for 1843. Columbia, South Carolina.

Sloan, E. 1908, Catalogue of the mineral localities of South Carolina: South Carolina Geological Survey Bulletin 2, 505 p.

Snipes, David S., 1969, Metasomatism and Granitization at Master's Kiln, Laurens County, South Carolina: Geological Society of America [Southeastern Section] Abstracts with Programs, p. 77.

Tuomey, M., 1844, Report of the Geological and Agricultural Survey of the State of South Carolina: Columbia, South Carolina.

Tuomey, M., 1848, Report on the Geology of South Carolina: Columbia, South Carolina.

Twitchell, 1911, Annual Report of the State Geologist: South Carolina Geological Survey, Series V, First Report, 38 p.

Willis, J., 1984, Geology of the Cross anchor area: The boundary between the Carolina terrane and the Inner Piedmont in northwestern South Carolina [M.S. thesis]: Columbia, University of South Carolina, p. 61.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 57-69

MAFIC MINERAL CRYSTALLIZATION IN SOUTH CAROLINA DIABASE

Richard D. Warner, Nicholas B. Kidd and David S. Snipes
Department of Geological Sciences
Clemson University
Clemson, SC 29634-1908

Jeffrey C. Steiner
Department of Earth and Planetary Sciences
City College
City University of New York
New York, NY 10031-9198

INTRODUCTION

The Mesozoic diabase dikes of South Carolina belong to the eastern North America (ENA) Magmatic Province which encompasses intrusions and extrusions of predominantly tholeiitic magma emplaced along the Atlantic margin of the Appalachian Mountains. Surficial exposures of diabase within the state are confined to the Piedmont region and are characterized exclusively by steeply dipping to vertical, northwest-trending dikes (Ragland, 1991). Diabase dikes also occur in the subsurface to the east of the Fall Line, where they are overlain by sediments of the Atlantic Coastal Plain (Popenoe and Zeitz, 1977; Daniels and others, 1983). Extrusive diabase has been reported only from the Clubhouse Crossroads cores near Charleston (Gottfried and others, 1983).

Most recent investigations of South Carolina diabase dikes have emphasized their geochemistry and geographic distribution. In their pioneering geochemical study of ENA diabase, Weigand and Ragland (1970) established that dikes in the South Carolina portion of the province are ubiquitously olivine-normative. Subsequent analyses published for diabase dikes in Greenville and Pickens Counties (Warner and others, 1985), Abbeville and Greenwood Counties (Warner and others, 1986) and Chester and Fairfield Counties (Warner and others, 1993) have all been olivine-normative. A similar conclusion was reached by Ragland and others (1992), who presented an extensive geochemical compilation of ENA diabase from South Carolina to central Virginia. The only reported instances of intrusive quartz-normative diabase in South Carolina are that for an exceptionally thick (342 m) dike in Lancaster County (Steele and Ragland, 1976) and one analysis of diabase from the Haile-Brewer area (Bell, 1988). In contrast, subsurface basalt flows cored by the Clubhouse Crossroads Test Holes # 1-3 in southern Dorchester County are mostly quartz-normative tholeiites (Gottfried and others, 1977; 1983).

The geologic map of the crystalline rocks of South Carolina compiled by Overstreet and Bell (1965) showed a decided prevalence of northwest trends for diabase dikes that had been mapped prior to 1960. Bell (1988) published a second map showing the locations of diabase dikes recognized since 1960, including a large number of dikes that had been mapped in the Haile-Brewer area (Bell and others, 1980). With very few exceptions the dikes plotted of Bell's map have a northwest strike. More recent maps of diabase dikes in Chester and Fairfield Counties (Butler, 1989; Warner and others, 1993) likewise indicate dominance of northwest strikes (mostly between N40°W and N15°W). In addition to the apparent structural control on dike orientations, Bell (1988) noted that dikes in South Carolina tend to occur in major outcropping swarms spaced approximately 20 miles apart. Some of these swarms extend across the entire Piedmont region.

Relatively few studies have focused on mineralogical aspects of South Carolina diabase. Chalcraft (1976) described the petrography of sixteen dikes for which Weigand (1970) had reported chemical analyses. Chalcraft estimated plagioclase An contents and Fo of olivine based on optical and X-ray data, respectively. Actual mineral analyses (via electron microprobe) for South Carolina diabase have been published only by our group (Warner and others, 1985; 1986; 1993). The mineral data we have accumulated have revealed surprisingly large (given the rather limited range in major element bulk chemistry) variations from one dike to another in the compositions of the major magmatic phases, particularly pyroxene and olivine. Furthermore, analyses of multiple samples within a given dike have indicated significant changes in mafic mineral chemistry related to distance from the contact (Warner and others, 1986; 1992).

In order to explore further the interrelationships between diabase composition, cooling rate and mafic mineral chemistry, we selected three dikes for detailed study. They were: the Easley diabase in Pickens County, Edgemoor diabase (herein named after the proximity of the type locality to the small community of Edgemoor) in Chester County and Shoals Junction diabase in Abbeville and Greenwood Counties (Fig. 1). Each dike was sampled at several intervals to obtain specimens from their contacts and interiors so as to assess the relative effects of rapid cooling (near contact) versus slower cooling (near center) on mafic mineral compositions.

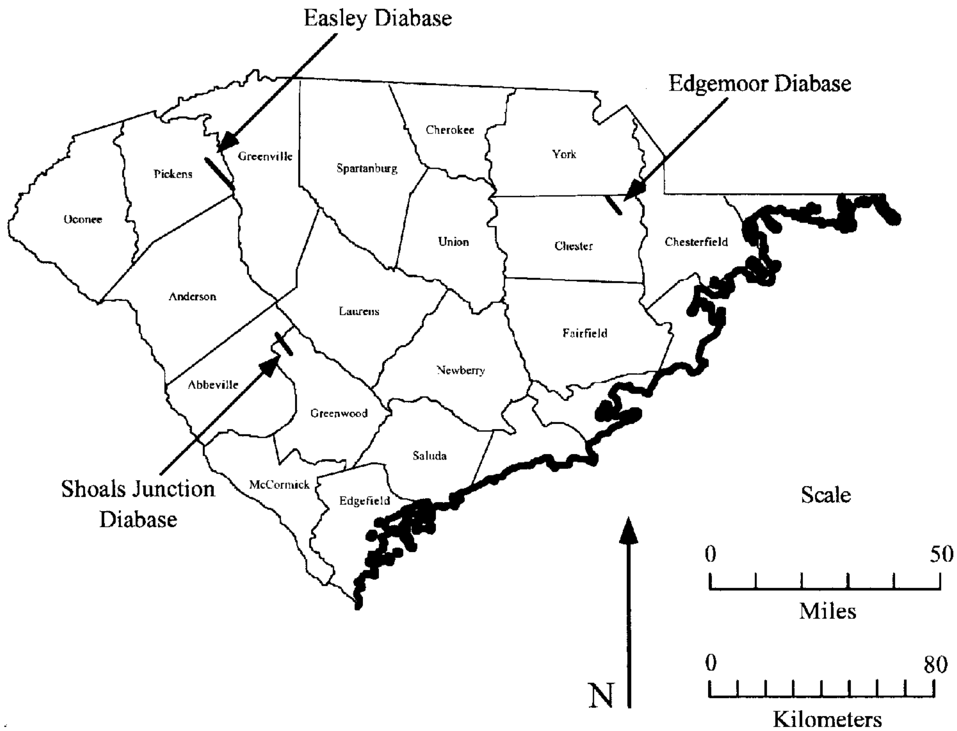


Figure 1. Index map showing the location of diabase dikes studied in this investigation.

Description of Dikes

Dike composition and outcrop exposure were the two principal criteria used to select the dikes studied in this investigation. The Easley diabase lies near the Fe, Ti-rich, Mg-poor end of the compositional spectrum displayed by South Carolina dikes; it is also higher in Na_2O than most of the dikes we have analyzed (Warner and others, 1985; 1992). In comparison to the Easley diabase, the Edgemoor diabase has lower iron oxide, TiO_2 and alkalis and higher MgO (Warner and others, 1993). The Mg-rich composition of this dike is typical of many of the dikes we have analyzed in Chester and Fairfield Counties. The third dike chosen for study (Shoals Junction diabase) was selected because it is one of two South Carolina diabase dikes known to be light REE-depleted (D type of Gottfried and Arth, 1985). This dike is also characterized by extreme depletion in K_2O, P_2O_5 and Th (Warner and others, 1985; 1992).

The Easley diabase was mapped and described by Snipes and Furr (1979). They documented that the dike has a nearly vertical dip and trends N40°W, and were able to trace its outcrop pattern for approximately 14 km along strike. The type locality for the Easley diabase is along an unnamed creek a few hundred meters south of the Southern Railroad tracks, 10 km east of Easley. Here there is 54 feet (16.5 m) of nearly continuous exposure of diabase transverse to strike. Samples were taken at the northeastern contact and at distances (from this contact) of 1, 6, 12 and 24 feet.

The dike that we refer to as the Edgemoor diabase is part of a swarm of diabase dikes that populate eastern Chester and northeastern Fairfield Counties (Warner and others, 1993). It was originally mapped by Butler (1989), who showed a segment of diabase dike 1 km long and trending about N25°W outcropping near Edgemoor in northern Chester County. An excellent exposure of this dike occurs about 200 meters east of the Clinton Branch of Fishing Creek, along a secondary road slightly more than 1 km northwest of Edgemoor. At this type locality we measured the thickness of the dike to be 61 feet (18.6 m) and estimated its trend to be N40°W. This is a greater thickness than observed for most dikes in the region (Warner and others, 1993), and suggests that we are dealing with a relatively large dike, almost certainly considerably longer than 1 km. (Butler's map shows another short diabase dike segment about 5 km southeast of Edgemoor; the projection of its trend intersects the Edgemoor diabase and, hence, we speculate that it is an extension of the same dike.) Samples of the dike were taken at the contact (best exposed on the southeast side of the road) and at distances of 1, 4, 12 and 30 feet from the contact.

The Shoals Junction diabase was described by Warner and others (1986). They mapped the dike's length to be 8.7 km, with the northern end in Abbeville County and its southern terminus in Greenwood County, about 5.8 km south of the county line. Its strike is somewhat variable, but the overall trend is approximately N40°W. Actual outcrops are rare; indeed, no exposure could be found extensive enough to warrant designation as a type locality. A magnetometer pro-

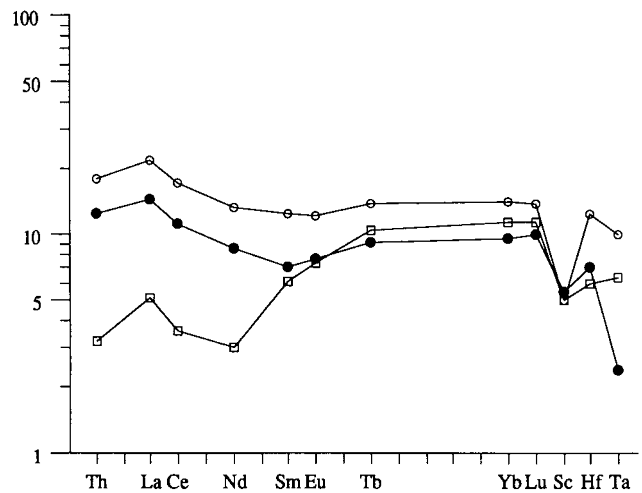


Figure 2. Plot of Chondrite-normalized Th, REE, Sc, Hf and Ta abundances in chilled margin samples of diabase dikes. Open circle, Easley diabase; closed circle, Edgemoor diabase; open square, Shoals Junction diabase.

file across the Shoals Junction diabase indicates that it consists of a swarm of small dikes instead of a single intrusive (Snipes and others, 1984). The maximum estimated thickness of any individual dike is about 10 m. Despite the poor exposure, we have included the Shoals Junction diabase in this study because of its unique geochemical signature (D type of Gottfried and Arth, 1985). At one locality northwest of Highway 420 and less than 100 m northeast of the Southern Railroad tracks in Shoals Junction, we were able to obtain a sample representative of the chilled margin, while along Mulberry Creek, about 4 km southeast of Shoals Junction, coarser-grained pieces of diabase float were collected as samples of the dike's interior.

The compositions of the three dikes studied, as indicated by analyses of the contact (chilled margin) samples, are reported in Table 1. The Easley diabase chilled margin has a high content of iron oxide (here reported as Fe_2O_3) which, coupled with its low MgO, yields a Mg number (Mg#) of 59, close to the lower limit found for South Carolina diabase. This sample also contains the highest Na_2O obtained for these rocks. The Edgemoor diabase has a higher Mg#, close to the midpoint of the range reported. Relative to the Easley diabase, the Edgemoor chilled margin sample has lower TiO_2 and alkalis (particularly NaO_2), slightly lower Al_2O_3 and slightly higher CaO, and more than twice as much of the compatible trace elements Cr and Ni. The Shoals Junction diabase has an intermediate Mg#; Al_2O_3 and CaO are higher, and SiO_2 is lower than in the Easley and Edgemoor dikes. Notably, K_2O is extremely low, and Cr is near the lower limit observed for South Carolina diabase.

Chondrite-normalized data for the REE and other incompatible trace elements (Th, Hf and Ta) are shown in Fig. 2. Both the Easley and Edgemoor diabases are light-REE enriched (negative slope for light REE) and have slightly positive slopes for the heavy REE. This type of REE pattern corresponds to the E group of Gottfried and Arth (1985) and, with slight variations, is typical of the vast majority of South Carolina diabase dikes. The only difference between these two dikes is in the absolute abundance of the REE: values for the Easley diabase are consistently about

Table 1. Bulk Chemical Analyses of Chilled Margin Samples[1]

	Easley	Edgemoor	Shoals Junction	South Carolina Diabase	Error
SiO_2 (%)	47.2	47.4	46.6	45.0-50.7	3%
TiO_2	0.81	0.51	0.60	0.26-0.94	2%
Al_2O_3	16.0	15.6	17.2	12.5-19.7	3%
Fe_2O_3	13.85	12.15	12.5	8.3-14.7	5%
MgO	9.0	11.4	9.7	8.3-19.2	3%
CaO	10.4	10.95	11.15	8.3-12.0	3%
Na_2O	2.43	1.80	2.21	1.19-2.43	3%
K_2O	0.27	0.19	0.06	0.05-0.61	2%
Mg#3	58.9	67.4	63.1	57-79	
Sc (ppm)	39	42	38	26-70	3%
Cr	329	827	194	44-2200	10%
Ni	204	433	250	130-747	12%
La	6.9	4.5	1.58	1.3-9.6	3%
Ce	14.0	9.0	2.9	2.9-23.9	7%
Nd	8.1	5.1	1.8	2.9-23.9	12%
Sm	2.44	1.37	1.20	1.8-9.3	5%
Eu	0.89	0.57	0.55	0.88-2.97	5%
Tb	0.65	0.43	0.49	0.38-0.99	5%
Yb	3.01	2.01	2.37	0.28-0.75	5%
Lu	0.45	0.32	0.37	1.43-3.24	5%
Hf	1.95	1.1	0.93	0.24-0.49	5%
Ta	0.20	0.05	0.13	0.7-2.2	5%
Th	0.72	0.5	0.13	0.05-0.3	5%

1 Major element concentrations normalized to 100 wt. % to facilitate comparisons0.12-1.7
2 Range for 64 analyses obtained by our group (including this study)
3 Mg Number, Mg# = 100 x (MgO/40.31)/((0.9 x Fe_2O_3)/79.85 + MgO/40.31)

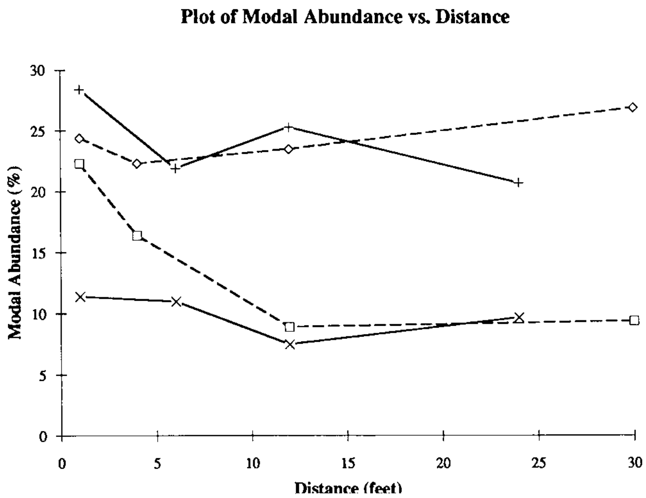


Figure 3. Plot of modal abundance of olivine and pyroxene in Easley and Edgemoor diabases vs. distance from contact. X's, Easley olivines; +'s, Easley pyroxenes; open squares, Edgemoor olivines; open diamonds, Edgemoor pyroxenes.

50% higher than for the Edgemoor diabase. In contrast, the REE pattern for the Shoals Junction diabase is depleted in the light REE and has a more pronounced positive heavy-REE slope. Consequently, this dike is classed as group D (Gottfried and Arth, 1985). This type of diabase is very rare in South Carolina; in fact, the only other documented instance is sample number 440 from the Haile-Brewer area (Bell, 1988).

MAFIC MINERALOGY

Plagioclase, pyroxene, and olivine, and their alteration (chiefly sericite, chlorite and iddingsite) constitute more than 90% of the rocks. The remainder of the diabase is composed of 2-3% opaque minerals (principally titanomagnetite with subordinate chromite) and up to 8% brownish, cryptocrystalline mesostasis. In all three dikes, plagioclase is the most abundant mineral present, often comprising more than 50% of the samples (up to a maximum of 58%). Pyroxene is usually more abundant than olivine, although one sample of the Shoals Junction diabase contains 2% more modal olivine than pyroxene. The samples of Easley diabase contain 8-11% modal olivine, with a very slight decrease in amount towards the interior of the dike (Fig. 3). The Edgemoor diabase shows a much greater variation in olivine content, decreasing from 22% near the contact to about 9% near the center of the dike (Fig. 3). The samples of Shoals Junction diabase contain 17-19% olivine, with the coarsest-grained rock having the highest amount.

Textures of the diabase show considerable variation related to distance from the contact. The chilled margin samples in all three dikes are microporphyritic with aphanitic groundmasses (Fig. 4). Olivine is the principal microphenocrystic mineral, occurring as equant to subequant crystals, frequently skeletal in form. Some tabular plagioclase microphenocrysts are present in the Shoals Junction contact sample (Fig. 4C). Grain size progressively increases towards the centers of the dikes. Interior samples of the Easley and Shoals Junction diabases are medium-grained with intergranular to subophitic textures (Fig. 4). The largest plagioclase crystals are 3 to 3.5 mm long, while maximum dimensions of both pyroxene and olivine grains are 1.5 to 2 mm in the Shoals Junction dike and 2 to 2.5 mm in the Easley dike. Ophitic textures predominate in the interior of the Edgemoor dike; the coarsest sample (EMD-30) contains plagioclase laths up to 2 mm long partly to wholly enclosed by large, anhedral pyroxene grains up to 1 cm in diameter. Subequant, partly resorbed olivine crystals up to 2.5 mm long are dispersed throughout the rock.

Mafic mineral compositions in the Easley, Edgemoor and Shoals Junction diabases are summarized in Figs. 5-7. Olivine compositions are indicated by histograms of mol% Fo; solid bars represent analyses of the cores of olivine crystals, and striped bars show compositions of olivine rims and small groundmass olivines (if present). Most large olivine crystals (microphenocrysts in aphanitic samples) have Fo $\geq$80 mol% (maximum, Fo_{85-87}). Rims and groundmass olivines are considerably less magnesian (as low as Fo_{30} in SJD-B). `

Pyroxene compositions are plotted in the pyroxene quadrilateral. Both augite and low-Ca pyroxene are present in the Easley and Edgemoor dikes. Cores of pyroxene crystals are represented by the most magnesian augite analyses; rims are more Fe-rich augite and/ or low-Ca pyroxene. Only calcic pyroxene (augite cores to ferroaugite rims) occurs in the Shoals Junction diabase.

DISCUSSION

The remainder of this paper focuses on factors affecting the chemistry of the mafic minerals in the three dikes. There are two principal aspects to consider. First, there is the question of how cooling rate affects pyroxene and olivine compositions. This can be addressed rather straightforwardly by comparing pyroxene/ olivine analyses among the samples collected at various positions (relative to the contact), within individual dikes. Once the parameters for compositional change on the basis of cooling history are established for each dike, we can then examine the second factor of how differences in magma chemistry influence mafic mineral composition. The differences in bulk composition among the three dikes are not pronounced (Table 1), but they are sufficient to produce clearly discernible differences in pyroxene quadrilateral trends and olivine end member plots

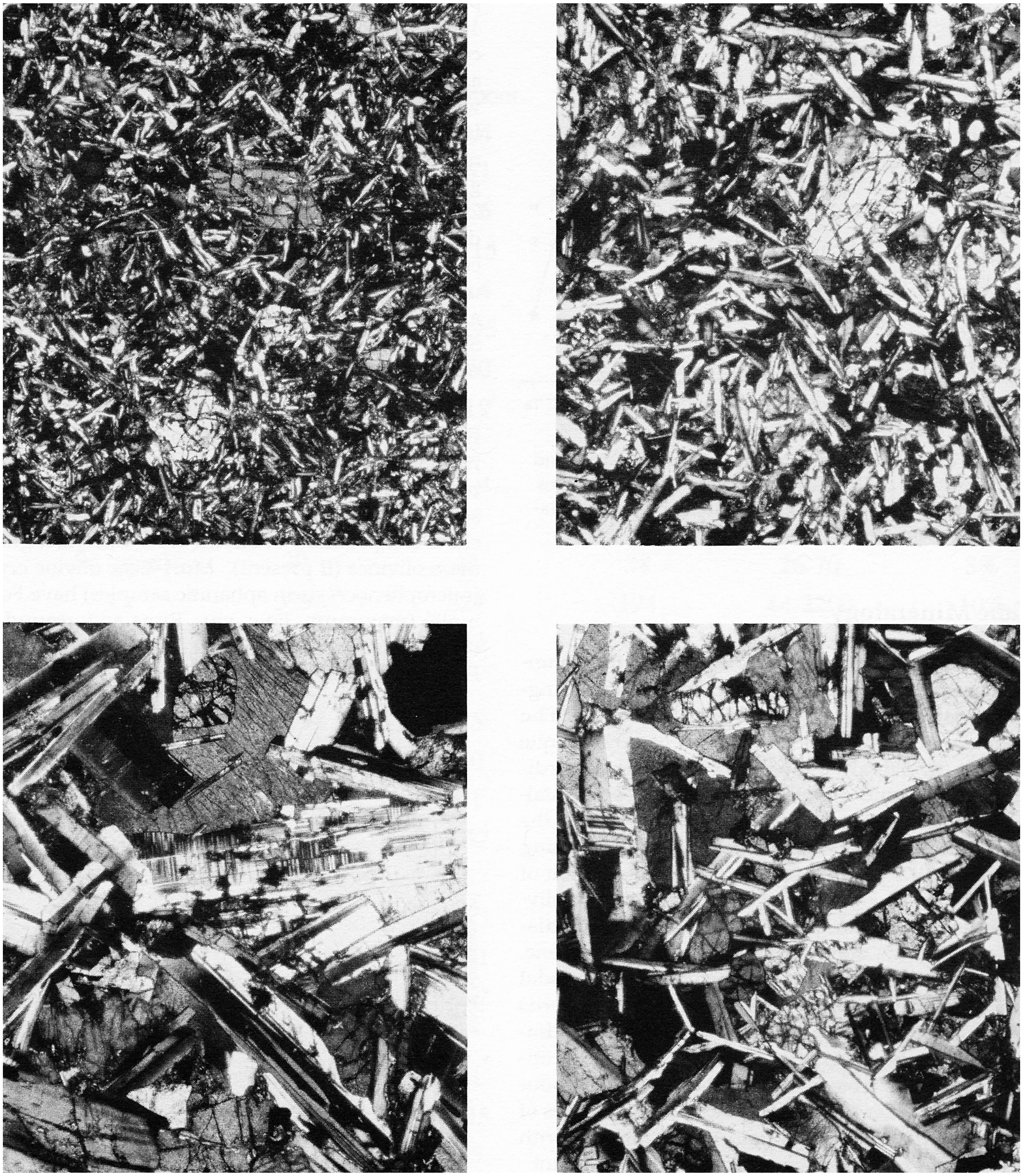


Figure 4. Photomicrographs (X nicols) of diabase thin sections showing textural changes related to position in dike. Long dimension is 4mm except in backscattered electron image (Fig. 4C) where bar in photo gives scale. A). Easley diabase. Samples are, clockwise from upper left, EAD-0; EAD-1; EAD-6 and EAD-24. Note change from microporphyritic texture (olivine microphenocrysts) in chilled margin to subophitic texture near center of dike.

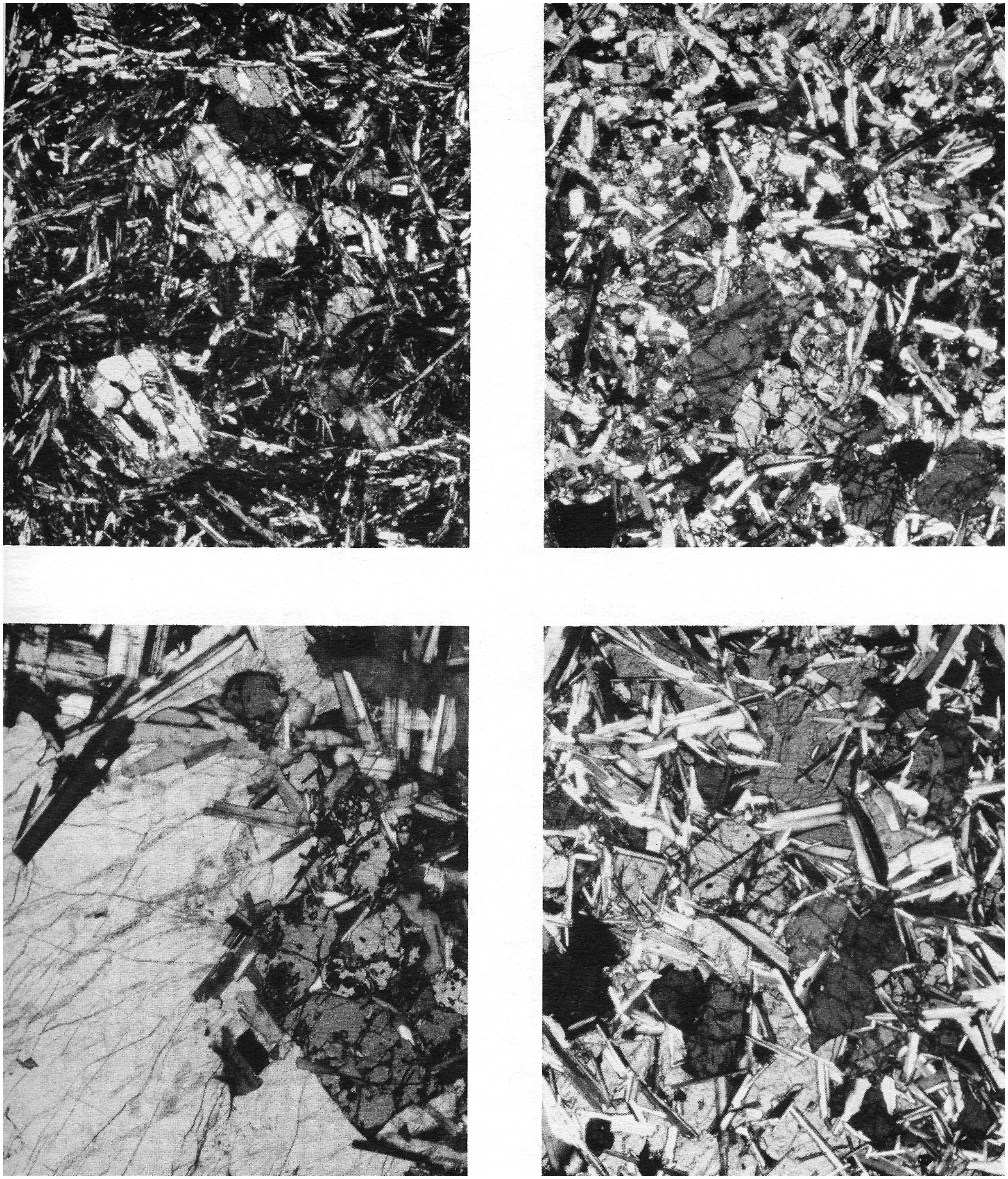


Figure 4B. Edgemoor diabase. Samples are, clockwise from upper left, EMD-0; EMD-1; EMD-4 and EMD-30. Texture goes from aphanitic with olivine microphenocrysts in chilled margin to ophitic with very large pyroxene grains in interior of dike.

