FOURTH TECHNICAL REPORT

Geologic Studies in an Area of Induced Seismicity at Monticello Reservoir, South Carolina

June, 1982

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GEOLOGICAL STUDIES IN THE AREA OF INDUCED SEISMICITY AT MONTICELLO RESERVOIR, SOUTH CAROLINA

by

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PREFACE

This report presents the results of geological and geophysical studies that have been underway in the area of induced seismicity at Monticello Reservoir, South Carolina, since March 1, 1980. The purpose of this study is to provide the geological information necessary for understanding the origin of the induced seismicity. In particular, the study was directed toward determining: 1) if there are laterally extensive faults in the region that might eventually slip, thus producing a large earthquake; 2) if there are lithological boundaries other than fault contacts in the vicinity of the reservoir controlling the distribution of seismic activity, and; 3) if there are foliations or systematic jointing directions along which slip might be initiated by the stress and pore pressure changes related to reservoir impoundment. The data base for making the above evaluations was obtained by: 1) preparing 1:24,000 scale geological maps of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (Plates 1-4); 2) measuring 125 kilometers of surface magnetic profiles (as an aid in locating Mesozoic diabase dikes, Plates 5-8); and 3) measuring the orientations of approximately 100 joint fractures at each of 50 localities in the study area (Plates 9-12).

The overall results and conclusions of this study are summarized in Chapter I which is modified from a paper that will be published in the Journal of Geophysical Research [Secor and others, in press]. The results of geological field studies in the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles are presented in Chapters 2-5, respectively. These chapters are modified from University of South Carolina M.S. theses by David H. Simpson [1981], Lawrence S. Peck [1981], William A. Smith [1982] and David M. Pitcher [1982], respectively. Geological maps (1:24,000 scale) for the above four quadrangles are presented in Plates 1-4. The surface magnetic profiles for the quadrangles are presented in Plates 5-8, and the results of joint orientation studies are presented in Plates 9-12.

We wish to thank R. E. Dooley, P. D. Fullagar, D. C. Prowell, A. W. Snoke, Pradeep Talwani and M. D. Zoback for providing us with research results prior to publication. D. C. Prowell of the U. S. Geological Survey arranged for the drilling of four shallow boreholes which were useful in the evaluation of the Wateree Creek fault zone. The cooperation of R. B. Whorton of the South Carolina Electric and Gas Company, William Smith of Dames and Moore, and N. K. Olson and Paul Nystrom of the South Carolina Geological Survey is greatly appreciated. Regional geological studies in the vicinity of Monticello Reservoir were supported by National Science Foundation grant EAR 8020474. The following University of South Carolina students assisted with geological and geophysical field studies: Mel Blackwell, Ken Bramlett, Bruce Crawford, Steve Durgin, J. C. Hare, Jack Horkowitz, Chris Jones, Phil Kimbrell, Sarah Logan, Mark Snyder, and John Willis. Many of the illustrations were drafted by Tania Lush, and the manuscript typing was done by Joyce Goodwin.

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CHAPTER I

GEOLOGY OF THE AREA OF INDUCED SEISMIC ACTIVITY AT MONTICELLO RESERVOIR, SOUTH CAROLINA: A SUMMARY

ABSTRACT

This study provides geological background information necessary for an evaluation of the earthquake hazard in an area of induced seismic activity at Monticello Reservoir, South Carolina. This region contains a thick stratified sequence of Proterozoic Z and Cambrian metasedimentary and metavolcanic rocks. In the early to middle Paleozoic, this sequence was recrystallized and deformed under metamorphic conditions that ranged from greenschist to amphibolite facies and experienced at least two episodes of folding. The region has been intruded by late- to post-kinematic granitoid plutons of Silurian and Carboniferous ages, and by numerous northwest-trending diabase dikes of Late Triassic and Early Jurassic age. The region south of Monticello Reservoir in the Carolina slate belt experienced two episodes of faulting in the late Paleozoic and/or early to middle Mesozoic. The older group of faults trends approximately east, has only small displacements, and is characterized by extensive silicification of the fault zones. The younger group of faults trends approximately north, has experienced dip-slip displacements up to 1700 m, and is characterized by carbonate mineralization in the fault zones. Both sets of faults are cut by an undeformed diabase dike of Late Triassic or Early Jurassic age. The induced seismic activity around Monticello Reservoir is occurring in a heterogeneous quartz monzonite pluton of Carboniferous age. Although laterally extensive faults have not been found in the vicinity of the reservoir, the pluton contains large enclaves of country rock and is cut by numerous, diversely oriented small faults and

joints. These local inhomogeneities in the pluton, together with an irregular stress field, are interpreted to control the diffuse seismic activity around the reservoir. In view of the apparent absence of lengthy faults, it is unlikely that a large magnitude earthquake will occur in response to the stress and pore pressure changes related to the impoundment of Monticello Reservoir.

INTRODUCTION

One of the most thoroughly documented cases of induced seismic activity in the eastern United States is located near the Virgil C. Summer nuclear station in Fairfield County, South Carolina [Talwani, 1979; Talwani and others, 1980]. Two artificial reservoirs (Parr Shoals and Monticello) have been impounded in this region (Fig. 1). Parr Shoals Reservoir was impounded in the valley of the Broad River in 1914, and had a volume of .005 km^3, a surface area of 7.5 km^2 and a maximum depth of 11 m. In 1976, as a result of modification of Parr Shoals Dam, the volume, surface area and maximum depth were increased to .039 km^3, 18 km^2 and 13 m respectively. Monticello Reservoir was impounded in the valley of Frees Creek during late 1977 and early 1978 and has a volume of approximately 0.5 km^3, a surface area of 27 km^2 and a maximum depth of 48 m. Most of the induced seismic activity (Fig. 1) is temporally and spatially associated with Monticello Reservoir.

Prior to the impoundment of Monticello Reservoir, this region had a very low level of seismic activity. Filling of the reservoir commenced on December 3, 1977, and was completed on February 8, 1978. About three weeks after filling was initiated, the frequency of local earthquakes abruptly increased by a factor of approximately 100. The largest events ($M_L \approx 2.6$-2.9) occurred during the first two years following impoundment. Although the general level of seismic activity has gradually decreased with time, it is still substantially greater than the pre-impoundment level of seismicity.

Monticello Reservoir has been the focus of an intense research effort aimed at evaluating the seismic hazard and developing a capability for predicting earthquakes [Talwani and others, 1978, 1980; Talwani, 1979; Zoback, 1979; Secor, 1980; Secor and others, 1981; Zoback and Hickman, in press]. The reservoir is located in a geologically complex area of the Charlotte belt in the Piedmont province of central South Carolina (Fig. 2, and Plates 1-4). The region is characterized by low relief, deep chemical weathering and extensive forest cover. Reliable geological maps can only be made by painstakingly traversing the intricate network of gullies and streams within the area. Although several geological studies had been completed in the vicinity of the reservoir [Kesler, 1936, 1972; McCauley, 1961; Overstreet and Bell, 1965a; McKenzie and McCauley, 1968; Secor and Wagener, 1968; Wagener, 1970, 1973, 1977a; Costain and others, 1976, 1977; South Carolina Electric and Gas Company, 1977, p. 2.5-1 - 2.5-324; Glover and others, 1977; Bourland and Farrar, 1980], these were mostly of a topical or reconnaissance nature and the structure and distribution of rock units was poorly known at the time of impoundment. The present study was initiated in order to provide a geological framework necessary for the interpretation of the seismic activity. In particular, our studies are directed toward determining: 1) if there are laterally extensive faults in the region that might eventually slip, thus producing a large earthquake; 2) if there are lithological boundaries other than fault contacts in the vicinity of the reservoir controlling the distribution of seismic activity and; 3) if there are foliations or systematic jointing directions along which slip might be initiated by the stress and

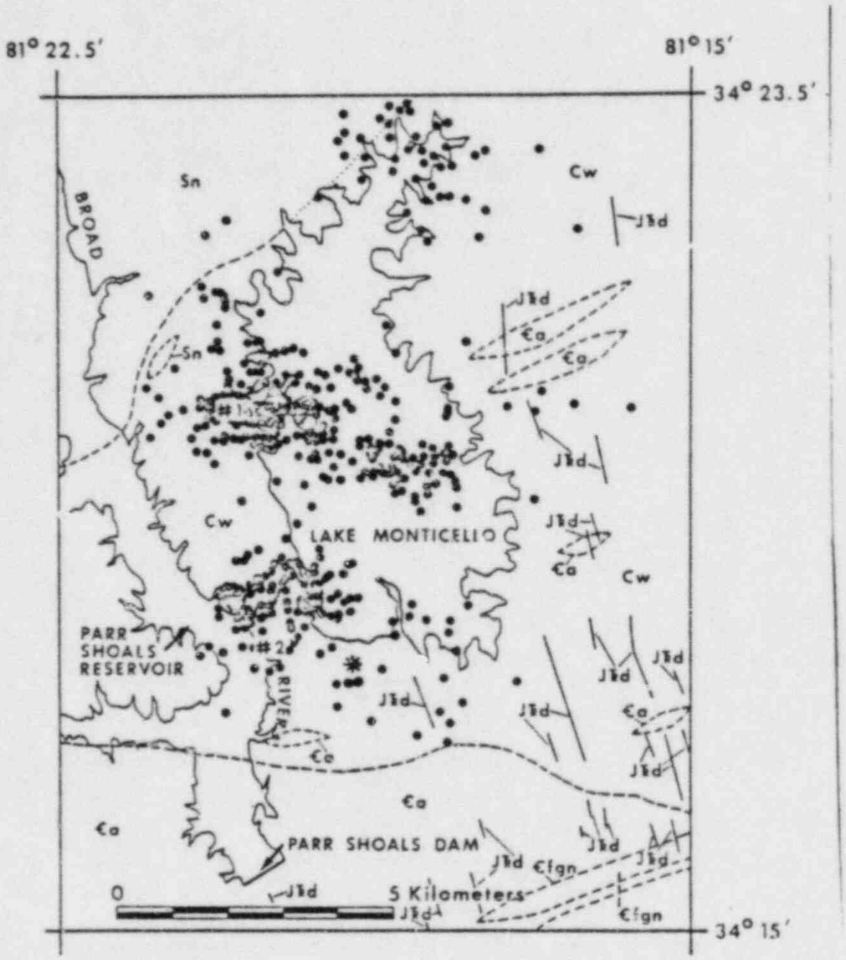

Figure 1. Distribution of induced seismic activity in the vicinity of Lake Monticello during the period June, 1978-September, 1979, inclusive (modified from Talwani and others [1980]). Dots indicate the locations of induced earthquakes. The locations of the U. S. Geological Survey boreholes #1 and #2 are indicated. The asterisk indicates the location of the Virgil C. Summer nuclear station. Geological symbols and contacts are from Figure 2.

pore-pressure changes related to reservoir impoundment. In order to make the above evaluations, we prepared detailed geological maps of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (U. S. Geological Survey 7 1/2' topographic series) surrounding the reservoir (Fig. 2, and Plates 1-4). These maps constitute the main data base for the following geological synopsis.

ROCK UNITS

The southern one-third of the study area is underlain by greenschist-facies metavolcanic and metasedimentary rocks of the Carolina slate belt, and the northern two-thirds of the area is underlain by amphibolite-facies metaigneous and metasedimentary rocks and post-kinematic plutonic rocks of the Charlotte belt (Fig. 2, and Plates 1-4). The stratified rocks in the central and southern part of the study area constitute a sequence several kilometers thick, and the metaplutonic rocks form lenticular masses in this sequence. This lithostratigraphic assemblage is considered by many geologists [e.g. Butler and Ragland, 1969b; Seiders and Wright, 1977; Black, 1978, 1980; Whitney and others, 1978] to have accumulated during the evolution of a Proterozoic Z to Cambrian magmatic arc. The older parts of this sequence are units of felsic gneiss (Єfgn) and amphibolite (Єa). Relict compositional layering and volcanic textures in these rocks suggest that they have resulted from the metamorphism of quartzofeldspathic sedimentary and volcanic rocks (Єfgn) interlayered with mafic tuffs and/or flows (Єa). The felsic gneiss and amphibolite units have been injected by numerous partially concordant sheets of granitoid intrusive rocks (Єggn) related to overlying coeval extrusive felsic metatuffs (Єtq). Both the intrusive granitoid orthogneiss

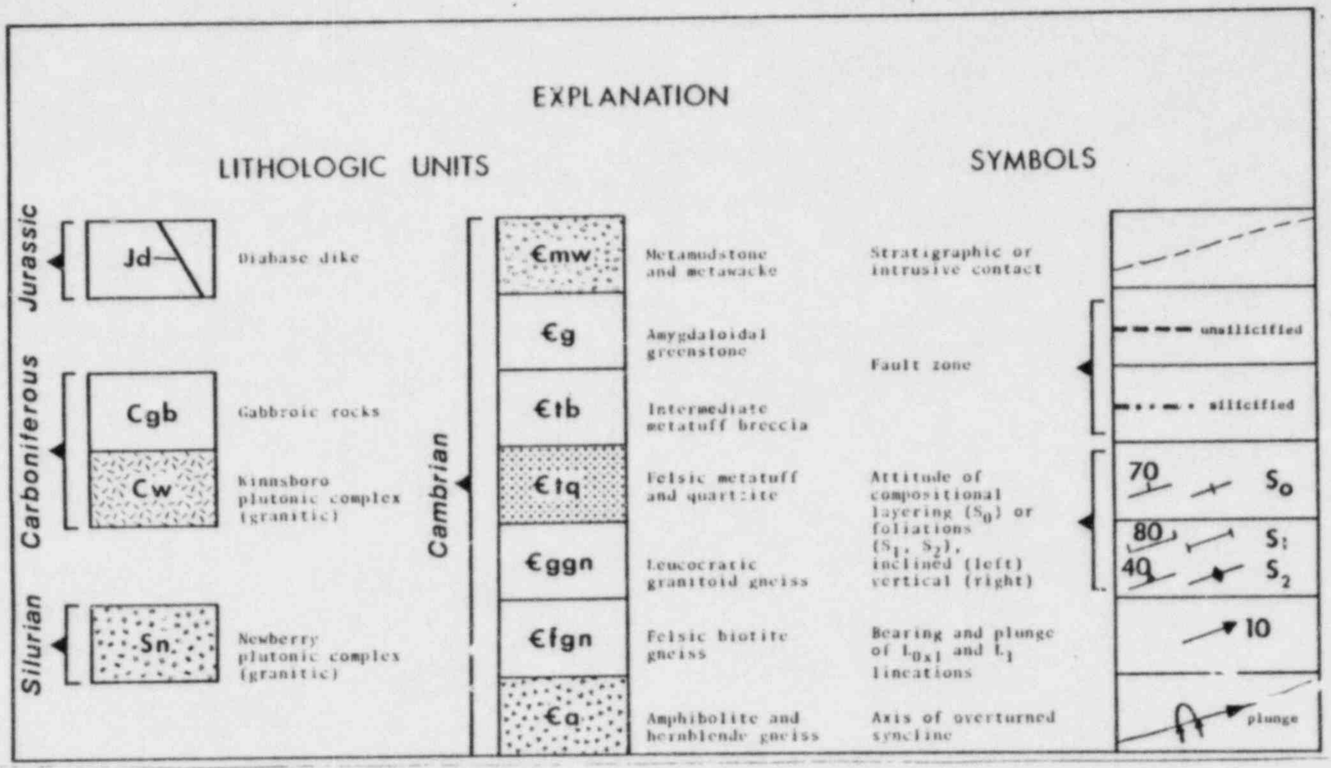

Figure 2. A geological map of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (U. S. Geological Survey 7½' topographic series).


MONTICELLO #1
LAKE MONTICELLO
MONTICELLO #2
VIRGIL C. SUMMER NUCLEAR STATION
POMARIA
PARR SHOALS DAM
JENKINSVILL
LITTLE MOUNTAIN
SPRING HILL ROADCUT
CHAPIN SYNCLINORIUM
CHAPIN
SUMMERS BRANCH FAULT ZONE
WATEREE CREEK FAULT ZONE
GEOLOGY
OF THE CHAPIN, LITTLE
MOUNTAIN, POMARIA AND
JENKINSVILLE QUADRANGLES,
SOUTH CAROLINA
KILOMETERS
0
2
4
6
8
CHARLOTTE BELT
CAROLINA SLATE BELT
POMARIA (PITCHER)
JENKINSVILLE (SMITH)
LITTLE MOUNTAIN (PECK)
CHAPIN (SIMPSON)
34° 22.5′
34° 7.5′
81° 30′
81° 15′
82°
80°
34°

Figure 2.

(Єggn) and the felsic metatuffs (Єtq) are characteristically sodic-rich, although the granitoid orthogneiss also includes a wider compositional spectrum from tonalite to granite. The thickness of orthogneiss sheets ranges from a few centimeters to a kilometer. Only a few of the thickest and most continuous sheets are shown on Figure 2 and on Plates 1-4. In many places the felsic metatuff unit (Єtq) has been silicified and accessory pyrite has been introduced. Locally (as on Little Mountain), the silicification is nearly complete and the rock is quartzitic. These highly altered rocks in the felsic metatuff unit are interpreted to mark a volcanic exhalative horizon that is found widely in the Carolina slate belt in South Carolina and Georgia [Espenshade and Potter, 1960; Kesler, 1972; Hartley, 1976]. Immediately above the exhalative horizon is a 1-2 km-thick sequence of intermediate to felsic lithic metatuff breccia (Єtb). This volcaniclastic deposit is in part probably a product of episodic subaqueous debris flows as evidenced by its coarse-grained and poorly sorted character and by the local occurrence of water-rounded pebbles of volcanic rock and quartzite in poorly sorted tuff breccia. The lithic metatuff breccia unit grades into an overlying sequence of metamudstone, metasiltstone and metawacke (Єmw) through an interval of a few hundred meters in which the several lithologies are interbedded. Elsewhere in the Carolina slate belt, well-preserved sedimentary structures in the Єmw unit suggest that it is a turbidite sequence deposited below wave base [Brown, 1971; Kearns and others, 1981]. The Єmw unit contains a sequence of amygdaloidal greenstone (Єg), 0-100 m thick, near its base, which is interpreted to have originally been a series of intermediate to mafic flows or flow breccias.

Most of the northern part of the study area is underlain by late- to post-kinematic granitoid plutonic rocks. Two distinctive groups of plutonic rocks can be recognized: the "Newberry" and the "Winnsboro" plutonic complexes.

The "Newberry" plutonic complex (Sn), which is found in the northwestern corner of the study area, is predominantly composed of medium-grained biotite quartz monzonite with some coarse-grained hornblende quartz monzonite. This unit also crops out extensively in regions north and west of the study area [McCauley, 1961a, Wagener, 1977a]. The "Newberry" plutonic complex has an irregular shape, consisting of a group of thick, partially concordant sheet intrusions enclosing numerous large enclaves of felsic gneiss (Єfgn). In some places, the "Newberry" quartz monzonite exhibits a faint compositional layering caused by subtle variations in the biotite content. A weak subhorizontal parting is evident in weathered outcrops. This parting may be of tectonic origin, or it may be the result of weathering and exfoliation. The initial $^{87}Sr/^{86}Sr$ ratio for the Newberry quartz monzonite is 0.7024 ± 0.0003, and the Rb-Sr whole-rock age is 415 ± 9 m.y. [Fullagar, 1981].