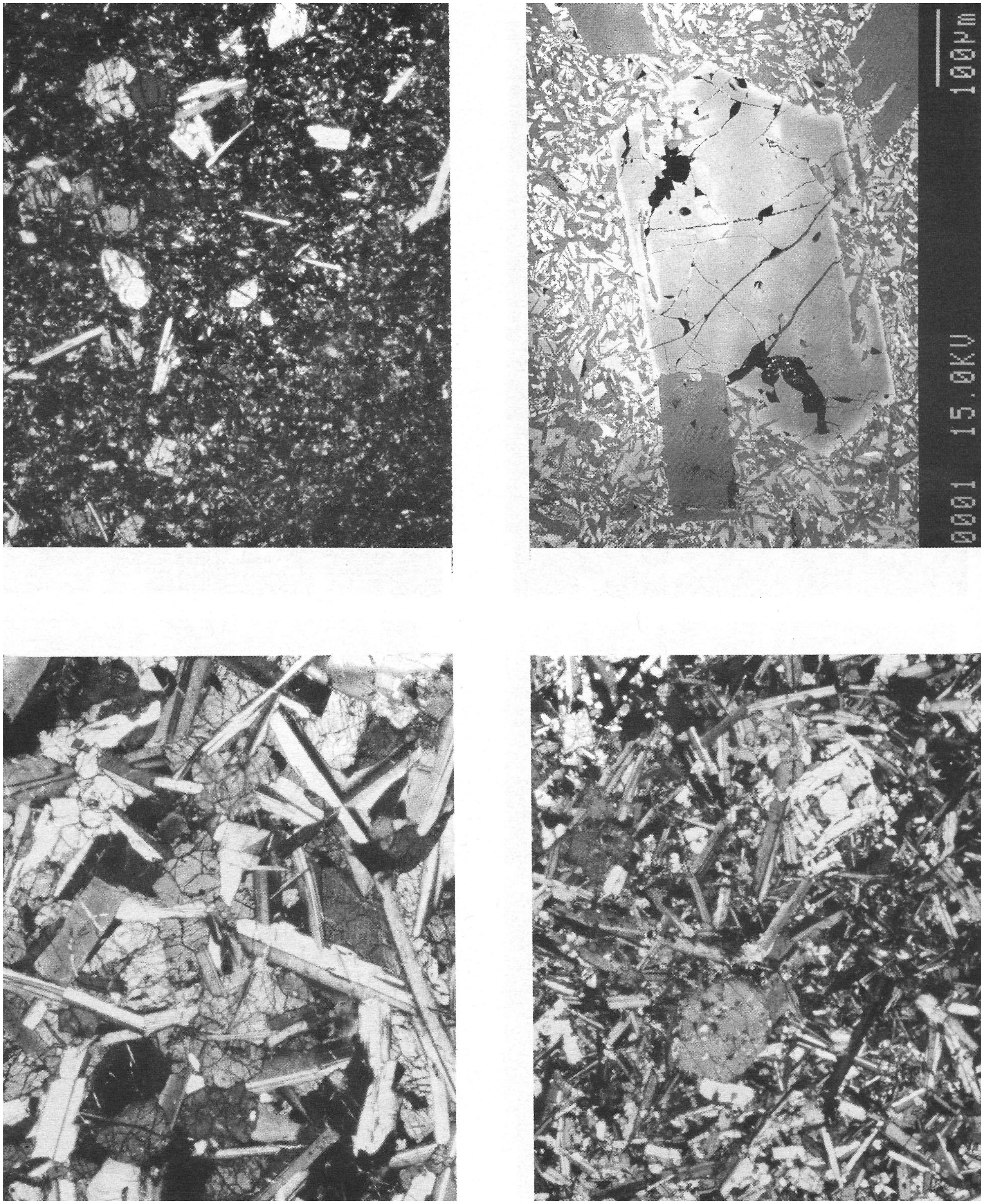


Figure 4C. Shoals Junction diabase. Samples are, clockwise from upper left, SJD-A; backscattered electron image showing euhedral olivine microphenocryst (center) and plagioclase laths (dark) in SJD-A; SJD-B and SJD-C. Progression is from microporphyritic to intergranular texture.

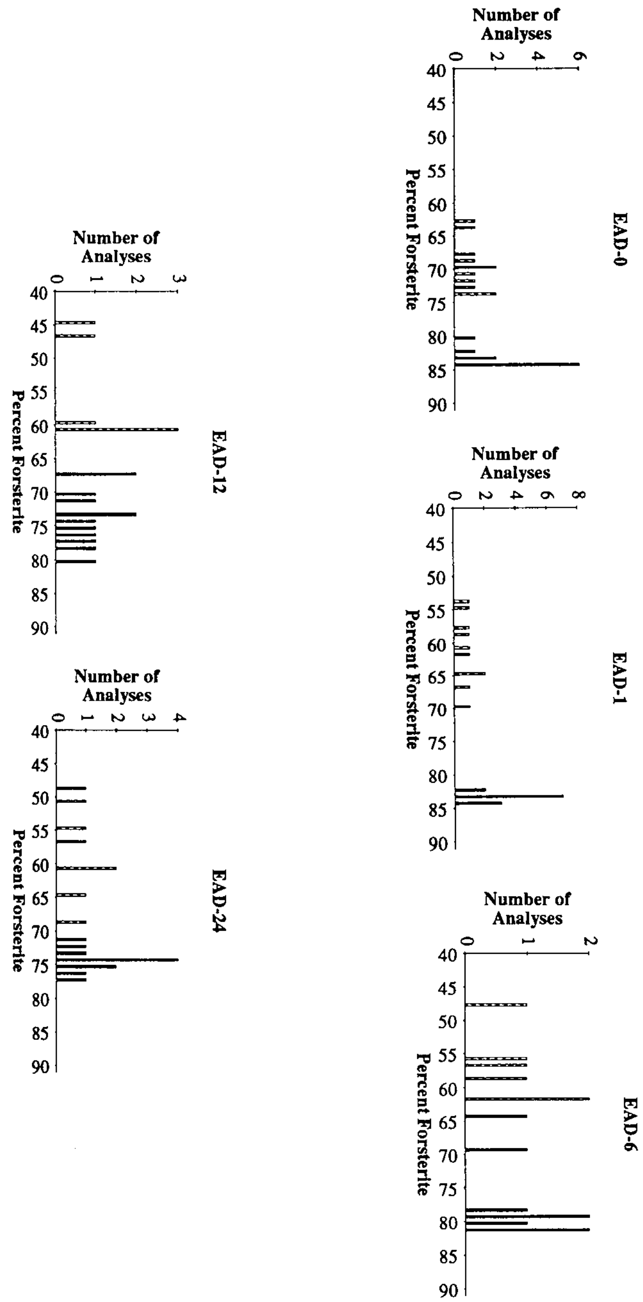


Figure 5A. Histograms showing composition of olivine in Easley diabase. Solid bars indicate composition of cores and striped bars give compositions of rims and/or groundmass olivines.

(Figs. 5-7).

EFFECT OF COOLING RATE

In both the Easley and Edgemoor diabases there is a progressive change in pyroxene and olivine compositions related to distance from the contact. In order to clarify this relationship, we have selected for comparison the compositions of the earliest-crystallizing (i.e., most magnesian) olivine and pyroxene in each sample from the two dikes. The results are plotted in Figure 8 as a function of distance from the contact. Examination of this figure reveals that there is a decrease of 7-8% in Fo content of the earliest-crystallizing olivine between the chilled margins and centers of both dikes, and that there is a concomitant increase of 12-16% in En content of the earliest-crystallizing pyroxene. A similar relationship of decreasing %Fo and increasing %En as a function of increasing grain size (slower cooling) was reported for the Due West diabase in Abbeville County (Warner and others, 1986) and for several thick dikes in Chester and Fairfield Counties (Warner and others, 1993). Thus, it appears to be a common feature of relatively thick diabase dikes. Other aspects of the cooling rate dependence become apparent when microprobe analyses of individual calcic pyroxene crystals are compared (Table 2). The data indicate that, in addition to MgO, there is a marked increase in SiO_2 and Cr_2O_3 in augite as one moves toward the centers of the dikes, while TiO_2, Al_2O_3 and FeO significantly decrease.

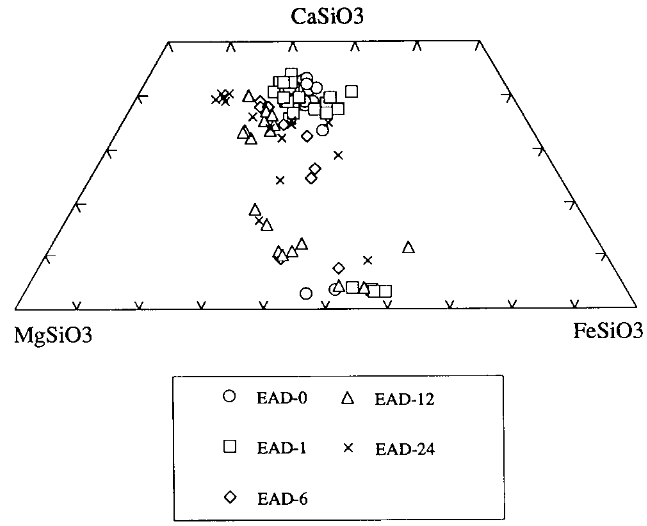


Figure 5B. Pyroxene quadrilateral plot showing composition of pyroxene in Easley diabase.

We attribute the compositional changes observed above to varying degrees of disequilibrium crystallization. Very rapid cooling at the dike contact effectively quenched the liquidus olivine compositions, allowing little opportunity for olivine crystals to react with the magma. Pyroxene compositions were also quenched: note how closely SiO2, FeO and MgO in the Easley/Edgemoor chilled margin pyroxenes resemble the values found in the bulk rocks (Table 1). Where slower cooling prevailed, toward the centers of the dikes, there was a closer approach to equilibrium. Under these conditions, early-formed olivines had time to partially react with the melt and convert to more Fe-rich crystals. The reactions were far from complete, however, as evidenced by extensive

Table 2. Pyroxene analyses in South Carolina diabase

	Easley Diabase					Edgemoor Diabase					Shoals Junction Diabase	
	EAD-0	**EAD-1**	**EAD-6**	**EAD-12**	**EAD-24**	**EMD-0**	**EMD-1**	**EMD-4**	**EMD-12**	**EMD-30**	**SJD-A**	**SJD-C**
SiO2	47.08	48.13	49.42	49.80	52.42	47.47	49.81	50.44	53.18	51.79	50.97	50.52
TiO2	1.25	1.26	0.77	0.62	0.32	1.25	0.85	0.35	0.18	0.26	0.43	0.48
Al_2O_3	4.52	4.77	4.20	3.65	2.77	6.43	3.81	3.37	2.11	2.25	3.19	3.18
Cr_2O_3	0.07	0.13	0.15	0.20	0.49	0.19	0.15	0.82	0.61	0.47	0.20	0.20
FeO	14.91	12.88	11.61	10.98	7.92	11.17	8.91	6.01	6.33	7.69	10.10	11.91
MnO	0.33	0.20	0.21	0.28	0.15	0.24	0.27	0.15	0.13	0.25	0.22	0.25
MgO	10.62	12.68	13.71	14.54	16.88	12.49	16.12	16.77	17.98	17.75	15.59	14.46
CaO	19.94	19.01	19.02	19.11	19.38	20.19	19.87	21.03	19.82	19.86	17.88	18.84
Na_2O	0.40	0.40	0.37	0.40	0.33	0.35	0.40	0.29	0.25	0.18	0.27	0.28
Total	99.12	99.46	99.46	99.58	100.66	100.50	100.19	99.23	100.59	100.50	98.85	100.11
Si	1.829	1.836	1.869	1.877	1.920	1.788	1.854	1.876	1.936	1.905	1.914	1.896
Ti	0.037	0.036	0.022	0.018	0.009	0.036	0.024	0.010	0.005	0.006	0.012	0.013
Al	0.207	0.241	0.187	0.162	0.120	0.285	0.167	0.148	0.091	0.097	0.141	0.140
Cr	0.002	0.004	0.004	0.006	0.014	0.006	0.006	0.024	0.018	0.013	0.006	0.005
Fe	0.484	0.411	0.367	0.346	0.243	0.352	0.277	0.187	0.193	0.236	0.317	0.373
Mn	0.011	0.006	0.007	0.009	0.005	0.008	0.008	0.005	0.004	0.007	0.007	0.007
Mg	0.615	0.721	0.773	0.817	0.922	0.701	0.894	0.930	0.976	0.972	0.873	0.808
Ca	0.830	0.776	0.770	0.772	0.761	0.844	0.793	0.838	0.773	0.782	0.720	0.0756
Na	0.030	0.030	0.028	0.029	0.024	0.025	0.029	0.021	0.018	0.012	0.019	0.020
Sum	4.045	4.034	4.027	4.036	4.018	4.045	4.051	4.039	4.014	4.030	4.009	4.019
Wo	43.0	40.7	40.3	39.9	39.5	44.5	40.3	42.9	39.8	39.3	37.7	39.0
En	31.9	37.8	40.5	42.2	47.9	37.0	45.5	47.6	50.3	48.8	45.7	41.7
Fs	25.1	21.5	19.2	17.9	12.6	18.6	14.1	9.6	9.9	11.9	16.6	19.3
2Ti	26.1	24.8	18.7	17.6	11.8	19.8	21.8	10.4	8.4	9.8	14.0	15.2
Al	73.1	43.8	79.6	79.4	78.9	78.5	75.9	77.1	76.5	79.5	82.5	81.9
Cr	0.7	1.4	1.7	2.9	9.2	1.7	2.3	12.5	15.1	10.7	3.5	2.9

zoning in larger olivine crystals. Two separate effects may have operated to increase Mg in pyroxene. To the extent that reaction of early magnesian olivines occurred, Mg would have been liberated, which could then be incorporated in pyroxenes. Also, under slower cooling conditions pyroxene crystallization likely would have commenced at a smaller degree of undercooling (higher temperature), where more Mg-rich compositions would be stable.

The samples of the Shoals Junction diabase show little change in mafic mineral chemistry related to cooling rate. The composition of the most magnesian olivine is approximately Fo85 in all three samples analyzed (Fig. 7) despite a significant difference in grain size (Fig. 4C). there is a modest change in the composition of the most magnesian pyroxene, with a slight increase in FeO and decrease in MgO between the chilled margin (SJD-A) and coarsest-grained (SJD-C) samples (Table 2). The compositional change is very much smaller and in the opposite direction to that observed for the Easley and Edgemoor diabases. Further, SiO2, TiO2, Al2O3 and Cr2O3 are virtually identical in the two samples.

The similarity in olivine and pyroxene compositions among the Shoals Junction diabase samples suggests a negligible cooling rate effect. Perhaps this simply reflects the fact that the dike is not as thick as the Easley and Edgemoor dikes, and disequilibrium crystallization may have prevailed throughout the intrusion. Support for this interpretation is provided by the extreme zoning (30-50 mol% Fe-enrichment from core to rim) displayed by olivine crystals in SJD-B (Fig. 7).

EFFECT OF DIKE COMPOSITION

The effect of bulk composition on mineral chemistry is simpler to assess in the case of olivine since (1) it is a liquidus phase and (2) its Fo content is primarily dependent only on the Mg# of the magma. To avoid complications that arise from changes in Fo due to reaction of olivine crystals with the melt, such as occur in the more slowly cooled interiors of the dikes, we consider here only the chilled margin samples. The most magnesian olivine compositions are found in the Edgemoor diabase (sample EMD-0, maximum Fo: 87.1). For comparison, the most magnesian olivine in the Easley dike is $Fo_{84.7}$, and in the Shoals Junction dike it is $Fo_{85.3}$. These are in general agreement with the bulk chemical analyses (Table 1), which show that the Edgemoor diabase has the highest Mg# and the Easley diabase the lowest. A more precise comparison is possible through calculation of liquidus olivine compositions using the olivine-liquid distribution coefficient (KD = 0.30) experimentally determined for basaltic liquids by Roeder and Emslie (1970). The results predict a liquidus Fo about 2 mol% too low ($Fo_{82.7}$) for the Easley diabase but give almost exact agreement for the Edgemoor ($Fo_{87.3}$ calculated vs. $Fo_{87.1}$ observed) and Shoals Junction ($Fo_{85.1}$ calculated vs. $Fo_{85.3}$ observed) dikes. The slightly low value calculated for the Easley diabase may indicate minor loss of olivine from the chilled margin sample due to crystal fractionation.

Assessment of how magma composition affects pyroxene chemistry is considerably more difficult. In the first place, pyroxene quadrilateral compositions depend not only on Mg# but also on the amount of CaO available. In addi-

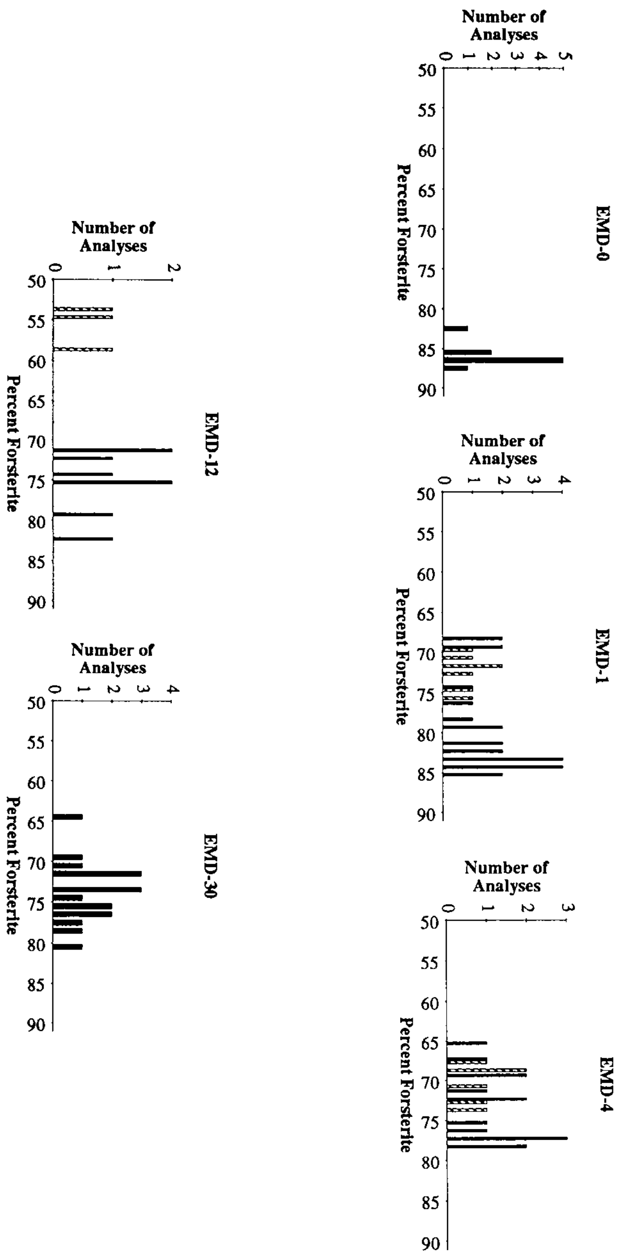


Figure 6A. Histograms showing composition of olivine in Edgemoor diabase. Symbols same as in Fig. 5A.

tion, non-quadrilateral components such as Al_2O_3, TiO_2, etc. can be significant. Secondly, pyroxene is not a liquidus phase in these rocks; its crystallization is preceded by that of olivine and, in some instances, plagioclase (chromite, too, often crystallizes before pyroxene, taking up Cr_2O_3 that otherwise would enter the pyroxene structure). As a result, the magma composition at the onset of pyroxene crystallization is not known. Nevertheless, some reasonable inferences can be made concerning the relationship between diabase composition and pyroxene chemistry.

Again, the most direct comparisons that can be made

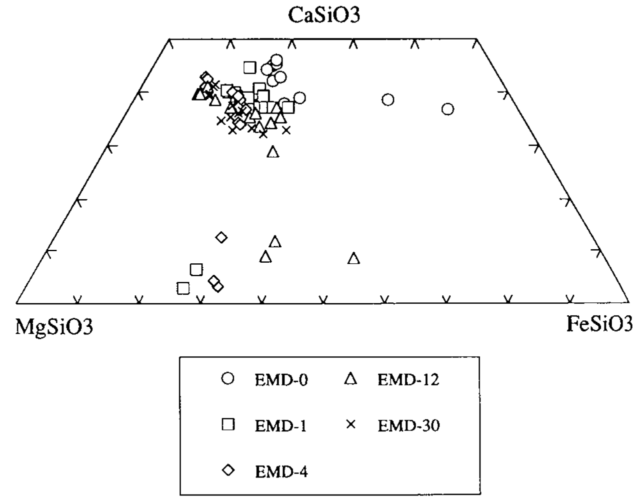


Figure 6B. Quadrilateral plot showing composition of Edgemoor pyroxenes.

involve the earliest crystallizing (i.e., most magnesian) pyroxenes. In all three dikes this is a calcic pyroxene, because the norms contain more diopside than hypersthene (Table 3). Inspection of the augite analyses in Table 2 reveals that, at corresponding distances from the contact, pyroxenes in the Edgemoor diabase are 1-8 mol% more En-rich than those in the Easley dike. Except for the chilled margin samples, calcic pyroxenes in the Edgemoor diabase are lower in Ti, Al and Na and higher in Cr than are Easley pyroxenes. These relations are in accord with the differences in bulk chemistry between the two dikes (higher MgO and Cr_2O_3 and lower TiO_2, Al_2O_3, Fe_2O_3, and Na_2O in the Edgemoor diabase).

Table 3. CIPW Norms for South Carolina Diabase[1]

	Easley	Edgemoor	Shoals Junction
Q	---	---	---
Or	1.6	1.1	0.3
Ab	20.6	15.2	18.7
An	32.0	33.9	36.9
Di	16.1	16.6	15.1
Hy	3.9	10.1	2.4
Ol	21.0	19.2	22.5
Mt	2.0	1.7	1.8
Cm	<0.1	0.2	<0.1
Il	1.5	1.0	1.1

[1] Computed from chilled margin sample analyses in Table 1, assuming 10% of the total iron is ferric.

A much different result is obtained when the Shoals Junction diabase is considered. This dike contains the lowest SiO_2 and highest Al_2O_3 and CaO of the three dikes studied, yet pyroxenes in the chilled margin sample (SJD-A) contain higher Si and lower Al and Ca than either the Easley or Edgemoor pyroxenes. Here we have the complicating factor that plagioclase, which is present as microphenocrysts in this

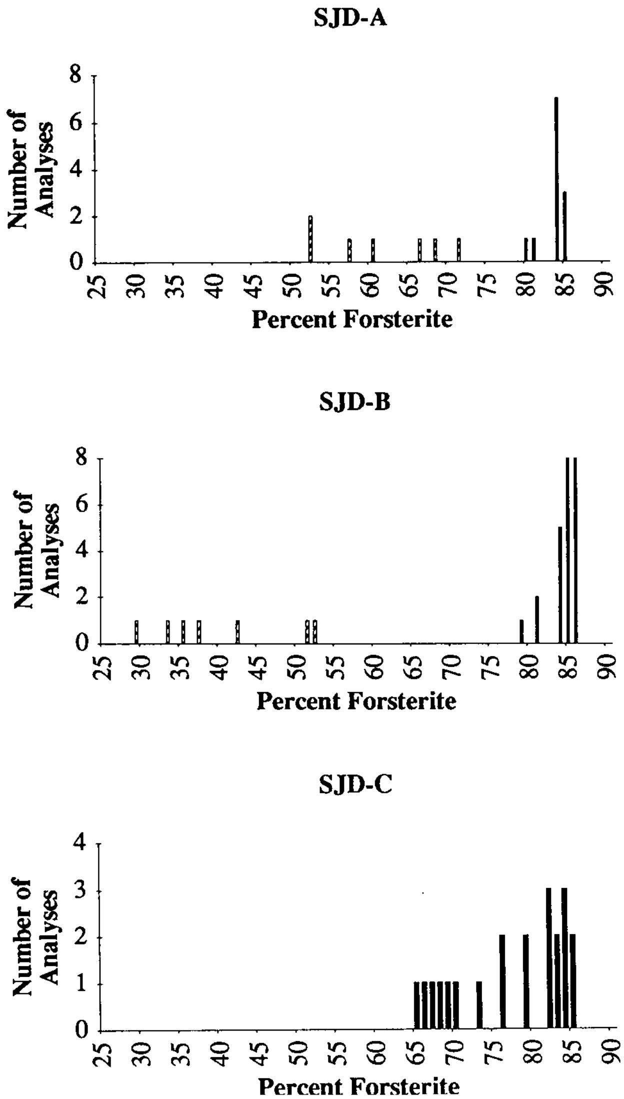


Figure 7A. Histograms of olivine composition in Shoals Junction diabase. Symbols same as in Fig. 5A.

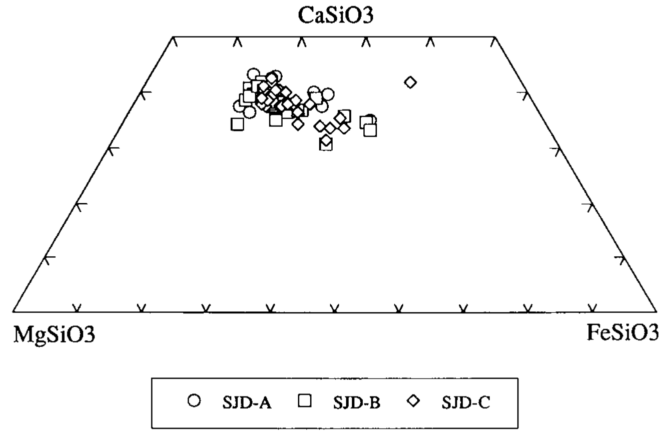


Figure 7B. Quadrilateral plot showing pyroxene compositions in Shoals Junction dike.

rock (Fig. 4C), crystallized along with olivine prior to the onset of pyroxene crystallization. Since the plagioclase is calcic (~An_{78}), its crystallization depleted the melt in both CaO and Al_2O_3. We infer that by the time pyroxene started to nucleate, the levels of CaO and Al_2O_3 in the residual liquid had dropped below those extant in the Easley and Edgemoor dikes.

The most obvious feature of the quadrilateral plots in Figs 5-7 is that both augite and low-Ca pyroxene are found in the Easley and Edgemoor dikes, whereas only calcic pyroxene crystallized from the Shoals Junction diabase. One possible explanation for this contrasting pattern relates to the amount of SiO_2. The Shoals Junction diabase has low SiO_2 (Table 1); consequently, the norm for this dike contains only 2.4% hypersthene (Table 3). One would therefore predict only a small amount of low-Ca pyroxene in this dike; instead, most of the pyroxene should be calcic. The complete absence of low-Ca pyroxene is perhaps the result of disequilibrium crystallization wherein olivine precipitated to the latest stages of crystallization (as evidenced by the extensive zoning of its crystals) and never reacted with the melt to form low-Ca pyroxene. Both the Easley and Edgemoor diabases have higher SiO_2 and, correspondingly, their norms contain more hypersthene (and slightly less olivine). As a result, one would expect more low-Ca pyroxene in these dikes and a somewhat shorter interval of olivine crystallization. Olivines in the Easley and Edgemoor dikes show less extensive zoning (typically10-30 mol% increase in Fe from core to rim), and low- Ca pyroxene did crystallize in both dikes. This is consistent with a history of early olivine crystallization followed by later reaction of olivine to form low-Ca-pyroxene. This explanation is not entirely satisfactory, however, because the Easley diabase contains more low-Ca pyroxene than the Edgemoor diabase (Figs. 5-6), yet its norm has less hypersthene (Table 3).

Another possible explanation for the contrasting pyroxene trends of the Shoals Junction vs. Easley/ Edgemoor diabases relates to the oxygen fugacity during magmatic crystallization. Osborn (1959) showed that differences in oxygen fugacity can produce different fractional crystallization trends in basaltic magmas. Under conditions of high oxygen fugacity, residual liquids are depleted in iron oxides and enriched in silica; if oxygen fugacity is low, residual liquids are enriched in iron oxides and depleted slightly in silica (Kushiro, 1979). In their study of the magnetic petrology of South Carolina diabase, Warner and Wasilewski (1990) found textural, mineral chemical and magnetic property evidence for variable amounts of oxidation in this suite of rocks. In particular, samples of the Easley diabase (e.g., SJ-22) were only slightly oxidized. If indeed the Easley diabase crystallized under higher oxygen fugacity conditions than

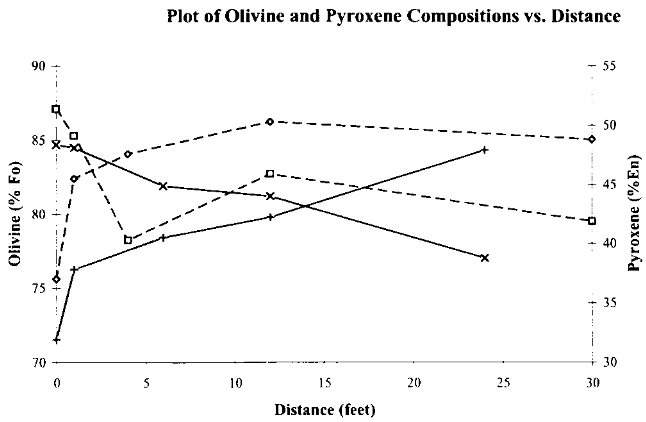


Figure 8. Plot of %Fo in olivine and %En in pyroxene showing composition of earliest crystallizing (most magnesian) grains in Easley and Edgemoor dikes as function of distance from contact. x's, Easley olivines; +'s, Easley pyroxenes; open squares, Edgemoor olivines; open diamonds, Edgemoor pyroxenes.

the Shoals Junction diabase, this may in part account for the trend of iron depletion/ silica enrichment shown by Easley pyroxenes (Fig. 8; Table 2). The contrasting rend of iron enrichment with slight depletion of silica that characterizes Shoals Junction pyroxenes (Fig. 7; Table 2) may thus reflect crystallization at a lower oxygen fugacity.

CONCLUSIONS

A petrographic and microprobe study was conducted of three diabase dikes in the South Carolina Piedmont. The Easley and Edgemoor diabases have well-exposed type localities at which samples were collected in traverses perpendicular to strike. The Shoals Junction diabase is poorly exposed but was included n this study because of its unusual geochemistry.

Mafic minerals in the Easley and Edgemoor diabases show a similar, progressive change in composition relative to distance from the dike contact. We attribute the compositional changes to differing degrees of disequilibrium crystallization caused by variations in cooling rate. In contrast, the Shoals Junction diabase samples show negligible effects due to cooling rate.

Olivine compositions in chilled margin samples from all three dikes closely match liquidus olivine compositions predicted from dike Mg#s. Pyroxene quadrilateral plots reveal a contrasting pattern for the Shoals Junction diabase in that only calcic pyroxene crystallized in this dike, whereas both augite and low-Ca pyroxene occur in the Easley and Edgemoor dikes. Possible explanations for this observation include: (1) Shoals Junction diabase did not crystallize low-C pyroxene because of its low SiO2 content, which resulted in low normative hypersthene; and/ or (2) Shoals Junction diabase crystallized at a lower oxygen fugacity than the other dikes, which resulted in residual liquids that were enriched in iron oxide and slightly depleted in silica.

ACKNOWLEDGEMENTS

We thank Chris Fleisher for his assistance with obtaining electron microprobe analyses and the back-scattered electron image photomicrograph (Fig. 4C) at the University of Georgia JEOL JXA-8600 scanning electron microprobe facility. This research was supported by research awards from Sigma Xi and the Geological Society of America to Nicholas Kidd and a travel grant from the Southern Regional Education Board to Richard Warner. We also acknowledge the USDOE Reactor Sharing Program for defraying the cost of instrumental neutron activation analyses at the Oregon State University Radiation Center. This paper has benefited from thoughtful review comments supplied by Ron Fodor and Scott Vetter.

REFERENCES

Bell, H., III, 1988, Map showing Mesozoic diabase dikes in South Carolina described since 1960: U.S. Geological Survey Miscellaneous Field Studies Map MF-2030, scale 1:250,000.

Bell, H., Books, K.G., Daniels, D.L., Huff, W.E., and Popenoe, P., 1980, Diabase dikes in the Haile-Brewer area, South Carolina, and their magnetic properties: U.S. Geological Survey Professional Paper 1123-C.

Butler, J.R., 1989, Geologic map of Chester County, South Carolina: South Carolina Geological Survey Open-File Report 63, p 1-4 + 1:125,000 map.

Chalcraft, R.G., 1976, The petrology of Mesozoic dolerite dikes in South Carolina: South Carolina Geologic Notes, Division of Geology, South Carolina State Development Board, v. 20, p. 52-61.

Daniels, D.L., Zietz, I., and Popenoe, P., 1983, Distribution of subsurface lower Mesozoic rocks in the southeastern United States, as interpreted from regional aeromagnetic and gravity maps, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886 – Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p. K1-K24.

Gottfried, D., Annell, C.S., and Byerly, G.R., 1983, Geochemistry and tectonic significance of subsurface basalts near Charleston, South Carolina: Clubhouse Crossroads test holes #2 and #3, *in* Gohn, G.S., ed., Studies related to the Charleston, South Carolina, earthquake of 1886 – Tectonics and seismicity: U.S. Geological Survey Professional Paper 1313, p A1-A19.

Gottfried, D., Annell, C.S., and Schwartz, L.J., 1977, Geochemistry of subsurface basalt from the deep corehole (Clubhouse Crossroads corehole 1) near Charleston, South Carolina – Magma type and tectonic implications, *in* Rankin, D.W., ed. Studies related to the Charleston, South Carolina, earthquake of 1886 – A preliminary report: U.S. Geological Survey Professional Paper 1028, p. 91-113.

Gottfried, D. and Arth, J.G., 1985, Sr and Nd isotope ratios and geochemistry of Mesozoic diabase dikes from Georgia [abs.]: EOS, Transactions of the American Geophysical Union, v. 66,

p. 399.

Kushiro, I., 1979, Chapter 6. Fractional crystallization of basaltic magma, *in* Yoder, H.S., Jr., ed., The Evolution of the Igneous Rocks: Fiftieth Anniversary Perspectives: Princeton University Press, Princeton, New Jersey, p. 171-203.

Osborn, E.F., 1959, Role of oxygen pressure in the crystallization and differentiation of basaltic magma: American Journal of Science, v. 257, p. 609-647.

Overstreet, W.C. and Bell, H., III, 1965, Geologic map of the crystalline rocks of South Carolina: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-413, scale, 1:250,000.

Popenoe, P. and Zietz, I., 1977, The nature of the geophysical basement beneath the Coastal Plain of South Carolina and northeastern Georgia, *in* Rankin, D.W., ed. Studies related to the Charleston, South Carolina, earthquake of 1886 – A preliminary report: U.S. Geological Survey Professional Paper 1028, p. 119-137.

Ragland, P.C., Chapter 10, Mesozoic igneous rocks, *in* The Geology of the Carolinas: Carolina Geological Society Fiftieth Anniversary Volume, The University of Tennessee Press, Knoxville, p. 171-190.

Ragland, P.C., Cummins, L.E., and Arthur, J.D., 1992, Compositional patterns for early Mesozoic diabases from South Carolina to central Virginia, *in* Puffer, J.H. and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 309-331.

Roeder, P.L, and Emslie, R.F., 1970, Olivine-liquid equilibrium: Contributions to Mineralogy and Petrology, v. 29, p. 275-289.

Snipes, D.S., Burnett, L.L., Wylie, J.A., Sacks, L.A., Heaton, S.B., Dalton, G.A., Israel, B.A., and Padgett, G.G., 1984, Indicators of ground water quality and yield for a public water supply in rock fracture zones of the Piedmont: Technical Completion Report No. 115, Water Resources Institute, Clemson, South Carolina, 80p.

Snipes, D.S. and Furr, J.E., 1979, Easley dolerite in the South Carolina Piedmont: Geologic Notes, Division of Geology, South Carolina State Development Board, v. 23, p. 129-145.

Steele, K.F., and Ragland, P.C., 1976, Model for the closed-system fractionation of a dike formed by two pulses of dolerite magma: Contributions to Mineralogy and Petrology, v. 57, p. 305-316.

Warner, R.D., Snipes, D.S., Burnett, L.L., Wylie, J.A., Sacks, L.A., and Steiner, J.C., 1986, Shoals Junction and Due West dolerites, South Carolina: Southeastern Geology, v. 26, p. 141-153.

Warner, R.D., Snipes, D.S., Hughes, S.S., Steiner, J.C., Davis, M.W., Manoogian, P.R., and Schmitt, R.A., 1985, Olivine normative dolerite dikes from western South Carolina: Mineralogy, chemical composition and petrogenesis: Contributions to Mineralogy and Petrology, v. 90, p. 386-400.

Warner, R.D., Snipes, D.S., Hughes, S.S., Walker, R.J., Schmitt, R.A., and Steiner, J.C., 1992, Geochemistry and petrology of Mesozoic dikes in South Carolina, *in* Puffer, J.H. and Ragland, P.C., eds., Eastern North American Mesozoic Magmatism: Geological Society of America Special Paper 268, p. 333-346.

Warner, R.D., Snipes, D.S., and Steiner, J.C., 1993, Diabase dikes of Chester and Fairfield Counties, South Carolina: South Carolina Geology, v. 36, p. 9-33.

Warner, R.D. and Wasilewski, P.J., 1990, Magnetic petrology of eastern North America Diabases, I. Olivine-normative dikes from western South Carolina: Earth and Planetary Science Letters, v. 98, p. 340-359.

Weigand, P.W., 1970, Major and trace element geochemistry of the Mesozoic dolerite dikes from eastern North America [Ph.D. dissertation]: Chapel Hill, The University of North Carolina, 162. p.

Weigand, P.W. and Ragland, P.C., 1970, Geochemistry of Mesozoic dolerite dikes from eastern North America: Contributions to Mineralogy and Petrology, v. 29, p. 195-214.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 71-76

AN INITIAL PETROGRAPHIC AND GEOCHEMICAL STUDY OF A RHYOLITIC ROCK RECOVERED FROM TEST WELL #1, HILTON HEAD, SOUTH CAROLINA

D. S. Snipes, N. B. Kidd, R. D. Warner, R. A. Hodges, and V. Price, Jr.
Geological Sciences
Clemson University
Clemson, SC 29634

T. J. Temples
United States Department of Energy
Savannah River Field Office
Aiken, SC 29808

INTRODUCTION

This paper deals with petrographic studies, x-ray diffraction data, bulk chemical analyses, electron microprobe data, and the geochronology of a sample of basement rock recovered from Hilton Head Test Well #1, situated on Hilton Head Island, just off the coast of South Carolina (Figure 1). The coordinates of the well site are 32°11'29"N and 80°42'14"W. This municipal water well was drilled in 1992 by the South Carolina Department of Natural Resources. A this location, the Coastal Plain section consists of Tertiary and Late Cretaceous sands, clays, and calcareous sediments which unconformably overlie basement rocks. Deep well control is sparse in this portion of South Carolina; however, Chowns and Williams (1983) have documented the occurrence of early Paleozoic or perhaps Precambrian crystalline rocks in wells situated about 50km southwest of Hilton Head.

The test well for this project was drilled through the entire thickness of the Coastal Plain section to a depth of 1,186 m (3,833 ft). Upon removing the drilling apparatus from the well, an 80 gram fragment of basement rock was recovered from the drill bit. In hand specimen, the sample is a medium-to-dark gray aphanitic igneous rock with white laths of plagioclase phenocrysts. Initially, it was field logged as a basalt (Mancini and Spigner, 1992); however, based on our analytical results, the specimen is a slightly-to-moderately hydrothermally altered rhyolite. This is the first occurrence of volcanic rhyolite reported for the subsurface of South Carolina, although other scientists have published papers on subsurface felsic volcanic rocks from southeast Georgia and northern Florida (Ross, 1958; Applin and Applin, 1964; Hurst, 1965; Milton and Grasty, 1969; Chowns and Williams, 1983; and Heatherington and others, 1995, in press).

GEOLOGIC SETTING

Figure 2 is a subsurface structure contour map on the top of the basement rocks of South Carolina. These rocks include Paleozoic and Precambrian (?) igneous and metamorphic rocks, and Triassic red beds of the Dunbarton and Florence basins and the South Georgia Rift/Summerville Basin. This map is based largely on the work of Colquhoun and others (1983) and Steele and Colquhoun (1985), with additional data from Snipes and others (1993), as well as ongoing research by the authors. Interestingly, the elevation of the basement in the Hilton Head well is within less than 200 feet of that predicted by Colquhoun and others (1983), despite the scarcity of well control near the South Carolina-Georgia border.

RESULTS

Figure 3 is a photomicrograph of a thin section of the Hilton Head volcanic rock. It shows an albite phenocryst in a fine-grained groundmass which consists chiefly of quartz and feldspar. The phenocrysts were identified as albite, based on characteristic albite and pericline twinning occurring within the crystals. Most of the phenocrysts were slightly-to-moderately sericitized, and a minor amount of sericite was observed in the groundmass. The quartz and feldspar grains of the groundmass were too small to identify separately in our modal analysis; therefore, we determined the relative amounts of "groundmass" and albite phenocrysts (Table 1). We also noted the degree of sericitization of the phenocrysts.

Table 1. Modal analyses of Hilton Head Test Well #1 Basement Rock Sample (1000 points counted).

Constituent	Percentage
Groundmass (chiefly quartz and feldspar)	89.9
Albite Phenocrysts	
Slightly sericitized	2.7
Moderately sericitized	7.4
Chlorite	Trace
Epidote	Trace
Opaque minerals	Trace
Total	100.0

We believe that both the sericite and albite were formed by hydrothermal replacement of preexisting minerals, not by low-grade regional metamorphism. This belief is supported

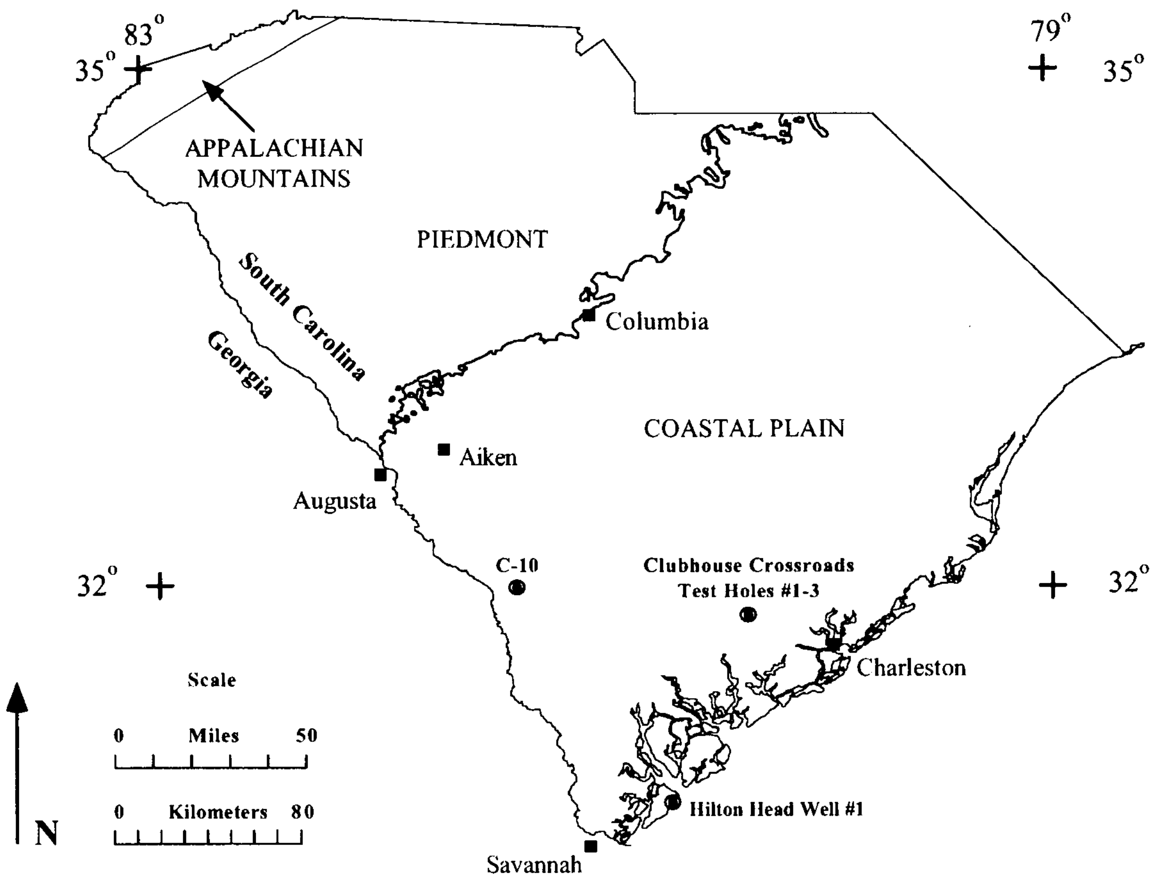


Figure 1. Map showing the location of Hilton Head Test Well #1, Well C-10, and Clubhouse Crossroads Test Holes #1-3.

by Deer, Howie, and Zussman (1992), who stated that alkali feldspars are very susceptible to replacement by hydrothermal solutions. Moreover, in thin section, except for the presence of the sericite and the albite phenocrysts, this rock exhibits a texture typical of aphanitic felsic volcanic rocks.

A portion of the sample was powdered and prepared for X-ray diffraction analysis in order to determine the dominant constituents present in the rock. The X-ray pattern showed that there were three major minerals present: quartz, albite, and sanidine, in that order of abundance.

Electron microprobe analyses were conducted at the University of Georgia using a JEOL JXA-8600 Superprobe, which is capable of analyzing a sample area as small as one micron in diameter. A non-random survey of the feldspars was conducted, with 32 crystals being analyzed. Albite was present in the sample as phenocrysts and groundmass particles, while potassium feldspar was present solely in the groundmass. Of the albite crystals analyzed, the average, non-weighted composition was $An_{.04}Ab_{.95}Or_{.01}$-$An_{.00}Ab_{.06}Or_{.94}$ (Figure 4), which is in agreement with the result of the x-ray diffraction analysis. There were no calcic plagioclase crystals observed in the specimen. Additionally, the probe data showed that the opaque minerals present in the sample were mainly iron oxides (magnetite and hematite) with an occasional iron sulfide (pyrite or pyrrhotite).

Major and trace elements in the rock were determined by bulk chemical analysis using x-ray fluorescence, directly coupled plasma, and neutron activation techniques (XRAL Activation Services, Inc., 1995). The overall composition of the sample is typical of a rhyolitic rock, with high weight percentages of SiO_2 and Na_2O and a low percentage of CaO (Table 2). A plot of $Na_2O + K_2O$ versus SiO_2 is shown in Fig. 5; the sample lies within the rhyolite field.

GEOCHRONOLOGY

Based on Nd data, Heatherington and Mueller (University of Florida, written communication, 1995) determined a depleted mantle model age of 1094 Ma for the Hilton Head volcanic rock. They stated that this age was an estimate for the minimum age of the lithosphere which melted to form the magma. Techniques for age-dating small rock samples by U-Pb geochronologic analyses of zircons (Heatherington and Mueller, 1995) could not be applied, since no zircons were found in the Hilton Head specimen.

A whole-rock K-Ar age determination was made by

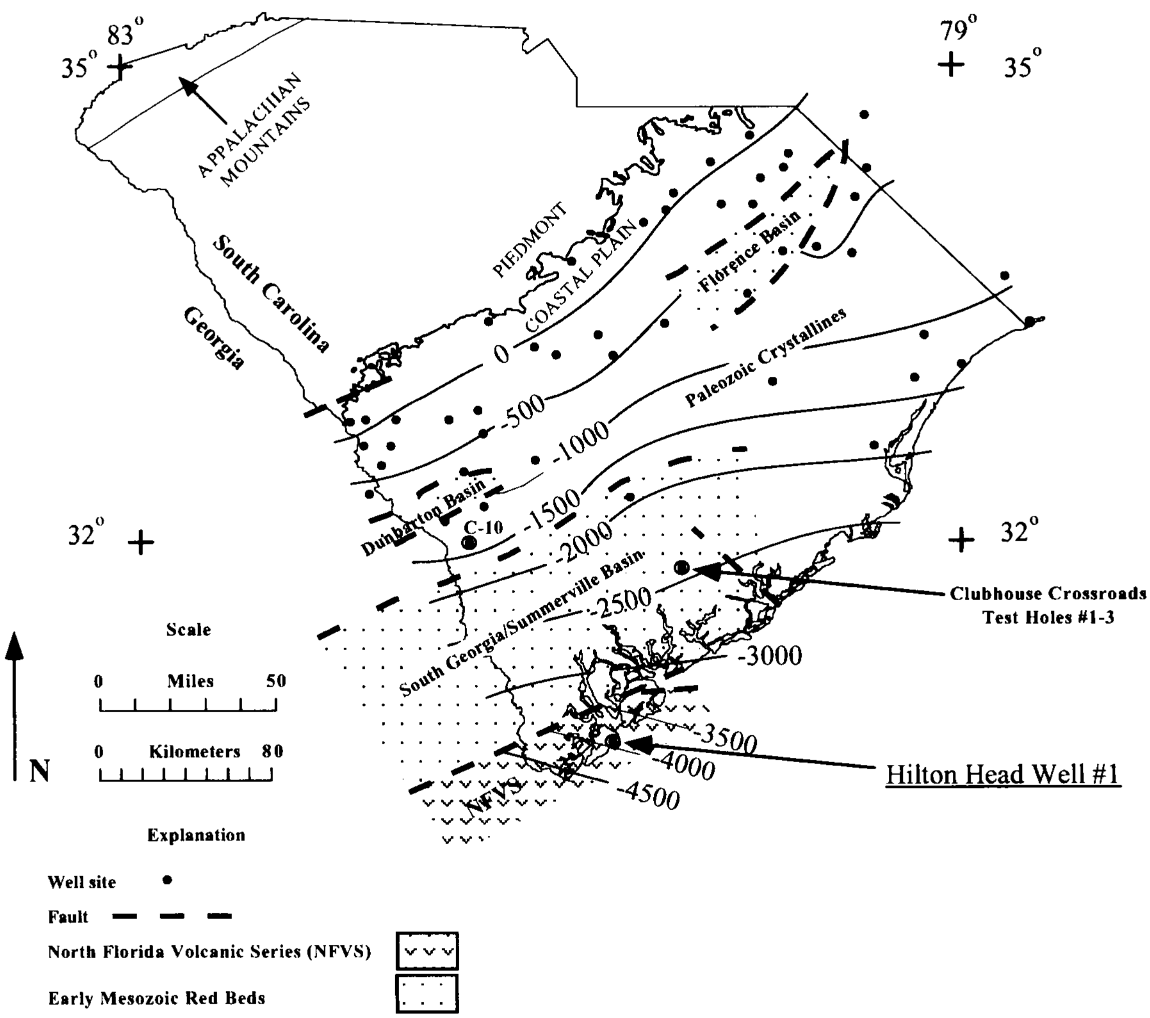


Figure 2. Structure contour map on the top of the basement rocks in South Carolina. Modified from Colquhoun and others (1983), Steele and Colquhoun (1985), and Snipes and others (1993). Contour interval is 500 feet.

Hops (Geochron Laboratories, written communication, 1995). Based on a 40*Ar/40K ratio of 0.02617, she estimated an age of 402±8Ma. Because this sample has undergone hydrothermal alteration, we believe that this is an estimate of the minimum age of crystallization of the rock.

Major Elements (weight percent)			
SiO_2	72.8	Fe_2O_3	2.94
Al_2O_3	14.3	MnO	0.07
CaO	0.98	Cr_2O_3	<0.01
MgO	0.39	TiO_2	0.35
Na_2O	5.15	P_2O_5	0.06
K_2O	2.49	LOI	0.50
Total	100.2		
Minor Elements (parts per million)			
Ba	640	Y	50
Nb	10	Zr	340
Rb	60	La	35.7
Sr	120	Nd	62
Ta	<1	Yb	5.4

Table 2. Bulk chemical analysis of major and trace elements in the Hilton Head basement rock sample (Frank Bernal, XRAL Activation Services, Inc., 1995)

DISCUSSION OF RESULTS

Unfortunately, only a small fragment of crystalline rock was recovered from the Hilton Head Test Well #1. Therefore, the possibility that the sample might be a clast cannot be excluded.

However, based on its elevation and the position of the well on the structure contour map (Figure 2), we believe that it is a sample of basement rock. Moreover, in the succeeding paragraphs, we argue that the composition and geologic age of this specimen are similar to other felsic volcanic rocks from the subsurface of northern Florida and southeast Georgia Chowns and Williams (1983) quoted K-Ar whole rock ages of 350-500 Ma for felsic tuffs from the subsurface of southeastern Georgia and defined a felsic volcanic terrane in

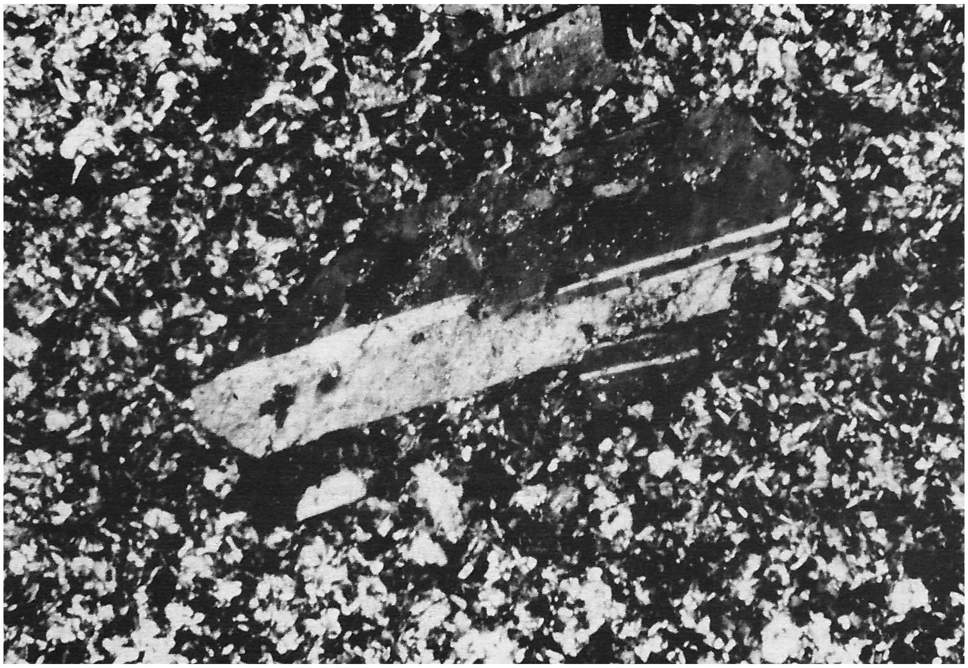


Figure 3. Photomicrograph of a thin section of volcanic rock recovered from the Hilton Head Test Well #1. Albite phenocrysts are enclosed in a fine-grained groundmass which consists of quartz, albite, and sanidine. Both the phenocrysts and the groundmass have been slightly-to-moderately sericitized.

the southeastern Georgia subsurface. Neoproterozoic basaltic andesites through rhyolites have also been recovered from drill holes in northeast Florida and southeast Georgia

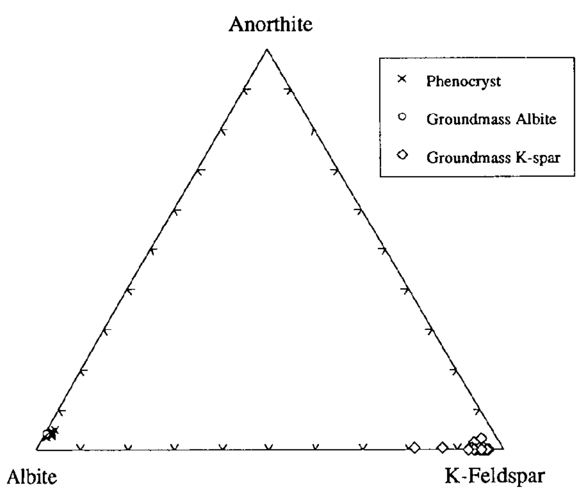


Figure 4. Ternary plot of feldspar compositions in the Hilton Head rhyolitic rock sample.

(Barnett, 1975; Chowns and Williams, 1983; and Heatherington and Mueller, 1995, in press). Heatherington and Mueller (1995, in press) argue that all of these volcanics belong to a single association which they call the "North Florida Volcanic Series".

Horton and others (1989) and Heatherington and Mueller (1995, in press) suggested that the North Florida Volcanic Series was part of the Suwannee terrane, which includes Paleozoic sediments as well as early Paleozoic-late Precambrian plutonic rocks. Moreover, they suggested that this terrane was coeval with the Carolina terrane. Kish (1992) published a geochemical and isotopic study of an altered granite recovered from Well C-10, situated north of the early Mesozoic South Georgia Rift/Summerville Basin shown in Figure 2. He reported a 87Sr/86Sr isotope model age of 440 to 550 Ma because most granites in the Piedmont have relatively low 87St/86Sr initial ratios. Furthermore, he suggested that the age of crystallization of the C-10 granite was coeval with the Carolina and Suwannee terranes.

In summary, the altered rhyolite from the Hilton Head well is younger than 1094 Ma (Heatherington and Mueller, written communication, 1995) and older than 402 Ma (Hops, written communication, 1995). Thus, it is late Precambrian to early Paleozoic in age, and it is probably coeval with the felsic volcanic rocks reported by Chowns and Williams (1983) and Heatherington and Mueller (written communication, 1995).

Based on similarities in composition, absolute age dates, and proximity, we conclude that the rhyolitic volcanic recovered from the Hilton Head Test Well #1 belongs to the North Florida Volcanic Series as defined by Heatherington and Mueller (written communication, 1995).