The northeastern and north-central parts of the study area are underlain by a sparsely porphyritic, medium- to coarse-grained, biotite-hornblende quartz monzonite (Cw), which is here interpreted to be a part of the "Winnsboro" plutonic complex [Wagener, 1970, 1977a]. The proportions of feldspar phenocrysts, biotite, and hornblende in the quartz monzonite are variable, and thin sheets of granite, aplite and pegmatite also are found. Numerous xenoliths and a few large enclaves of gneiss and amphibolite are present (Fig. 2, and Plate 3). The results of drilling and detailed geological mapping at the V. C. Summer nuclear station indicate that, in this area, approximately 30%-70% of the volume of the pluton is occupied by enclaves or large xenoliths of gneiss and amphibolite up to a few hundred meters in length [South Carolina Electric and Gas Company, 1977, Figs. 2.5-15, 2.5-16, 2.5-17]. Two 1.0-1.1 km-deep boreholes were drilled into the area of induced seismicity along the west side of Lake Monticello by the U. S. Geological Survey (Monticello #1 and #2, Figs. 1, 2). These boreholes were used to measure stresses and to determine the character of the rock in the region of seismic activity. Visual inspection of core and cuttings from Monticello #2 indicates that enclaves and xenoliths of gneiss and amphibolite are concentrated mostly in the top 830 m of the hole and constitute approximately 15% of the total volume of the pluton (Fig. 3). Cores and cuttings from Monticello #1 indicate that there the pluton is relatively free of inclusions (Fig. 3). Several extensive outcrop areas of amphibolite are found in the eastern part of the Jenkinsville quadrangle north of the main amphibolite belt (Fig. 2, and Plate 3). These are interpreted to be enclaves surrounded by quartz monzonite. There almost certainly are additional large enclaves of country rock within the "Winnsboro" plutonic complex that were not detected during our field studies because of the thick mantle of residual soil and the sparse exposures. The irregular character of the magnetic field over the "Winnsboro" (Fig. 4) may be partly a result of the compositional inhomogeneity of the quartz monzonite, but it may also indicate irregularity in the subsurface distribution of enclaves and xenoliths. Leucocratic dikes of aplite and pegmatite are extremely abundant in the amphibolite unit (Єa) where it is in contact with the "Winnsboro" in the southern part of the Jenkinsville quadrangle. These dikes locally constitute more than 50% of the total volume of exposed rock. The initial $^{87}Sr/^{86}Sr$ ratio of the "Winnsboro" is 0.7047 ± 0.0004 and its Rb-Sr whole-rock age is 295 ± 4 m.y. [Fullagar, 1971; Fullagar and Butler, 1979]. Several Rb-Sr and K-Ar mineral ages in the range 309-286 m.y. were determined for the quartz monzonite in the foundation rock of the

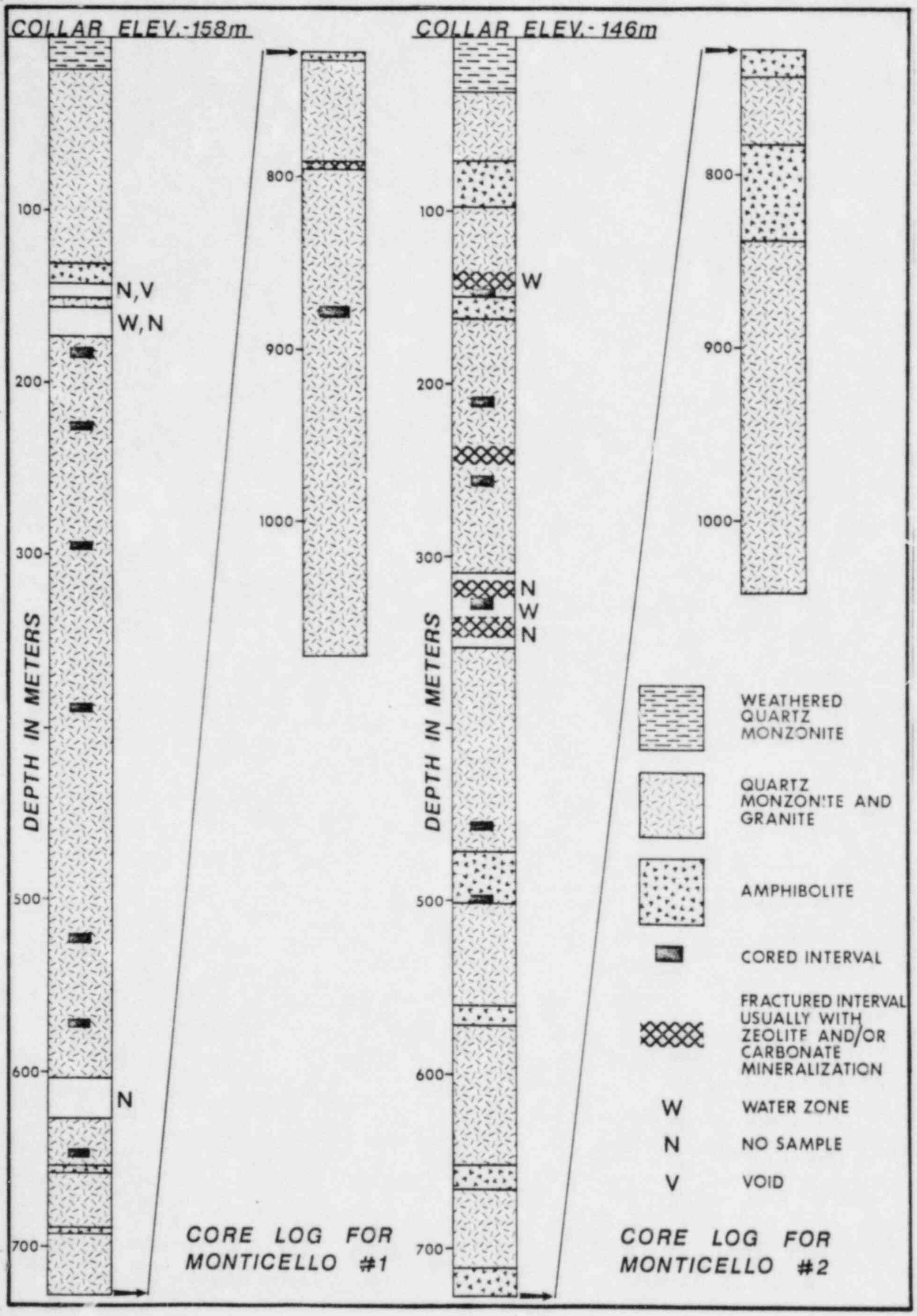

Figure -. Lithologic log for Monticello #1 and #2, compiled from core and cutting samples.

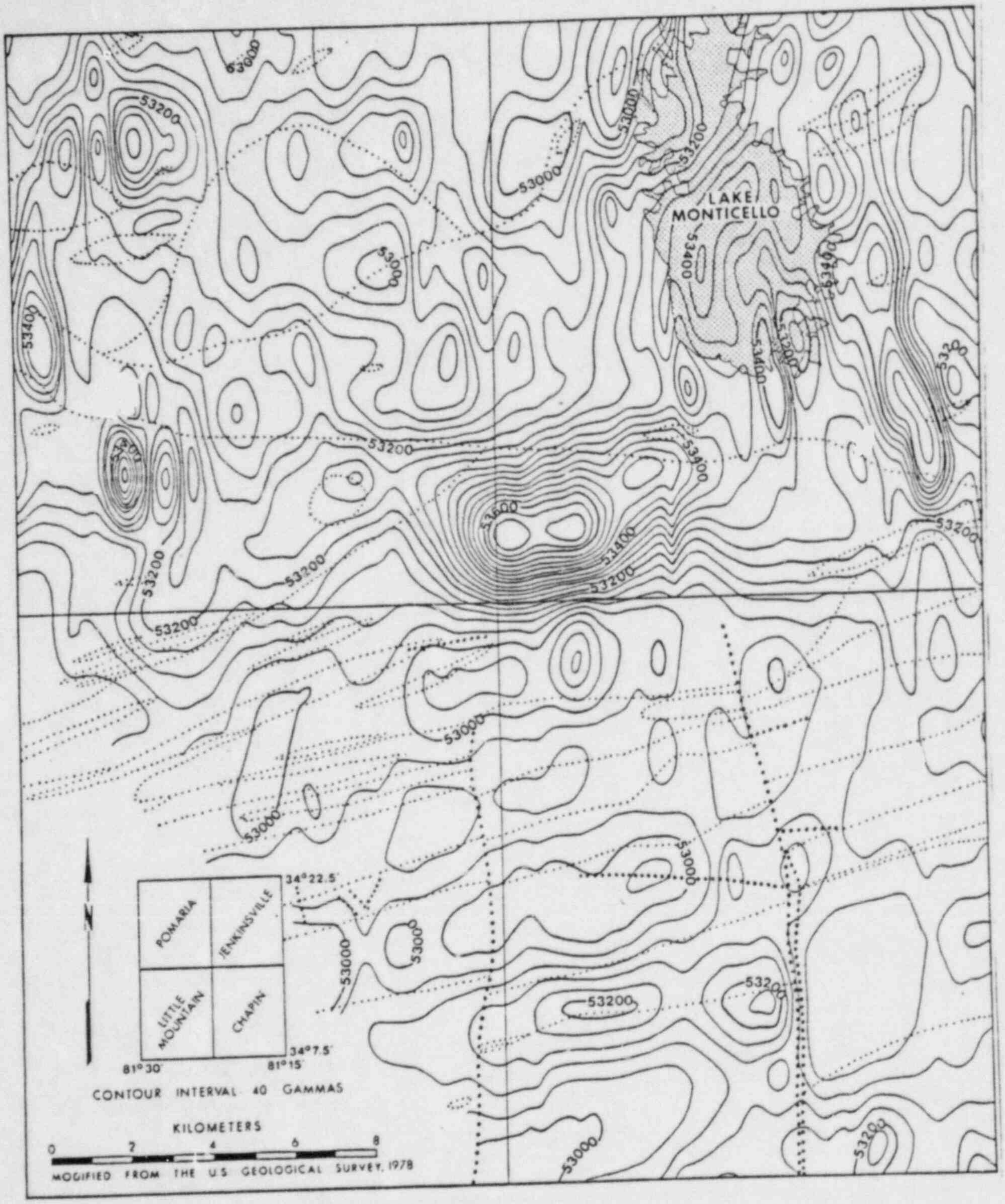

Figure 4. Aeromagnetic map of the Chapin, Little Mountain, Jenkinsville and Pomaria quadrangles (modified from U. S. Geological Survey [1978]). Contour interval 40 gammas. Dotted lines indicate the positions of geological contacts from Figure 2.

V. C. Summer nuclear station at the south end of Lake Monticello [South Carolina Electric and Gas Company, 1977, Table 2.5-3; Fullagar and Kish, 1981].

Several small plugs and sheets of gabbroic rock (Cgb, Fig. 2, and Plate 2) intrude the rocks of the Carolina slate belt in the southern part of the Little Mountain quadrangle. These clearly are post-metamorphic because the associated contact metamorphism overprints the regional greenschist-facies metamorphism and anneals the S_1 foliation. They are tentatively interpreted to be of Carboniferous age because mafic plutonic rocks are associated with Carboniferous granitic rocks elsewhere in the Piedmont [Waskom and Butler, 1971].

The youngest rocks in the study area are a series of steeply dipping olivine diabase dikes. These dikes are 0-10 m thick, up to several kilometers long, and trend N.15W.-N.30W. Paleomagnetic studies have been conducted on 24 different dikes from the South Carolina Piedmont [Dooley and Smith, in press]. Their average pole position (83.9°E., 66.1°N.) is similar to that reported for other North American diabases of early Mesozoic age [deBoer, 1967; Smith and Noltimier, 1979; Sutter and Smith, 1979]. Although previous studies have indicated that many of the diabase dikes in the Piedmont have anomalously old K-Ar whole-rock ages because of excess argon contamination [Dooley and Wampler, 1977], eleven dikes in the present study have K-Ar whole-rock ages in the range 207-180 m.y., in excellent agreement with the paleomagnetic results (The K-Ar whole-rock ages were determined by R. E. Dooley using facilities at the Georgia Institute of Technology.). An anomalous age of 288 m.y. was determined for one dike from the Salem Crossroads area north of Monticello Reservoir. The paleomagnetic pole positions and most of the

K-Ar whole-rock ages, therefore, indicate a Late Triassic and/or Early Jurassic age for the diabase dikes in the study area.

DEFORMATIONAL HISTORY AND MAJOR AND MINOR STRUCTURES

The rocks in the study area have been affected by two strong episodes of folding (D_1, D_2), and are cut by a variety of later faults and joints.

The earliest deformation (D_1) was an episode of tight to isoclinal passive folding. The associated regional metamorphism (M_1) ranges from greenschist facies in the Carolina slate belt to amphibolite facies in the Charlotte belt. The Chapin synclinorium is a major northeast plunging F_1 fold crossing the southern part of the study area. The initial compositional layering in the stratified rocks (S_0) has been strongly transposed by S_1 slaty cleavage. S_1 contains a strong elongation lineation (L_1) which parallels the L_{0x1} intersection lineation. The average orientations of L_1 and L_{0x1} in the study area (Figs. 5a, b) indicate that the Chapin synclinorium plunges 11° to the N.75E. The 415 m.y.-old "Newberry" plutonic complex contains rotated xenoliths which carry the S_1 foliation and hence the time of D_1 must be Silurian or older. Whole-rock K-Ar studies of slates from the Carolina slate belt in North Carolina, which have never been heated significantly above the argon retention temperature, indicate that the most probable time for M_1 is Early Ordovician [Kish and others, 1979].

The S_1 foliation has been extensively reoriented by mesoscopic to macroscopic F_2 flexural flow folds (Fig. 5c). In most places F_2 folds are coaxial with L_1 and L_{0x1}. The intensity of F_2 folding increases progressively from south to north in the study area. The time of D_2 is thought to be pre-295 m.y. because F_2-style folds have been observed in rotated xenoliths in the "Winnsboro" plutonic complex.

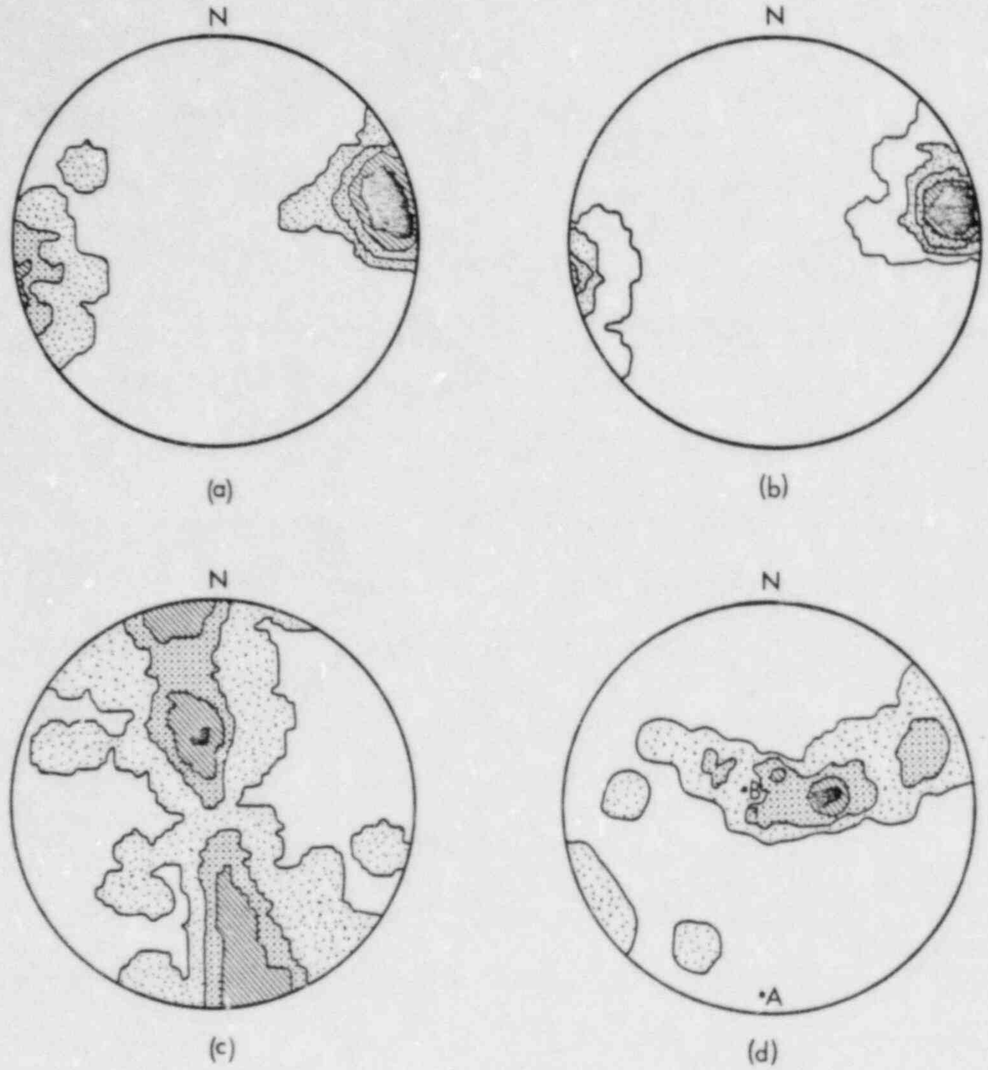

Figure 5. Lower hemisphere, equal-area projections of structural data from the region south of Monticello Reservoir. (a) 63 L_1 elongation lineations from the slate belt portion of the Chapin and Little Mountain quadrangles. Contours: 1, 5, 15 and 25%. (b) 41 L_{0x1} intersection lineations from the slate belt portion of the Chapin and Little Mountain quadrangles. Contours: 1, 5, 15, 25 and 35%. (c) Poles to 713 S_1 foliation planes from the slate and Charlotte belts in the Chapin and Little Mountain quadrangles. Contours: 0.5, 2, 5 and 10%. (d) 106 L_{0x1} lineations from the Wateree Creek fault zone in the vicinity of Spring Hill in the Chapin quadrangle. Contours: 1, 5, 12 and 20%. "A" is the axis of drag folding, "B" is the net-slip vector for the Wateree Creek fault zone.

The post-D_2 brittle faults in the study area are divided into several groups on the basis of their orientation and the character of the mineralization that has taken place in the fault zones.

The oldest group of faults, striking approximately east and dipping steeply, is characterized by repeated episodes of brecciation and silicification. The adjacent wall rocks are cut by numerous irregular extensional veins partly infilled with comb quartz. The displacement along faults of this group has apparently been small, for generally the same rock unit is present on both sides of the fault surface. Faults containing silicified breccia are widespread in the Appalachian Piedmont [Conley and Drummond, 1965; Odom and Hatcher, 1980]. Those in the eastern Piedmont of South Carolina are thought to be of late Paleozoic or early Mesozoic age because they cut Carboniferous metagranitic rocks near the Fall Line and are themselves cut by Upper Triassic and/or Lower Jurassic diabase dikes.

The east-trending silicified fault zones are displaced by a later set of steeply dipping faults trending N. to N.15°W. The Wateree Creek fault zone in the central and southern parts of the Chapin quadrangle (Fig. 2, and Plate 1) is the most thoroughly documented example of this north-trending fault set. The Wateree Creek fault zone displaces stratigraphic units on the flanks of the Chapin synclinorium in a manner suggesting down-to-the-east, predominantly dip-slip displacement (Fig. 2). The apparent offset of the axis of the Chapin synclinorium in cross section also indicates predominantly dip-slip displacement of approximately 1700 m (compare A-A', B-B', and C-C', Figs. 2 and 6). In the vicinity of the Wateree Creek fault zone, the L_1 and L_{0x1} lineations have been dispersed along a portion of a small circle on the stereonet (Fig. 5d) by fault-related drag. The axis of the drag fold derived

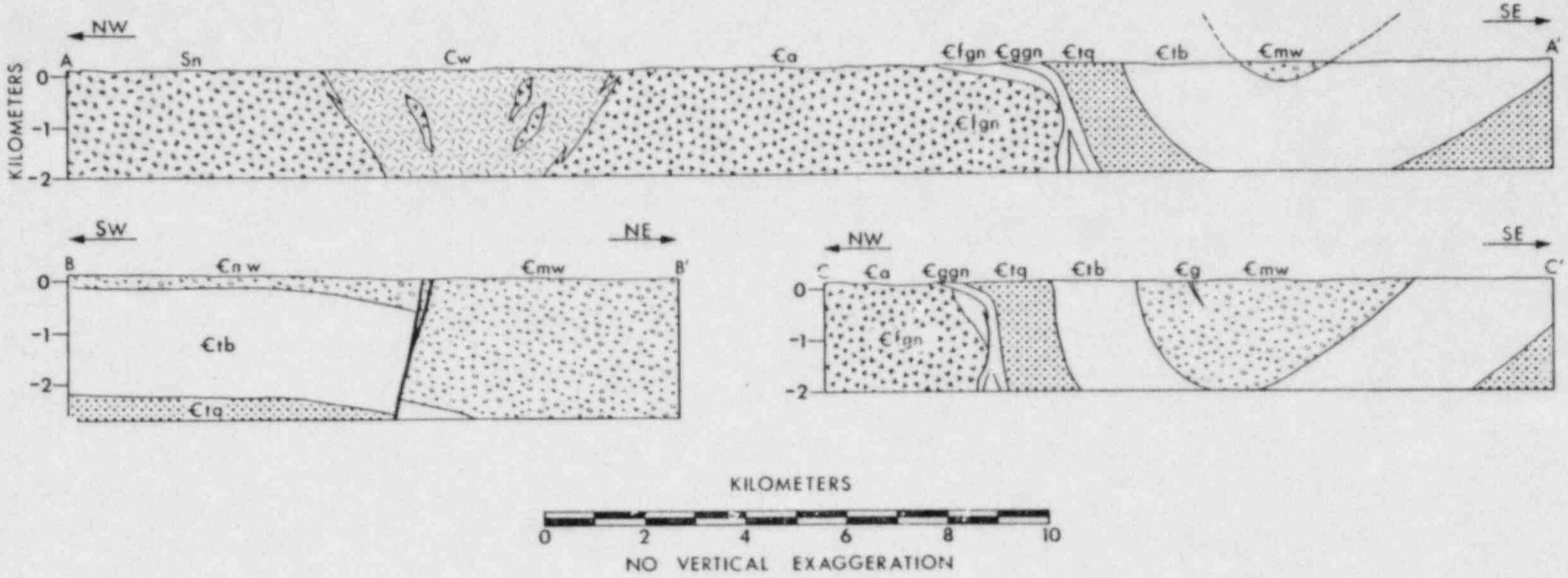

Figure 6. Geological cross sections across the Pomaria, Jenkinsville and Chapin quadrangles. See Figure 2 for location of section lines.

from the data in Figure 5d (4°S.3°W.) is subhorizontal, indicating predominantly dip-slip displacement in the fault zone.