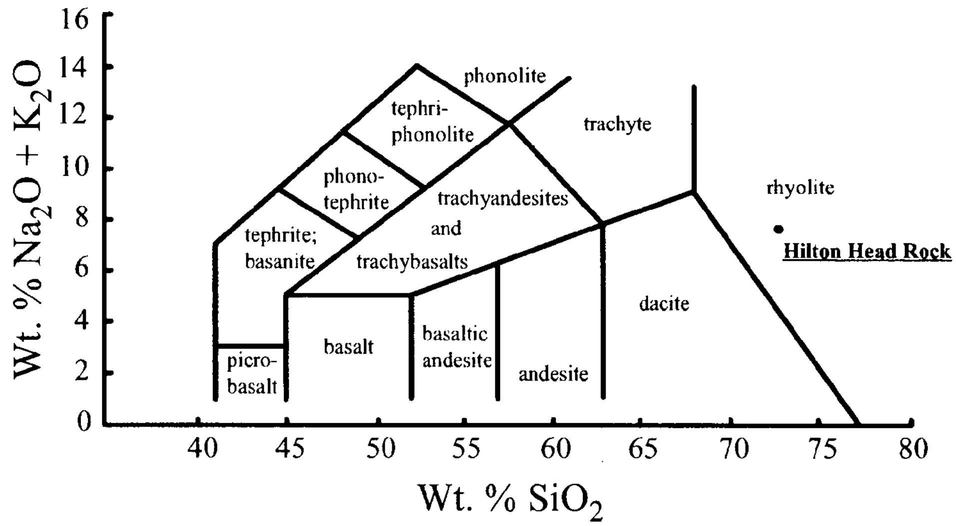


Figure 5. Plot of alkali oxides versus silica, showing the composition of the Hilton Head specimen with respect to the compositions of various igneous rocks (Le Bas and others, 1986; Heatherington and others, 1995, in press). The Hilton Head rock plots within the rhyolite field of the diagram.

ACKNOWLEDGEMENTS

The authors thank Camille Ransom (SC Department of Health and Environmental Control) and Joe Cellici (SC Department of Natural Resources-Water Resources Division) for providing the Hilton Head rock sample for analysis. We are grateful to Harmon Maher (University of Nebraska, Omaha) for reviewing this manuscript and making suggestions for its improvement. Christopher Fleischer (University of Georgia Microprobe Center) provided assistance in obtaining the microprobe analyses and in their interpretation. Paul Mueller and Ann Heatherington (University of Florida) conducted radiometric age determinations for the Hilton Head model ages and provided insight into their interpretation. Erik Caldwell (Clemson University) made the x-ray diffraction pattern. Funding for this project was provided under South Carolina Universities Research and Education Foundation (SCUREF) Task Order #29-94 (Judith Bostock, Chief Operating Officer).

REFERENCES

Applin, E.R., and Applin, P.L., 1964, Logs of selected wells in the Coastal Plains of Georgia: Georgia Geologic Survey Bulletin 74, 229 p.

Barnett, R.S., 1975, Basement structure of Florida and its tectonic implications: Transactions of the Gulf Coast Association of Geological Societies, v. 25, p. 122-142.

Chowns, T.M., and Williams, C.T., 1983, Pre-Cretaceous rocks beneath the Georgia Coastal Plain – Regional Implications: in G.S. Gohn, ed., Studies Related to the Charleston, South Carolina Earthquake of 1886 – Tectonics and Seismicity: U.S. Geological Survey Professional Paper 1313-L, p. L1-L42.

Colquhoun, D.J., Woolen, I.D., van Nieuwenhuise, D.S., Padgett, G.G., Oldham, R.W., Boylam, D.C., Bishop, J.W., and Howell, P.D., 1983, Surface and subsurface Stratigraphy, structure, and aquifers of the South Carolina Coastal Plain: south Carolina Department of Health and Environmental Control, Governor's Office, and University of South Carolina, Columbia, South Carolina, 78 p.

Deer, W.A., Howie, R.A., and Zussman, J., 1992, An introduction to the rock forming minerals, Longman House, Essex, England, p. 419.

Heatherington, A.L., and Mueller, P.A., 1995, Geochemistry and origin of Florida crustal basement terranes: in A. Randazzo and D. Jones, eds., The Geology of Florida, University of Florida, in press.

Hetherington, A.L., Mueller, P.A., and Nutman, A.P., 1995, Neoproterozoic magmatism in the Suwannee Terrane and possible correlations with Avalonian rocks: in Nance and Thompson, eds., Avalonian and Related Terranes of the Circum-North Atlantic, Geological Society of America Special Paper, in press.

Horton, J.W., Jr., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachians, in R.D. Dallmeyer, ed., Terranes in the Circum-Atlantic Paleozoic orogens, GSA Special paper 230, p. 213-246.

Hurst, V.J., 1965, Oil tests in Georgia – A compilation: Georgia Geologic Survey Information Circular 19, 16 p.

Kish, S.A., 1992, An initial geochemical and isotopic study of granite from core C-10, Savannah River Site, South Carolina: in W. Fallaw and V. Price, eds., Geological Investigations of the Central Savannah River Area, South Carolina and Georgia, Carolina Geological Society Field Trip Guidebook, November 13-15, 1992, p. CGS-92-B-IV-1-CGS-92-B-IV-4.

Le Bas, M.J., Le Maitre, R.W., Streckstein, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745-750.

Mancini, A., and Spigner, B.C., 1992, Phase I report, Cretaceous aquifer test well, Hilton Head, South Carolina, Atlanta Testing and Engineering Report No. 92-1001, 30 p.

Milton, C., and Grasty, R., 1969, “Basement” rocks of Florida and Georgia: American Association of Petroleum Geologists Bulletin, v. 53, no. 12, p. 2483-2493.

Ross, C.S., 1958, Welded tuff from deep-well cores from Clinch County, Georgia: American Mineralogist, v. 43, nos. 5-6, p. 537-545.

Snipes, D.S., Fallaw, W.C., Price, V., Jr., and Cumbest, R.J., 1993, The Pen Branch Fault: documentation of Late Cretaceous-Tertiary Faulting in the Coastal Plain of South Carolina: Southeastern Geology, v. 33(4), p. 195-218.

Steele, K.B., and Colquhoun, D.J., 1985, Subsurface evidence of the Triassic Newark Supergroup in the South Carolina Coastal Plain: South Carolina Geology, v. 28, p. 11-22.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 77-85

STRUCTURAL CONTRASTS OF THE CAROLINA SLATE BELT AND CHARLOTTE BELT IN SOUTH CAROLINA

Terry W. Offield
U.S. Geological Survey
Reston, Virginia 22092

INTRODUCTION

Since 1987, a USGS mineral resources project on the Carolina slate belt has included geologic reconnaissance aimed at defining the structural framework of the belt. This work has focused particularly on the internal structural patterns and the relationships of the Carolina slate belt and adjacent lithotectonic belts of the Piedmont. Field observations emphasized the geometry of mesoscopic structural elements, the areal patterns of deformation, indications of overprinting and sequence of deformations, and the relation f mineralization to structure. This paper presents some of the observations made in the Carolina slate belt and Charlotte belt of South Carolina from the area around the Winnsboro pluton westward to the Savannah River. The data do not represent an attempt at systematic geologic mapping, but rather observations o lithology and of features indicative of structural geometry and style and deformation history. Figure 1 is a map summarizing the reconnaissance data; it shows the location of field stations where observations were made and areas of both belts for which structural-domain data are presented.

SETTING AND PREVIOUS VIEWS

The nature of the contact and relation of the Carolina slate belt and Charlotte belt has long been debated. In the type area around Charlotte, North Carolina (King, 1955), the Charlotte belt consists mostly of a metamorphosed mixture of granitoid and gabbroic intrusives (Late Proterozoic to early Paleozoic?), with numerous, sharply defined younger granite and gabbro plutons that are probably of Devonian age, and granites of late Paleozoic age. There, a roughly defined boundary with the Carolina slate belt is considered (Butler and Secor, 1991) to be the Gold Hill shear zone (probably Acadian), but felsic and intermediate volcanic rocks of slate-belt character, barely deformed or metamorphosed, occur west of the boundary zone in patches upon the older granitoid-gabbroic rocks of the Charlotte belt assemblage (Goldsmith and others, 1988). Exposures are poor in that area, and relations of rocks of the two belt assemblages may be either an unconformity or a thrust (Offield, 1994). It seems clear that the two contrasting assemblages have very different histories. In the South Carolina area discussed here, a similar pattern of Devonian granite and gabbro plutons and late Paleozoic granite plutons marks the Charlotte belt (McSween and others, 1991), but the host matrix for the intrusives is conspicuously different than in the North Carolina area. Granitoids and metagabbros like those in North Carolina are present, but the part of the Charlotte belt in South Carolina that is considered here consists dominantly of well-foliated amphibolitic and granitic gneisses and mica schists, a typical, complexly deformed, amphibolite-facies assemblage.

In contrast, the Carolina slate belt that borders the Charlotte belt consists of low greenschist-facies metavolcanic and metasedimentary rocks in tight to open folds; axial-plane cleavage ranges from absent to well-developed, locally to the point that the rock is phyllitic. Previous students of areas along the belt boundary have concluded that the boundary is a metamorphic gradient, and 1) rock units of both belts are the same, the differences between belts being a function of structural position during deformation (e.g., Secor and Wagener, 1968; Bourland and Farrar, 1980, Secor and others, 1982; Lawrence, 1987), or 2) the slate belt rocks lie atop the Charlotte belt rocks in a suprastructure-infrastructure stack, and their differences reflect depth during deformation (e.g., McCauley, 1961; Griffin, 1978, 1979). A summary article recounting the different interpretations and laying out the regional setting was published recently by the Carolina Geological Society (Butler and Secor, 1991). In contrast to the prior work, observations in the present reconnaissance appear to support the idea of a structural contact at the belt boundary rather than a metamorphic gradient.

Geologic map showing Carolina slate belt-Charlotte belt boundary, reconnaissance field stations (dots), quadrangle names, and areas of other figures. Slate belt unit distribution largely after Secor and others (1986). NOTE: On the figures in this paper, the Richtex is labeled as Cambrian in age, rather than the usual Proterozoic. This assignment is proposed in Offield (1994). It is based on a map pattern of the Carolina slate belt in South Carolina and North Carolina that makes stratigraphic equivalences seem likely for the Persimmon Fork Formation and Flat Swamp member of the Cid Formation (together with much of the Floyd Church Formation) and for the respectively overlying Richtex and uppermost Floyd Church Formations. The age assignment and correlations fit with the late Proterozoic age determined for the Persimmon Fork Formation and the occurrence of the late Proterozoic Ediacaran fossils (Gibson and others, 1984) in the Floyd Church Formation. This correlation probably would remove he need to hypothesize a structural disjunction or even two different arc sequences to explain strati-

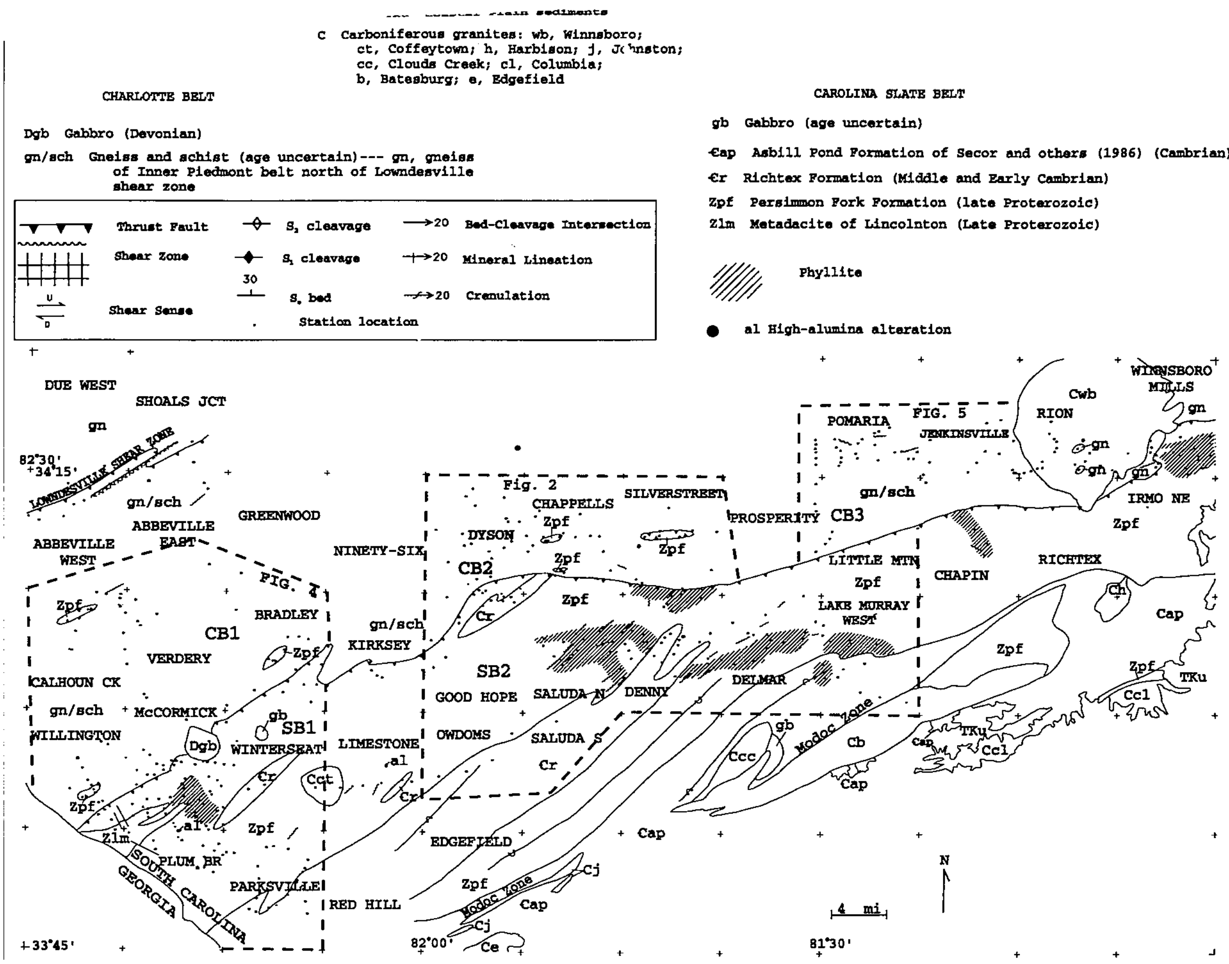


Figure 1. Geologic map showing Carolina slate belt-Charlotte belt boundary, reconnaissance field stations (dots), quadrangle names, and areas of other figures. Slate belt unit distribution largely after Secor and others (1986). NOTE: On the figures in this paper, the Richtex is labeled as Cambrian in age, rather than the usual Proterozoic. This assignment is proposed in Offield (1994). It is based on a map pattern of the Carolina slate belt in South Carolina and North Carolina that makes stratigraphic equivalences seem likely for the Persimmon Fork Formation and Flat Swamp member of the Cid Formation (together with much of the Floyd Church Formation) and for the respectively overlying Richtex and uppermost Floyd Church Formations. The age assignment and correlations fit with the late Proterozoic age determined for the Persimmon Fork Formation and the occurrence of late Proterozoic Ediacaran fossils (Gibson and others, 1984) in the Floyd Church Formation. This correlation probably would remove the need to hypothesize a structural disjunction or even two different arc sequences to explain stratigraphic relationships between South Carolina and North Carolina. The picture takes on new complications, however, with the report (Koeppen and others, in press) of late Cambrian or Ordovician fossils in strata beneath the Flat Swamp in North Carolina. Major structural discontinuities or revisions in Stratigraphy must be considered.

graphic relationships between South Carolina and North Carolina. The picture takes on new complications, however, with the report (Koeppen and others, in press) of Late Cambrian or Ordovician fossils in strata beneath the Flat Swamp in North Carolina. Major structural discontinuities or revisions in stratigraphy must be considered.

Carolina Slate Belt Structural Pattern

From the Modoc shear zone that roughly marks the southeast boundary of the Carolina slate belt (Fig. 1), to the northwest boundary with the Charlotte belt, the map pattern in the Carolina slate belt features alternating bands of rhyolitic rocks and mudstones. These bands have been considered, variously, as possibly several different stratigraphic units in a stack (e.g., Pirkle, 1978, 1981), or as two lithostratigraphic units, with mudstone lying above rhyolitic rocks, across a series of folds (Secor and others, 1986). In the latter interpretation (which I adopt for this reconnaissance study), the rhyolitic rocks are assigned to the Persimmon Fork Formation and the mudstones to the Richtex Formation. The Persimmon Fork overlies and is perhaps party coeval with the metadacite of Lincolnton dated at 566±15 Ma (U-Pb; Carpenter and others, 1982) at the west end of the area in

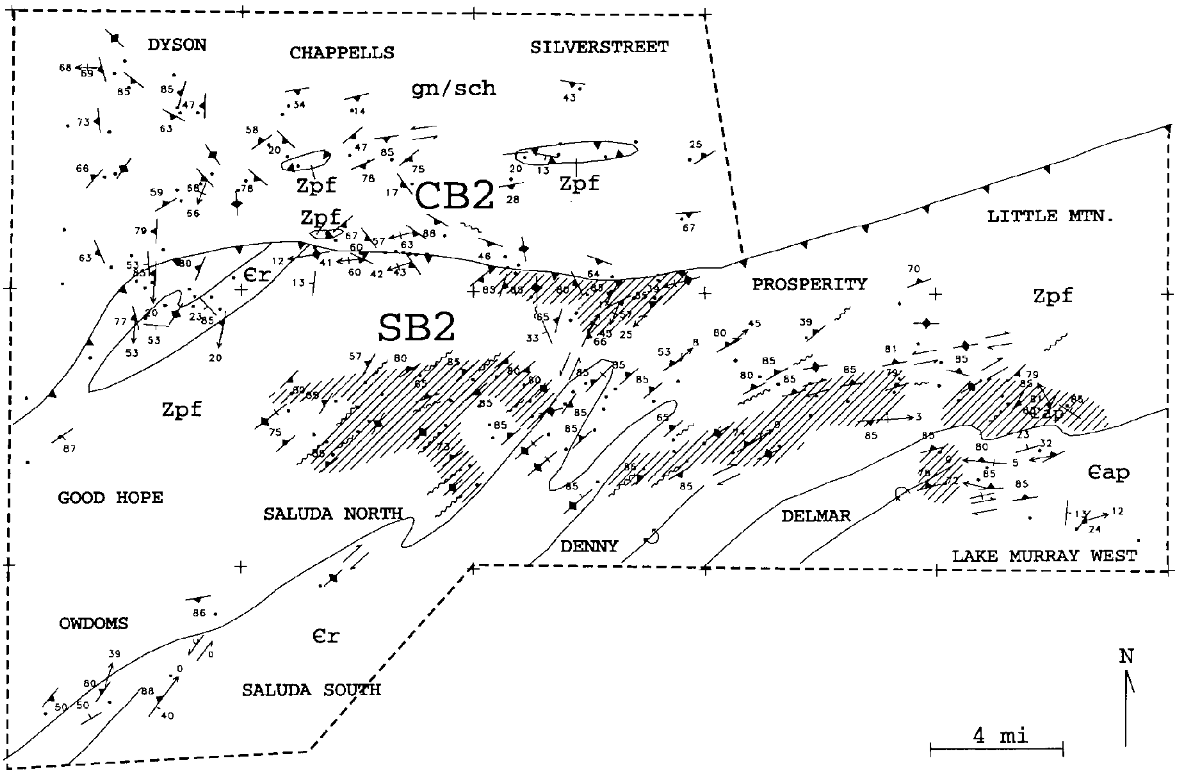


Figure 2. Reconnaissance information in areas SB2 and CB2. Legend as in Figure 1.

Figure 1. Just east of the area in Figure 1, rhyolite mapped as Persimmon Fork has been dated as 550 Ma (U-Pb; Barker and others, 1933). These dates place the Persimmon Fork as Late Proterozoic, if the recent Precambrian-Cambrian boundary date (544 Ma) of Bowring and others (1933) and Brasier and others (1994) is accepted. The Richtex has been considered to overlie the Persimmon Fork; Secor and Wagener (1975) and Secor and Snoke (1978) reported a gradational contact, but Secor and others (1986) and Secor (1988) commented that the contact could be either depositional or structural. At the southeast side of the Carolina slate belt, however, the Persimmon Fork is reported to be overlain conformably by the Asbill Pond Formation of Secor and others (1986), which contains Middle Cambrian fossils (Secor and others, 1983). The relationship of Richtex to Asbill Pond is not clear, and may be one of facies on opposite sides of a regional fold, or perhaps one involving tectonic emplacement of one of the different rock packages at the same apparent stratigraphic level.

Northward from the Modoc zone, an area of overprinted and complex Alleghanian deformation, Carolina slate belt rocks mostly exhibit relatively simple structure, produced in a single episode that Secor and others (1986) named the Delmar deformation. The structural pattern shown in Figure 1, largely from Secor and others (1986) and Pirkle (1978, 1981), from the Georgia border to about the middle of the area, has a regional strike of about N46-54°E. Toward the east edge of the cluster of observations (Delmar, Lake Murray W. Quads), however, the structural trend bends to a more easterly strike. This accords with observations by McCauley (1961) and Secor and Wagener (1968), who described folds in that area as trending N80°E. The cross-sectional shapes of the map-scale folds are not known with certainty. Indeed, from the modest number of reconnaissance measurements I could not prove the alternating swaths of lithologies are in fact folds. However, they presumably are folds and, interpreting from bed dips and bed-cleavage angles, the folds are open to close, and even isoclinal in some areas. Observed minor folds bear this interpretation out; they range from open to close, but at places are tight to isoclinal. Spaced cleavage is generally present and is axial planar to folds where they can be seen in outcrop. In a few zones where shear fabric is especially evident, folds tend to be tight and the cleavage continuous and anastomosing. Some cleavage dips steeply southeast, but most cleavage dips vertically to steeply northwest, and the folds are upright to southeast-vergent. In fine-grained volcanoclastic rocks of the Persimmon Fork, and especially in the mudstones of the Richtex, discrete, narrow zones display small-scale crenulations of the regional S_1, and, in a few places, have a coarsely spaced (cm) S_2 crenulated cleavage.

Little direct information on the Persimmon Fork-Richtex contact relation was obtained. The swath of Richtex from the Parksville Quadrangle northeastward to the Denny Quadrangle (Fig. 1) contains small-scale isoclinal folds at the northeast end, and tight to close folds at the southwest end. At several places along the contact, beds dip the wrong way for Richtex to overlie Persimmon Fork in undisturbed order; more generally, attitudes of beds and cleavage in the two units are not concordant, suggesting a disjuctive contact involving post-cleavage rotations. The two smaller areas of Richtex to the west (Fig.1) could mark synclinal keels, but the data seem to indicate a disjunctive contact, with structural elements in rocks above and below the contact somewhat differently oriented. In both formations throughout the area, even where nearby cleavages are similarly oriented and do not seem to have been rotated relative to each other, bed-cleavage intersections representing F1 fold axes may vary in plunge from shallow to steep. Some of the axial plunges mark reclined folds, a geometry commonly associated with folding in a thrust regime.

Toward the east side of area SB2 (Fig.2), where the structural grain shows the more easterly trend, McCauley (1961) and Secor and Wagener (1968) described the folds as northwest vergent, but, in the part of that area I reconnoitered, I found cleavage dipping dominantly northwest and minor folds to be southeast vergent. The area of easterly trend, however, displays some complications associated with overprinting by a second structural event. Cleavage in phyllites or semischistose rocks occurs in an apparent east-trending zone in the area of Figure 2 (the zone may be more apparent than real because of the lack of observations outside the hachured areas). Where this fabric trends northeast, it records the main D_1 tectonic event of the region; where it trends more easterly, outcrops display S_1 cleavage apparently rotated from the usual northeast strike, and at least in a few outcrops a generally subparallel, overprinted crenulation cleavage, S_2. The presence of the younger cleavage typically is associated with conspicuous shear fabrics (S-C) that dominantly indicate dextral strike slip. Where mesoscopic folds can be seen, both F1 and F2 folds tend to be tight and upright to slightly southeast vergent. For area SB2, stereographic plots are presented in Figures 3a, b. Bed data, excluding the locally confused zone right along the belt boundary, and the few measurements in the area of easterly trend, show a poorly defined girdle with beta-axis of S46°W16°, effectively on the mean cleavage plane. The plots show the mean cleavage (S1) for the western two-thirds of the SB2 area to be N49°E86°NW, and for the eastern third to be N71°E83°NW. In that eastern area, Secor and others (1982) demonstrated significant F2 folding of S1 by map-scale folds of ESE trend.

In area SB1 (Fig. 4), mesoscopic folds generally are very tight to isoclinal, slightly southeast-vergent, with axial-plane S1 cleavage that trends northeast and dominantly dips northwest. The Barite Hill and other nearby gold deposits occur within a patch of pyllite with strongly oriented S1 cleavage, and in which S2 cleavage is also present at places. The later cleavage typically is parallel in strike with the older cleavage and within 15-20 degrees of parallel in dip. Shear indicators (S-C fabric and rotated grains or clasts) record both strike slip (dextral and sinistral) and dip slip (west-up and east-up). The lack of obviously preferred shear sense, together with the presence in lithic tuffs of clasts up to 10 cm long strongly flattened and aligned on cleavage, but not sheared, suggests regional pure shear and flattening during S_1 cleavage development. There is a suggestion of dominantly strike slip movement involved in the S_2 cleavage formation in the phyllite (and in rare places elsewhere), but not enough data are available to confirm the point. The S_2 cleavage clearly is zonal and not pervasively developed in the area; S_1 is more nearly pervasive (allowing for lithologic susceptibility) but is not everywhere developed. North of McCormick, east of the large gabbro body, well-bedded red and green mudstones are barely metamorphosed and virtually uncleaved, even though less than a kilometer to the west the same rocks are well cleaved and strongly sheared, at places containing thin mylonitic zones. Southwest of McCormick, the metadacite of Lincolnton shows little cleavage except in discrete zones of phyllite, which may well be of the S_2 generation. Figures 3c, d show stereographic plots of structure data for area SB1. Bed data define a somewhat scattered girdle with a beta-axis at S46°W1°; despite the scatter, the plot does not seem to indicate systematic dispersion, as in a second folding event. The cleavage plot defines N49°E84°NW for the mean cleavage; although bed-cleavage intersection lineations are scattered, with a range of plunges, they fall in general on or near the cleavage great circle, and their pattern does not suggest small-circle dispersion that would indicate a second folding. The data are consistent with a single main folding event, with subsequent relatively minor rotations and adjustments, presumably associated with the event that locally resulted in the S_2 cleavage.

The distribution of phyllite presumably marks areas of increased temperature and fluid flow that promoted the crystallization of white mica in unusual amounts during deformation. Elsewhere in the Carolina slate belt, patches of phyllite prominently coincide with areas of volcanogenic alteration, and it appears that prepared ground focused later deformation. In the area of Figure 1, the phyllite patch around the gold deposits near McCormick seems to fit that situation. On the other hand, the two localities (Plum Branch, Limestone Quads) where high-alumina volcanogenic alteration was noted do not have phyllite. The east-west elongate zone of phyllite in area SB2 is not associated with known alteration or mineralization, but it is preferentially developed in the rhyolitic Persimmon Fork Formation.

Charlotte Belt Structural Pattern

No attempt was made to define internal Stratigraphy or structure in the Charlotte belt portion of the reconnoitered

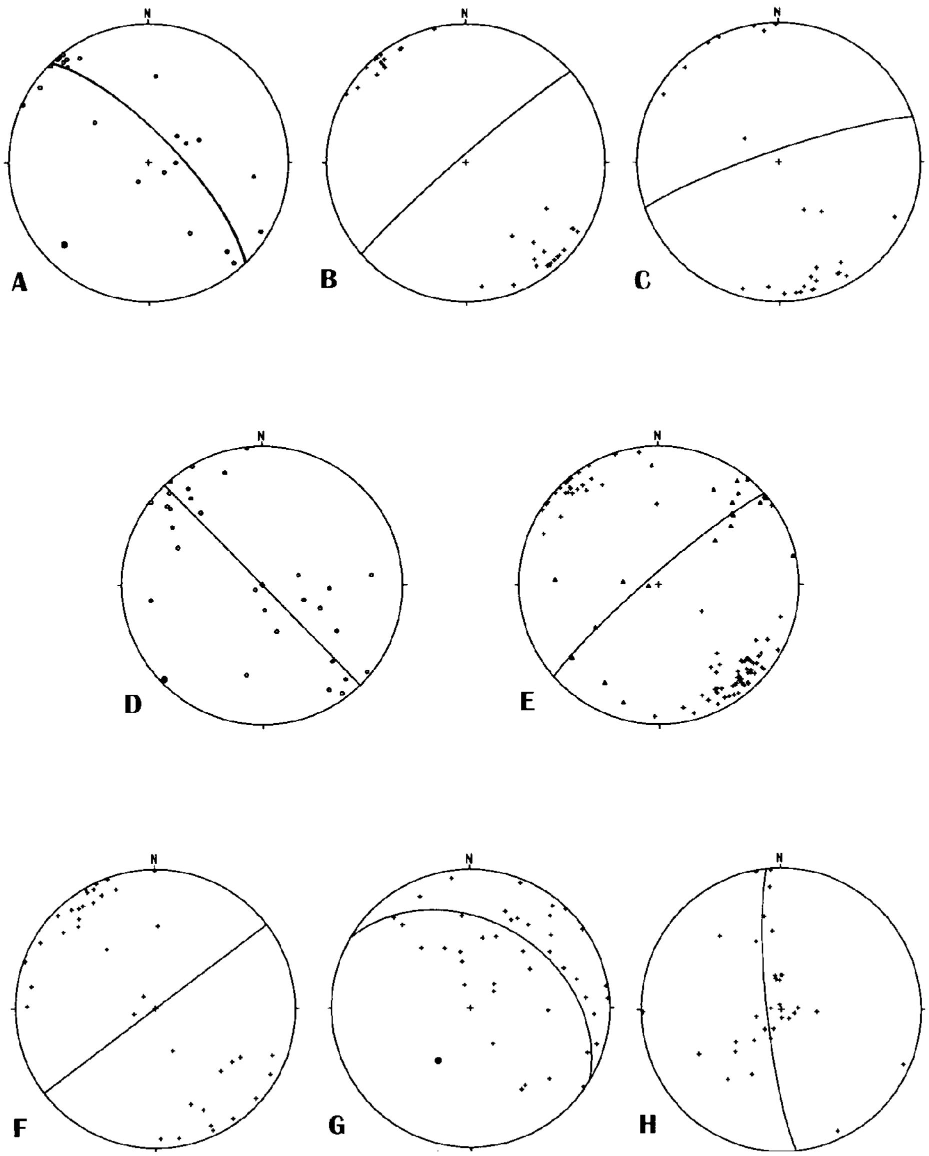


Figure 3. Stereographic plots for Carolina slate belt and Charlotte belt areas. Slate belt area SB2: a) Beds, excluding boundary zone and east end (Delmar, Lake Murray West Quads), n-28; girdle with beta-axis (large dot); b) S_1 cleavage, excluding east end; n-40: c) S1 cleavage, east end; n=29. Slate belt area SB1: d) Beds, n=32; girdle with beta-axis (large dot); e) crosses, S_1 cleavage, n=85; triangles, bed-cleavage intersections, n=21. Charlotte belt areas: f) CB1 foliation, n=40; girdle with beta axis (large dot); g) CB2 foliation, n=43; great circle = mean foliation; h) CB3 foliation, n=32; great circle = possible girdle.

area (Fig. 1). The western end of the area was mapped by Griffin (1978, 1979) and Nelson and others (1989); their maps show fairly similar patterns of rock distribution. Swaths of phyllitic and schistose rocks identified as metavolcanic were considered by these mappers to be slate-belt lithologies atop, but complexly infolded into, an assemblage of granitic gneiss, biotite and hornblende gneisses, and metagabbros. Nelson and others (1989) noted the two suites as rocks "commonly assigned" to the Carolina slate belt ant Charlotte belt, respectively, and interpreted them to be parts of a "Charlotte thrust sheet."

In this reconnaissance, despite particular effort to examine rocks within the Charlotte belt but previously identified as "slate belt", I found within the gneiss and schist units virtually no examples of rock I would describe as phyllite. Some fine-grained parts of some schist units provided evidence of high strain, and are more accurately considered phyllonite. If they were once volcanic rocks of slate belt type, the schistose rocks provided little remaining indication of such an origin. In addition, at places, the schistose units contain lithologies not seen in the slate belt: cross-bedded quartzite (as at Parsons Mt., Verdery Quad); quartzose rocks

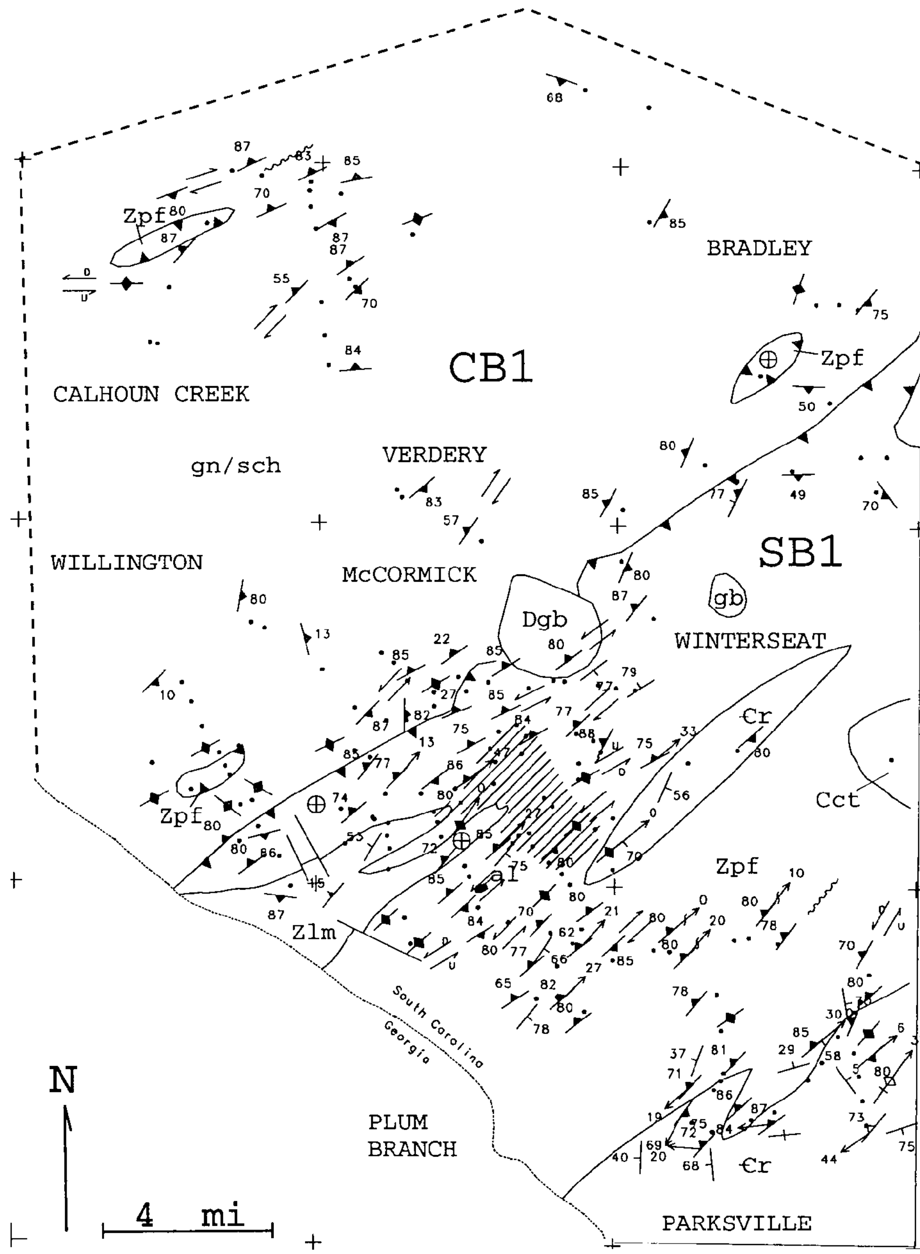


Figure 4. Reconnaissance information in areas SB1 and CB1. Legend as in Figure 1.

with up to 50 percent pyrite content; and highly ferruginous (mostly magnetite) quartz-rich rocks. Even more significant, patches of rhyolite rocks, primarily tuffs, were found at six places in the reconnoitered parts of the Charlotte belt (Figs. 1, 2, 4, 5). These rocks are lithologically like the slate-belt rocks just south of the mapped belt boundary. They have horizontal or gentle dips of layering and virtually no cleavage or effects of metamorphism, but they lie within or on amphibolite-facies gneisses and schists with steeply dipping layer-parallel foliation and complex internal structure. Some of the high-grade rocks on which they lie are those referred to by others as slate-belt lithologies; I infer instead from the observations that the gneisses and schists are at least two separate assemblages, probably of different histories, but together they form a package that can be considered as Charlotte belt, atop which the low-grade slate-belt rocks of profoundly different character and history lie in apparent outlier remnants.

Figures 3 e,f,g present stereographic plots of foliation data from areas CB1, CB2, and CB3 (see Fig. 1 and Figs. 2,4,5). In area CB1, the data define a mean foliation of N53°E89°SE, with a hint that the foliation might have been folded around a beta-axis at N54°E4°. This is not materially different than the geometry shown in Figure 5 for area SB1,

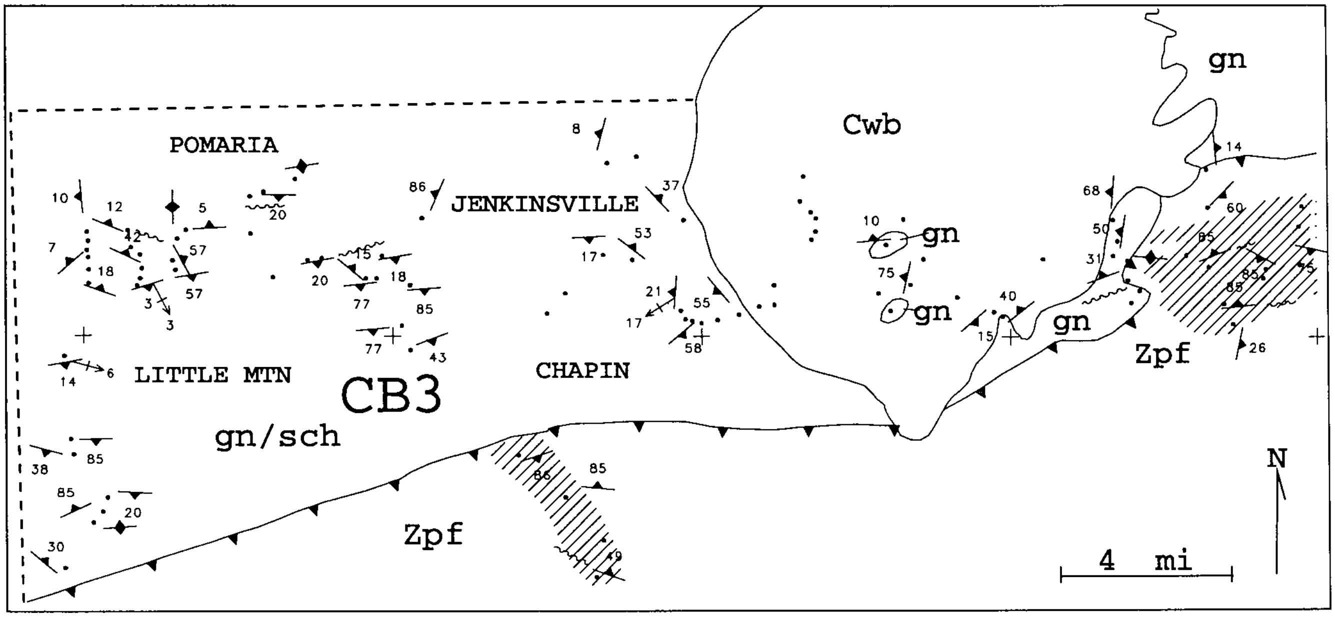


Figure 5. Reconnaissance information in area CB3. Legend as in Figure 1.

but the apparent similarity does not take into account the fact that the Charlotte belt foliation is layer-parallel, connoting an earlier isoclinal fording, totally unlike the deformation in the Carolina slate belt. The plot of foliation for area CB2 does not give a pattern of obvious meaning. A statistically defined girdle put through the scatter of foliation poles indicates a beta-axis at S32°W53°, but this axis probably is not significant. Of more importance is the contrast with the pattern of NE-trending Carolina slate belt cleavage seen in area SB2 just to south (Fig. 3b). The Carolina slate belt area appears to evidence a single deformation, whereas the Charlotte belt area has a complicated pattern of deformation, with gneisses and schists with layer-parallel foliation (again, marking an earlier isoclinal folding) in markedly different orientations than tectonic foliation in adjacent granitoid gneisses.

The age of the foliation-producing metamorphism is not known, but if it predated the granite of Newberry (Rb-Sr 415 Ma; Fullagar, 1981) that occurs in this area, the foliation may have been additionally disarranged by the intrusion. In area CB3, foliation poles are dispersed, possibly defining a girdle indicating folding around an axis at N84°E8°, approximately on the structural trend of cleavage in the slate belt area just to the southwest. However, these are tectonic foliations in granitoid gneisses, and there seems little likelihood that they share a geometry of deformation with the Carolina slate belt rocks. In that vein, the general observation must be emphasized that, whereas most slate belt cleavage is conspicuously uniform in its orientation on an area trend, the Charlotte belt foliation is conspicuously variable in trend.

RELATION OF THE TWO BELTS AND SPECULATIONS ON TECTONICS AND TIMING

Different styles, geometries, and intensities of deformation, and markedly different metamorphic levels, characterize the two belts. Nelson and others (in press) describe the amphibolite-facies Charlotte belt rocks as "polymetamorphic and polydeformed" and as making up a westward-transported thrust sheet. Carolina slate belt rocks, in sharp contrast, are barely metamorphosed and only weakly to moderately folded and cleaved, primarily in a single episode. In numerous outcrops along the boundary, even susceptible lithologies are not significantly cleaved. Folds are southeast-vergent, presumably connoting transport in that direction. These differences are displayed consistently along the Charlotte belt-Carolina slate belt boundary in outcrops as little as 300 meters apart (more detailed work almost certainly would turn up examples even closer). Cleavage along the margin of the Carolina slate belt commonly is highly variable in orientation, as compared with the relatively uniform trends seen away from the boundary.

The cleavage at the belt margin also commonly is at large angles to the foliation in the nearest outcrops seen in the Charlotte belt. In any case, the cleavage and the foliation represent different processes and histories. As described above, the contrast of structure is equally marked in the outlier patches of Carolina slate belt rocks within the Charlotte belt. Quartz veins in the Carolina slate belt rocks, either small veins in or large single veins, are common in the outpatches and also along the. belt boundary; throughout the Carolina slate belt, such quartz veins typically mark faults or shear zones.

At map scale, it is obvious that the Charlotte belt- Carolina slate belt boundary trends variously parallel to and across the internal structural trends of the Carolina slate belt. The discordant contact and discordant character and apparent histories of the Carolina slate belt and Charlotte belt suggest tectonic juxtaposition of the two lithotectonic assemblages. A regional thrust relationship could easily account for the observed features, including the Carolina slate belt outliers as klippen. Given the opposite vergence of structures in the two belts, emplacing the slate belt by southeastward slip on a regional detachment fault may be an even more likely mechanism than thrust faulting. Differences in metamorphic grade and structural style between the belts are such as to suggest that a few kilometers of crust was cut out in the inferred thrusting or listric movement. Opposite movement senses in the two belts may imply that thrusting or detach occurred after both belts had (separately) acquired their structure. Absence in the Carolina slate belt of the Devonian plutons so numerous in the Charlotte belt also suggests separateness of the belts until after the Devonian intrusive episode. Timing of metamorphism and deformation in either belt is not certainly constrained, but it seems clear that the Charlotte belt had been deformed and metamorphosed before intrusion of the Devonian plutons (ca. 415-400 Ma; McSween and others, 1991). The type and style of deformation and associated low green- schist-facies metamorphism seen in the Carolina slate belt of South Carolina is identical to that in North Carolina, where biotite and muscovite on the regional cleavage have been dated as Late Ordovician (40Ar/39Ar; Offield and others, 1990). Based on this information, possibilities are 1) that the two assemblages, though nonadjacent, were deformed and metamorphosed in an Ordovician event (Taconian), or 2) that they were separately deformed and metamorphosed, one in Ordovician and the other perhaps in Devonian (Acadian) time. In either scenario, the configuration seems to require that they were then juxtaposed after the Devonian plutons were emplaced, probably during the major regional Alleghanian thrusting that affected the entire Piedmont and provinces farther west.

REFERENCES

Barker, C.A., Secor, D. T., Jr., Pray, J.R., Dallmeyer, R.D., Jr., and Wright, J.E., 1993, Tectonothermal history of the slate belt in northeast South Carolina: South Carolina Academy of Sciences Bulletin, v. 55, p. 63.

Bourland, W.C., and Farrar, Stewart, 1980, Tectogenesis of the rocks surrounding the Winnsboro intrusive complex: South Carolina Geological Survey, South Carolina Geology, v. 24, p. 1-18.

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

Brasier, M., Cowie, J., and Taylor, M., 1994, Decision on the Precambrian-Cambrian boundary stratotype: Episodes, v. 17, p. 3-8.

Butler, J.R., and Secor, D. T., Jr., 1991, The central Piedmont, in Horton, J.W., Jr. and Zullo, V.A., eds., The geology of the Carolinas: Carolina Geological Society 50th Anniversary volume, Knoxville, University of Tennessee Press, p. 59-78.

Carpenter, R.H., Odom, A.L., and Hartley, M.E., III, 1982, Geochronological investigation of the Lincolnton metadacite, Georgia and South Carolina, in Bearce, D.N., Black, W.W., Kish, S.A., and Tull, J.F., eds., Tectonic studies in the Talladega and Carolina slate belts, southern Appalachian orogen: Geological Society of America, Special Paper 191, p.145-152.

Fullagar, P.D., 1981, Summary of Rb-Sr whole-rock ages for South Carolina: South Carolina Geological Survey, South Carolina Geology, v. 25, p. 29-32.

Gibson, G.G., Teeter, S.A., and Fedonkm, M.A., 1984, Ediacarian fossils from the Carolina slate belt, Stanly County, North Carolina: Geology, v. 12, p. 387-390.

Goldsmith, R., Milton, D.J., and Horton, J.W., Jr., 1988, Geologic map of the Charlotte Miscellaneous Investigations Series Map I-1251-E, scale 1:250,000.

Griffin, V.S., Jr., 1978, Geology of the Calhoun Creek, Calhoun Falls, and portions of the Chennault and Verdery Quadrangles, South Carolina: Columbia, South Carolina Geological Survey, Map Series, MS-23, 47 p.

________, 1979, Geology of the Abbeville East, Abbeville West, Latimer, and Lowndesville Quadrangles, South Carolina: Columbia, South Carolina Geological Survey, Map Series, Ms-24, 58 p.

King, P.B., 1955, A geologic section across the southern Appalachians: An outline of the geology in the segment in Tennessee, North Carolina, and South Carolina, in Russell, R.J., ed., Guides to southeastern geology: New York, Geological Society of America, p. 332-373.

Koeppen, R.P., Repetski, J.E., and Weary, D.J., 1995, Microfossil assemblages indicate Ordovician or Late Cambrian age for Tillery Formation and mudstone member of Cid Formation, Carolina slate belt, North Carolina: Geological Society of America, Abstracts with Programs, in press.

Lawrence, D.P., 1987, Geology of the Good Hope Quadrangle: South Carolina Geological Survey, South Carolina Geology, v. 31, p. 67-82.

McCauley, J.F., 1961, Relationships between the Carolina slate belt and the Charlotte belt in Newberry County, South Carolina: Columbia, South Carolina, Division of Geology, State Development Board, Geologic Notes, v. 5, p. 59-79.

McSween, H.Y., Jr., Speer, J.A., and Fullagar, P.D., 1991, Plutonic Rocks, in Horton, J. W., Jr. and Zullo; V.A., eds., The geology of the Carolinas: Carolina Geological Society 50th Anniversary volume, Knoxville, University of Tennessee Press, p. 109-126.

Nelson, A.E., Horton, J.W., Jr., and Clarke, J.W., 1989, Geologic map of the Greenville 1°x2° quadrangle, Georgia, South Carolina, and North Carolina: U.S. Geological Survey Open-file report 89-9, scale 1:250,000.

_______________, (in press), Geologic map of the Greenville 1°x2° quadrangle, South Carolina, Georgia, and North Carolina: U.S. Geological Survey, Miscellaneous Investigations Map 1-2175, scale 1:250,000, with pamphlet.

Offield, T.W., Kunk, M.J., and Koeppen, R.P., 1990, Style and age of deformation in the Carolina slate belt of central North Carolina: Geological Society of America, Southeast Section, Abstracts with Programs, p. 54.

Offield, T. W., 1994, Lithotectonic map and field data---Reconnaissance geology of the Carolina slate belt and adjacent rocks from southern Virginia to central South Carolina: U.S. Geological Survey Open-File Report OF 94-420; two diskettes (including maps of parts of 13 100,000-scale quadrangles, field-data spreadsheets, 58-p. text).

Pirkle, W.A., 1978, Preliminary report on the geology of the Parksville Quadrangle, McCormick and Edgefield Counties, South Carolina Geologic Survey, Geologic Notes, v. 22, p. 95-104

_______________, 1981, Geology of the Limestone Quadrangle, west-central South Carolina: South Carolina Geological Survey, South Carolina Geology, v. 25, p. 21-27.

Secor, D.T., Jr., 1988, Geology of the eastern Piedmont in central South Carolina, in Secor, D.T., Jr., ed., Southeastern geological excursions: South Carolina Geological Survey, Geological Society of America, Southeastern Section, Field Trip Guidebook for 1988, p. 204- 225.

Secor, D. T., and Wagener, H.D., 1968, Stratigraphy, structure and petrology of the Piedmont in central South Carolina: Columbia, South Carolina, Division of Geology, State Development Board, Geologic Notes, v. 12, p. 67-84.

Secor, D. T., Jr., and Snoke, A. W., 1978, Stratigraphy, structure, *and plutonism in the central South Carolina Piedmont,* in Snoke, A.W., ed., Geological investigations of the eastern Piedmont, southern Appalachians: south Carolina Geological Survey, Carolina Geological Society Guidebook for 1978, p. 65-123.

Secor, D.T., Jr., Peck, L.S., Pitcher, D.M., Prowell, D.C., Simpson, D.H., Smith, W.A., and Snoke, A.W., 1982, Geology of the area of induces seismic activity at Monitcello Reservoir, South Carolina: Journal of Geophysical Research, v. 87, p. 6945-6957.

Secor, D. T., Jr., Samson, S.L., Snoke, A. W., and Palmer, A.R., 1983 Confirmation of the Carolina slate belt as an exotic terrane: Science, v. 221, p. 649-651.

Secor, D.T., Jr., Snoke, A.W., Bramlett, K.W., Costello, O.P., and Kimbrell, O.P., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part I, Alleghanian deformation in the eastern Piedmont of South Carolina: Geological Society of America, Bulletin, v. 97, p.1319-1328.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 87-92

THE RUSSELL LAKE ALLOCHTHON - A NEGLECTED TECTONOSTRATIGRAPHIC UNIT IN THE SOUTHERN APPALACHIANS

Giles Allard and James Whitney
Department of Geology
University of Georgia
Athens, GA 30602

INTRODUCTION

The Russell Lake Allochthon is a newly-identified tectono-stratigraphic unit not yet recognized by the many workers who have produced models of the Southern Appalachians (Bird and Dewey, 1970; Dallmeyer, 1988; Dallmeyer and others, 1986; Hatcher, 1972, 1978, 1987; Hatcher and others, 1977; Hatcher and Odom, 1980; Higgins and others 1988; Secor and others, 1986a, 1986b; Williams and Hatcher, 1982). Our mapping in a limited area of northeast Georgia (Allard and Whitney, 1994) has identified eighty-eight occurrences of ultramafic-mafic rocks (Figure 1), and we suspect that many more will be found with additional small-scale mapping.

In general, these occurrences are small and overlie a variety of rock types within the Carolina terrane. The presence of flat shears at the base of some occurrences, the very low grade of metamorphism, the lack of penetrative deformation, and the lack of magnetic signature led us to postulate that these individual occurrences of ultramafic-mafic rocks are part of a large allochthonous sheet we have called the Russell Lake Allochthon. Ultramafic rocks in the Appalachians have been recognized for a long time (Butler, 1989; Hess, 1939, 1955; Misra and Keller, 1978; Mittwede and Stoddard, 1989). Larrabee (1966) compiled a map showing the distribution of ultramafic and mafic bodies within the Appalachians from New Jersey to Alabama.

Within our map-area, only one occurrence of serpentinite and soapstone is reported by Larrabee as opposed to the eighty-eight occurrences we have observed.

GENERAL GEOLOGY OF THE AREA

Many classic papers mentioned above cover the historical development of the geology of the Southern Appalachians. We will not review this here for lack of space but

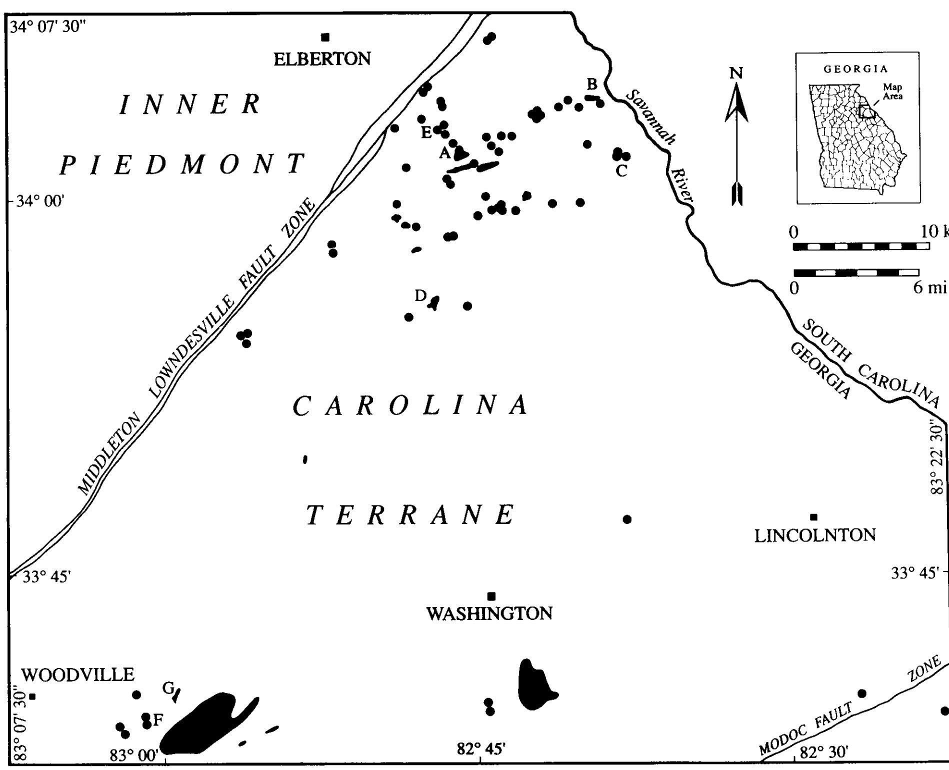


Figure 1. Ultra-mafic rocks in northeast Georgia.

discuss the preliminary results of our mapping.

Our map-area straddles the Inner Piedmont terrane, the Carolina terrane (consisting of the Charlotte belt and Slate belt of former authors, e.g. King, 1955), and the Modoc fault zone (Allard and Whitney, 1989, 1994; Whitney and Allard, 1990). To the northeast, Secor and others (1986a) found evidence that the Modoc zone is a gradational boundary between the suprastructure (Carolina slate belt) and the infrastructure (Kiokee belt).

The Inner Piedmont is made up of a series of superposed nappes (Griffin, 1978b; Nelson and others, 1987) with northwest vergence. It consist~ of paragneisses, orthogneisses, amphibolites, minor schists, quartzites and volcanogenic banded iron formation. The Middleton-Lowndesville fault zone separates the Inner Piedmont from the Carolina terrane. The fault zone has a variable width and consists of an early ductile deformation zone followed by a late brittle fault zone marked by intense brecciation and silicification. The Carolina terrane is a volcanic terrane of island arc affinity (Whitney and others, 1977). Dennis and Shervais (1991) suggested intra-arc rifting to explain some of the lithologic and stratigraphic relationships they observed in northwestern South Carolina. Within this terrane, the rocks are metamorphosed to the greenschist facies in the former Slate belt and amphibolite facies in the former Charlotte belt. The rocks are also intensely deformed with development of a very strong foliation, hence the name Slate belt. In the study area the majority of the volcanic rocks are dacitic in composition and occur as flows, tuffs of many varieties, and dikes. Minor lenses of pillowed metabasalts, basaltic tuffs, banded volcanogenic iron formation, and argillites have been identified (Allard and Whitney, 1994). A few fossil localities have been observed in the Carolinas (St. Jean, 1965, 1973; Samson, 1984). The fossils are Cambrian in age. The dacites have been radiometrically dated at 568 Ma (Carpenter and others, 1982). A number of pre and post-metamorphic granitic bodies are intruded in the volcano-sedimentary assemblage.