A portion of the Wateree Creek fault zone is exposed in a large roadcut near Spring Hill in the east-central part of the Chapin quadrangle (Fig. 2). The average dip of fault surfaces in this outcrop is 78° to the west, indicating that at this level of exposure the faults in the Wateree Creek zone are high-angle reverse. Thoroughly brecciated rock is exposed in several places along the fault zone. Samples recovered from several core holes drilled into the fault zone below the level of weathering indicate that veins and open spaces in the breccia have been infilled predominantly with carbonate minerals and accessory quartz. The apparent brittle character of the breccia and the mineralogy of the associated vein fillings suggests that the faulting occurred at low temperatures and pressures within a few kilometers of the earth's surface. Detailed field investigations, including backhoe trenching, in the southern part of the Chapin quadrangle indicate that a diabase dike, petrologically similar to the Upper Triassic and Lower Jurassic diabase dikes, intrudes across the Wateree Creek fault zone and is apparently not displaced along the fault zone (Fig. 2, and Plate 1). Therefore, the faulting is thought to have occurred prior to the Early Jurassic.

The north-trending Summers Branch fault zone in the Little Mountain quadrangle (Fig. 2, and Plates 1, 2) offsets stratigraphic units on the flanks of the Chapin synclinorium in a manner suggesting down-to-the-west, dip-slip displacement. The Summers Branch fault zone is interpreted to be similar to the Wateree Creek fault zone, although actual outcrops of rock from within the fault zone have not been found.

During excavation for the foundations of the V. C. Summer nuclear station (located in the "Winnsboro" complex), a distinctive group of fractures containing druses and vein fillings of laumontite were found. Although there is considerable variability to the attitudes of the mineralized fractures, two steeply dipping sets that strike N.60°E. and N.28°W. can be recognized [South Carolina Electric and Gas Company, 1977, p. 2.5-38 to 2.5-40, and Fig. 2.5-25]. Fractures of the northeast-trending set have undergone oblique-slip displacements up to 2 m. Fractures of the northwest-trending set displace those of the northeast set and have undergone oblique-slip displacements up to several centimeters. Undeformed laumontite crystals fill openings along both sets. A K-Ar age of 45 ± 5 m.y. has been determined on laumontite crystals from the N.60°E. trending fracture set. This age is regarded as a minimum estimate of the time of fault movement [South Carolina Electric and Gas Company, 1977, p. 2.5-47].

Fractures and alteration zones containing zeolite and carbonate minerals were found at several levels in Monticello #2, and in some cases were associated with a substantial influx of groundwater (Fig. 3). Zeolite mineralization has also been observed nearby along northwest-trending fractures in the spillway to the Parr Shoals dam, and in a borehole in the "Winnsboro" plutonic complex east of the study area [Costain and others, 1977]. These local occurrences of zeolite mineralization in fractures are thought to be a manifestation of a Mesozoic deformational event, perhaps associated with the emplacement of diabase dikes, that has affected a large area in the central Piedmont of North and South Carolina [Privett, 1973a, 1973b, 1974a, 1974b, 1977; Brown and Gilbert, 1977; Butler, 1977; Wagener, 1977b].

In most outcrops in the study area, the rocks are cut by one or more joint sets in which the individual fractures have little or no lateral displacement. The joints are usually 10-200 cm in length, although in most places a few longer joints are present which extend beyond the limits of exposure. Short joints often are arranged in echelon patterns located near the termination of a nearby long joint. Approximately 100 joint measurements have been made at each of 50 localities in the study area. In general, the orientations of the sets and the joint frequency are variable from one locality to another (Fig. 7, and Plates 9-12), although in most places one or more sets are oriented at a high angle to S_1 and L_{0x1} or L_1. The controls on orientation and frequency are not well understood, although the orientations of other fabric elements and the extent of lithological heterogeneity probably are important. In general, joint frequency is lowest in the "Winnsboro" plutonic complex, and highest in the low-grade metamorphic rocks of the Carolina slate belt. However, even in otherwise homogeneous structural and lithological domains, joint orientation and frequency are variable.

DISCUSSION

In order to make judgments about the possible earthquake hazard at Monticello Reservoir, it is necessary to evaluate the above geological information in light of the ambient stress field in the region of seismic activity. Information about the stresses is available from the following sources: 1) composite-fault-plane solutions derived from seismic data [Talwani and others, 1980; South Carolina Electric and Gas Company, 1980], 2) stress measurements made in the U. S. Geological Survey boreholes, Monticello #1 and #2, by the hydraulic-fracturing technique [Zoback, 1979; Zoback and Hickman, in press], and 3) stress measurements made in the foundation excavation of the V. C. Summer nuclear station by the overcoring technique [South Carolina

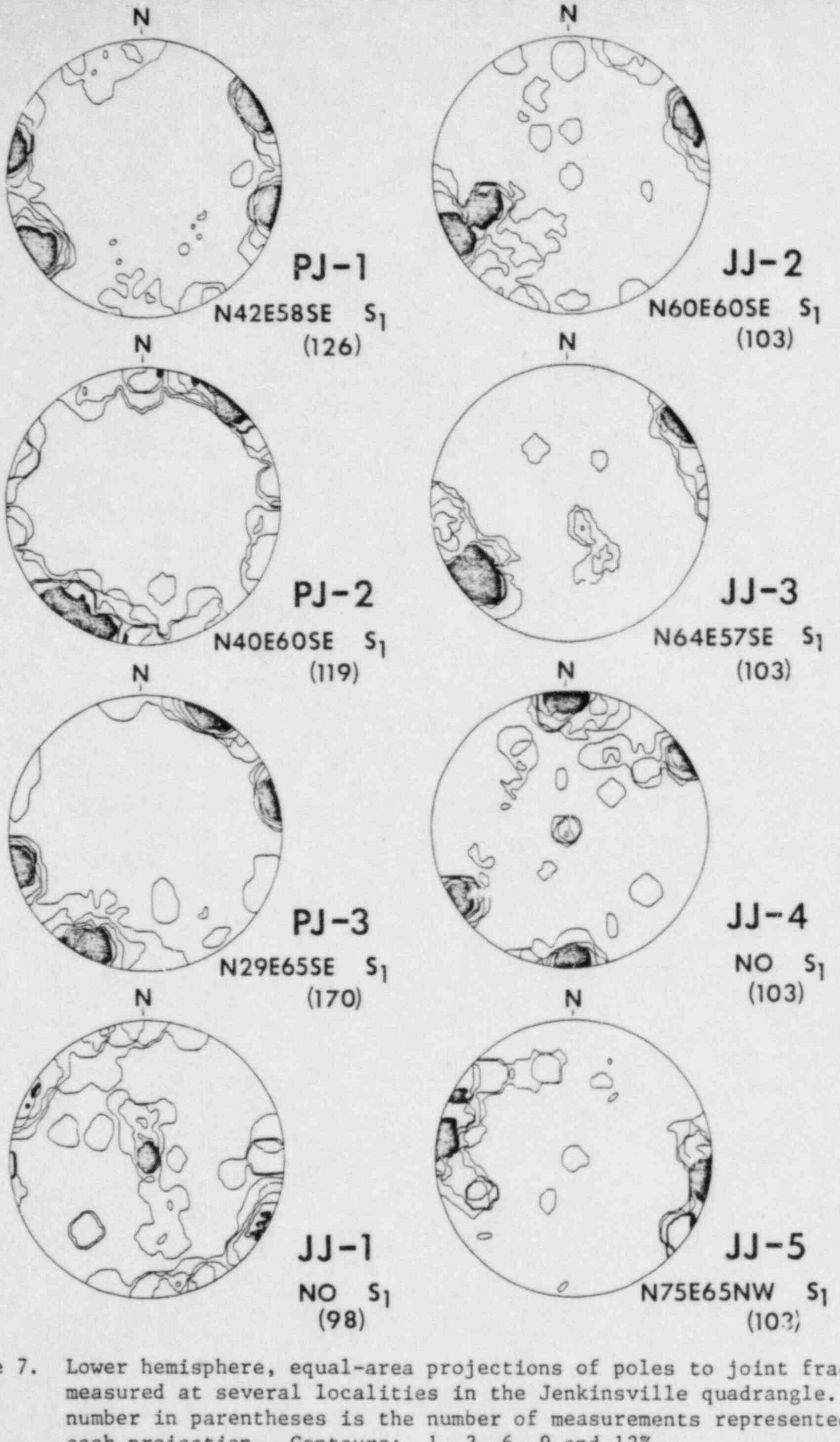

Figure 7. Lower hemisphere, equal-area projections of poles to joint fractures measured at several localities in the Jenkinsville quadrangle. The number in parentheses is the number of measurements represented on each projection. Contours: 1, 3, 6, 9 and 12%.

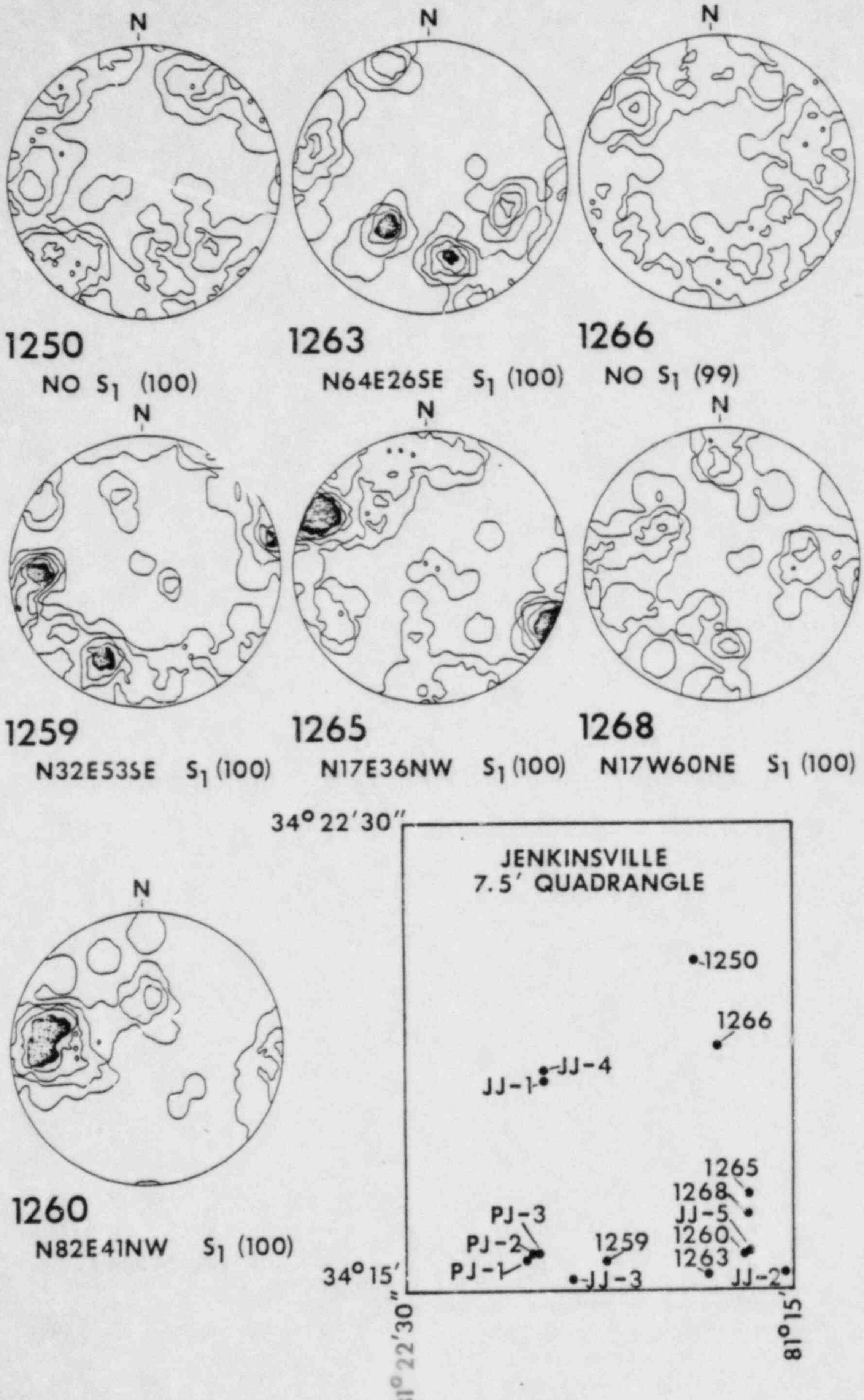
N
1250
NO S1 (100)
1263
N64E26SE S1 (100)
1266
NO S1 (99)
1259
N32E53SE S1 (100)
1265
N17E36NW S1 (100)
1268
N17W60NE S1 (100)
1260
N82E41NW S1 (100)
34° 22′30″
JENKINSVILLE
7.5′ QUADRANGLE
1250
1266
JJ-4
JJ-1
1265
1268
JJ-5
1260
1263
JJ-2
PJ-3
PJ-2
PJ-1
1259
JJ-3
34° 15′
81° 22′30″
81° 15′

Figure 7.

Electric and Gas Company, 1977, p. 2.5-226].

The seismic studies at Monticello Reservoir indicate that the epicenters of induced earthquakes are occurring in three groups (Fig. 1) located in areas underlain by rocks of the "Winnsboro" plutonic complex. One large group is located at the southwest corner of Lake Monticello, near both the V. C. Summer nuclear station and the site of Monticello #2. Another large group is located in the west-central part of the lake around the site of Monticello #1. A third smaller group is located at the north end of the lake. Almost all of the foci are located at depths of less than 2 km, and composite-fault-plane solutions indicate that the mechanism of faulting is predominantly thrusting with the P axes approximately horizontal and having directions ranging from N.34°E. through due east to S.76°E. [Talwani and others, 1980]. Analysis of the source characteristics of some of the earthquakes suggests that the seismicity is occurring along pre-existing fractures [Duc, 1980; Talwani, 1981]. The apparent scatter in the locations of the earthquake foci suggest that the foci are not located along a single major fault but instead are located along numerous small fractures pervading the rock. Variability in the orientation of nodal planes for various sub-groups of earthquakes [Talwani and others, 1980] suggests variability in the orientation of pre-existing fractures and also perhaps temporal and/or spatial variability in the orientation of the principal stresses.

The above observations are further reinforced by stress measurements and fracture orientation studies made in the U. S. Geological Survey boreholes Monticello #1 and #2 which are located in the two clusters of most intense seismic activity [Zoback, 1979; Zoback and Hickman, in press]. Hydraulic fracturing stress measurements made in these holes indicate that within a few hundred meters of the earth's surface the rock is in a state of incipient failure by thrust faulting. At greater depths the rock is generally not critically stressed, although the magnitudes of the horizontal principal stresses vary erratically with depth [Zoback and Hickman, in press]. Fracture studies made with a borehole televiewer [Zoback and Hickman, in press] indicate that the rock at Monticello #2 is much more intensely fractured than the rock at Monticello #1. Although a weak preferred orientation is evident in some restricted intervals of the boreholes, in general the fracture orientations are variable and erratic. Comparison of fracture orientations with the orientations of nodal planes derived from composite fault plane solutions indicates that there are fractures having an orientation favorable for reactivation in the regions of seismicity [Talwani, 1981; Zoback and Hickman, in press].

Several determinations of the magnitudes and directions of the horizontal principal stresses were made by the strain-relief, overcoring technique in the foundation excavation for the V. C. Summer nuclear station [South Carolina Electric and Gas Company, 1977, p. 2.5-226]. The magnitude of the greatest horizontal principal compressive stress ranged from +31 to +97 bars, and its direction ranged from N.35°W. through due north to N.15°E. These directions are approximately perpendicular to the direction of greatest horizontal compressive principal stress inferred from composite-fault-plane solutions [Talwani and others, 1980; South Carolina Electric and Gas Company, 1980, Appendix IV, Tables 1 and 3].

One of the primary objectives of this study was to determine if there are laterally extensive faults or other major lithological boundaries in the vicinity of Monticello Reservoir having orientations favorable for reactivation in connection with the induced seismic activity. Because the directions of the principal stresses are variable, it is difficult to predict the planar orientations that would be most susceptible to reactivation. However, the average direction for the greatest horizontal compressive principal stress derived from composite-fault-plane solutions is N.71°E. The most favorable orientations for thrust faults resulting from a greatest compressive principal stress having this orientation would be N.19°W.30°SW. or N.19°W.30°NE. In the Chapin and Little Mountain quadrangles two sets of major faults having orientations E.-W.65°S. (silicified faults) and N.15°W.78°SW. (Wateree Creek and Summers Branch faults) are present. These are not orientations favorable for reactivation, and furthermore, no field evidence has been found indicating that long faults are present in the vicinity of the reservoir. The northernmost outcrop on the Wateree Creek fault zone (Fig. 2, and Plate 1) is located in the Chapin quadrangle approximately 8 km south of Monticello Reservoir.

Several Jurassic and/or Triassic diabase dikes striking N.15°W. to N.30°W. were found in the region surrounding Monticello Reservoir (Figs. 1, 2, and Plates 1-4), and it is possible that similar dikes occur in the subsurface in the regions of seismic activity. However, the diabase dikes are steeply dipping to vertical and hence are oriented at a high angle to the planes preferred for the development of thrust faults. Thus, it is unlikely that the intrusive contacts between diabase dikes and the enclosing granitic rocks would function as guides for the development of new long fractures.

The only other major lithological boundaries near the region of seismic activity are the contacts between the "Winnsboro" plutonic complex and surrounding rocks. These strike almost perpendicular to the preferred faulting directions and are interpreted to be irregular intrusive contacts having numerous apophyses extending outward into surrounding rocks. Because of their orientation, irregularity, and intrusive character, these contacts probably retain substantial cohesion and would be unlikely to function as guides for new long fractures.

Another objective of this study was to determine if there are foliation directions along which slip might be initiated by the stress and pore-pressure changes related to reservoir impoundment. Almost all of the seismic activity is located in the "Winnsboro" plutonic complex which underlies Monticello Reservoir. The "Winnsboro" is post-kinematic and is generally unfoliated, although in some places an emplacement related irregular gneissic layering is present. In addition, the "Winnsboro" complex contains numerous foliated xenoliths and enclaves of felsic gneiss and amphibolite having a maximum length on the order of 1-2 km. Because the larger enclaves are sparsely distributed, and because the foliation in them is folded and diversely oriented, it is unlikely that the enclaves could function as guides for the development of new long fractures.

The above geological and geophysical studies indicate that the "Winnsboro" plutonic complex contains numerous diversely oriented small fractures and lithological inhomogeneities having a maximum length on the order of 1-2 km. These local inhomogeneities, together with an irregular stress field, are interpreted to control the diffuse seismic activity that is occurring around Monticello Reservoir. In view of the apparent absence of long faults in the vicinity of the reservoir, it is unlikely that a large magnitude earthquake will occur in response to the stress and pore pressure changes [Zoback and Hickman, in press] related to reservoir impoundment.