The Charlotte belt is made up of gneisses, schists, amphibolites, minor quartzites volcanogenic metachert), and aluminosilicate schists/ granofels (metamorphosed leached pumice lapilli tuff). The majority of the gneisses are orthogneisses of plutonic origin intruded in the volcanic rocks of the Slate belt. Within our map-area, the higher grade of metamorphism of the Charlotte belt is a “regional” contact metamorphic effect of the numerous plutons on the Slate belt volcanics. The contact is a gradual metamorphic change from the greenschist facies of the Slate belt to the amphibolite facies of the Charlotte belt (Allard and Whitney, 1994).

The Modoc fault zone separates the Carolina terrane from the Kiokee belt to the southeast. Part of the Kiokee belt has been called Savannah River terrane (Secor and others, 1989; Maher and others, 1994). Within our map-area, on the Carolina terrane side of the fault zone, the deformation is very intense and the phyllites and phyllonites are easily eroded causing the main axis of Thurmond Lake (formerly Clark Hill Lake). In a southeast direction, the phyllites give place to mylonitized septa of granite becoming thicker and more abundant to the southeast and interlayered with lenses of mylonitized amphibolites and long linear ridges of quartz-sillimanite-muscovite schists with a pronounced C-S fabric indicating a dextral sense of movement. Dennis and Secor (1987) presented a model to explain the crenulations they observed where the Irmo shear zone intersects the Modoc fault zone.

RUSSELL LAKE ALLOCHTHON

Graduate students at the University of Georgia have mapped nearly twenty 7.5-minute quadrangles, mostly in the Carolina terrane. Isolated occurrences of ultramafic-mafic rocks have been reported by many of them (Conway, 1986; Hutto, 1986; Legato, 1986; Lovingood, 1983; McFarland, 1992; Rozen, 1978; Turner, 1987; Yon der Heyde, 1990, Young, 1985). McFarland (1992) has done extensive petrographic and chemical work on the mafic-ultramafic bodies of the Russell Lake Allochthon. Her thesis contains many small-scale maps of the various occurrences, color photographs of some occurrences, and photomicrographs of many lithologies. She also reports a number of microprobe analyses and chemical analyses of 35 samples. Legato (1986) mapped the Heardmont Quadrangle. Along the shore of Lake Russell (outcrop B of Figure 1), he identified an occurrence of ultramafic lithologies (lherzolite) resting on a subvolcanic highly foliated dacitic intrusive with a very strong steeply-dipping S2 cleavage. The ultramafic rocks show a pronounced flat shearing for a few inches at the lower contact (the rock is a talc-chlorite schist) but do not show the penetrative foliation above the few inches of the lower contact. The presence of the shear at the base, the lack of foliation above, and the lack of a magnetic signature led Legato to suggest a large allochthonous sheet of ultramafic rocks lying in a near horizontal position on top of Slate belt and Charlotte belt lithologies. Whitney and others (1987) called attention to the discovery of Legato. Since 1988, we have compiled the existing theses, remapped some areas and completed the mapping of a block of twenty one quadrangles in northeast Georgia. Eighty-eight occurrences (Figure 1) of the ultramafic-mafic thrust sheet have been located within our map-area (Allard and Whitney, 1994). On his map, Legato (1986) joined many small separate occurrences into a large klippen. Our remapping does not support this conclusion. We find a large number of small erosional remnants belonging to one allochthonous sheet (the Russell Lake Allochthon) lying above an intrusive complex we have called the Heardmont Complex. It consists of hornblende meladiorite grading into hornblende-biotite granodiorite and granite to the north and gabbro to the south. The meladiorite can easily be confused with gabbros of the Russell Lake Allochton. Rozen

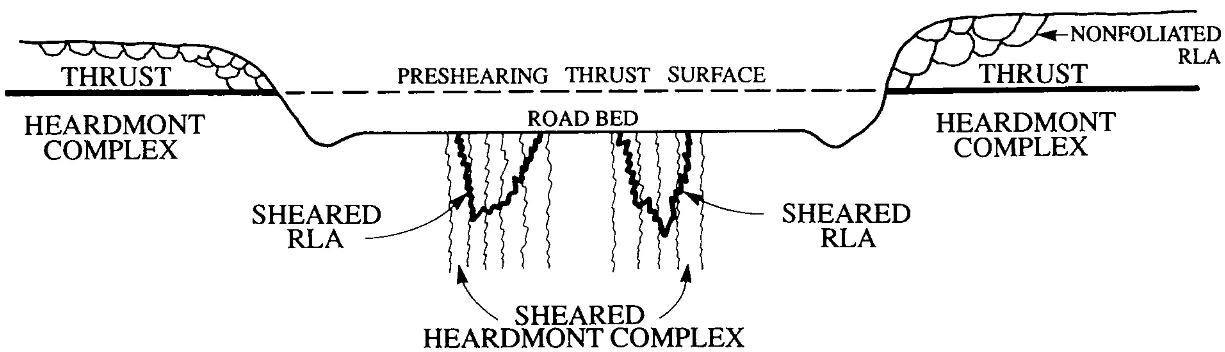


Figure 2.

(1978) gives detailed descriptions of both rock groups; the allochthonous nature of the mafic-ultramafic rocks had not been discovered at the time of Rozen's work. The meladiorite is an igneous rock which has suffered amphibolite grade metamorphism. It has a granoblastic texture preserving, in thin sections, traces of the original igneous texture. It consists of hornblende, plagioclase (An 30 to An 35), biotite, quartz, and minor amounts of ilmenite and sphene. The gabbros within the Russell Lake allochthon are coarse-grained dark-colored rock consisting of plagioclase (original highly calcic plagioclase is reported by McFarland), amphiboles, serpentine, and clinozoisite/zoisite replacing the plagioclase and preserving the typical cumulate texture. The saprolite and the soils derived from these two rock types are very different: the meladiorite rarely outcrops and underlies large cultivated fields while the mafic-ultramafic lithologies of the Russell Lake Allochthon occur as small uncultivated hills, commonly forested, underlain by outcrops and large boulders. The magnesium-rich and calcium- and potassium-poor chemistry of the ultramafic rocks does not lead to the generation of fertile soils. For this reason, the klippen are left untilled and forested and easy to identify in many instances. The best ones are labeled A,B,C etc. on Figure 1. In many instances, the original cumulate texture of the mafic-ultramafic rocks can be identified readily with a hand lens. The most common rock types (McFarland, 1992) are websterites, harzburgites, pyroxenites, dunites, lherzolites, gabbros, and quartz gabbros. In sampling the area for petrographic work, there is a tendency to oversample the gabbros and quartz-bearing gabbros since they are more resistant producing better samples than the olivine-rich dunites and peridotites which are more easily decomposed and too friable for thin section preparation.

In some localities, such as along the road leading to the quarry at the top of the hill in Jackson Crossroads 7.5-minute quadrangle (outcrop D in Figure 1) and in a few others, one can find a multitude of rock types within a single locality indicating magmatic differentiation and a certain coarse layering of the rock types. Rozen (1978, Figure 14, page 59) illustrates an excellent example of small scale cumulate layering in a norite. The minerals identified by McFarland (1992) are olivine, pyroxene (both ortho and clino), chromite and ferrochromite, plagioclase, serpentine, tremolite/ actinolite, hornblende, anthophyllite, chlorite, talc, epidote, and magnetite. Traces of spinel, sphene, and ilmenite have also been identified. The preservation of cumulate and intercumulate textures and the nature of the minerals reported suggest deuteric alteration and/ or low grade greenschist facies metamorphism.

A number of localities have narrow vertical shears cutting the mafic-ultramafic rocks of the Russell Lake Allochthon. The shears are generally very narrow, from 10 centimeters to one meter wide, producing a talc-chlorite schist while the enclosing rocks show no foliation and well preserved igneous textures. In one locality, within the Heardmont quadrangle, the sheared portion was in the middle of a well-graded dirt road and gave the impression of sheared lenses of ultramafic rocks within the sheared Heardmont meladiorites. McFarland (1992, Figure 34, p. 66) has illustrated this occurrence (Figure 2). A few feet away from the intense shear zones, the rocks show no foliation and good igneous textures.

In all instances, the lack of a steep foliation, the lack of aeromagnetic signature, the presence of cumulate texture and minerals, and the very low degree of metamorphism (it could be described as deuteric alteration or very low grade greenschist facies), give convincing evidence that we are dealing with a series of klippen on a thin allochthonous sheet.

AREAL EXTENT OF THE RUSSELL LAKE ALLOCHTHON

Figure 1 is adapted from the map of Allard and Whitney (1994). Three types of mafic-ultramafic rock bodies occur within the map-area:

1. A few gabbro bodies have been identified within the bedded pyroclastics of the Slate belt. They are thin lensoid steeply-dipping bodies sharing the metamorphic mineralogy

and steeply-dipping penetrative deformation of the enclosing rocks. They are clearly synvolcanic and prekinematic.

2. A number of small intrusive gabbro bodies have been identified. They are post kinematic and are easily identified by the strong bull's-eye signature on aeromagnetic maps, the lack of metamorphic overprint, and the presence of a hornfels halo. Good examples are the Chafin and Georgia Farm gabbros mapped by Davidson (1981) on the boundary of the Lexington-Rayle 7.5-minute quadrangles and the Rose Hill gabbro mapped by Rozen (1978) and Legato (1986) on the boundary of the Elberton East-Heardmont 7.5-minute quadrangles.

3. The distribution of Russell Lake Allochthon lithologies (Figure 1) suggest a large areal extent. All occurrences of mafic and ultramafic rocks in the Southeast Appalachians should be investigated with this new paradigm in mind. We have not studied occurrences outside of our map-area. However, they have been reported in other parts of Georgia and in South Carolina (Cocker, 1991a, 1991b; Griffin, 1975, 1978a, 1979; Maybin and Niewendorp, 1993; Sacks and others, 1989; Secor and Snoke, 1978).

Further afield, Soapstone Ridge in Atlanta is a large body of ultramafic rocks lying on a flat fault as well illustrated at the Georgia Geological Society field trip in 1984 (Higgins and others, 1984).

In South Carolina, the Hammett Grove Complex also lies on a flat fault that was well illustrated at the Geological Society of America Southeastern Section field trip of 1988 (Mittwede, 1988b, p. 259). It is not possible at this time to conclude whether these bodies belong to the Russell Lake Allochthon, but their mineralogy and petrology (Mittwede, 1988b) and the fact that they lie on relatively flat fault surfaces suggest a potential correlation.

TECTONIC IMPLICATIONS

We have no doubt on our interpretation of the Russell Lake Allochthon as a major tectonic unit within our map-area. The provenance of this lithotectonic unit is not known and the exact timing of emplacement is also unknown. However, we know that it has to postdate the metamorphism and deformation of the Heardmont Complex and the other lithologies of the Carolina terrane and predate some of the Alleghanian shear zones. The mineralogy and texture of the rocks suggest a layered dunite-to-gabbro body similar to oceanic crust as described by many authors. It was clearly thrusted onto tightly folded and metamorphosed rocks of the Carolina terrane and possibly over the Inner Piedmont as well. The only deformation which it has suffered are narrow vertical shears probably associated with the Alleghanian deformation (synchronous with the Middleton-Lowndesville fault zone and the Modoc fault zone). These narrow shears locally create an imbrication of sheared ultramafic rocks with sheared country rocks of the Carolina Terrane leading the casual observer to the conclusion that they are contemporaneous with the enclosing volcanic rocks (Figure 2). Current seismic work in progress (outcrop A of Figure 1) (Clippard and Hawman, 1994 and this volume) will greatly help us, in establishing the depth and shape of the ultramafic lenses of the Russell Lake Allochthon.

ACKNOWLEDGMENTS

We appreciate thoughtful reviews of an early draft of this paper by Harmon Maher and Clark Niewendorp. A portion of the field work was supported by the Georgia Geologic Survey. We also thank Gisela Weis-Gresham who drafted the figures. Thanks to Allen Dennis who prodded us in preparing this paper.

REFERENCES

Allard, G.O. and Whitney, J.A., 1994, Geology of the Inner Piedmont, Carolina Terrane, and Modoc Zone in Northeast Georgia: Georgia Geologic Survey, Project Report 20, 36 p. & map.

Allard, G.O. and Whitney, J.A., 1989, Structure, tectonics, and ore potential along a transect across the Inner Piedmont, Charlotte belt, and Slate belt of eastern Georgia., in Fritz, W.J., ed., Excursions in Georgia Geology, Georgia Geological Society Guidebooks, v: 9, p. 77-118.

Bird, J.M. and Dewey, 1970, Lithosphere plate-continental margin tectonics and the evolution of the Appalachian orogen: GSA Bulletin, v. 81, p. 1031-1060.

Butler, J.R., 1989, Review and classification of ultramafic bodies in the Piedmont of the Carolinas: Geological Society of America Special Paper 231, p. 19-31.

Carpenter, R.H., Odom, A.L., and Hartley, M.E., 1982, Geochronological investigation of the Lincolnton metadacite, Georgia and South Carolina: Geological Society of America Special Paper 191, p.145-152.

Clippard, J.E. and Hawman, R.B., 1994, High resolution seismic survey over an ultramafic complex in the Carolina Terrane, Georgia: EOS, Transactions American Geophysical Union, v. 75, p. 239.

_____________, 1995, Shallow seismic reflection profiling over an ultramafic complex in the Carolina terrane, this volume.

Cocker, M.D., 1991a, Geology and geochemistry of altered serpentinites in the Burks Mountain Complex, Columbia County, Georgia: Georgia Geologic Survey Bulletin 124, 112p.

_____________, 1991b, Economic Geology of altered serpentinites in the Burks Mountain Complex, Columbia County, Georgia: Georgia Geologic Survey Bulletin 123, 89 p.

Conway, K.M., 1986, The geology of the northern two-thirds of the Philomath quadrangle, Georgia: University of Georgia, unpublished M.S. thesis, 136 p.

Dallmeyer, R.D., 1988, Late Paleozoic tectonothermal evolution of the Western Piedmont and eastern Blue Ridge, Georgia: Controls on the chronology of terrane accretion and transport in the southern Appalachian orogen: Geological Society of America Bulletin, v. 100, p. 702-713.

Dallmeyer, R.D., Wright,J.E.,Secor, D.T., and Snoke, A.W., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part II. Geochronological constraints on the tectonothermal evolution of the eastern Piedmont in South Carolina: GSA Bulletin, v. 97 p. 1329-1344.

Davidson, J.W., 1981, The geology, petrology, geochemistry, and economic mineral resources of East-Central Oglethorpe County, Georgia: University of Georgia unpublished M.S. thesis, 224 p.

Dennis, A.J. and Secor, D.T., 1987, A model for the development of crenulations in shear zones with applications from the Southern Appalachian Piedmont: Journal of Structural Geology, v. 9, p. 800-817.

Dennis, A. J. and Shervais, J.W., 1991, Arc rifting of the Carolina terrane in northwestern South Carolina: Geology, v. 19, p. 226-229.

Griffin,V.S., 1975, Geology of the Seneca, Westminster, and portions of the Avalon and Oakway quadrangles, South Carolina: South Carolina Division of Geology, MS-20, 42 p.

Griffin, V.S., 1978a, Geology of the Calhoun Creek, Calhoun-Falls and portions of the Chennault and Verdery quadrangles, South Carolina; South Carolina Geological Survey, M5-23,47 p.

_____________, 1978b, Detailed analysis of tectonic levels in the Appalachian Piedmont: Geologische Rundschau, v. 67, p.18D-201.

_____________, 1979, Geology of the Abbeville East, Abbeville West, Latimer and Lowndesville quadrangles, South Carolina: South Carolina Geological Survey, MS-24, 58 p.

Hatcher, R.D., 1972, Developmental model for the Southern Appalachians: GSA Bulletin, v. 83, p. 2735-2760.

Hatcher, R.D., 1978, Tectonics of the Western Piedmont and Blue Ridge, Southern Appalachians: review and speculation: American Journal of Science, v. 278, p. 276-304.

_____________, 1987, Tectonics of the Southern and Central Appalachian Internides: Annual Review Earth and Planetary Science, v.15, p. 337-362.

Hatcher, R.D.,Howell, D.E., and Talwani, P., 1977, Eastern Piedmont fault system: speculations on its extent: Geology, v. 5, p. 636-640.

Hatcher, R.D. and Odom, A.L., 1980, Timing of thrusting in the southern Appalachians, USA: model for orogeny?: Journal of the Geological Society, v. 137, p. 321-327.

_____________, 1955, Serpentines, orogeny, and epeirogeny: Geological Society of America Special Paper 62, p. 391-408. Hess, H.H., 1939, Island arcs, gravity anomalies and serpentine intrusions: International Geological Congress, Moscow 1937, Report 17, vol. 2, p. 263-283.

Higgins, M.W., Atkins, R.L., Crawford, T.J., Crawford, R.F. and Cook, R.B., 1984, A brief excursion through two thrust stacks that comprise most of the crystalline terrane of Georgia and Alabama: Georgia Geological Society 19th Annual Field trip guidebook, 67 p.

Higgins, M.W., Atkins, R.L., Crawford, T., Crawford, F., Brooks, R., and Cook, R.B., 1988, The structure, stratigraphy, tectonostratigraphy, and evolution of the southern-most part of the Appalachian orogen. U.S.G.S. Prof. Paper 1475, 173 p.

Hutto, T.D.W., 1986, The geology of the Rayle quadrangle within Wilkes county, Georgia: University of Georgia unpublished M.S. thesis, 128 p.

King, P.B., 1955, A geologic section across the Southern Appalachians: an outline of the geology in the segment in Tennessee, North Carolina, and South Carolina: in Russell, R.J., ed. Guides to Southeastern Geology, Geological Society of America, p. 332-373.

Larrabee, D.M., 1966, Map showing distribution of ultramafic and intrusive mafic rocks from northern New Jersey to Eastern Alabama; United States Geological Survey, Miscellaneous Investigation Map 1-476, 1:500,000.

Legato, J.M., 1986, The geology of the Heardmont quadrangle, Georgia-South Carolina: University of Georgia unpublished M.S. thesis, 144 p.

Lovingood, D.A., 1983, The geology of the southern one-third of the Philomath and northern one-third of the Crawfordville, Georgia, quadrangles: University of Georgia unpublished M.S. thesis, 243 p.

Maher, H.D. Jr, Dallmeyer, R.D., Secor, D.T., Jr., and Sacks, P.E.,1994: $^{40}Ar/^{39}Ar$ constraints on chronology of Augusta fault zone movement and late Alleghanian extension, Southern Appalachian Piedmont, South Carolina and Georgia: American Journal of Science, v. 294, p. 428-448.

Maybin, A.H. III and Niewendorp, 1993: The central Piedmont allochthon: an Alleghanian terrane in the central Piedmont of South Carolina: South Carolina Geology, v. 36, p.47-57.

McFarland, T.L., 1992, Geochemical and petrographic study of the Russell Lake Allochthon in Northeast Georgia; University of Georgia unpublished M.S. thesis, 315 p.

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

Mittwede, S.K., 1988, Road Log for stops in the Ora, Pacolet, and Pacolet Mills Quadrangles; in Secor, D.T., ed., Southeastern Geological Excursions, Geological Society of America Southeastern Section field trips, p. 250-265.

Mittwede, S.K. and Stoddard, E.F., 1989, ed. Ultramafic rocks of the Appalachian Piedmont: Geological Society of America Special Paper 231.

Nelson, A.E., Horton, J.W., and Clarke, J.W.,1987, Generalized tectonic map of the Greenville 10 by 20 Quadrangle, Georgia, South Carolina, and North Carolina: United States Geological Survey Miscellaneous Field Studies Map MF-1898, 1: 250,000.

Rozen, R. W., 1978, The geology of the Elberton-east quadrangle: University of Georgia unpublished M.S. thesis, 110 p.

Sacks, P.E., Maher, H.D., Secor, D.T., and Shervais, J.W., 1989, The Burks Mountain complex, Kiokee belt, southern Appalachian Piedmont of South Carolina and Georgia: Geological Society of America Special Paper 231, p. 75-85.

St. Jean, 1965, New Cambrian trilobite from the Piedmont of North Carolina: Geological Society of America, Abstracts with program, p. 307-308.

St. Jean, 1973, A new Cambrian trilobite from the Piedmont of North Carolina: American Journal of Science, v. 273A, p.196-216.

Samson, S.L., 1984, Middle Cambrian fauna of the Carolina slate belt, central South Carolina: University of South Carolina unpublished M.S. thesis, 54 p.

Secor, D.T. and Snoke, A.W., 1978, Stratigraphy, structure, and plutonism in the central South Carolina Piedmont: in Snoke, A.

W., ed., Geological Investigations of the eastern Piedmont, southern Appalachians, Carolina Geological Society Guidebook, p. 65-99.

Secor, D.T.,Snoke, A.W., Bramlett, K.W., Costello, D.P. and Kimbrell, D.P., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part I. Alleghanian deformation in the eastern Piedmont of South Carolina: Geological Society of America Bulletin, v. 97, p. 1319-1328.

Secor, D.T., Snoke, A.W., and Dallmeyer, R. D., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part III. Regional tectonic relations: Geological Society of America Bulletin, v. 97, p. 1345-1353.

Secor, D.T., Dennis, A.J., Maher, H.D., and Sacks, P.E., 1989: Geology and terrane analysis of the Eastern Piedmont, South Carolina and Georgia: in Dallmeyer, R.D., ed., Tectonostratigraphic expression of terrane accretion in the Southern Appalachian orogen: a geotraverse excursion; I.G.C.P. Project 233 Guidebook series, v. 4, p. 8-30-8-79.

Turner, W. L., 1987, The geology of the Vesta 71/2" quadrangle, Georgia: University of Georgia, unpublished M.S. thesis, 204 p.

Von der Heyde, W.S., 1990, The geology of the Washington East 71/2' Quadrangle, Wilkes County, Georgia: University of Georgia, unpublished M.S. thesis, 130 p.

Whitney, I.A. and Allard, G.O., 1990, Structure, tectonics, and ore potential along a transect across the Inner Piedmont, Charlotte Belt, and Slate Belt of Eastern Georgia: Georgia Geological Society Guidebooks, v. 10, no 1,45 p.

Whitney, J.A., Paris, T.A., Carpenter, R.H., and Hartley, M.E., 1977, Volcanic evolution of the Southern Slate Belt of Georgia and South Carolina: a primitive oceanic island arc: Journal of Geology, v. 86, p. 173-192.

Whitney, J.A., Herz, N., and Legato, J.M., 1987, Allochthonous mafic and ultramafic lithologies from near the Russell reservoir, eastern Georgia: evidence for late Paleozoic thrust emplacement of a dismembered ophiolite: Geological Society of America Abstracts with programs, v. 19, p.l36.

Williams, H. and Hatcher, R.D., 1982, Suspect terranes and accretionary history of the Appalachian orogen: Geology, v.10, p.530-536.

Young, R.H., 1985, The geology of the Jacksons Crossroads 7 1/2' quadrangle, Georgia: University of Georgia, unpublished M.S. thesis, 220 p.

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1995 Annual Meeting
Pages 1-21

SHALLOW SEISMIC REFLECTION PROFILING OVER AN ULTRAMAFIC COMPLEX IN THE CAROLINA TERRANE, NE GEORGIA

Jeffrey E. Clippard and Robert B. Hawman
Department of Geology
University of Georgia
Athens, Georgia, 30602

ABSTRACT

Shallow seismic reflection profiling carried out in the Carolina Terrane of Northeast Georgia has imaged reflectors that correlate with exposed contacts between ultramafic rocks of the Russell Lake Allochthon (RLA) and intermediate to mafic rocks of the Heardmont Complex. Reflections interpreted as the base of the RLA reach a maximum depth of 16.5 to 21.5 m and can be traced to depths as shallow as 7 m, where they project to the surface contact between the two units, supporting the interpretation of the ultramafics as isolated klippen in thrust-fault contact with surrounding rocks. These events appear on both common-offset and CMP-stacked sections. Dominant frequencies range from 60 to 250 Hz; corresponding vertical resolution (the minimum detectable layer thickness) ranges from less than one meter to four meters. The mapping of the reflection horizon on two closely spaced, parallel profiles suggests a surface that is concave upward. The reflectivity of the contact may be due to preferred orientation of talc and serpentine within the shear zone at the base of the RLA. We suggest that the juxtaposition of this zone of transverse acoustic anisotropy, with the slow P-wave velocity oriented near-vertically, perpendicular to foliation, with more isotropic rocks of the allochthon and Heardmont Complex gives rise to a substantial acoustic impedance contrast which should be traceable beneath larger occurrences of the allochthon as well. Variations in fracture density associated with the contact may enhance its reflectivity.

This study demonstrates the utility of seismic techniques for imaging shallow structure within crystalline rock even where thick weathering horizons are present. The determination of refraction statics corrections was a key factor in the construction of useful seismic images. Apparent velocity filtering improved the clarity of near-surface reflections by suppressing direct shear waves.

INTRODUCTION

Throughout the Carolina Terrane of Georgia there are a number of very small, discontinuous exposures of mafic and ultramafic rock that unconformably overlie a variety of rock types and structural features (Legato, 1986; Allard and Whitney, 1994). While mapping a portion of the Heardmont Quadrangle in northeast Georgia, Legato (1986) discovered exposures which suggested that many of these mafic and ultramafic units are not dikes as previously interpreted but klippen in thrust contact with surrounding rocks. Allard and Whitney (1994; this volume) mapped additional exposures of this mafic/ ultramafic complex which they named the Russell Lake Allochthon (RLA) and interpreted as the remnants of a thrust sheet emplaced late in the Alleghanian orogeny.

The purpose of this study was to use the seismic reflection method to help determine the nature of the contact between one of these outcrops and surrounding rocks. In particular, we sought to distinguish between low-dipping contacts such as thrust faults and steeper contacts associated with more deeply rooted intrusive features. Although the seismic reflection method does not sample the subsurface directly, it does allow continuous profiling of subsurface structure, thus generating continuous two-dimensional information that drill holes cannot provide.

In planning this work it was anticipated that several problems would be encountered in the construction of useful seismic images over the study area. In hydrocarbon and crustal surveys, faults and fault zones have proved to be highly reflective targets. The reflectivity of thrust faults in particular has been attributed to: 1) the planar geometry and small dip of the contacts, 2) the acoustic impedance contrast between juxtaposed units, and 3) the enhancement of this impedance contrast by preferred orientation of minerals within associated shear zones (Smithson, 1979; Fountain et al., 1984; Hurich et al., 1985; Christensen and Szymanski, 1988).

For the present study area, however, the lithologic/ acoustic contrast between unweathered rocks of the RLA and surrounding Heardmont Complex is quite small. One important aim of this study, therefore, was to determine whether the contrasts in mineralogies produced by weathering of these units and the shear zone between them would be great enough to generate detectable reflections. It was also expected that reflection continuity would be disrupted by erratic variations in travel time caused by the highly variable zone of saprolite. The profiles collected for this study therefore provide a valuable database for characterizing physical properties of near-surface crystalline rocks and for testing a variety of seismic processing techniques.

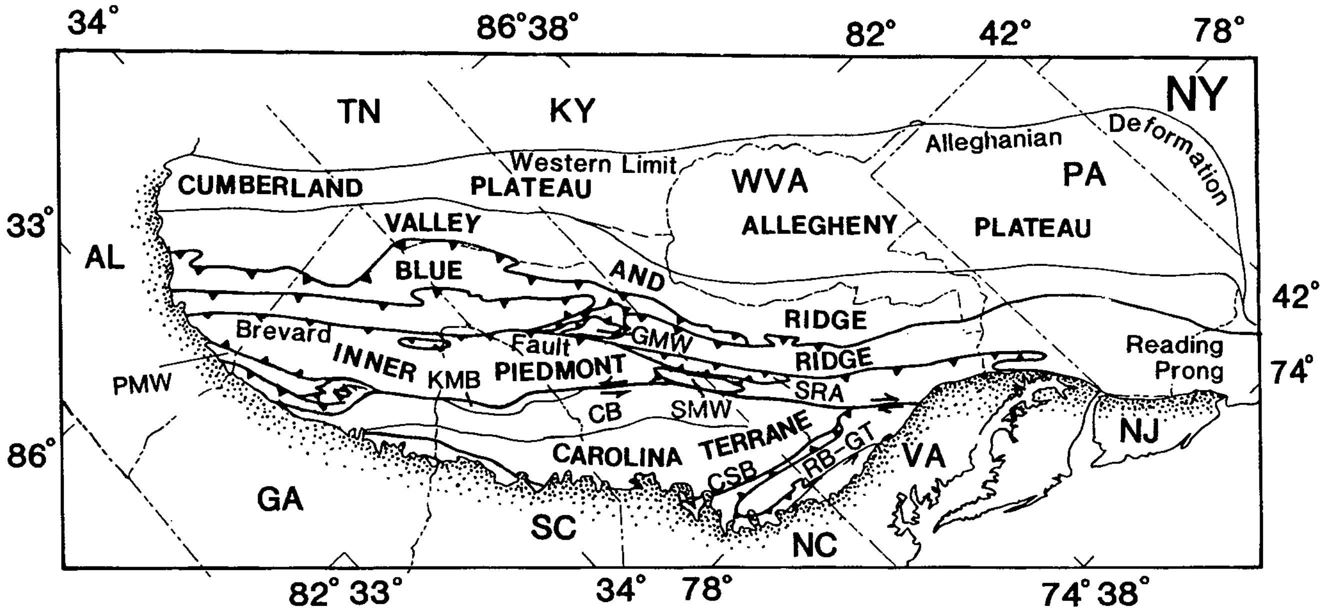


Figure 1a. Tectonic map of the southern Appalachians showing the principal terranes (after Hatcher, 1989). The study area was in the Carolina Terrane of northeast Georgia.