CHAPTER II

THE WATEREE CREEK FAULT ZONE

ABSTRACT

The Wateree Creek fault zone is a region of north trending high angle reverse faulting located in the Chapin quadrangle in the Piedmont province of central South Carolina. The location and character of this fault are established from the following evidence: 1) offset of stratigraphic contacts and pre-existing structural features, 2) abrupt termination of a prominent aeromagnetic anomaly, 3) occurrence of fault breccia along the zone, 4) drag of pre-existing rock fabric elements adjacent to the zone, and 5) observation of three of the major component faults in the zone in the Spring Hill roadcut. Structural analysis of the Wateree Creek fault zone indicates that the ∿ 1700 m displacement is predominantly dip-slip and down to the east. The youngest geologic feature which is clearly offset by the Wateree Creek fault zone is an east trending silicified breccia zone of unknown age. Preliminary studies indicated that a major N.20°W. trending diabase dike contains a dextral en echelon offset in the region of the Wateree Creek fault zone, however, a series of detailed magnetometer profiles combined with backhoe trenching have shown that the diabase locally intrudes across the fault zone. Therefore most, if not all, of the displacement along the Wateree Creek fault zone occurred prior to the emplacement of the diabase dike. Neither the silicified breccia zone nor the diabase dike have yet been accurately dated. However we suggest an early to middle Mesozoic age for the Wateree Creek fault zone based on a presumed age of late Paleozoic to early Mesozoic for the silicified breccia zone and a presumed Late Triassic or Early Jurassic age for the diabase.

INTRODUCTION

A major zone of brittle faulting of probable Mesozoic age occurs in the Chapin quadrangle, northwest of Columbia, South Carolina, and is especially well exposed in a portion of the Carolina slate belt. This structure is referred to as the Wateree Creek fault zone and outcrops as several parallel fault surfaces with varying displacement across a zone 250 m wide. The major movement on the fault was probably Mesozoic and predates the intrusion of a Late Triassic or Early Jurassic diabase dike. The fault offsets Paleozoic rock units and structures, the slate belt/Charlotte belt boundary, and an earlier east-west trending fault containing silicified breccia.

This study is part of a project initiated by workers at the University of South Carolina in 1978 to study the geology and geophysics of the area surrounding the Virgil C. Summer nuclear station near Monticello, South Carolina (Fig. 1). The station is eight kilometers north of the northernmost confirmed outcrop of the Wateree Creek fault zone. Beyond purely academic goals, there is a need to gather as much data as possible to aid in an assessment of the earthquake risk potential for such man-made structures in this area. Moreover, considerable low-level induced seismic activity is associated with an adjacent pump-storage reservoir (Monticello Reservoir) [Talwani, 1979; Secor, 1980], and the Wateree Creek fault zone may be one of the important geologic boundary constraints influencing this activity.

This study was geared toward understanding the faulting using data gathered from six avenues of research. The project goals were to study the evidence for faulting and determine if a fault actually existed, to analyze the nature and displacement of the faulting, and to bracket the age, if possible, using available constraints. The first of the six avenues of research was an analysis of the regional geologic data gathered by detailed field mapping. This provided the prima facie evidence for faulting including the offsets of geologic contacts and the existence of deformed structures plus certain geologic features (such as diabase dikes) which could be studied in greater detail to consider their relationships to the fault. Some of this information could then be used to approximate the net-slip on the fault. The next step was a detailed study of a roadcut exposure of the fault zone, referred to as the Spring Hill roadcut. This roadcut contains all the elements available for establishing the maximum age for the faulting. A structural study of the rotation of a pre-existing L_{1} intersection lineation by drag associated with the Wateree Creek fault zone was carried out in order to establish a net-slip direction independent of that found in the study of the regional relationships. Four holes were drilled within the fault zone to observe the extent of faulting and drag folding, to determine the dip direction of the fault surfaces within the zone, and to determine if zeolite minerals suitable for age dating occurred in the breccia zone. Detailed magnetometer profiles were used to determine outcrop patterns of a Jurassic(?) diabase dike in a region where it crosses the fault zone to determine the age relations. Finally, backhoe trenching was undertaken to determine if magnetic peaks actually represented diabase and to permit study of fresh diabase in key locations in or near the fault zone.

AREAL GEOLOGY

Much of the information concerning the age and net slip of the Wateree Creek fault zone is derived from the apparent displacement and deformation of various pre-existing structures and rock bodies by the fault zone. In order to present this evidence, some discussion of the areal geology is necessary. The reader is referred to the following sources for additional documentation of the regional geological information summarized below: Overstreet and Bell [1965]; Secor and Wagener [1968]; Secor and Snoke [1978]; Secor [1980]; Snoke and others [1980].

The boundary between the Carolina slate belt and the Charlotte belt trends N.75°E. across the northern part of the Chapin quadrangle (Fig. 2). In this region, the oldest part of the stratigraphic section outcrops in the Charlotte belt. In South Carolina the Charlotte belt may be distinguished from the Carolina slate belt by its higher grade of regional metamorphism (epidote amphibolite and amphibolite, as opposed to greenschist) and by the presence of stratiform sheet intrusions of granitic orthogneiss up to 1 km in thickness (Єggn, Fig. 2).

The stratigraphic sequence is a thick (~10 km) section of metasedimentary and metavolcanic rocks that are thought to have been deposited in a late Precambrian and Cambrian volcanic arc [Butler and Ragland, 1969b; Hills and Butler, 1969; Fullagar, 1971; Glover and Sinha, 1973; St. Jean, 1973; Butler and Fullagar, 1975; Black and Fullagar, 1976; Seiders and Wright, 1977; Black, 1978; Carpenter and others, 1978; Whitney and others, 1978]. The oldest stratigraphic units are sequences of amphibolite (Єa) and biotite schist and paragneiss (Єfgn) which occur in the Charlotte belt in the northern part of the Chapin quadrangle. To the south, in the Carolina slate belt, the following successively younger stratigraphic units outcrop in order from north to south: felsic metavolcanic rock and quartzite (Єtq); intermediate to felsic metavolcanic tuff breccia (Єtb); and metamudstone and metawacke (Єmw). The Єmw unit contains lenticular layers of amygdaloidal andesitic greenstone (Єg) at or near its base. The distribution of the above stratigraphic units on the geologic map (Plate 1, and Fig. 2) is primarily related to the cumulative effects of two strong deformational episodes (D_1, D_2) which affected the area during Paleozoic time.

The first deformation (D_1) was an episode of regional metamorphism and passive folding that resulted in the formation of a major F_1 synclinorium (the Chapin synclinorium), the axis of which passes through the central part of the Chapin quadrangle trending N.75°E. (Fig. 2). The D_1 deformation produced a prominent metamorphic foliation (S_1) which is the dominant fabric element in both the slate and Charlotte belts and which approximately parallels the axial surface of the Chapin synclinorium. In many places the S_1 foliation contains a prominent elongation lineation (L_1) and/or an intersection lineation between compositional layering and S_1 (L_{0x1}). L_1 and L_{0x1} are parallel to each other (Fig. 5a, 5b), and in the region of the Chapin synclinorium, they plunge gently to the northeast parallel to the axis of the synclinorium. The timing of the D_1 deformation is known only within broad limits. It must postdate the youngest stratigraphic unit which carries the D_1 fabric (~520 m.y. [Hills and Butler, 1969], and it must predate the emplacement of a 415-385 m.y. series of granitic plutons in the Charlotte belt which do not carry the D_1 fabric [Fullagar, 1971; Fullagar and others, 1971; Butler and Fullagar, 1978; Fullagar, 1981].

In middle to late Paleozoic time the rocks in the central and northern parts of the Chapin quadrangle were refolded by a series of mesoscopic and macroscopic flexural folds (D_2, F_2) (Fig. 5c). The style and axial surface inclination of these later folds is variable, and more than one distinct sub-episode may be present [Bourland and Farrar, 1980]. In most places the axes of F_2 folds are parallel to L_{0x1} and L_1 so that F_2 folding did not result in the dispersion or reorientation of L_{0x1} and L_1.

Two distinct sets of steeply dipping to vertical faults formed in the area in latest Paleozoic and/or Mesozoic time. The oldest set trends east to northeast and the fault zones were extensively silicified during movement. These fault zones are characterized by silicified breccia and by the presence of numerous irregular gash veins partly infilled with comb quartz. The direction and magnitude of the displacement associated with the east to northeast trending faults is unknown, but the displacement is generally too small to produce measurable offsets of major stratigraphic units at the 1:24,000 scale. The youngest set of faults is oriented approximately north-south and is characterized by intense calcite veining and by dip-slip displacements up to 1700 meters. The Wateree Creek fault zone belongs to this youngest group, and in the central part of the Chapin quadrangle the Wateree Creek fault zone clearly offsets stratigraphic units, the axis of the Chapin synclinorium, and a prominent east trending silicified breccia zone (Plate 1, and Fig. 2). A diabase dike of probable Late Triassic or Early Jurassic age contains a dextral en echelon offset in the region of the Wateree Creek fault zone in the south-central part of the Chapin quadrangle. However our investigations in this region indicate that this offset is the result of a primary irregularity in the shape of the dike and that the dike was emplaced after most and perhaps all of the displacement had occurred on the Wateree Creek fault zone.

The geological history of the Wateree Creek fault zone is of considerable importance because of its proximity to Lake Monticello and the Virgil C. Summer nuclear station. In the following section we present the results of field investigations concerning the geological character, age, and displacement of the Wateree Creek fault zone.

EVIDENCE FOR THE WATEREE CREEK FAULT ZONE

Regional Relations

Several aspects of the regional geology/geophysics indicate that a north trending fault occurs along Wateree Creek. In the south central part of the Chapin quadrangle, a very prominent east-trending magnetic anomaly, coinciding with the axis of the Chapin synclinorium, is abruptly terminated at Wateree Creek (Fig. 4). In this same region the stratigraphic contacts between the metamudstone and metawacke unit (Ꞓmw) and the intermediate to felsic metavolcanic tuff breccia sequence (Ꞓtb), on the flanks of the Chapin synclinorium, are clearly offset in a manner suggesting predominantly dip-slip displacement with the eastern block down relative to the western block (Plate 1, and Fig. 2). Projection of the traces of the stratigraphic contact between Ꞓmw and Ꞓtb in the limbs of the Chapin synclinorium onto the plane of the Wateree Creek fault zone (Fig. 8) also indicates predominantly dip-slip displacement with a net slip of approximately 1700 m. In the central part of the Chapin quadrangle a prominent east-trending silicified breccia zone is similarly offset (Plate 1, Fig. 2). Throughout most of the Chapin quadrangle the mesoscopic rock fabric contains a prominent subhorizontal lineation (L_{0x1} and/or L_i). At several places along Wateree Creek this lineation has an anomalous steeply plunging orientation that is interpreted to be a consequence of drag in and adjacent to the Wateree Creek fault zone. Finally, at several locations along the zone, non-silicified fault breccia occurs, and in the vicinity of Spring Hill steeply dipping to vertical north trending faults occur in outcrop. The above observations suggest that the Wateree Creek fault zone formed late in the tectonic history of the region under conditions of relatively low temperature and confining pressure such

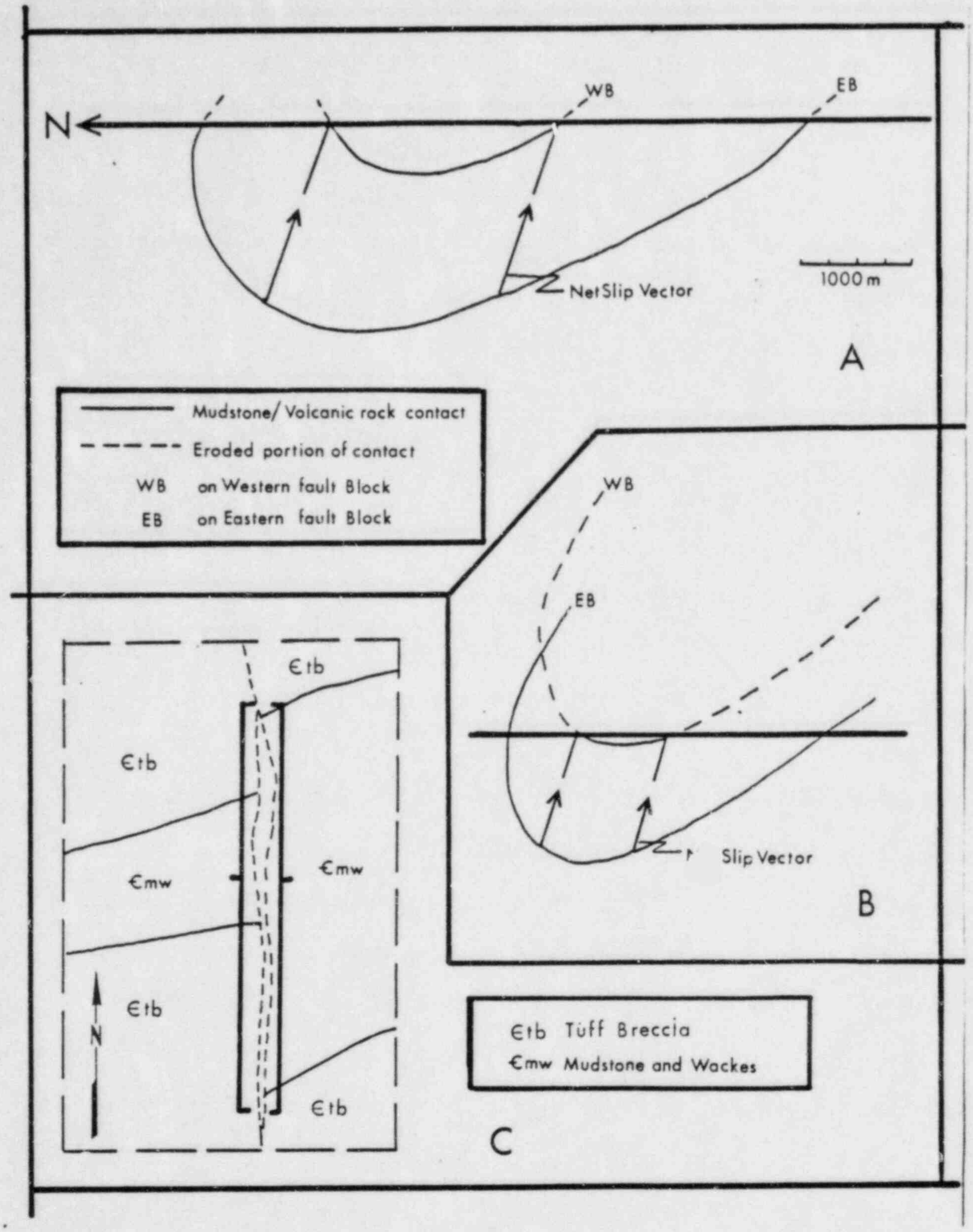

Figure 8. Diagram illustrating the projection of the contact between Єmw and Єtb in the axial zone of the Delmar synclinorium onto the plane of the Wateree Creek fault zone.

that widespread brittle deformation occurred. These conclusions are further substantiated by observations made in a large roadcut located about two kilometers northwest of Spring Hill in the central part of the Chapin quadrangle (Fig. 2, and Plate 1).

The Spring Hill Roadcut

The Spring Hill roadcut is the best exposure for viewing the characteristics of the rocks in and adjacent to the Wateree Creek fault zone, and observations made here have played a central role in the formulation of our conclusions about the zone. The saprolite exposed in the Spring Hill roadcut is thoroughly weathered and very friable. The quality of this exposure has degraded substantially during the past 18 months, and in order to permanently document the evidence for the Wateree Creek fault zone, a detailed geological sketch map and cross sections have been prepared for this important locality (Fig. 9). The cross sections of the northwest and southeast faces of the roadcut were made in the field from an uncontrolled photo-mosaic. The geological relationships shown on the road surface are reconstructed from observations made in the faces of the roadcut. The roadway is paved and the actual geologic relationships in the roadway have not been observed.

The southwestern end of the Spring Hill roadcut is interpreted to be west of the Wateree Creek fault zone. A gently dipping intrusive contact (A, Fig. 9) between massive diorite and spotted hornfels occurs at the west end of the cut. The precursor to the spotted hornfels is interpreted to have been interlayered mudstone and metavolcanic rock from near the top of the Ꞓtb unit (Fig. 2) in the north limb of the Chapin synclinorium. Relict lapilli and relict L_{0x1} and L_1 lineations ($\sim$ 12°N.75°E.) locally can be recognized in the spotted hornfels. The contact metamorphism is interpreted

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☒ FILMED ON APERTURE CARD NO 8210190457-01 to have been overprinted on deformed and regionally metamorphosed strata during emplacement of a small stock of massive diorite in post D_1 time. The orientations of D_1 fabric elements in the southwestern end of the roadcut is similar to the orientations observed elsewhere in the Chapin synclinorium and hence the southwestern end of the cut is interpreted to be outside the region affected by drag associated with the Wateree Creek fault zone.

The rocks in the northeastern two-thirds of the Spring Hill roadcut are broken by two distinct groups of faults. The oldest group occur in a 5-10 meter thick zone, oriented ~N.70°W.65°SW., and characterized by intense silicification and brecciation (B, C, Fig. 9). Numerous irregularly oriented extensional veins, partly infilled with comb quartz, occur adjacent to the silicified fault zone on the southwest side in the diorite. The silicified fault breccia at locality B (Fig. 9) is interpreted to be the easternmost end of a major silicified fault zone that extends at least 5 km to the west (Plate 1, and Fig. 2). The youngest group of faults in the Spring Hill roadcut (D, E, F) oriented ~N.3°E.78°NW., are part of the Wateree Creek fault zone. These north trending faults clearly displace all of the bedrock map units as well as the west trending silicified fault zone, but they do not displace a thin irregular layer of surficial colluvium of unknown age found in the southeast face of the roadcut (G). The roadcut is divided into four blocks by the faults of the Wateree Creek fault zone (see insert, Fig. 9). Block 2 displays many of the same rock types and structures as block 1, however, a thin felsic dike in the diorite (H, I) and the silicified fault zone (B, C) display left separations of 5 and 30 meters, respectively, along fault D. Blocks 3 and 4 contain metamudstone breccia and metamudstone respectively, and it is not possible to correlate specific geological features across faults

E and F. The orientations of the L_1 and L_{0x1} lineations in block 4 (~58°N.77°E) clearly differ from the regional average (14°N.78°E.) and their anomalous orientation is interpreted to be the result of rotation and/or drag within the Wateree Creek fault zone. The fault zone therefore continues beyond the northeastern end of the Spring Hill roadcut and may contain additional blocks and fault surfaces.

Determination of the Net-Slip Direction

In the Spring Hill roadcut and at several other locations along the Wateree Creek fault zone the L_1 and L_{0x1} lineations are anomalously oriented as a result of drag folding and rotation in the fault zone. When a pre-existing foliation (in this case S_1) is refolded, linear elements in the foliation plane may be dispersed along a small circle on a stereonet, the center of which coincides with the axis of secondary folding. It is assumed here that the net-slip direction is perpendicular to the axis of secondary (drag) folding in the plane of the fault. Measurements of L_1 and L_{0x1} were taken from within a circular area of radius one mile surrounding a prominent creek exposure of the Wateree Creek fault zone just to the east of the Spring Hill roadcut (Fig. 10). This data set, containing 106 lineation measurements from both within and outside the area affected by fault drag, is plotted in Figure 5d. The points fall on a portion of a small circle having an axis oriented 4°S.3°W., and assuming an average orientation of N.3°E.78°NW. for the Wateree Creek fault zone, the indicated direction of net slip is 77°N.64°W. The rotation of L_1 and L_{0x1} lineations by drag in and adjacent to the Wateree Creek fault zone therefore indicates that the fault displacement is predominantly dip slip, with a minor component of left lateral slip, a result in agreement with the displacement inferred from the apparent offset of the axis of the Chapin synclinorium (Fig. 8).