GEOLOGIC SETTING

The geology and tectonic setting of the Carolina Terrane and surrounding areas are summarized by Al1ard and Whitney (this volume). The seismic reflection profiles were recorded over exposures of the Heardmont Complex and the RLA, about 5 km southeast of the Middleton-Lowndesville shear zone (Fig. 1a). Locally the Heardmont Complex is composed of hornblende-biotite meladiorite and quartz diorite which grade into hornblende-biotite granodiorite and granite, to the north, and gabbro, to the south (Allard and Whitney, 1994). At the site the predominate lithology is a hornblende-quartz diorite. Foliation is quite variable but the complex is cut by numerous veins and felsic dikes. This unit has been interpreted as a compound zoned pluton composed of many crosscutting phases (Allard and Whitney, 1994).

The RLA has been mapped as several scattered,.isolated, bouldery outcrops of mafic to ultramafic rock (Allard and Whitney, 1994). Lithologies range from metaperidotite and metapyroxenite to meta-olivine gabbro and meta-feldspathic gabbro. Although affected by post-Alleghanian deformation events, the RLA shows no consistent foliation except within a thin zone at its base. Despite the presence of magnetite within the rock, outcrops of RLA do not produce detectable anomalies on aeromagnetic surveys. This is probably due to the small thicknesses of the individual bodies and the presence of minor amounts of magnetite in the surrounding rock.

The high degree of weathering prevalent throughout the Southeast has had an effect on the nature of the exposures of RLA (Allard and Whitney, 1994). The scattered exposures of RLA occur as bouldery, hill-capping outcrops whereas the Heardmont has been weathered into a gently rolling, drainage controlled, topography. It was anticipated that the contrast. in degree of weathering of the two rock types would strongly affect their acoustic contrast (Christensen' and Szymanski, 1988).

DESCRIPTION OF RECORDING SITE

Given the small station spacing required for imaging the shallow targets it was decided to focus on a relatively small study area. Therefore it was important to choose an outcrop or outcrops that would be fairly representative of the outcrops across the region. In particular, we sought an area where geologic mapping provided control on the extent and probable thickness of exposures for correlation with the seismic image. The goal was to establish the seismic expression of the thrust contact for use as a guide in the interpretation of future profiles over units for which the geometry of the contact is not as well constrained by mapping.

The seismic profiles were recorded along the shoulder of a dirt road that passes through farmland southeast of Elberton, Georgia, just outside the small town of Fortsonia (Fig. 1b). This county road was fairly straight and level with an orientation of roughly N10°E (Fig. 1b). The road bed cut through several well mapped exposures of RLA and allowed for continuous, roll-along, CDP profiles straddling more than one outcrop. The initial thickness estimate for the RLA outcrops at the site, based on topographic expression and the assumption of a flat thrust contact, was about ten meters. This estimate suggested that the profile would be imaging

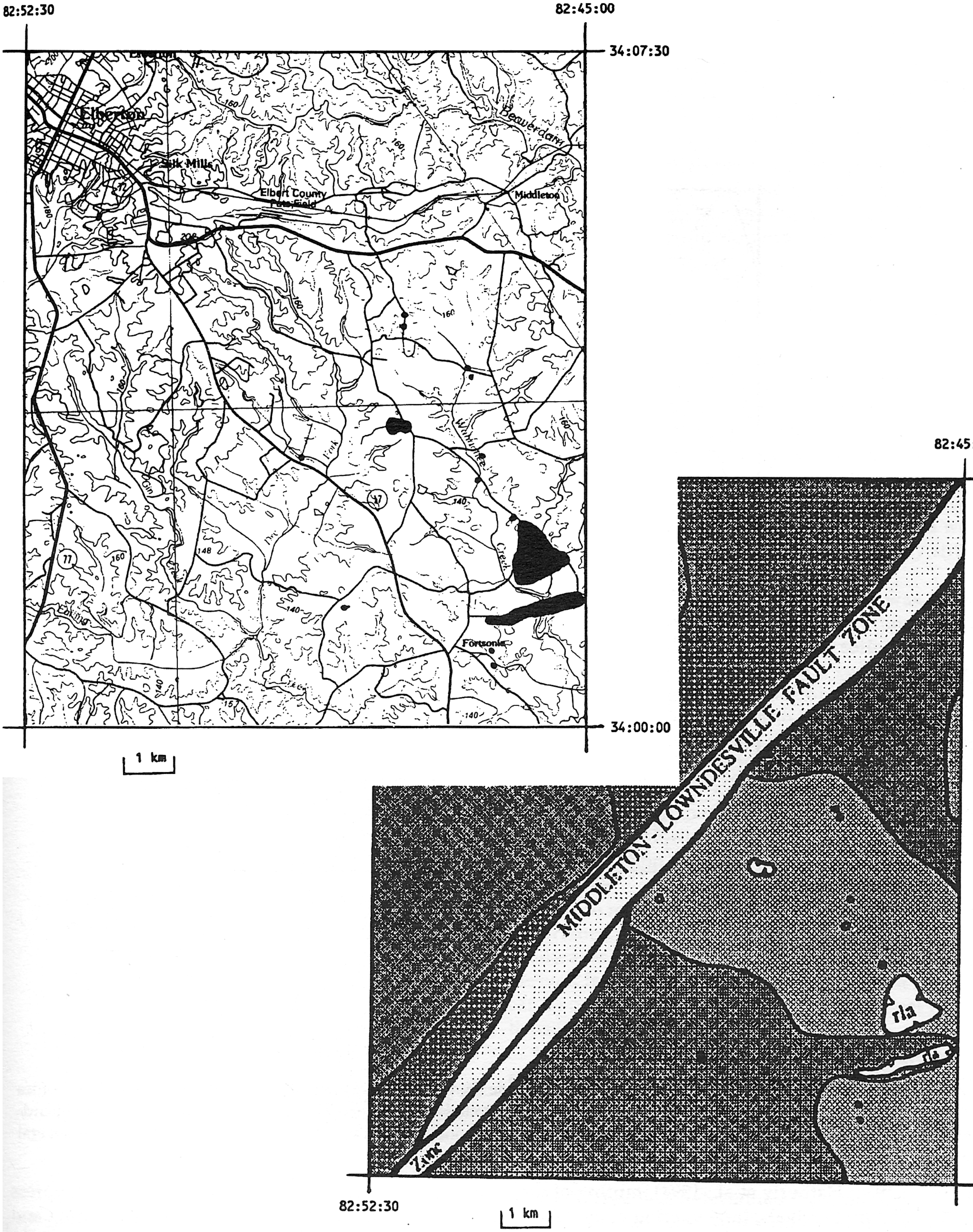


Figure 1b. Upper left: portion of the Abbeville, South Carolina 1:100,000 topographic map, with occurrences of mafic and ultramafic rocks of the Russell Lake allochthon (RLA) shaded. Lower right: same map area, after the geologic map of Allard and Whitney (1994), showing the Middleton-Lowndesville Fault Zone and occurrences of RLA.

geologic contacts within the saprolitic, or intensely weathered, horizon. Therefore it was expected that seismic velocities would be low, perhaps more appropriate for sediments rather than for rocks (Bonini and Woollard, 1960; Bahorich et al., 1982),

RECORDING PARAMETERS

The profiles were recorded with a 24-channel, digital, gain-ranging, signal-enhancement seismograph using 100-Hz geophones and a 7-kg sledgehammer as a seismic source. Recording parameters are summarized in Table 1.

Table 1. Recording Parameters

Recording System	Bison 9024 Signal Stacking Seismograph
Source	6-kg sledge hammer, stack of 8 light taps
Receivers	single 100-Hz geophones
Source spacing	1 m
Receiver spacing	1 m
Number of recording channels	24
Near offset	1 m
Far offset	24 m
Nominal CMP fold	12
Sampling increment	0.2 ms
Record length	200 ms
Analog filter settings	
low-cut	192 Hz
high-cut	2000 Hz
Number of shot points	
Line A	572
Line A1	120
Line A2	219
Line B	115
Line C	165

The recording spreads were off-end; Lines A and B were pushed from north to south, and Line C from south to north. The offset range of 1 to 24 m was suitable for recording shallow reflections at near offsets as well as refractions at farther offsets for velocity analysis (Hunter et al., 1984). All lines were recorded at an angle of 20 to 30 degrees to regional strike (Fig. 1b). The longest line (Line A) was intended to give a relatively continuous image of the subsurface across two isolated exposures of the RLA. The shortest line (Line B) was recorded parallel to Line A over the most prominent occurrence of the RLA to provide three-dimensional control. A third line (Line C) was recorded entirely over the Heardmont Complex to provide a comparison of velocities for each unit. Relative elevations along the survey line were measured with rod and transit. Geographic coordinates of the endpoints and a few defining intermediate points along the seismic lines were surveyed using a GPS receiver. The accuracy of these positions after differential correction using base station files from the South Carolina Geodetic Survey was about 3 meters.

Arrivals on the shot gathers include P-wave reflections, direct and refracted P waves and S waves, air waves, and surface waves or "ground roll" (Fig. 2). First arrivals include both direct and refracted P waves, which were used for determining near-surface velocities and for estimating statics corrections. Because first arrivals may stack in phase during the common-midpoint (CMP) stacking process, especially at large angles of incidence where normal moveouts for reflections are roughly linear, these arrivals can easily be misidentified as near-surface reflections. First arrivals therefore were muted (zeroed out) prior to CMP stacking. Surface waves and direct and refracted shear waves arrive after the direct and refracted P waves and sometimes interfere with P-wave reflections. Because these waves are usually dominated by low-frequency energy they can be attenuated by low-cut frequency filtering, although care must be exercised to ensure that the filter does not eliminate a substantial amount of P-wave energy as well. Surface waves and shear waves are partially attenuated automatically during CMP stacking; in severe cases these arrivals can be removed from shot gathers by velocity filtering before carrying out the CMP stack:

SEISMIC DATA PROCESSING

Processing of the seismic data was guided by four principal goals: 1) elimination of static effects due to near-surface velocity variations to improve the coherence of reflections, 2) attenuation of shear waves and surface waves, 3) generation of a P-wave velocity model of the subsurface using travel times of both reflections and refractions, and 4) construction of constant-offset sections and CMP-stacked sections for imaging the subsurface (Sheriff and Geldart, 1985). The processing steps are summarized in Table 2.

Processing Flow

1.	muting of bad traces
2.	sorting into common-offset gathers
3.	muting of air wave
4.	amplitude scaling (AGC)
5.	refraction statics: surface-consistant
6.	refraction statics: non-surface-consistant
7.	muting of first arrival
8.	bandpass filter: zero-phase, trapezoid filter with cutoffs at 40 Hz and 500 Hz; linear tapers to 20 Hz and 600 Hz
9.	sorting into shot gathers for apparent velocity filtering (optional)
10.	apparent velocity filtering (optional)
11.	sorting into CMP gathers
12.	stacking velocity analysis
13.	correction for normal movement
14.	CMP stacking

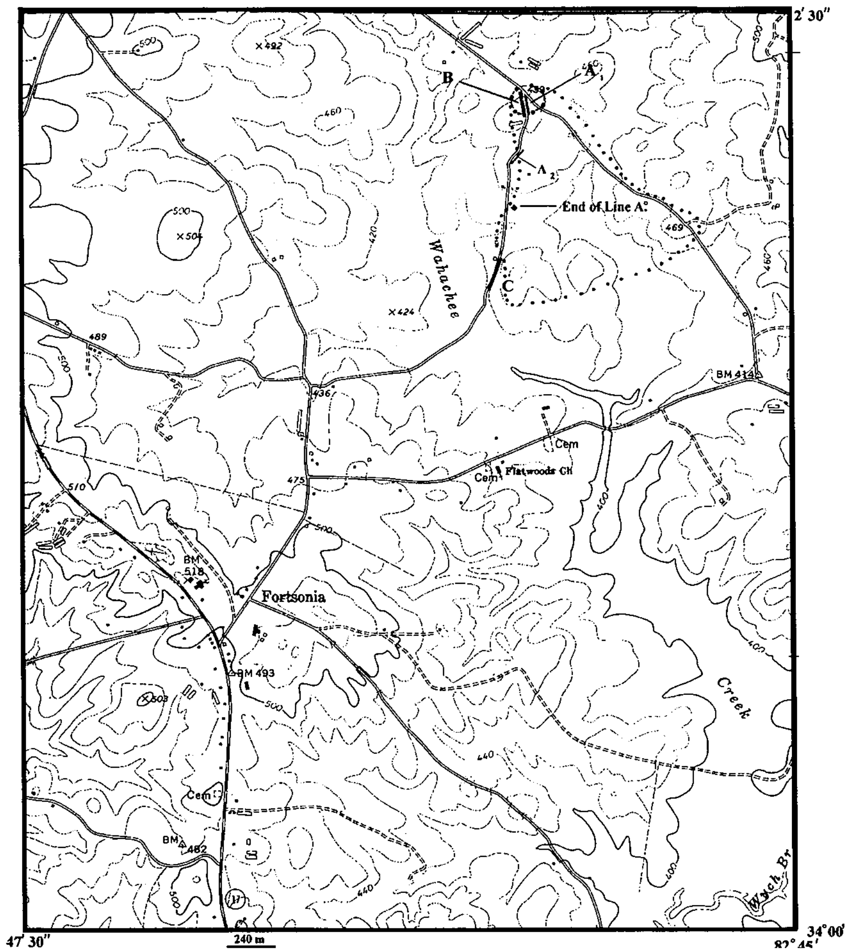


Figure 1c. Portion of the Elberton East 7-1/2 minute quadrangle showing the locations of shallow seismic reflection profiles A, A1, A2, B, and C. line B is offset from Line B by about 19 m. Dotted outline: generalized contact between RLA and Heardmont Complex as shown in Figure 1b. Dot-dash outline: mapped contact showing actual distribution of the RLA as several isolated bodies.

Processing included trace editing, bandpass filtering, elevation statics using a sloping datum, surface-consistant and non-surface-consistent automatic refraction statics applied to common-offset gathers (Coppens, 1985); Hatherly et al., 1994), muting of the air wave and first arrivals, time-varying gain (AGC), sorting into common-midpoint (CMP) gathers, estimation of stacking velocities, normal-moveout corrections, and CMP stacking. We also experimented with apparent velocity filtering of shot gathers to suppress surface waves and S waves prior to CMP sorting and stacking; details are discussed by Hawman et al. (in preparation).

PRELIMINARY DATA PROCESSING

Preliminary data processing included the elimination of noisy traces and surgical muting of the airwave. Because of strong air-wave and surface-wave interference at the nearest offsets only the outermost 18 offsets were used in the construction of CMP stacked sections.

Because of the large data volume for Line A (about 570 shot points) this line was broken into two smaller lines, Line Al and A2, for further processing. Line A1 was shot over the topographically highest portion of the RLA. Line A2 straddles a bouldery, less prominent outcrop of the RLA which occurs very near the projected end of mafic outcrops along the road (Fig. Ic). Both lines cross mapped contacts between the RLA and Heardmont complex.

STATICS CORRECTIONS

Statics corrections were applied after the preliminary data processing to improve the continuity of arrivals disrupted by lateral variations in near-surface velocities. Elevation statics corrections were applied using a sloping datum and near-surface velocities estimated from travel times for near-offset first arrivals. These statics corrections were found to be small, however, compared with statics shifts associated with near-surface lateral heterogeneities in velocity structure.

A second round of statics corrections was determined by automatic statics analysis (Taner et al., 1974). For this analysis the data were sorted into common-offset gathers (Fig. 3). This type of sorting removes the offset-dependence of travel time for a given gather, making it easier to identify variations in first-arrival time due to lateral variations in near-surface velocities (Coppens, 1985). The determination of statics shifts from first arrivals on common-offset gathers is based on the assumption that all raypaths in the very low-velocity surface layer are near-vertical due to refraction (Taner et al., 1974; Bahorich et aI, 1982).

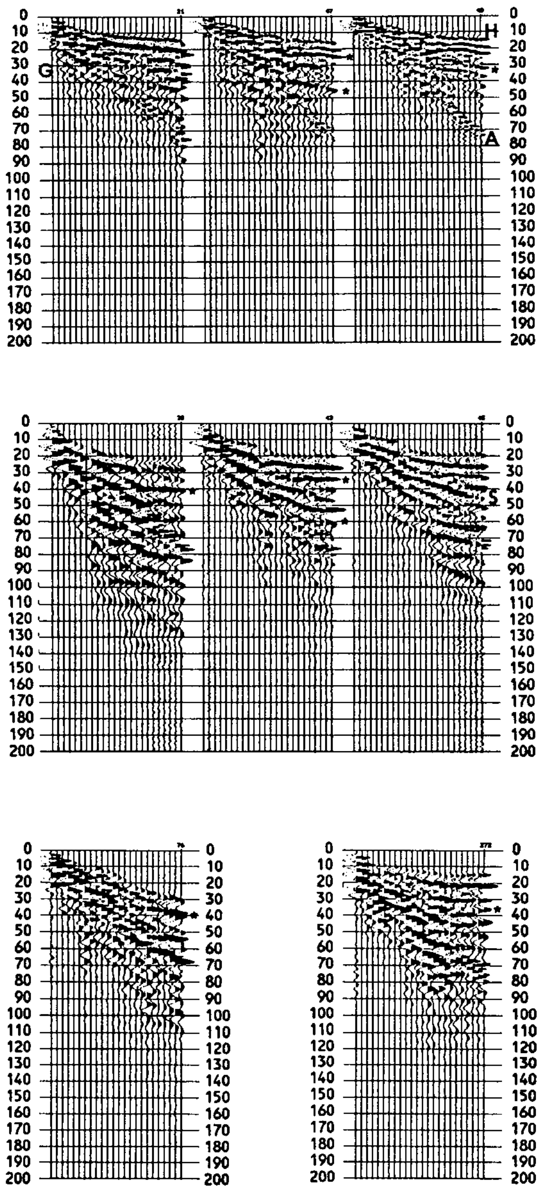


Figure 2. Sampling of unprocessed field gathers. Recording parameters are summarized in Table 1. Gathers show direct and refracted P waves (H), surface waves or ground roll (G), air waves (A), direct shear waves (S) and reflected P waves (*).

Because reflections arriving at a given receiver will experience virtually the same travel-time delay as headwaves from shallower depths, statics corrections derived from the more easily identified first arrivals can be used to improve the coherence of deeper reflections (Miller and Steeples, 1990).

In the initial application of the automatic statics procedure, it was assumed that the statics are "surface-consistent", i.e. that the static correction associated with a given station is independent of source- receiver offset (independent of raypath trajectory). First a preliminary estimate of the statics correction for each trace was determined from the shift giving the maximum cross-correlation with a pilot trace formed by summing all the traces in the gather. Because each station was sampled by 18 shot-receiver offsets, the solution for the corresponding statics corrections was overdetermined; therefore the cross-correlation was performed for all the common-offset gathers and the optimum static correction for each station was determined by least squares (Taner et al., 1974).

A final, "residual" static correction, also based on cross-correlation, was applied to the traces of each common-offset gather independently to enhance the alignment of the first arrivals. This final adjustment was not surface-consistent, rather it allowed for offset-dependent variations in static shifts at a given station due to minor offset-dependent variations in near-surface raypaths. An example of a common-offset gather before and after the application of both types of automatic statics is shown in Fig. 3.

APPARENT VELOCITY FILTERING

To suppress direct shear waves and surface waves we experimented with the application of an apparent velocity filter to the shot gathers before CMP sorting and stacking. The velocity filtering was carried out by slant stacking shot gathers over a desired range of ray parameters (inverse apparent velocities) and then inverse slant stacking. The method of hyberbolic velocity filtering (Noponen and Keeney, 1986; Duncan and Beresford, 1994) was used to incorporate bounds on stacking velocity in the construction of the slant stacks. The method is similar in principle, to frequency-wavenumber (f-k) filtering except that time-varying apparent-velocity filter settings are much easier to incorporate. Details of the process as applied to several shallow data sets recorded over crystalline rock are discussed by Hawman et al. (in prep.)

Based on arrivals identified in slant stacks generated for a representative sampling of shot gathers, each shot gather for Lines A and B was slant stacked using a ray-parameter increment of 0.02 s/km over a ray-parameter range from – 0.10 to 1.20 s/km (positive apparent velocities as small as 833 m/s). Shot gathers for Line C were slant stacked over a broader range of ray parameters (-0.100 to 1.40 s/km) to allow for the lower P-wave velocities beneath that line.

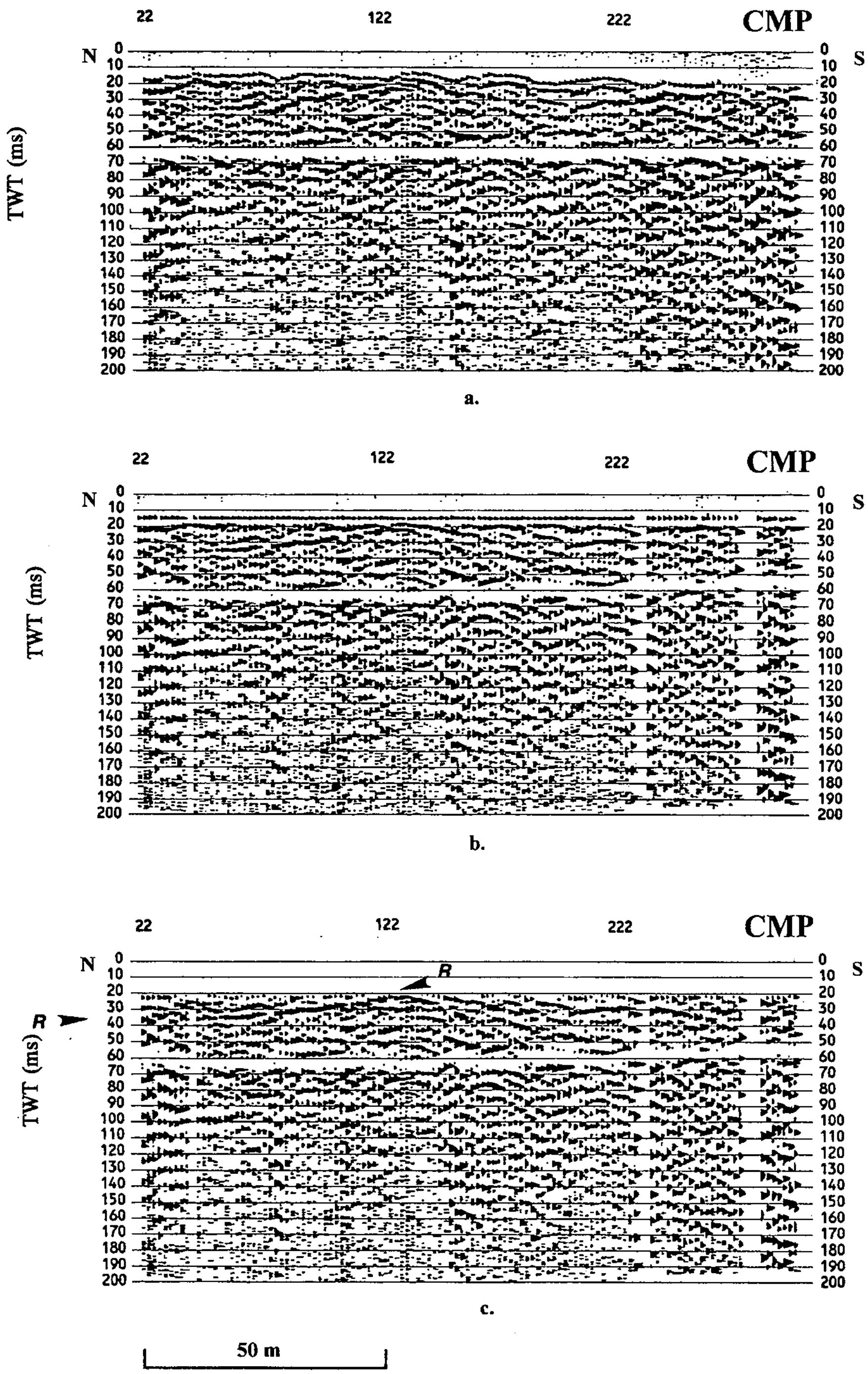


Figure 3. Common-offset gathers for Line A1 (Fig. 1c) for an offset of 20 m. Trace spacing is 1 m. (a.) Common-offset gather prior to application of refraction statics. Processing includes time-varying gain (AGC) and muting of the air wave starting at 60 ms. (b.) Common-offset gather in Fig. 3a after the application of refraction statics. Note the improved coherence of event R, interpreted here as a reflection from the thrust-fault contact between ultramafics of the RLS and underlying rocks of the Heardmont complex. c. Common-offset gather in Fig. 3b after muting first arrivals. Compare with Figs. 4a and 4b; travel times for event R in the common-offset section are slightly greater because they have not been corrected for normal moveout.

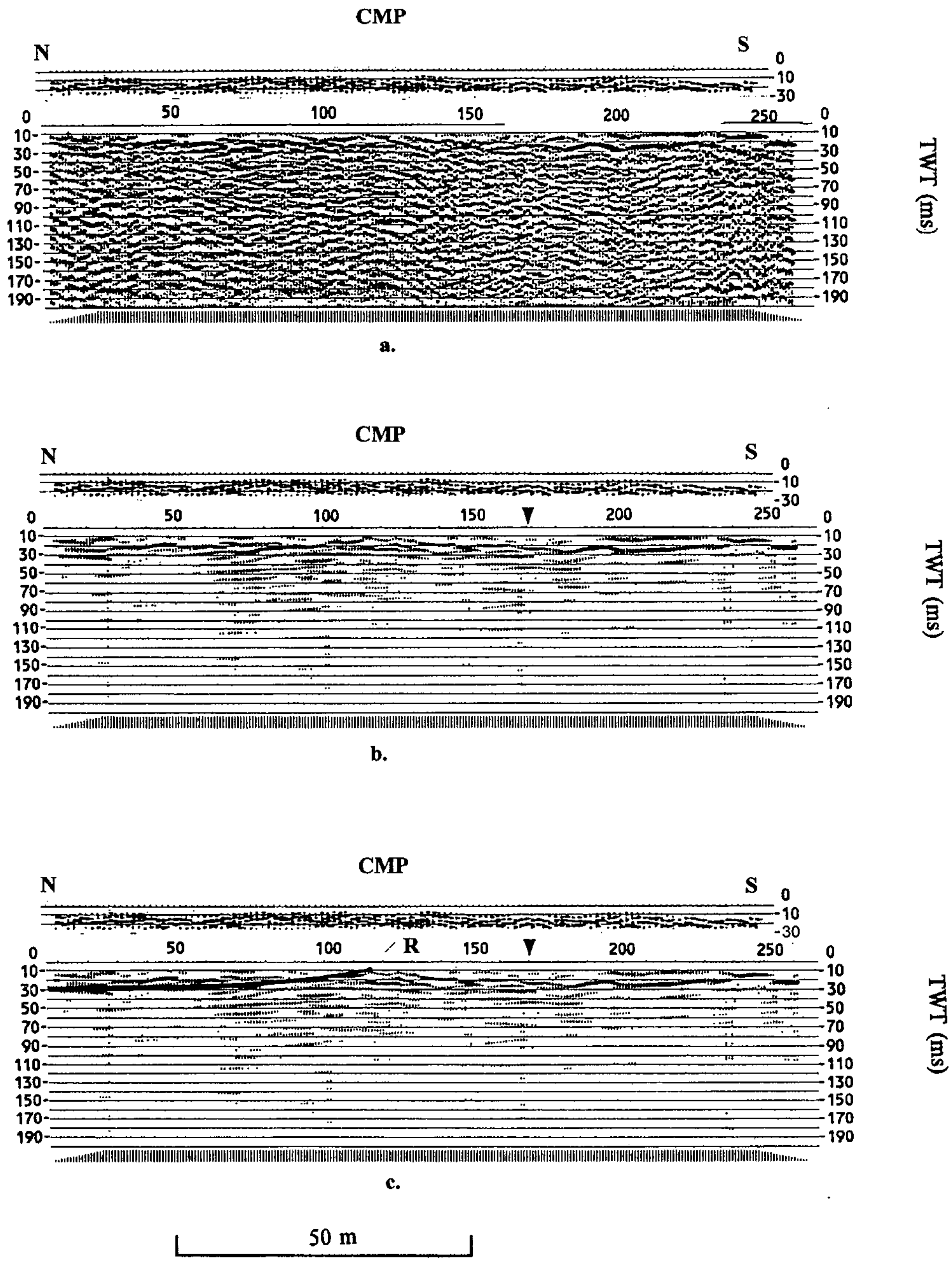


Figure 4. CMP-stacked section for Line A1. Processing is outlined in Table 2. Trace spacing is 0.5 m. Horizontal exaggeration at 30 ms is about 4x. a. CMP stack after all processing outlined in Table 2 except for the apparent filtering. The narrow strip at top is the common offset gather for 7-m offset showing first arrivals before statics corrections. This gather is plotted at the same scale as the stacked section, with each trace plotted at the approximate midpoint position. b. CMP stack after apparent velocity filtering of shot gathers to suppress surface waves and direct S waves. c. Same as Fig. 4b, with interpreted contacts. "R" is the event interpreted as a reflection from the thrust fault-contact between ultramafics of the RLA and underlying rocks of the Heardmont complex. The arrow marks the mapped surface contact between the RLA and Heardmont. The coherent arrivals of lower dominant frequency in the right (south) half of the section may be reflections caused by variations in fracture density and intensity of weathering, perhaps related to compositional layering, within the Heardmont Complex.