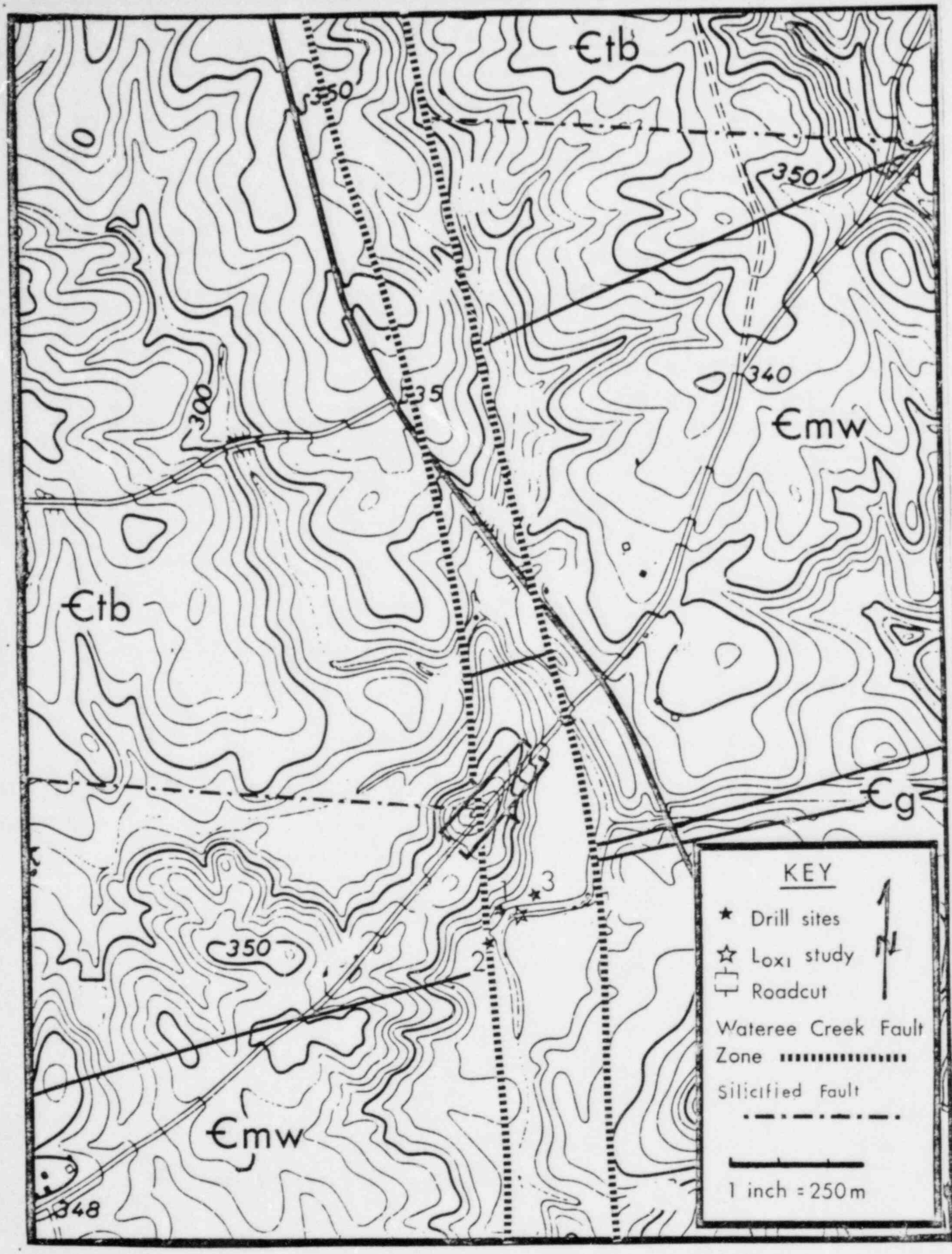

Figure 10. Location map for the Spring Hill roadcut and vicinity.

Results of Drilling Investigations

All of the natural or roadcut exposures of the Wateree Creek fault zone have undergone some degree of chemical weathering, and the thoroughly brecciated rock along and adjacent to fault surfaces is particularly susceptible to alteration. In order to obtain fresh samples of cataclastic rocks for petrographic study, and in hopes of finding datable secondary minerals (such as zeolites) associated with the faulting, it was decided to drill four shallow core holes into the fault zone. Three of these holes were located along the projected trace of the fault zone near Wateree Creek, about 0.3 km south of the Spring Hill roadcut (Fig. 10). The fourth hole was located adjacent to an outcrop of partly weathered fault breccia about 3.5 km south of the Spring Hill roadcut (Fig. 11).

Mudstone, brecciated to varying degrees, was encountered in all of the drill holes at location 1, 2, and 3 near the Spring Hill roadcut (Fig. 10). Most of the rock encountered in holes 1 and 2 was relatively intact mudstone, although thin brecciated zones were encountered at several levels. The rock in hole 3 was much more intensely brecciated. The plunge of the L_1 and L_{0x1} lineations varies between 25° and 80° in holes 1-3. No systematic variation in the plunge of the lineations with depth could be detected in the cores (Fig. 12). From X-ray diffraction studies of whole-rock powder and from examination of thin sections, the mineral assemblage in both intact and brecciated rock was determined to be: quartz-muscovite-chlorite-calcite-dolomite. Several episodes of veining and brecciation can be inferred from mesoscopic inspection of the core. The vein fillings are predominantly carbonate with a trace of quartz. No zeolite minerals were recognized. In thin section, the carbonate appears to have recrystallized following the last episode of brecciation. Aside from some twinning of the carbonate, no

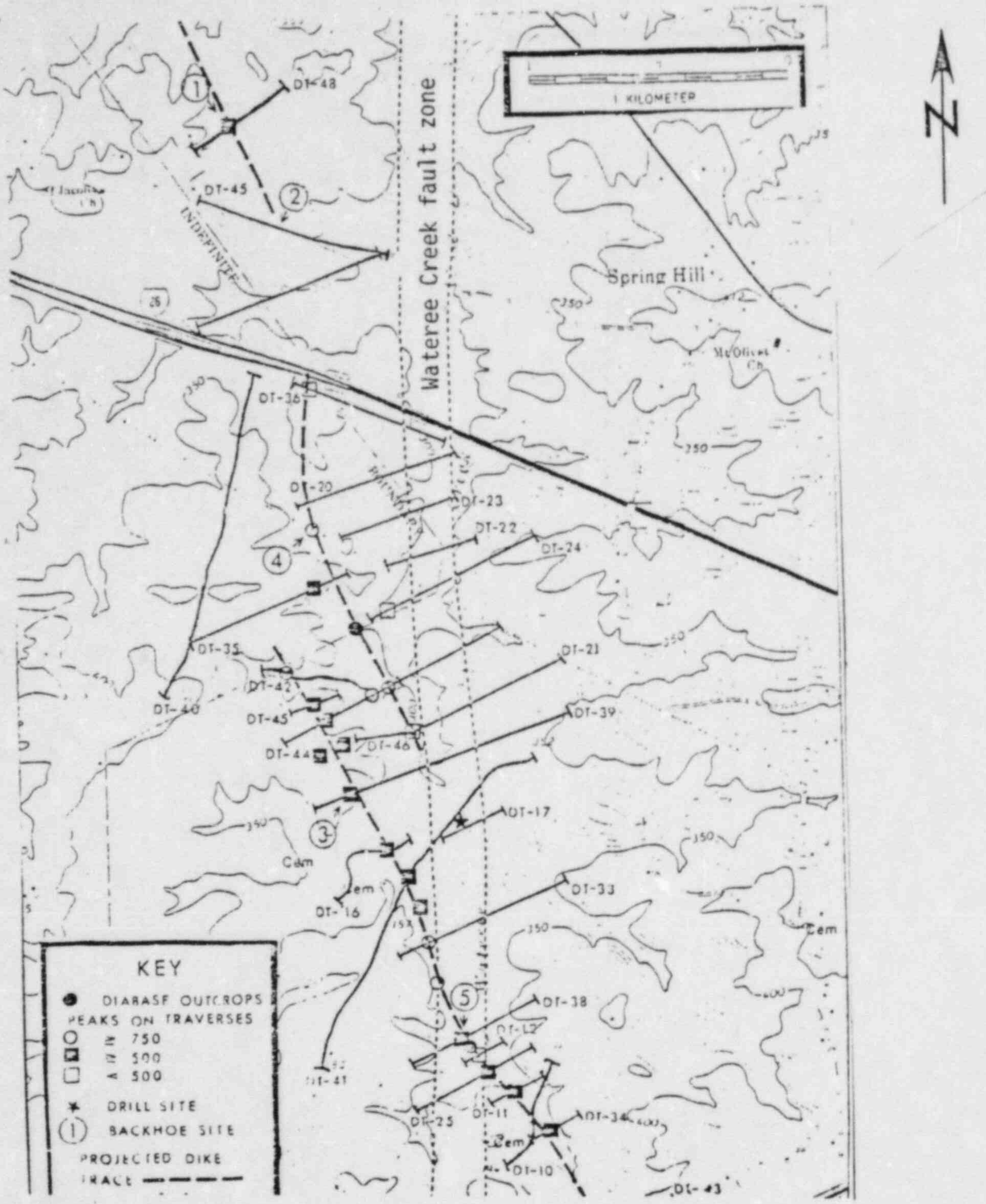

Figure 11. Geologic map showing the configuration of a diabase dike in the vicinity of the Wateree Creek fault zone in the south-central part of the Chapin quadrangle.

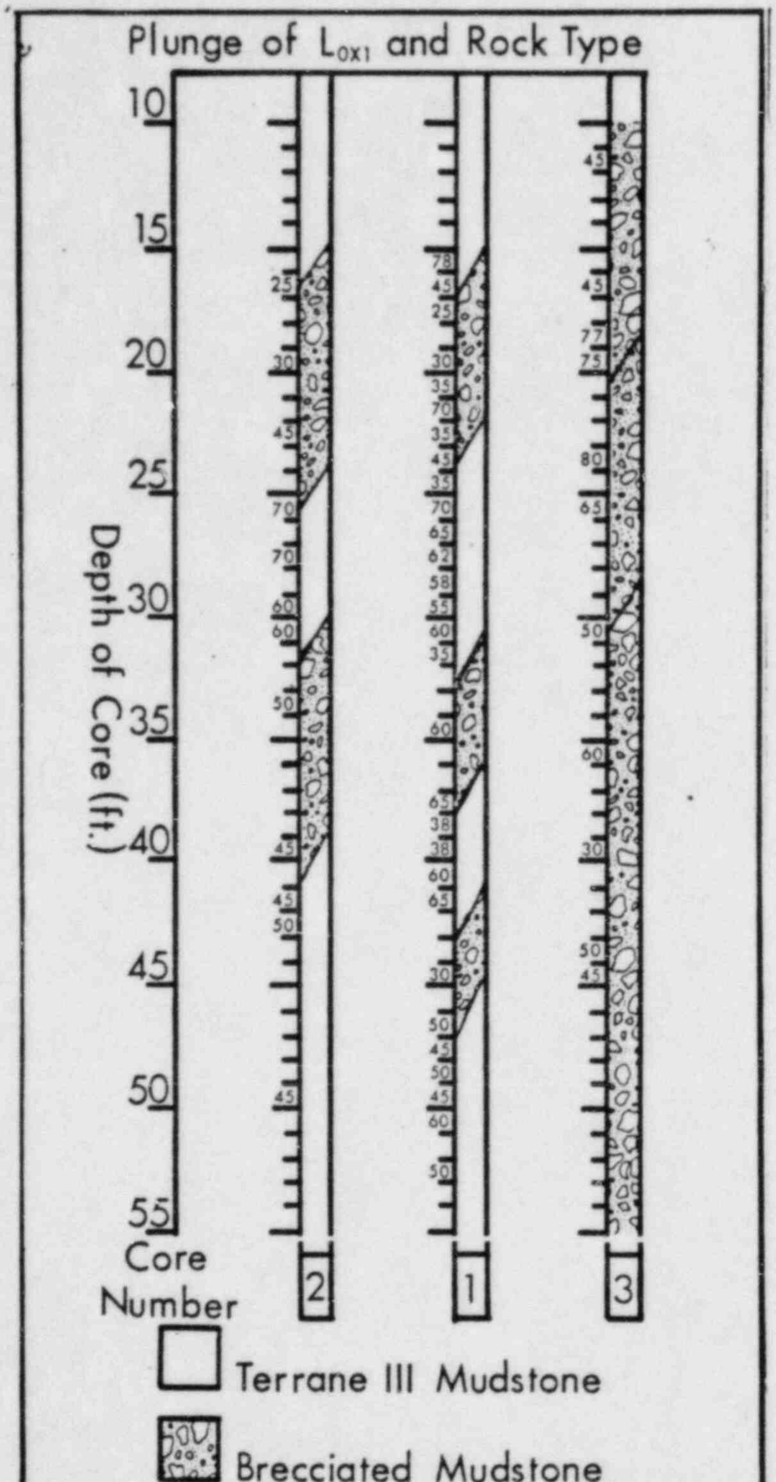

Figure 12. Core logs for drill holes 1, 2 and 3, from the Wateree Creek fault zone near the Spring Hill roadcut (Fig. 10).

evidence for post recrystallization cataclasis or ductile deformation was observed. At several locations in the cores, carbonate veins are clearly offset by small normal faults following the S_0 compositional layering. This displacement sense seems compatible with the slip that would be expected to result from down to the east movement along the Wateree Creek fault zone.

Hole 4 was drilled into brecciated metavolcanic rock of intermediate composition along the west side of the Wateree Creek fault zone in the south limb of the Chapin synclinorium (Fig. 11). The mineral assemblage here is quartz-albite-muscovite-chlorite-epidote-calcite-dolomite. All of the rock recovered from this hole down to a total depth of 64' is thoroughly brecciated and characterized by intense calcite veining. As in the first three holes, there seems to have been multiple episodes of veining and brecciation. In thin section, the carbonate seems to have recrystallized following the last episode of cataclasis and strain. However, the brecciated rock in hole 4 is relatively weak and friable. Even at the bottom of the hole, at a depth of 62' and more than 40' below the base of the weathered zone, the core recovery rate was only about 50% of the amount drilled.

The above studies of the petrological character of the cataclastic rocks in the Wateree Creek fault zone suggest that the faulting occurred under conditions of relatively low temperature and confining pressure such that carbonates were the only mineral components that were sufficiently mobile to contribute appreciably to vein fillings.

Interaction of a Diabase Dike with the Wateree Creek Fault Zone

Some considerable antiquity for the Wateree Creek fault zone is suggested by the lack of a fault scarp and the fact that the faults do not displace a layer of surficial colluvium in the Spring Hill roadcut. Regional geological studies have indicated that a major diabase dike experiences a dextral offset in the vicinity of the Wateree Creek fault zone in the south-central part of the Chapin quadrangle [Secor, 1980], (also see Plate 1 and Fig. 2). In hope of more precisely determining the time of faulting, we have undertaken detailed geological and geophysical studies in the region of apparent offset of the diabase dike.

The diabase dike is very susceptible to chemical weathering, and natural outcrops are known from only a few locations (Fig. 11). However, previous studies [Secor, 1980] had indicated that most diabase dikes in this region of the Carolina slate belt are characterized by strong positive magnetic anomalies of magnitude 100-1500 gammas. Therefore, in order to precisely map the configuration of the diabase in the vicinity of the Wateree Creek fault zone, a series of closely spaced detailed surface magnetometer profiles were measured. The locations of these profiles and the configuration of the diabase dikes inferred from the measurements are shown in Figure 11. In order to be absolutely certain that the magnetic anomalies were related to diabase dikes, several trenches were excavated at critical locations (Fig. 11). The results at trench #1 were indeterminate because surficial colluvium extended to the deepest levels of the excavation. Only mudstone saprolite was recovered from trench #2. The amplitude of the magnetic anomaly at this locality is only 150 gammas, and the dike may be very thin or may not extend completely to the surface. Hornfels, presumably resulting from contact metamorphism of the diabase was encountered in trench #3. Diabase saprolite and residual boulders of diabase were encountered in trenches #4 and #5.

Trench site #5 is located at a particularly important place where the diabase dike from the east block appears to penetrate across the fault zone and into the west block. Three separate holes were actually excavated at trench site #5. The first was located ten meters west of Wateree Creek on strike with a creek outcrop of diabase saprolite interpreted as being in the east block. Diabase saprolite was encountered in the hole, and fresh residual boulders of diabase were recovered from a depth of six meters. The diabase saprolite contained thin quartzo-feldspathic veins similar to north trending vertically oriented veins observed in the adjacent creek outcrop of diabase saprolite. Some slickensided surfaces were observed in the diabase saprolite removed from the excavation, however these are interpreted as weathering phenomena or as excavation related deformation structures, because no deformation structures were observed in the fresh diabase recovered from the trench. Two additional holes were excavated along the projected strike of the diabase dike about 100 meters northwest of Wateree Creek. Diabase saprolite and residual boulders of hornfels were recovered from these holes. The excavations at trench site #5 clearly indicate that the diabase dike from the east block penetrates well into the Wateree Creek fault zone, and the continuity of the associated magnetic anomaly on to the northwest indicates that the dike continues for more than 1 km into the west block.

Although the diabase dike contains a dextral en echelon offset near the Wateree Creek fault zone, the detailed geological and geophysical studies described above demonstrate that this offset actually occurs west of the fault zone, and that the dike was emplaced after most or all of the displacement had occurred along the fault. The geometrical irregularity of the diabase dike in the region immediately west of the Wateree Creek fault zone is here interpreted to be the result of a discontinuity in the stress field caused by the fault, and not a direct result of the fault displacement. The evidence therefore indicates that the Wateree Creek fault zone was already in existence when the diabase dike was emplaced. At present there is no conclusive evidence indicating that slip occurred along the fault after the emplacement of the diabase. If such slip did occur, the resulting horizontal separation of the diabase must be less than a few tens of meters.

SUMMARY

The location and character of the Wateree Creek fault zone is established from the following evidence: 1) offset of stratigraphic contacts and pre-existing structural features, 2) abrupt termination of a prominent aeromagnetic anomaly, 3) the occurrence of fault breccia at several locations along the zone, 4) drag and rotation of pre-existing fabric elements within the zone, 5) observation of three of the component faults in the zone in the Spring Hill roadcut. Examination of cataclastic rocks from four shallow holes drilled into the Wateree Creek fault zone suggest that the brittle faulting occurred at relatively low temperature and confining pressure such that carbonate minerals were the only components sufficiently mobile to contribute appreciably to gash vein fillings. Study of the rotation of pre-existing rock fabric elements, as well as the offset of the axis of the Chapin synclinorium indicates that the 1700 m displacement is predominantly reverse dip-slip (down to the east), with a minor component of left-lateral slip.

The youngest geological feature that is clearly offset by the Wateree Creek fault zone is an east trending silicified breccia zone. Similar appearing silicified breccia zones have been described from many places in the Piedmont [Conley and Drummond, 1965; Overstreet and Bell, 1965a; Secor and Wagener, 1968; Snipes and others, 1979; Odom and Hatcher, 1980], but their absolute age is uncertain. East trending silicified breccia zones clearly

postdate Carboniferous deformation and regional metamorphism in the Kiokee belt of South Carolina [Secor and Snoke, 1978]. Silicified breccia zones are associated with some of the faults bordering Mesozoic grabens in the Piedmont, however some of the border faults are thought to be reactivated Paleozoic faults [Butler and Dunn, 1968; Glover and others, 1980], and it is uncertain whether the silicified breccias are related to late Paleozoic or Mesozoic movement. Snipes and others [1979] have described a silicified breccia zone in northwestern South Carolina which clearly offsets a Mesozoic diabase dike. Based on the above considerations, the time of earliest movement on the Wateree Creek fault zone is certainly post Carboniferous and probably post early Mesozoic.

The oldest geological feature that clearly cuts the Wateree Creek fault zone is a northwest trending diabase dike. This dike is similar to many others that have been observed in this region and throughout the Piedmont province. These diabase dikes are difficult to date radiometrically because they contain excess argon [Dooley and Wampler, 1977]. They are commonly considered to be Upper Triassic and/or Lower Jurassic based on their paleomagnetic pole position [deBoer, 1967; Smith and Noltimier, 1979; Sutter and Smith, 1979; Dooley and Smith, in press].

The geological evidence therefore indicates that the main period of movement along the Wateree Creek fault zone was post-Carboniferous and pre-Jurassic. Although we cannot completely rule out the possibility that a limited amount of more recent movement has occurred, there is, at present, no evidence indicating such movement.

CHAPTER III

GEOLOGY OF THE LITTLE MOUNTAIN AND CHAPIN QUADRANGLES, SOUTH CAROLINA: A STUDY OF THE STRATIGRAPHIC RELATIONSHIP BETWEEN THE CAROLINA SLATE BELT AND THE CHARLOTTE BELT

ABSTRACT

Located about 50 kilometers northwest of Columbia, South Carolina, the Little Mountain and Chapin quadrangles straddle the boundary between the Charlotte belt and the Carolina slate belt. Field mapping in this area has revealed that the slate belt stratigraphically overlies the Charlotte belt. Throughout the entire study area the Charlotte and slate belts are separated by a large tabular intrusion, the Little Mountain pluton, which cuts the study area approximately in half striking about N.70°E. South of the intrusion, within the slate belt portion of the study area, outcrop distribution is controlled by a major F_1 synclinorium, the Chapin synclinorium, which extends across the entire southern portion of the study area trending N.75°E. and plunging to the northeast at about 11°. This structure is offset by two north-south faults, the Wateree Creek and the Summers Branch faults, which also offset the Charlotte belt - slate belt boundary, the Little Mountain pluton, and units within the Charlotte belt portion of the study area.

Offsets of stratigraphic contacts on both limbs of the Chapin synclinorium indicate that both the Wateree Creek and the Summers Branch faults are dip-slip faults. The Little Mountain pluton and several Charlotte belt units north of the intrusion are offset in the same direction as the slate belt units on the northern limb of the Chapin synclinorium. For that reason the Little Mountain pluton is considered to be concordant with bedding (S_0). Additionally, this indicates that the pluton and the offset Charlotte belt

units north of it stratigraphically underlie the slate belt units which comprise the Chapin synclinorium.

INTRODUCTION

The Little Mountain and Chapin 7 1/2 minute quadrangles, located about fifty kilometers northwest of Columbia, South Carolina, straddle the boundary of the Carolina slate belt and the Charlotte belt. Because of its location relative to this major boundary, the area provides an excellent opportunity to study the relationships between these belts. Hopefully this study, as part of an ongoing systematic effort to map this part of the Appalachian Piedmont in detail, can contribute to a better understanding of the Piedmont province of the southern Appalachians. Additionally, these quadrangles are adjacent to Monticello Reservoir, South Carolina, which is one of the best documented examples of reservoir induced seismicity in the United States [Duc and others, 1978; Talwani and others, 1978; Talwani, 1979; Talwani and others, 1980]. It is hoped that this study and additional field mapping north of the study area will provide a firm geologic base for interpretation of the large quantity of geophysical data which has been amassed in the induced seismicity study.

The purpose of this study is to delineate and describe the lithologic units within the study area, determine structural and stratigraphic relationships between and within these units and consider the nature of the Charlotte belt - slate belt boundary. The Little Mountain quadrangle was mapped by Larry Peck and the Chapin quadrangle was mapped by David Simpson. Field mapping in this area consisted mainly of traversing stream beds. Other outcrops were found along dirt roads, railroad cuts, roadcuts, and along the shores of Lake Murray, but generally exposure in the area is poor. In addition to field mapping, several core holes drilled in the Chapin quadrangle provided information on a major north-south fault zone, the Wateree Creek fault zone. Also, information was obtained from rock staining and standard petrographic studies.

REGIONAL GEOLOGY

The southern Appalachian Piedmont has been subdivided into several northeast trending belts on the basis of unique lithologic, structural, and/or metamorphic characteristics [King, 1955] (Figure 13). The Little Mountain - Chapin area straddles the boundary between two of these subdivisions, the Charlotte belt and the Carolina slate belt.

The Charlotte Belt

The Charlotte belt is a belt of medium to high grade metamorphic rocks extending from North Carolina to Georgia. The lithologies of this belt are predominantly intrusive, but amphibolites, hornblende gneisses, biotite gneisses and schists also occur and are considered to have been derived from sedimentary, pyroclastic and volcanic protoliths. These country rocks have been affected by several generations of plutonism. The oldest intrusions range in age between 705 and 520 m.y. [Hills and Butler, 1969; Fullagar, 1971] and generally carry a metamorphic overprint. Several intrusions of this generation have been interpreted as epizonal intrusions genetically related to the metavolcanic rocks of the Charlotte and slate belts [Fullagar, 1971; Whitney and others, 1978; Weisenfluh and Snoke, 1978]. The second generation of intrusions, radiometrically dated at 415 to 385 m.y., are considered to be late kinematic [Fullagar, 1971], and

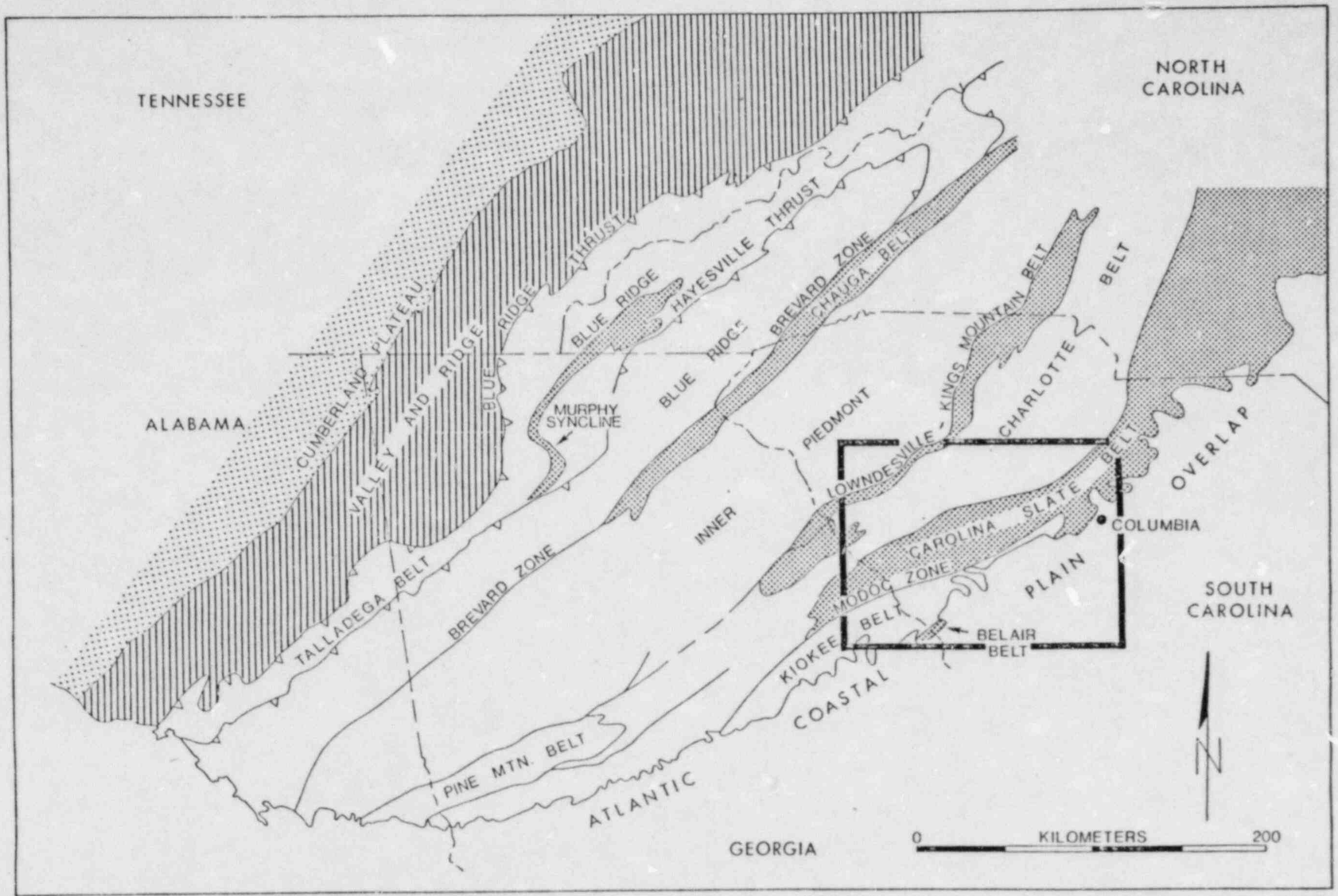

Figure 13. Map showing major geologic subdivisions of the southern Appalachians (modified from Williams [1978]). Box encloses area shown in Figure 14.

the third generation of plutons, emplaced between 325 and 265 m.y., are post kinematic. They do not carry a metamorphic fabric and resulted in contact metamorphism of the rocks which they intrude [Fullagar and Butler, 1979]. These plutons are probably related to a major Hercynian deformational event which resulted in penetrative amphibolite facies metamorphism in the Kiokee and Raleigh belts and small scale F_2 folding [Secor and Snoke, 1978] in the slate belt. In addition to these three periods of plutonism the Charlotte belt has been intruded by many thin mafic dikes which at some locations compose 50-75% of the rock occurring as "mafic dike swarms" [Overstreet and Bell, 1965]. A wide age range can be attributed to these through various cross-cutting relationships with rocks of the different major intrusive episodes, textural and metamorphic characteristics. The final period of igneous activity in both the Charlotte and slate belts was the emplacement of Upper Triassic and/or Lower Jurassic diabase dikes [Dooley and Smith, in press].

The Carolina Slate Belt

To the southeast of the Charlotte belt is the Carolina slate belt, a northeast trending zone of low to medium grade metamorphic rocks extending about 650 kilometers from central Virginia through the Carolinas into eastern Georgia. It is flanked on the northwest by medium to high grade metamorphic rocks of the Charlotte belt while to the southeast it disappears under Cretaceous and Tertiary age Coastal Plain sediments except where it is bounded by medium grade metamorphic rocks of the Kiokee belt in Georgia and southern South Carolina and the Raleigh belt of North Carolina and Virginia (Fig. 13). The slate belt is a thick sequence of metavolcanic and metasedimentary rocks which have been locally intruded by igneous rocks of varying age and composition.

Two major lithologic sequences are widely distributed throughout the slate belt. The older sequence, called the Uwharrie Formation [Conley and Bain, 1965; Stromquist and Sundelius, 1969] in North Carolina, the Persimmon Fork and Wildhorse Branch Formations [Secor and Wagener, 1968] and terranes II and IV [Secor and Snoke, 1978] in South Carolina, and the Lincolnton metadacite and felsic pyroclastic sequence [Carpenter, 1976; Whitney and others, 1978] in Georgia, consists mainly of intermediate to felsic metavolcanic rocks. The younger sequence, on the other hand, consists mostly of metaclastic rocks with some thin layers of metatuffs and metabasalts. It is called the Albemarle Group [Conley and Bain, 1965; Stromquist and Sundelius, 1969] in North Carolina, the Richtex Formation [Secor and Wagener, 1968] and terranes I and III [Secor and Snoke, 1978] in South Carolina and the upper sedimentary sequence [Carpenter, 1976; Whitney and others, 1978] in Georgia. The distribution of these units within western South Carolina, including the study area, is shown in Figure 14. These sequences have not been unequivocally correlated by complete detailed mapping, but the equivalence is widely accepted even though the structural and stratigraphic relationships within the units are controversial [see Secor and Wagener, 1968; Daniels, 1974; and Costello and others, 1981].

The Carolina slate belt is generally interpreted to have been deposited in a magmatic arc environment. Whether the arc formed on oceanic crust [Whitney and others, 1978; Black, 1978] or on continental crust [Butler and Ragland, 1969; Hatcher, 1972; Glover and others, 1978] is still a matter of contention, however. Radiometric dating of slate belt metavolcanic rocks has indicated that the arc was active during the late Precambrian and early Cambrian [Fullagar, 1971; Butler and Fullagar,

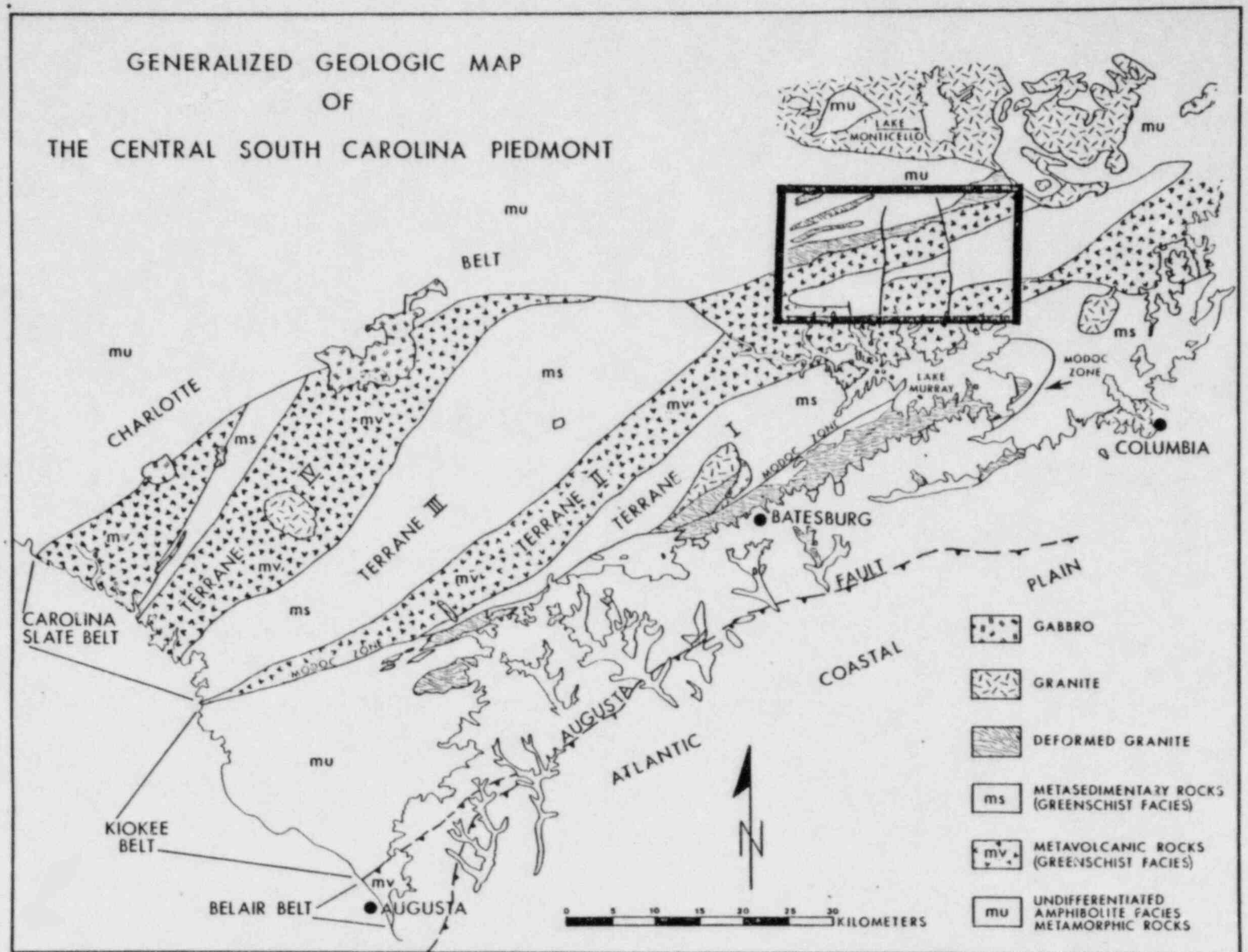

Figure 14. Geologic map of the western Carolina slate belt of South Carolina (map modified from Overstreet and Bell [1965a]; Carpenter [1976]; Brown [1971]; Pirkle [1977]; Pirkle [1978]). Box encloses the Chapin and Little Mountain quadrangles (see also Fig. 2).

1975; Black, 1978]. Fossil evidence supports a Cambrian age based on trilobites found in the slate belt of North Carolina [St. Jean, 1973] and South Carolina [Samson and others, 1982].

Regional Deformation

Both the Charlotte and slate belts have undergone several episodes of deformation. Bourland and Farrar [1980] reported evidence for six distinct deformational events accompanying two major thermal events in the Charlotte and slate belts around the Winnsboro pluton, South Carolina. The oldest deformational event in the slate belt, the Virgilina Deformation, was a late Precambrian or early Cambrian period of folding and faulting. This event affected only the oldest, northernmost, portion of the slate belt in Virginia and North Carolina [Glover and Sinha, 1973; Black and Fullagar, 1976], the southern portion being too young to have been affected by it.

A later event was the first and the strongest deformational event (D_1) to affect the Charlotte and slate belts in South Carolina. It accompanied a period of regional metamorphism being characterized in the slate belt by greenschist facies metamorphism, tight isoclinal folding and formation of penetrative slaty cleavage and in the Charlotte belt by amphibolite facies metamorphism, isoclinal folding and axial plane foliation [Secor and Snoke, 1978; Bourland and Farrar, 1980]. The timing of this event has been bracketed by radiometric dating of the prekinematic plutons and post kinematic plutons which crosscut deformational fabric, establishing a time frame of 520 to 300 m.y. [Fullagar, 1971]. The exact timing of the D_1 event, however, is quite controversial. An Acadian age has been indicated by U-Pb zircon dates in the slate belt of North Carolina [Seiders and Wright, 1977; Briggs and others, 1978]. A Taconic age has been suggested by Rb-Sr dating of metamorphic minerals in metavolcanic rocks [Black and Fullagar, 1976] and K-Ar dating of phyllites [Kish and others, 1979] in the slate belt of North Carolina. Recent radiometric dating of rocks from the undeformed Newberry Granite north of this study area which contains xenoliths carrying the S_1 foliation indicated a cooling date of 415 ± 9 m.y. [Fullagar, 1981] supporting a Taconic age for D_1.

DESCRIPTION OF THE ROCKS

Nine mappable lithologic units have been differentiated within the Little Mountain and Chapin quadrangles as shown on the geologic map of this area (Fig. 2). Seven of these units are of sedimentary or volcanic origin; the remaining two being of intrusive igneous origin. Metamorphosed rocks within the Charlotte belt and within the slate belt will be discussed separately, and post-tectonic intrusive rocks will be considered as a third group.

Charlotte Belt Units

Three Charlotte belt units have been differentiated within the study area. They include a unit of amphibolite of volcanic and/or sedimentary origin (Єa) and a unit of metasedimentary biotite schist and biotite paragneiss (Єsp). Also, granitic orthogneisses (Єggn) intrude much of the Charlotte belt portion of the study area. Mineral assemblages of samples from these units are shown in Table 1.

Amphibolite (Єa). Amphibolite is found extensively throughout the Charlotte belt portion of the study area, occurring as large lenticular sheets which are locally migmatized by granitic gneisses. Charlotte belt amphibolites have been interpreted as metamorphosed basaltic flows

Sample No.	MINERALS quartz	plagioclase	hornblende	biotite	epidote	white mica	potassium feldspar	opaque oxides	Rock Unit
265		X	X	T				T	Єa
353	X	X	X	T	X			T	Єa
288	X	X	X	X	X	X		X	Єfgn
369	X	X	X	X			X	X	Єfgn
268	X	X		X		X		X	Єggn
298	X	X		X	X	X		X	Єggn
313	X	X		T		X	X	T	Єggn
601	X	X			T	X	T	T	Єggn

X indicates presence of a mineral

T indicates presence in trace amounts

Table 1. Mineral assemblages of samples from the Charlotte belt portion of the Chapin and Little Mountain quadrangles.

[McCauley, 1961b; Overstreet and Bell, 1965a] with less mafic amphibolites being interpreted as metasedimentary rocks and metatuffs [Overstreet and Bell, 1965a]. Found within the amphibolite are tabular intrusions of orthogneisses, thin layers of biotite schist and layers of biotite paragneiss. Locally the amphibolite grades into the schist or paragneiss indicating a sedimentary or pyroclastic origin. The metalava flows within this unit may be genetically related to the amygdaloidal greenstones found in the slate belt. The large volume of suspected metalava flows present in the Charlotte belt compared to the relatively small amount in the slate belt (Fig. 2) argues against this correlation. More likely, they occupy different levels in the stratigraphic column and the reduced volume of metabasalt in the slate belt represents a waning of mafic magma generation through time.

Amphibolites within the study area are fine to medium grained rocks with a typical mineral assemblage of blue-green hornblende, plagioclase, epidote, quartz, and minor amounts of biotite and opaque oxides. The hornblende crystals are elongate and anhedral. Plagioclase occurs as anhedral crystals.

Biotite schist and biotite paragneiss (Єfgn). Like the amphibolite, the unit composed of biotite schist and biotite paragneiss outcrops extensively within the Charlotte belt portion of the study area. Within this unit are thin layers of amphibolite as well as large tabular intrusions of granitic orthogneiss. The biotite schist is most often found in association with these intrusions. Poor exposure, complex deformational history, questionable protolith interpretation, and rapid facies variations all combine to make structural and stratigraphic interpretations within the Charlotte belt difficult at best. Due to the fact that they are interfingered and interlayered this unit and the amphibolite are considered to be stratigraphically equivalent.

The biotite paragneiss and biotite schist unit consists of fine to medium grained inequigranular foliated rocks. They are predominantly quartz, plagioclase, and biotite. Additionally, they may contain blue-green hornblende, potassium feldspar, muscovite, and opaque oxides in varying percentages (Table 1). There is wide mineralogical variation within this unit.