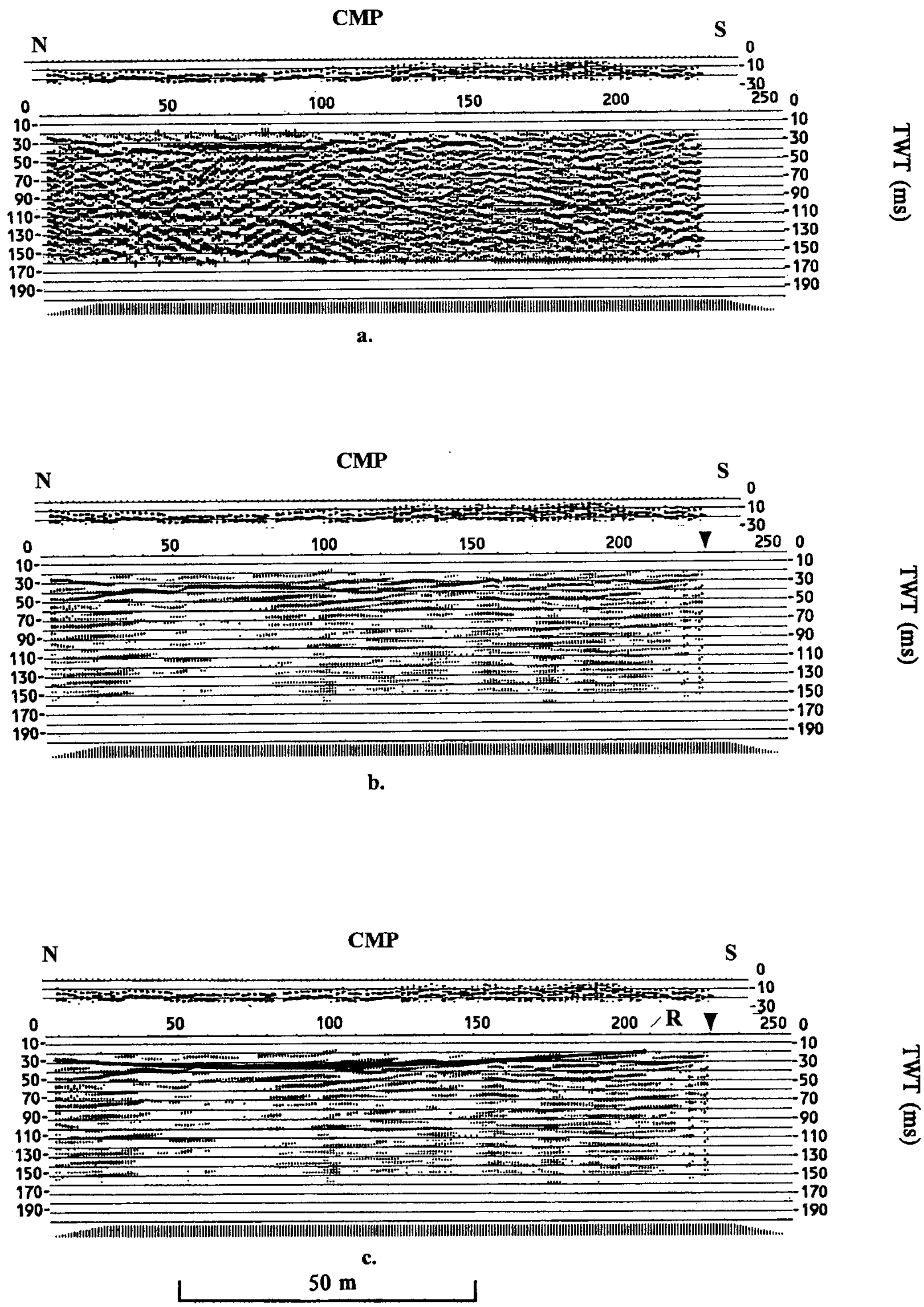


Figure 5. CMP-stacked section for Line B. See Figure 4 for processing and plotting parameters. a. CMP stack after applying all processing outlined in Table 2 except for the apparent velocity filtering. b. CMP stack after apparent velocity filtering of shot gathers to suppress surface waves and direct S waves. c. Same as Fig. 5B, with interpreted contacts. See comments for Fig. 4c.

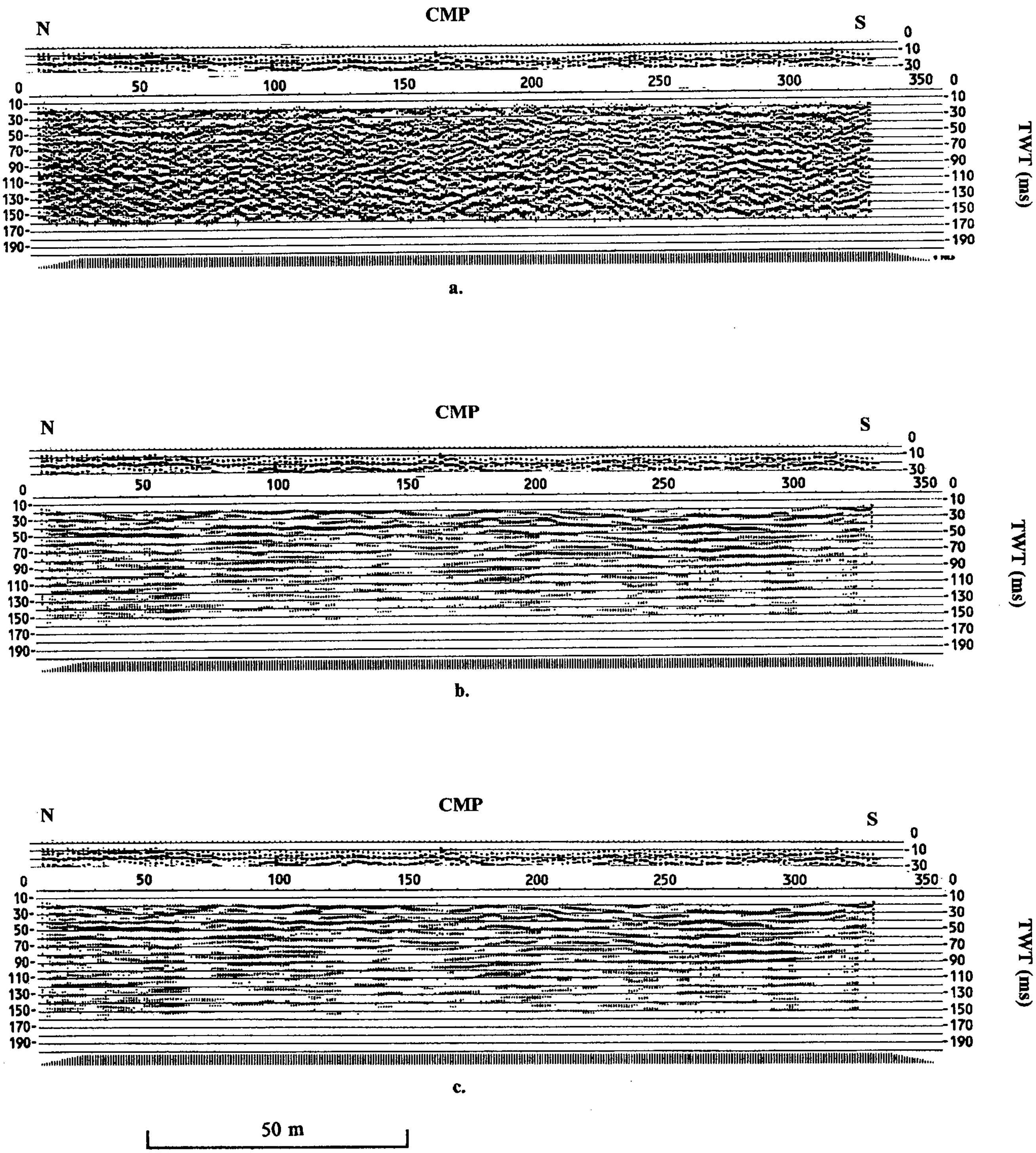


Figure 6. Sampling of unprocessed field gathers. Recording parameters are summarized in Table 1. Gathers show direct and refracted P waves (H), surface waves on ground roll (G), air waves (A), direct shear waves (S) and reflected P waves (*).

These ranges passed all the P waves while eliminating most of the S waves and surface waves. The pass range was adjusted further by incorporating a mute which zeroed out those portions of the slant stack corresponding to combinations of ray parameter and intercept time that were inconsistent with reasonable bounds on stacking velocity (Noponen and Keeney, 1986; Duncan and Beresford, 1994). It was found that even rather broad bounds on stacking velocity (0.8 - 100 km/s for lines A and B; 0.7 - 100 km/ s for Line C) eliminated most of the remaining shear-wave and surface wave arrivals. After the filters were applied, each shot gather was inverse slant stacked into the travel-time-offset domain and resorted into CMP gathers for velocity analysis and stacking.

STACKING VELOCITY ANALYSIS AND CMP STACKING

We used constant-velocity analysis (Sheriff and Geldart, 1985) to determine stacking velocity as a function of zero-offset time for normal-moveout (NMO) corrections. This method involved plotting a series of NMO-corrected CMP gathers for a given CMP for a range of constant stacking velocities; we used a stacking velocity increment of 100 m/ s. The stacking velocity which "flattened" (removed the offset dependence of) each reflection at a given zero-off-set time then was noted and used to construct a stacking velocity-zero-offset-time function for that CMP gather. This procedure was repeated for every fifth COP and the results interpolated in space and time to construct an optimum stacking velocity function for the whole line. The traces in each CMP gather then were corrected for NMO using the appropriate stacking velocity function.

The final "zero-offset" or "CMP-stacked" sections (Figs. 4-6) were formed by stacking the NMO-corrected traces in the CMP gathers to form a single trace for each CMP. The estimation of stacking velocities from CMP gathers rather than shot gathers tends to remove the biasing effect of dip on estimates of average velocities and interval velocities for dips less than 30 degrees (Diebold and Stoffa, 1981). Dip information is preserved, however, in the final CMP stacked section. One can recover true dips from stacked sections by migration (below); for data of sufficient quality this can be carried out digitally (Sheriff and Geldart, 1985; Black et al., 1994).

REFRACTION ANALYSIS

Travel times of first arrivals without statics corrections were used to obtain independent estimates of the near-surface velocity structure. Reversed profiles were synthesized by sorting the traces into receiver gathers and exploiting the principle of reciprocity, allowing the estimation of dips (Jurdy and Brocher, 1980). The velocity estimates obtained for this study are consistent with velocities from other refraction studies carried out in the Southeast under similar highly weathered near-surface conditions (Bonini and Woollard, 1960; Bahorich et al., 1982); see the Discussion.

RESULTS

Description of CMP Stacked Sections

Figures 4-6 show the final CMP-stacked sections for each line. The final bandpass- and velocity-filtered, CMP-stacked section for Line A_1 shows a fairly high-amplitude, continuous event which can be traced across about half the section (Fig. 4). This event originates on the north (left) side of the section at approximately 29 ms, reaches a maximum time of 30 ms at CMP 50, then gently rises to 14 ms (depth: about 7.5 m) at CMP 114. Bounds on maximum depth (at 30 ms) for this reflector are 15-19.5 m; these values were computed using bounds of 1000 m/ sand 1300 m/ s on average velocity estimated from stacking velocities. Based on the correlation of the surface projection of this event with the mapped RLA-Heardmont contact, we interpret this event (hereafter referred to as "event R") and a similar event on Line B as reflections from the base of the RLA, in thrust-fault contact with rocks of the Heardmont complex. Assuming a constant dip of 20° (see below), event R on Line A_1 projects to the surface at CMP 158, about 6 m north of the mapped contact. The appearance of these events on CMP stacks generated both with and without velocity filtering demonstrates that they are not velocity-filtering artifacts. However, some of the more discontinuous events deeper in the sections could be processing artifacts generated by spatially aliased surface-wave energy that has been passed by the velocity filter and has survived CMP stacking (Hawman et al., in prep.). Event R also appears on constant-offset sections generated with minimal processing (Fig. 3), demonstrating that the coherence of the event has not been imposed artificially by the CMP stacking process itself. The divergence of this event from the first arrival on the constant-offset section (Fig. 3b) indicates that it is not part of a reverberating headwave train.

The continuous events south of CMP 170 are dominated by lower frequencies than those associated with the base of the RLA; the geologic interpretation of these events is discussed in the final section.

In the final stacked section for Line B (Fig. 5) event R begins at 27 ms on the north (left) side of the section, drops gently to about 31 ms at CMP 30, remains relatively flat until CMP 100, then breaks up somewhat between CMPs 100 and 140 before it rises to 21 ms and leaves the unmuted portion of the section at CMP 210. The continuity of this reflection is enhanced by velocity filtering prior to stacking (Fig. 5b), especially south of CMP 150 where it encounters interference from direct shear waves on approaching the surface. Bounds on the maximum depth of this reflector are 15.5-20 m. Assuming a constant dip of 25° (below), event R projects to the surface at CMP 258, about 13 m south of the mapped contact; surface mapping indicates an abrupt cutoff of the southern edge of the allochthon along this line as opposed to the more gradual thinning observed along Line A1.

The final section for Line A2 (not shown) displays numerous short, discontinuous events which could be artifacts caused by residual shear-wave energy or random noise. No clear, continuous event is present.

In contrast with Lines Al and B, Line C (Fig. 6) shows few coherent events shallower than 30 ms. Coherent events appear on both versions of the CMP stack at about 50 ms (depth bounds: 25 - 38 m) at the south (left) side of the section (CMPs 11-70) and between 40 and 90 ms (depth bounds: 20 to at least 70 m) near the north end of the section. Hand-migration of the reflections interpreted as the base of RLA indicates near-surface dips up to 20-27°. Migration is sensitive to the velocity distribution above the reflector, the depth of the reflector, and the orientation of the subsurface feature giving rise to the reflection (Sheriff, 1991). In general, the amounts of vertical and lateral shift for a given reflection are proportional to the dip and depth of the reflector and the average velocity of material above it (Black et al., 1994). Because targets for this investigation were very shallow (less than 20 m) and the calculated near-surface velocities were very low (less than 2000 m/s), predicted lateral shifts brought about by migration generally are less than the CMP spacing, indicating that digital migration would result in little change in the appearance of the upper parts of the sections.

The results of refraction analysis for the four lines yielded depths for refracting horizons ranging from 0.5 m to nearly 5 m, with one estimate of about 7.5 m, well above the maximum depths estimated for the base of the RLA. These horizons display little to no dip; layer velocities range from about 330 m/s to 2445 m/ s. Because the offset range used to calculate apparent velocities for some of the later travel-time branches was quite small, the uncertainties associated with those velocity estimates are generally quite large. Source-receiver offsets were not long enough to record refractions from the base of the RLA as first arrivals.

Resolution

Dominant frequencies on the shot gathers and stacked sections range from 64 to 250 Hz. Corresponding seismic wavelengths for P-wave velocities between 1000 and 2000 m/ s range from 4 to 30 m. Minimum resolvable layer thicknesses (quarter wavelengths) range from 1 to 8 m; minimum detectable layer thicknesses are about half these values (Widess, 1973). Horizontal resolution estimated from Fresnel-zone widths for these frequencies ranges from 3-5 m for two-way times of 14 ms to 5-10 m for two-way times of 30 ms.

The appearance of dominant energy as low as 60 Hz over portions of the CMP stacks may be due to unaccounted-for residual statics or variations in stacking velocity that attenuate higher frequencies during stacking (Steeples et al., 1990). The lower dominant frequencies of reflections on Line C could be due to enhanced absorption associated with more intense weathering.

INTERPRETATION AND DISCUSSION

Velocities

The stacking velocities used in constructing the CMP-stacked sections range from 900 m/ s to 1600 m/ s. The corresponding depths of events used for NMO analysis range from 16.5 to 21.5 meters. Refraction analysis yielded depths from 0.2 m to 7.5 m with corresponding interval velocities of 900 m/ s to 2444 m/ s.

These values are consistent with estimates of near surface velocity obtained for other surveys in the Southeast. Bonini and Woollard (1960) conducted several seismic refraction studies within the Carolina Terrane of eastern Georgia and the Coastal Plain of North and South Carolina. The rock types they sampled included granites, gneisses, schists, and slates of the Carolina Terrane and sedimentary rocks of the Coastal Plain. Basement rock velocities calculated from the reversed refraction profiles taken within the Carolina! Terrane portion of eastern Georgia ranged from 4999 m/ s to 5944 m/ s. Velocities for the near-surface weathered zones (depths: 1- 30 m) were between 1190 and 2970 m/ s. The near-surface velocities from their Coastal Plain studies ranged from 685 m/ s to 1356 m/s. These velocities correspond to surface material ranging in depth from 4 to 64 meters. Velocities corresponding to depths between 18 and 444 meters were 1768 m/s to 2225 m/s.

Bahorich et al. (1982) used a combination of reflection and refraction surveys to image a subsurface contact between a gneiss and an amphibolite in a terrane characterized by heavily weathered near-surface conditions similar to those found in Georgia. Their refraction data yield velocities from 406 m/ s to 2077 m/ s for depths between 1 and 20 meters.

Structure and Reflectivity

In the sections for Line A1 and B, event R is slightly concave upward, indicating a maximum thickness for the ultramafic unit that is greater than the initial estimate based on topographic expression and the assumption of a flat contact. The curvature may reflect post-emplacement warping; other examples of post-emplacement deformation of the allochthon are described by Allard and Whitney (this volume).

Several factors may contribute to the reflectivity of the base of the RLA. As described by Allard and Whitney (1994), the RLA contains "varying proportions of serpentine, amphiboles, talc, chlorite, epidote, magnetite, and ilmenite" with small amounts of albite in the more gabbroic samples. The Heardmont Complex consists of "plagioclase, hornblende, biotite, and quartz. Accessory minerals include ilmenite, sphene, magnetite, and apatite. Actinolite and epidote are found as alteration products from plagioclase and hornblende," Although there is a difference in mineralogy between the two rock units the relative compositional contrast is quite low as is the acoustic impedance contrast. Therefore a contrast in bulk mineralogy of the two units is probably not an important factor in the generation of event R. Instead, we suggest that the reflectivity of the contact is due to preferred orientation of minerals within the shear zone at the base of the RLA. As noted by Allard and Whitney (1994) for several other exposures, "The base of the allochthon is characterized by a narrow ductilely deformed zone with a subhorizontal orientation. This horizon is commonly rich in talc and serpentine. Above this zone the unit becomes more massive with relic (igneous) textures being observed within a few feet of the base". Preferred orientation of these acoustically anisotropic minerals with the slow P-wave velocity oriented near-vertically, perpendicular to foliation, within a shear zone encased by more isotropic rock of the allochthon and Heardmont Complex,

should produce a significant acoustic impedance contrast (Christensen and Szymanski, 1988). Although the thickness of this shear zone (about 1-3 m) is probably too small to resolve given the available range of wavelengths sited above, it should be large enough (larger than /8 wavelength) to generate a detectable reflection (Widess, 1973).

It should be noted, however, that fractures and variations in fracture density exert strong controls on velocity structure that can dominate the effects of lithology, especially in the near-surface (Moos and Zoback, 1983; Kim et al., 1994; Juhlin, 1995). Observations from drill cores taken in crystalline rock, including cores in the Charlotte Belt (Carolina Terrane) of South Carolina (Zoback and Hickman, 1982), show that fractures are quite common, even at depths up to 1 km. Fractures in crystalline rock, including the samples from drillcores in South Carolina, often show diverse orientations that do not appear to be controlled by the regional stress field (Seeburger and Zoback, 1982; Moos and Zoback, 1983). The low P-wave velocities seen at Fortsonia are probably due in part to pervasive fractures in the weathered subsurface. At the shallowest depths imaged at Fortsonia, fractures would not be fluid-filled. In general, the presence of randomly oriented, unsaturated, macro- and microfractures should lower P-wave velocities and inhibit the continuity of other reflectors (Crampin, 1987). However, fractures parallel to foliation within the shear zone at the base of the RLA may enhance the high reflectivity produced by the strong talc and serpentine horizon (Christensen and Szymanski, 1988); acoustic impedance contrasts associated with variations in fracture density and intensity of weathering, perhaps related to compositional layering within the Heardmont Complex, could explain the continuous reflections of relatively low dominant frequency on Line C and south of the RLA/Heardmont contact on Line A1.

CONCLUSIONS

This study demonstrates the utility of seismic techniques for imaging shallow structure within crystalline rock even where thick weathering horizons are present. The determination of refraction statics corrections was a key factor in the construction of useful seismic images. Apparent velocity filtering improved the clarity of near-surface reflections by suppressing direct shear waves. Shallow seismic reflection profiling carried out in the Carolina Terrane of Northeast Georgia has imaged reflectors that correlate with exposed contacts between ultramafic rocks of the Russell Lake Allochthon (RLA) and intermediate to mafic rocks of the Heardmont Complex. Reflections interpreted as the base of the RLA reach a maximum depth of 15 to 20 m and can be traced to depths as shallow as 7 m, where they project to the surface contact between the two units, supporting the interpretation of the ultramafics as klippen in thrust-fault contact with surrounding rocks. These events appear on both common-offset and CMP-stacked sections. The mapping of the reflection horizon on two closely spaced, parallel profiles suggests a surface that is concave upward. The reflectivity of the contact may be due to preferred orientation of talc and serpentine within the shear zone at the base of the RLA. We suggest that the juxtaposition of this zone of transverse acoustic anisotropy, with the slow P-wave velocity oriented near-vertically, perpendicular to foliation, with more isotropic rocks of the allochthon and Heardmont Complex gives rise to a substantial acoustic impedance contrast which should be traceable beneath larger occurrences of the allochthon as well. Variations in fracture density associated with the contact may enhance its reflectivity.

Future work that should help to resolve the nature and extent of the RLA includes: 1) examination of the contrast in metamorphic grade between rocks of the RLA and surrounding units (Mark Colberg, work in progress at University of Georgia), 2) ground magnetometer surveys for modeling subtle contrasts in magnetite content between RLA and other units, 3) additional seismic profiles over thicker occurrences of the ultramafics, and 4) coring of representative outcrops.

ACKNOWLEDGMENTS

We thank Gilles Allard for introducing us to the RLA problem and for showing us numerous outcrops. We also thank Jim Whitney for helpful discussions. Harmon Maher and an anonymous reviewer provided constructive comments. Routine processing was carried out using the Eavesdropper software package written by the staff at the Kansas Geological Survey. This work was supported by a grant from Sigma XI to J. Clippard, NSF grants EAR-9105716 and EAR-9305511, and a grant from the Petroleum Research Fund administered by the American Chemical Society.

REFERENCES

Allard, G.O., and Whitney, J.A., 1994, Geology of the Inner Piedmont, Carolina Terrane, and Modoc Zone in North-east Georgia: G.A. Geol. Surv. Report #71.

Allard, G.O., and Whitney, J.A., (this volume), The Russell Lake Allochthon -- an orphan in the Southern Appalachians.

Bahorich, M.S., Coruh, C., Robinson, E.S., and Costain, J.K., 1982, Static corrections on the southeastern Piedmont of the United States: Geophysics, 47,1540-1549.

Black, R.A., Steeples, D.W., and Miller, R.D., 1994, Migration of shallow seismic reflection data: Geophysics, 59, 402-410.

Bonini, W.E., and Woollard, G.P., 1960, Subsurface geology of North Carolina-South Carolina Coastal Plain from seismic data: AAPG Bull., 44, 298-315.

Christensen, N.I., and Szymanski, D.L., 1988, origin of reflections from the Brevard Fault Zone: J. Geophys. Res., 93,1087-1102.

Coppens, F., 1985, First arrival picking on common-offset trace collections for automatic estimation of static corrections: Geophys. Prosp., 33, 1212-1231.

Crampin, S., 1987, Geological and industrial implications of extensive-dilatancy anisotropy: Nature, 491-496.

Diebold, J.B., and Stoffa, P.L., 1981, The traveltime equation, tau-p mapping, and inversion of common midpoint data: Geophysics, 46, 238-354.

Duncan, G., and Beresford, G., 1994, Slowness adaptive f-k filtering of prestack seismic data: Geophysics, 59, 140-147.

Fountain, D.M., Hunch, C.A., and Smithson, S.B., 1984:, Seismic reflectivity of mylonite zones in the crust: Geology, 12, 195-198.

Hatcher, R.D., Jr., 1989, Tectonic synthesis of the U.S. Appalachians, in Hatcher, Jr., R.D., Thomas, W.A. and Viele, G. W., Eds., The Appalachian-Ouachita orogen in the United States, The Geology of North America, v. F-2: Geol. Soc. Am., 551-535.

Hatherly, P.J., Urosevic, M., Lambourne, A., and Evans, B.J., 1994, A simple approach to calculating refraction statics corrections: Geophysics, 59,156-160.

Hunter, J.A., Pullan, S.E., Burns, R.A., Gagne, R.M. and Good, R.L., 1984, Shallow seismic reflection mapping of the overburden-bedrock interface with the engineering seismograph--Some simple techniques: Geophysics, 49, 1381-1385.

Hurich, C.A., Smithson, S.B., Fountain, D.M., and Hunphreys, M.C., 1985, Seismic evidence of mylonite reflectivity and deep structure in the Kettle) Dome metamorphic core complex, Washington: Geology, 13, 577-580.

Juhlin, C., 1995, Imaging of fracture zones in the Finnsjon area, central Sweden, using the seismic reflection method: Geophysics, 60, 66-75.

Jurdy, D.H., and Brocker, T.M., 1980, Shallow velocity model of the Rio Grande rift near Socorro, New Mexico: Geology,8,185-189.

Kim, J.S., Moon, W.M., Lodha, G., Serzu, M., and Soonawala, N., 1994, Imaging of reflection seismic energy for mapping shallow fracture zones in crystalline rocks: Geophysics, 59, 753-765.

Legato, J.M., 1986, The geology of the Heardmont quadrangle, Georgia-South Carolina: M.Sc. thesis, Univ. of Georgia.,

Miller, R.D., and Steeples, D.W., 1990, A shallow seismic reflection survey in basalts of the Snake River Plain, Idaho: Geophysics, 55, 761-768.

Moos, D., and Zoback, M.D., 1983, In situ studies of velocity in fractured crystalline rocks: J. Geophys. Res., 88, 2345-2358.

Noponen, I., and Keeney, J., 1986, Attenuation of water- borne coherent noise by application of hyperbolic velocity filtering during the tau-p transform: Geophysics, 51, 20-33.

Seeburger, D.A., and Zoback, M.D., 1982, The distribution of natural fractures and joints at depth in crystalline rock: J. Geophys. Res., 87, 5517-5534.

Sheriff, R.E., 1991, Encyclopedic Dictionary of Exploration Geophysics, 3rd ed., 376 pp., Soc.Expl.Geophys., Tulsa, Oklahoma.

Sheriff, R.E., and Geldart, L.P., 1985, Exploration seismology, Vol.2: Cambridge University Press.

Smithson, S.B., Brewer, J., Kaufman, S., Oliver, J., and Hurich, C.A., 1979, Structure of the Larimide Wind River Uplift, Wyoming, from COCORP deep reflection data and from gravity data: J. Geophys. Res., 84, 5955-5972.

Steeples, D.W., Miller, R.D., and Black, R.A., 1990, Static corrections from shallow reflection surveys: Geophysics, 55, 769-775.

Taner, M. T., Koehler, F. and Alhilali, K.A., 1974, Estimation and correction of near-surface time anomalies: Geophysics, 39, 441-463.

Widess, M.B., 1973, How thin is a thin bed?: Geophysics, 38, 1176-1180.

Zoback, M.D., and Hickman,S., 1982, In situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina: J. Geophys. Res., 87,6959-6974.