Undifferentiated granitic orthogneisses (Єggn). Two major types of granitic orthogneiss are found in the Charlotte belt portion of the study area. Rock staining has revealed one type as potassium poor while the other is potassium rich. The first type occurs almost exclusively within the largest intrusion in the study area, the Little Mountain pluton. This pluton is a large tabular intrusion cutting the study area approximately in half, trending about N.70°E. along the northern boundary of the slate belt. The length of its outcrop area is unknown, but it crosses the study area for 24 km with an average width of about 1.5 km. Due to its low potassium content this rock may be genetically related to the potassium poor metavolcanic rocks of the slate belt. If so, it is almost as old as the slate belt rocks, having intruded its own volcanic ejecta.

In the Little Mountain pluton are several small masses of granitic orthogneiss which are potassium rich. Within this large pluton the orthogneisses are not differentiated due to extremely poor exposure in that part of the study area. This second type of orthogneiss occurs most often, however, deeper in the Charlotte belt as smaller concordant tabular intrusions.

The ages of these rocks are unknown. Additionally, since no outcrop revealing a cross-cutting relationship between the two gneisses has been found, their relative ages are also uncertain. If they are the same age they could represent different phases of the same parent magma or could have resulted from two different magmas.

Except for the differences in feldspar composition, the rocks of this unit are mineralogically similar (Table 1). A typical mineral assemblage consists of quartz (55%), feldspar (33%), white mica (10%), opaque oxides (2%), and epidote (trace). Texturally, they reveal a complex deformational history, but have considerable variation between samples. The rocks vary widely in the degree of foliation visible and in grain size. Rocks in the north are generally fine to medium grained and equigranular, but are sometimes porphyritic. The rocks in the Little Mountain pluton are medium grained and almost always porphyritic.

Carolina Slate Belt Stratigraphic Units

Four stratigraphic units have been mapped in the slate belt portion of the study area. These units include: a unit composed of impure quartzite, metatuff and white mica schists (Ꞓtq); a metavolcanic debris flow sequence (Ꞓtb); an evenly laminated to massive mudstone and wacke unit (Ꞓmw); and amygdaloidal greenstone (Ꞓg). The first two units probably correlate with the Persimmon Fork Formation of Secor and Wagener [1968] and the other two probably equate to their Richtex Formation. Mineral assemblages of samples from these units are shown in Table 2.

Impure quartzite, metatuff, and white mica schist (Ꞓtq). The stratigraphically lowest slate belt unit within the study area is a unit composed of impure quartzites, metatuffs, and white mica schists. This unit extends as a ½ to 1½ km wide band across the entire study area adjacent to the southernmost Charlotte belt unit, the Little Mountain pluton (Fig. 2,

Sample No.	MINERALS	quartz	plagioclase	microcline	biotite	chlorite	white mica	opaque oxides	epidote	tourmaline	garnet	Rock Unit
147		X	X			X	X	X	X			Єmw
229		X	X			T	X	X	X			Єmw
281		X	X			X	X	T	X			Єg
400		X	X			X	X	X	X			Єg
104		X	X		X		X		X			Єtb
160		X	X				X		X			Єtb
167		X	X			X	X	X	X			Єb
169		X	X				X	T	X			Єtb
194		X	X		X	X	X	X	X			Єtb
213		X	X			X	X	X	X			Єtb
319		X	T			T	X	X	X			Єtb
4		X	X	X	X	X	X	X				Єtq
128		X	T		X		X	X	X	T	T	Єtq
306		X	X		X		T	T	X		T	Єtq
347		X	X		X	X	X		X			Єtq
354		X	X	X	X		X	T			T	Єtq

X indicates presence of a mineral

T indicates presence in trace amounts

Table 2. Mineral assemblages of samples from the slate belt portion of the Chapin and Little Mountain quadrangles.

and Plates 1, 2). The most prominent feature in this northernmost slate belt unit is the Little Mountain - Cannon Hills Monadnock, a feldspathic quartzite ridge about 7½ km in length, rising up to 60 meters above the surrounding area. Several layers of kyanite-quartzite occur within the monadnock, some of which are over 300 meters long and 30 to 60 meters wide. The protolith was probably layers of tuff which were enriched in silica by hydrothermal fluids [Espenshade and Potter, 1960] possibly resulting from emplacement of the Little Mountain pluton. The resulting altered cherty clay-rich tuff was then probably transformed into lenses of kyanite-quartzite during D_1 greenschist facies metamorphism as described by Hartley [1976] at Graves Mountain, Georgia.

In the field it is often difficult to differentiate between the quartzite and locally silica enriched metatuff. White mica schist occurs as layers interbedded with layers of quartzite in the monadnock. Rocks of this unit dip consistently to the southeast at about 45 degrees.

The metatuffs of this unit are texturally similar to those of the overlying tuff breccia unit but differ mineralogically because they contain biotite instead of, or in addition to, muscovite and chlorite found in the tuff breccia unit. In some layers within the Ꞓtq unit the micas are highly concentrated, forming layers of white mica schist and chlorite schist. Quartzites within this unit occur as medium grained equigranular mosaics generally consisting of quartz (65%), kyanite (5%), white mica (20%), opaque oxides (mostly pyrite) (5%), potassium feldspar (5%), and chlorite (trace). Locally, kyanite occurs in greater concentrations forming lenses of kyanite quartzite.

The contact between this unit and the overlying tuff breccia (Ꞓtb) unit is a gradational one. Indeed, this unit may be part of the tuff breccia sequence representing a transition between the low grade metamorphic rocks of the slate belt and the higher grade rocks of the Charlotte belt [McCauley, 1961a], or it may have been altered as a result of emplacement of the Little Mountain pluton.

Metavolcanic tuff breccia unit (6tb). Overlying the impure quartzite metatuff, and white mica schist unit is a sequence of metavolcanic tuff breccias. It extends as a 2.5 km wide band across the entire study area south of the impure quartzite, metatuff, and white mica schist unit, down the western edge of the Little Mountain quadrangle and across most of the southern boundary of the study area (see Figure 2, and Plates 1 and 2). This unit forms the limbs of a plunging major F_1 synclinorium, hereafter referred to as the Chapin synclinorium.

The northern limb of this structure is equivalent to terrane IV and the southern limb is equivalent to terrane II of Secor and Snoke [1978]. An unusual layer of metafelsic tuff containing rounded crystals of blue quartz, outcrops along the shore of Lake Murray at the center of the southern boundary of the Little Mountain quadrangle. This outcrop correlates with the same distinctive lithology in the same relative position within the sequence on the southern edge of terrane II (Fig. 14), confirming terrane II as an anticlinorium sharing a common limb with the Chapin synclinorium to its north.

Although this unit is extremely heterogeneous with rapid lithologic change both vertically and laterally, a mineral assemblage typical of this unit consists of plagioclase (50%), quartz (20%), white mica (16%), chlorite (2%), epidote (8%), and opaque oxides (4%). The matrix of rocks of this unit consists of fine grained subangular to subrounded quartz, plagioclase and opaque oxides and platy micas. Alignment of mica grains within the matrix delineates S_1 foliation which is also the orientation of quartz stringers and stringers of opaque oxides found in some samples. Relict lapilli commonly found in rocks of this unit are revealed by microscopic study to be fine grained, pancake shaped quartz-feldspathic masses differing from the matrix by their lack of micas or other minerals. They range in size from microscopic to over 10 cm in diameter, but are normally less than 15 mm in diameter. Large euhedral to anhedral quartz and feldspar grains are also found. The upper contact of this unit is gradational with metatuff breccia interbedded with metamudstone through an interval of about a hundred meters.

Evenly laminated to massive metamudstone-wacke unit (Єmw). Graded layers of metamudstone or wacke ranging in thickness from ½ to 3 meters comprise most of this unit. These are interbedded with thin bedded evenly laminated metamudstone and an occasional thin bed of meta lapilli tuff clearly showing the orientation of bedding (S_0). This unit is the youngest stratigraphic unit in the study area. It forms the core of the northeast plunging Chapin synclinorium and has an outcrop area which extends from beyond the eastern boundary of the study area across both quadrangles, pinching out just before reaching the western limit of the Little Mountain quadrangle. Convergence of stratigraphic contacts combined with structural data from S_0 measurements confirms this as a major F_1 synclinorium. This structure controls outcrop patterns throughout the entire slate belt portion of the area. The width of outcropping of this unit ranges from 6 km in the southeastern part of the Little Mountain quadrangle to about 1.2 km where a block between the Wateree Creek and Summers Branch faults has been uplifted and eroded in the western half of the Chapin quadrangle.

Rocks of this unit typically consist of a very fine grained equigranular subrounded quartz and plagioclase matrix making up about fifty percent of the rock and larger fine grained crystals of subrounded to subangular quartz and plagioclase. The matrix contains white mica and chlorite growths among the quartz and feldspar grains. Alignment of these minerals forms the S_1 foliation within this unit. Additionally, the matrix is frequently cut by quartz stringers oriented along S_1. The plagioclase crystals composing about 25% of the coarse grains are zoned and are larger than the much more abundant large quartz grains. Typical mineral assemblages for this unit consist of quartz (60%), plagioclase (20%), white mica (10%), epidote (7%), opaque oxides (2%) (mostly pyrite and limonite after pyrite), and chlorite (1%).

Amygdaloidal greenstone (Єg). Occurring within and often at the base of the metamudstone-wacke unit are layers of amygdaloidal greenstone. This unit may have originated as layers of basaltic lava flows or flow breccias [McCauley, 1961; Overstreet and Bell, 1965a] although the quartz content may indicate a less mafic protolith. The layers tend to increase in abundance and thickness toward the east. The best exposures of amygdaloidal greenstone within the study area are along Wateree Creek in the Chapin quadrangle.

Thin section study of rocks of this unit reveals a matrix consisting mainly of very fine grained chlorite, epidote, quartz, and albite crystals. Additionally, the matrix contains larger crystals of broken subhedral albite, and anhedral epidote, fibrous white mica and trace amounts of opaque oxides. The amygdule fillings consist mostly of quartz and epidote and range up to 5 mm in diameter.

Post-Metamorphic Intrusive Rocks

Two units of post-metamorphic intrusive rocks have been mapped in this area. They are: gabbroic rocks (Cgb) and Upper Triassic and/or Lower Jurassic diabase dikes (JTrd). The gabbros are considered to be related to the 325 to 265 m.y. period of plutonism due to their lack of metamorphic fabric and the presence of hornfels aureoles around them. Mineral assemblages of samples from these units are shown in Table 3.

Gabbro (Cgb). All of the gabbro intrusions in the study area are found within the metamudstone-wacke unit (Ꞓmw) in the Little Mountain quadrangle. Two small gabbro plugs intrude the southwestern corner of this area. Evidence for two other gabbroic intrusions exists in the southeastern part of the Little Mountain quadrangle. Although they have not been seen in outcrop, gabbro boulders, sometimes over one meter in diameter, occur extensively as float rock in association with hornfels also occurring as float. The float can be traced for over three kilometers trending about N.40°E. until it terminates at the Summers Branch fault. Another area of gabbroic float rock occurs in the same vicinity but can not be traced. It is therefore interpreted as a small plug.

The gabbro plugs at the western edge of the metamudstone unit have fine grained ophitic textures whereas the gabbro in the eastern part of the Little Mountain quadrangle is medium grained. Subhedral plagioclase crystals are surrounded by anhedral crystal of pyroxene with opaque oxides and some broken subhedral olivine crystals.

Diabase dikes (JTrd). All other rock units and geologic structures within the study area are cut by diabase dikes of Upper Triassic and/or Lower Jurassic age [Dooley and Smith, in press]. These dikes trend about N.20°W. with a vertical or near vertical dip. They range up to ten meters

Sample No.	MINERALS	plagioclase	opaque oxides	clinopyroxene	olivine	orthopyroxene	Rock Unit
404		X	X	X	X	X	Cgb
414		X	X	X	X		JTrd
423		X	X	X			JTrd
435		X	X	X	X		JTrd

X indicates presence of a mineral

T indicaces presence in trace amounts

Table 3. Mineral assemblages of samples from the post-tectonic intrusive rocks of the Chapin and Little Mountain quadrangles.

in thickness and several kilometers in length. The dikes are highly jointed with columnar cooling joints normal to their walls, making them susceptible to weathering. The jointing pattern breaks the rock into angular blocks whose corners are broken down as the blocks are spheroidally weathered. For this reason the dikes most often occur as angular to rounded boulders in road cuts, soil float and stream beds.

Petrographic studies of samples of diabase from the Little Mountain and Chapin quadrangles indicate typical mineral assemblages of plagioclase (61%), olivine (15%), clinopyroxene (20%), opaque oxides (4%), and biotite (trace). The rocks display ophitic to subophitic texture. Plagioclase in the diabase has a composition of about An 65, appearing as randomly oriented lath-shaped crystals. The pyroxene occurs as anhedral intercumulate crystals and the olivine appears as euhedral to subhedral fractured crystals, both of which are slightly altered along cracks and grain boundaries. Opaque oxides are found as euhedral to subhedral crystals and occasionally as small crypto-crystalline patches.

STRUCTURAL GEOLOGY

Ductile Deformational Chronology

Rocks of the Little Mountain - Chapin area reveal a history including at least two major ductile deformational episodes, the earlier and stronger of these being the early to mid Paleozoic D_1 event described elsewhere in the Charlotte and slate belts. This event accompanying greenschist facies metamorphism in the slate belt and amphibolite facies metamorphism in the Charlotte belt, is characterized by large scale isoclinal folding (F_1) of original bedding and compositional layering (S_0) and produced a metamorphic foliation (S_1) which is oriented approximately parallel to F_1 fold axial surfaces. In the slate belt portion of the study area S_1 is a slaty cleavage formed by the parallel alignment of white micas and chlorite whereas in the Charlotte belt portion it results from planar alignment of higher grade minerals. Throughout most of the study area the S_1 foliation contains a strong subhorizontal elongation lineation (L_1). Figures 5a and 15 show lower hemisphere equal-area projections of L_1 lineations measured in the slate belt and Charlotte belt portions of the study area, respectively. This lineation is expressed within the Little Mountain pluton by elongation of quartz phenocrysts and within the slate belt tuff breccia unit (Ꞓtb) by elongation of lithic lapilli clasts. Within the metamudstone-wacke unit (Ꞓmw), an intersection lineation (L_{0x1}) is formed by the intersection of S_1 foliation with bedding planes (S_0). L_{0x1}'s are shown in Figure 5b. This lineation has approximately the same orientation as L_1 in adjacent units (compare Figure 5a and Figure 5b).

The most prevalent D_1 structure within the study area is the large F_1 Chapin synclinorium which trends across the entire southern portion of both quadrangles and beyond. It is recognized by convergence of the stratigraphic contact between Ꞓmw and Ꞓdf and by folding of S_0. Poles to 79 S_0 measurements from the slate belt portion of the study area are plotted in Figure 16. These S_0 poles have a great circle distribution along a girdle having a pole oriented 4°N.78°E., approximately parallel to the L_1 and L_{0x1} lineations, and indicating that the Chapin synclinorium plunges gently to the northeast.

There is disagreement in the literature as to the precise timing of the second deformational event (D_2) to affect this area. Bourland and Farrar [1980] describe a D_2 event in the slate and Charlotte belts which closely followed D_1, occurring at or just after the thermal peak of regional metamorphism. They estimated the timing of this event as about 350 m.y.

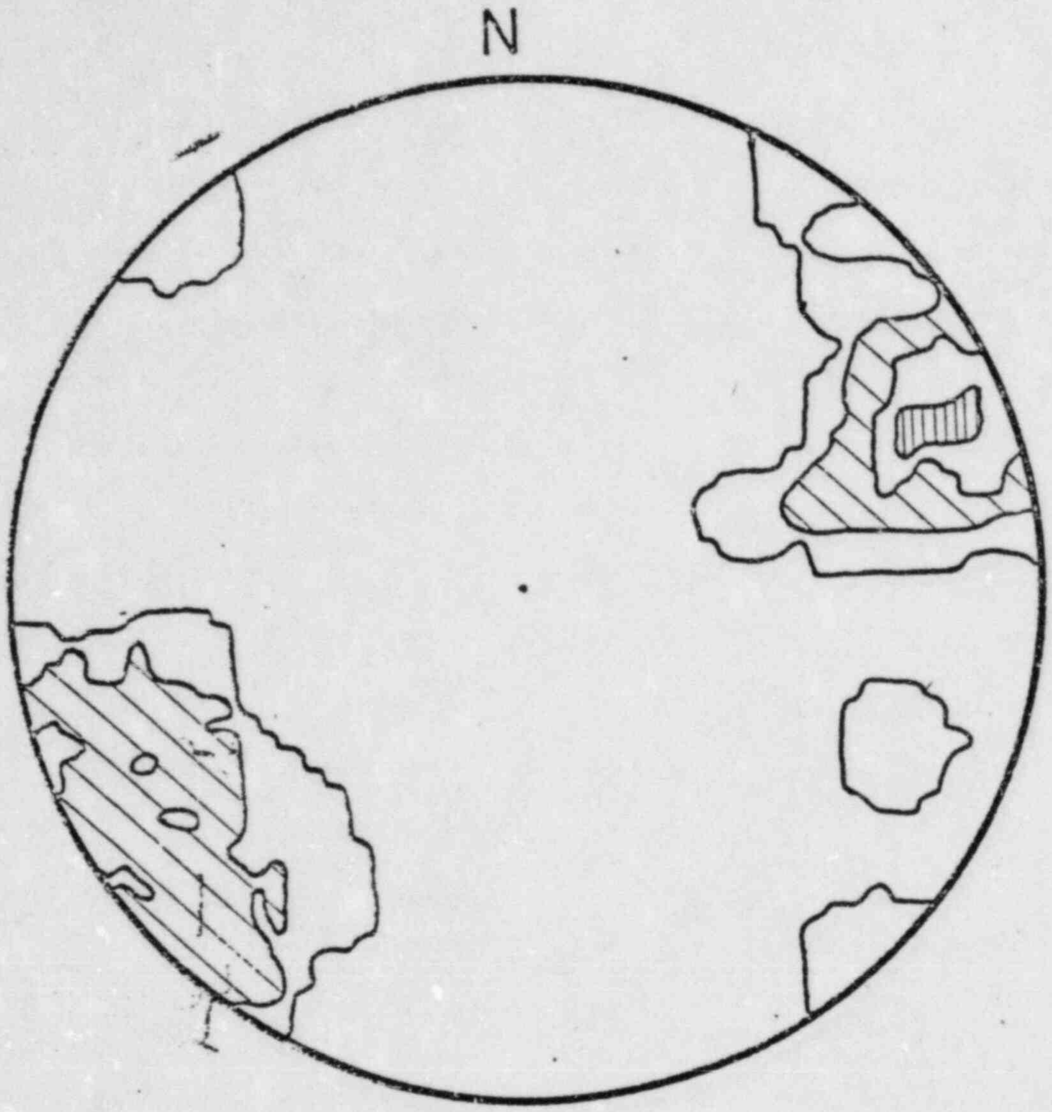

Figure 15. Lower hemisphere, equal-area projections of 42 L_1 elongation lineations measured in the Charlotte belt portion of the Little Mountain and Chapin quadrangles. Contours: 1, 5, 15 and 25%.

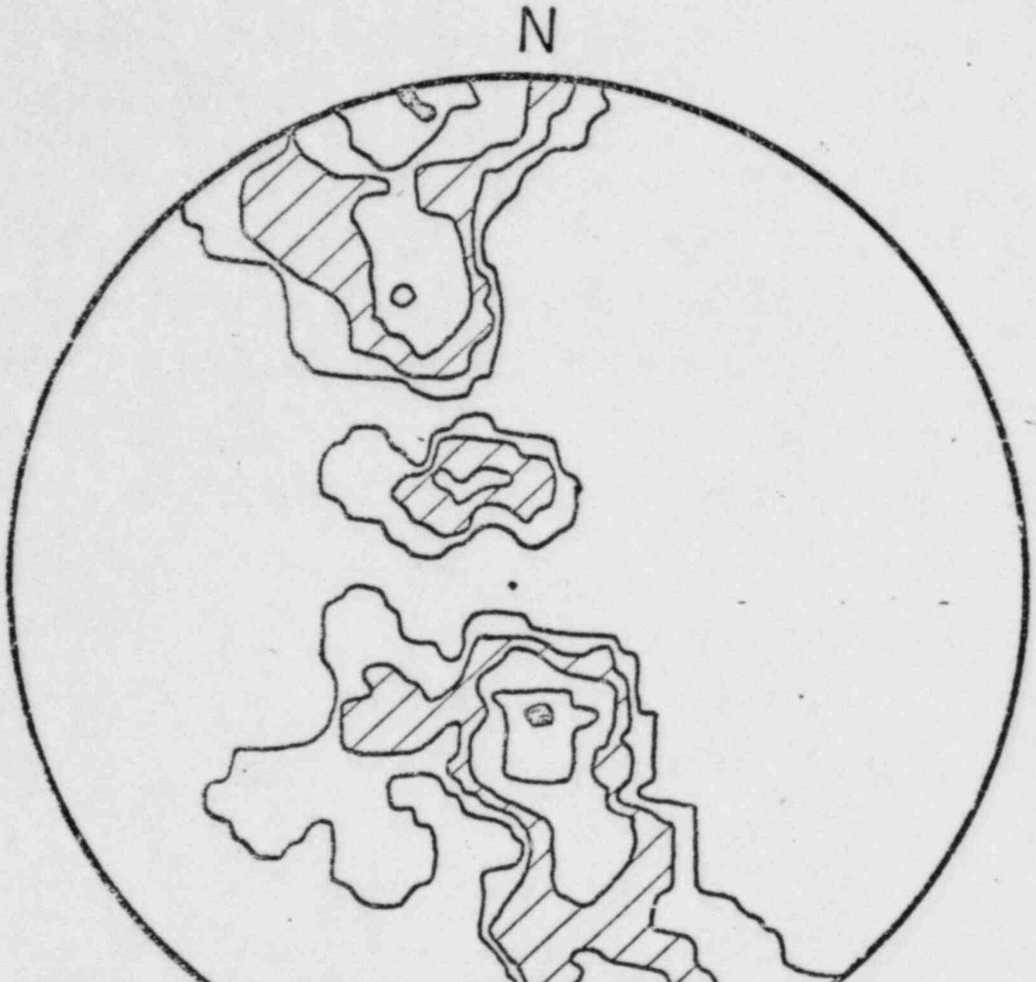

Figure 16. Lower hemisphere, equal-area projection of poles to 79 S_0 bedding planes measured in the slate belt portion of the Little Mountain and Chapin quadrangles. Contours: 1, 2, 5, 10 and 15%.

Additionally, they describe two other events which predate emplacement of the undeformed Winnsboro pluton, establishing a older age limit of 301 ± 4 m.y. [Fullagar, 1971] for the D_2 event. Secor and Snoke [1978] described D_2 in the slate and Kiokee belts as Hercynian in age. Snoke and others [1980] bracketed this event with a younger age limit in the slate belt established by emplacement of the prekinematic Clouds Creek pluton dated at 313 ± 2 m.y. and a younger limit set by the synkinematic Edgefield Granite dated at 254 ± 11 m.y. in the Kiokee belt. Enough overlap exists between these two periods of time so that the "D_2" deformational styles seen all the way across the slate belt and into the Charlotte belt could be at least in part synchronous; this is unlikely, however, since D_2 within the study area had to end before emplacement of the 301 m.y.-old Winnsboro pluton.

The D_2 event is characterized in both belts within the Little Mountain-Chapin area by folding of S_0 and S_1. These folds vary in style, orientation, and size. Poles to S_1 foliations from the Charlotte belt and from the slate belt are plotted in Figures 5c, 17 and 18. No penetrative cleavage phase of D_2 is recognized within the study area, although F_2 folds are abundant. Within this area the axis of F_2 folds generally parallel L_1 and L_{0x1} lineations, but they do vary locally probably due to sub-episodes of D_2 synchronous to events described by Bourland and Farrar as mentioned above.

Faulting

The study area has been affected by two periods of brittle faulting. The first of these resulted in a group of generally east-west trending silicified faults which are late Paleozoic and/or Mesozoic in age (see Chapter II). They are characterized by quartz brecciation and open cavities in which euhedral quartz has crystallized. Although these faults

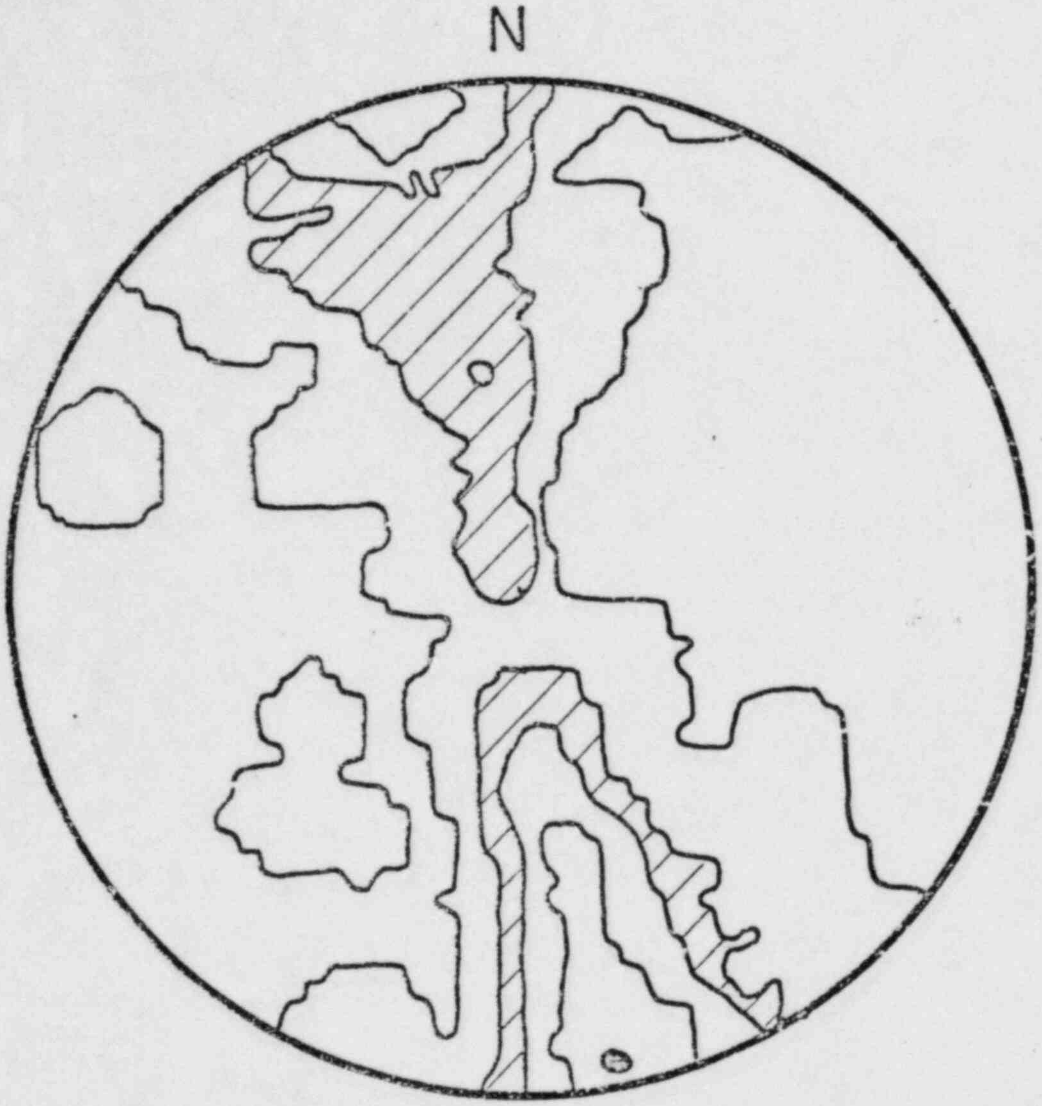

Figure 17. Lower hemisphere, equal-area projection of poles to 438 S_1 foliation planes measured in the slate belt portion of the Little Mountain and Chapin quadrangles. Contours: ½, 2, 5, 10 and 15%.

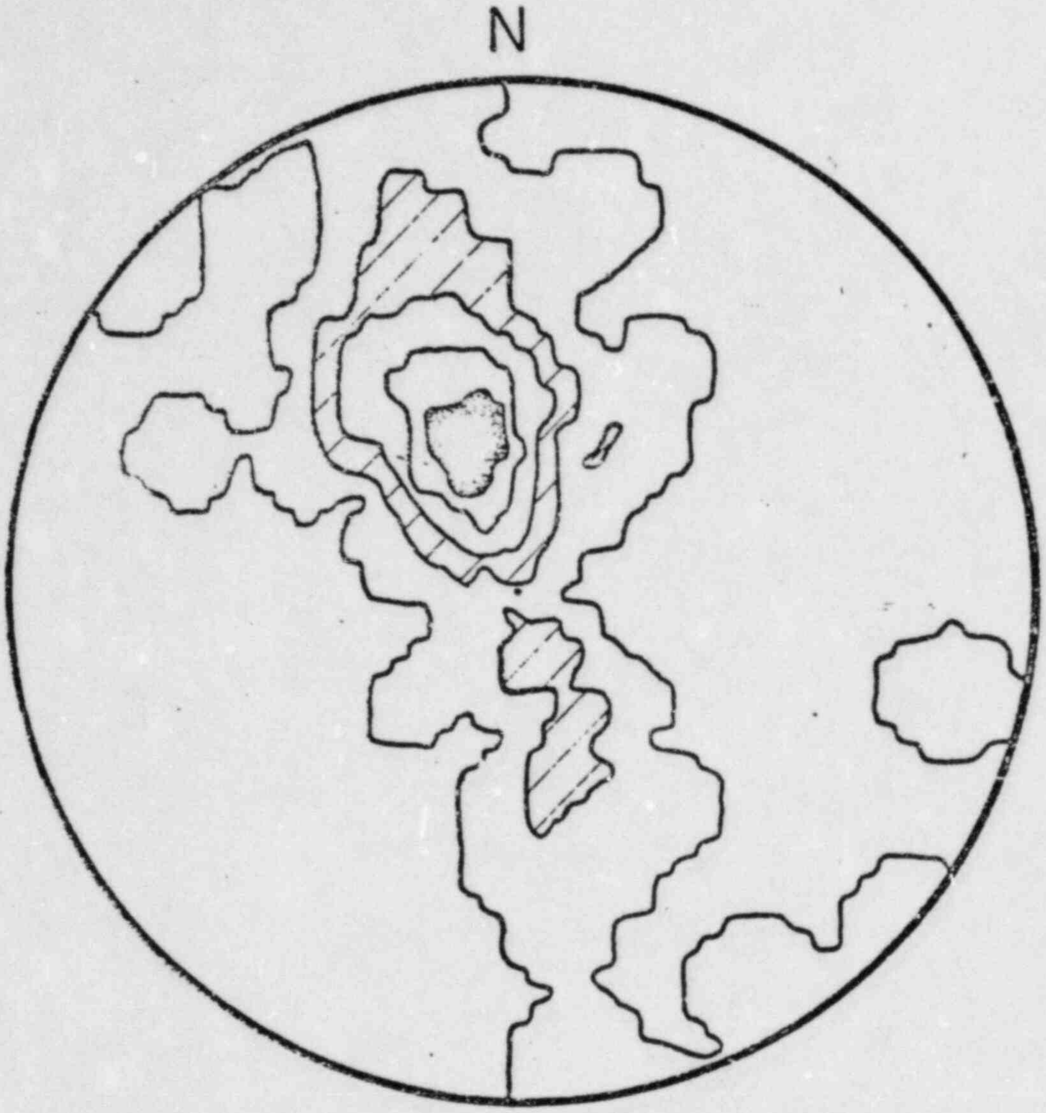

Figure 18. Lower hemisphere, equal-area projection of poles to 275 S_1 foliation planes measured in the Charlotte belt portion of the Little Mountain and Chapin quadrangles. Contours: ½, 2, 5, 10 and 15%.

can often be traced for several kilometers, there seems to be little appreciable movement along them as no displacement of contacts or structures has been observed.

The second period of brittle faulting is characterized by major high angle reverse faults trending generally north-south. These faults postdate the east-west faulting but predate emplacement of Jurassic(?) diabase dikes (see Chapter II). Two of these faults have been recognized within the study area: the Wateree Creek fault located in the center of the Chapin quadrangle, and the Summers Branch fault trending along the eastern boundary of the Little Mountain quadrangle. Of the two, the Wateree Creek fault is better exposed and has been the subject of a detailed study (Chapter II). The Summers Branch fault, on the other hand, is poorly exposed, its existence being supported primarily by the offset of stratigraphic contacts. Offsets are most dramatic in the metamudstone-wacke unit (Єmw) forming the core of the Chapin synclinorium where the width of this unit changes from over 5 kilometers west of the fault to about 1.2 km east of the fault (see Figure 2 and Plates 1 and 2). The axial surface of the Chapin synclinorium dips to the northwest, accounting for a much larger apparent offset of geological contacts on the southern limb of the synclinorium than on its northern limb. The Chapin synclinorium is broken by the Wateree Creek and Summers Branch faults in such a way that the block between the two faults is the upthrown block for both faults. Judging from the outcrop width of the Єmw unit in the core of the Chapin synclinorium, the block east of the Wateree Creek fault is upthrown relative to the block west of the Summers Branch fault. Additional evidence for the Summers Branch fault comes from the truncation of a Carboniferous gabbroic intrusion in the southwest corner of the Little Mountain quadrangle (Fig. 2 and Plates 1 and 2).

DISCUSSION AND CONCLUSIONS

The nature of the boundary between the Carolina slate belt and the Charlotte belt and the relationship between these two belts are matters of fundamental importance in Piedmont geology and have been of long standing controversy. In south-central North Carolina the belts are bounded by the Gold Hill and Silver Hill faults [Stromquist and Sundelius, 1969]. In Georgia, a portion of the boundary has been interpreted as an unconformity [Scheffler, 1976; Whitney and Thurmond, 1979]. Elsewhere, similar stratigraphic sequences have been recognized on each side of the boundary leading to the interpretation of the boundary as a metamorphic gradient from greenschist facies rocks in the slate belt to amphibolite facies rocks in the Charlotte belt [Overstreet and Bell, 1965a; Secor and Wagener, 1968; Griffin, 1972; Stromquist and Sundelius, 1979; Bourland and Farrar, 1980]. These differing interpretations of the nature of the boundary have led to the widely accepted view that a combination of relationships are involved [Chowns, 1976].

Work which has been done in or near the study area include McCauley [1961], Secor and Wagener [1968], and Bourland and Farrar [1980]. Secor and Wagener [1968] traced stratigraphic units across the boundary demonstrating that it is a metamorphic gradient. Bourland and Farrar [1980], working immediately northeast of the study area, arrived at the same conclusion based upon structural interpretations. McCauley [1961], on the other hand, suggested that the Carolina slate belt and Charlotte belts in Newberry County were derived from different pre-metamorphic protoliths because of geochemical differences between the two belts.

The Carolina slate belt is generally considered to have been deposited in an island arc environment. Whether the arc developed, at least in part, on sialic continental crust [Butler and Ragland, 1969; Hatcher, 1972; Glover and others, 1978] or oceanic crust [Whitney and others, 1978; Black, 1978] is still a matter of contention. Studies in modern and ancient island arcs have revealed a consistent sequence of magma genesis beginning with potassium-poor magmas generated at shallow depths along a Benioff zone with increases in potassium content of magmas generated at greater depths along the Benioff zone [Dickinson and Hatherton, 1967; Hietanen, 1975]. This increase is reflected in both plutonic and volcanic rocks with an increase in potassium content in volcanic rocks stratigraphically higher in the volcanic pile [Jakes and White, 1972].

When it was first discovered that the Little Mountain pluton extended across the entire study area, the area's value for consideration of the origin of the Charlotte belt - slate belt boundary was doubted, but then some fundamental questions arose. Why is this pluton tabular? Why is it oriented along regional strike? Also, why is this intrusion located along the Charlotte belt - slate belt boundary?

One explanation for the shape and orientation of the Little Mountain pluton is that it is pre- or synkinematic, its shape and orientation being a consequence of regional ductile deformation. This would also account for the shape of the smaller orthogneiss bodies within the Charlotte belt portion of the study area. Another explanation for the shape of the Little Mountain pluton is that it was emplaced along a major stratigraphic or structural feature such as an unconformity or a fault. This is considered unlikely, however, since no evidence has been found to indicate the existence of such features along the boundary within the study area.

Moreover, this explanation does not account for the similar shape and orientation of the smaller orthogneiss bodies north of the Little Mountain pluton.

A more likely explanation than either of the above is the mechanism considered for emplacement of the Main Donegal Granite, Ireland [Pitcher and Berger, 1972; Pitcher, 1979] in which lateral spreading of a granitic diapir along dominant country rock fabric, in this case bedding, occurs as upward motion is arrested. Either this mechanism for emplacement of a single magma body or emplacement of the pluton as a lacolith from a much larger magma body would have the same result, forming a concordant tabular pluton. Emplacement as sills would also account for the tabular concordant nature of the smaller intrusions to the north.

Emplacement along bedding is supported by field data. Where the contact between granite and country rock can be seen it dips to the southeast. Offsets of the pluton by the Summers Branch and Wateree Creek faults also indicate a dip to the southeast whereas S_0 measurements indicate the same orientation for metasedimentary rocks found just south of the pluton. Similar fault offsets indicate that Charlotte belt rocks also dip toward the southeast. This orientation has important implications for establishing a stratigraphic section of the study area. Although the reason for its emplacement in what would become an important boundary is uncertain, the Little Mountain pluton's orientation indicates that Charlotte belt rocks structurally underlie the slate belt.

Due to its lower structural position and generally more mafic composition, the Charlotte belt is considered to represent the lower part of a magmatic arc. The amphibolite unit (Ꞓa) in the Charlotte belt may (at least in part) represent a mafic basement on which the arc was constructed, although it is also possible that the amphibolite (Ꞓa) and felsic gneiss (Ꞓfgn) units represent arc-related volcanic-sedimentary rocks. The eruptive felsic tuffs and metasedimentary rocks of the Carolina slate belt are interpreted to represent the upper part of the same arc. The leucocratic granitoid gneisses (Ꞓggn, Little Mountain Pluton) in the Charlotte belt may represent hypabyssal intrusive rocks equivalent to eruptive felsic tuffs in the Carolina slate belt. The hydrothermally altered and silicified felsic volcanic rocks (Ꞓtq unit) along the border between the slate and Charlotte belts may represent a volcanic exhalative horizon genetically and temporally associated with the emplacement of the adjacent hypabyssal intrusive rocks of the Little Mountain Pluton.

In the Little Mountain - Chapin area, the boundary between the Carolina slate belt and Charlotte belt is therefore characterized by the following:

1) an intrusive boundary between hypabyssal felsic plutonic rocks and hydrothermally altered and silicified felsic tuff, and
2) a metamorphic gradient between the amphibolite facies rocks of the Charlotte belt and the greenschist facies rocks of the Carolina slate belt.

The former is a stratigraphic feature of Proterozoic Z or Cambrian age, whereas the latter is a metamorphic feature of probable Ordovician (Taconian) age. Because these features are of different ages, there is no reason to expect that they are genetically related to each other. Although the intrusive boundary coincides with the metamorphic gradient in the Little Mountain - Chapin area, elsewhere these features may not coincide, and the metamorphic gradient characterizing the boundary between the Carolina slate and Charlotte belts may occur at a different stratigraphic level. Clearly additional detailed geologic studies are needed along the border between the slate and Charlotte belts in adjacent regions to test the above interpretations.

CHAPTER IV

THE BEDROCK GEOLOGY OF THE JENKINSVILLE 7½' QUADRANGLE, SOUTH CAROLINA

INTRODUCTION

Geological studies were undertaken in the Jenkinsville quadrangle to provide a geological framework needed for the evaluation of possible earthquake hazards in an area of induced seismic activity at Lake Monticello, South Carolina, which might pose a threat to the safe operation of the Virgil C. Summer nuclear station. Monticello Reservoir, associated with the Virgil C. Summer station (Fig. 1), is one of the most thoroughly documented cases of induced seismicity within the United States [Duc and others, 1978; Talwani and others, 1978, 1980; Talwani, 1979; Talwani and Rastogi, 1979]. A marked increase in earthquake activity began shortly after the impoundment and infilling of the reservoir. Many earthquake events, with magnitudes ranging from <1.0 to 3.0, apparently occur at depths less than 1 kilometer. These earthquakes are interpreted as resulting from thrust type fault motion on naturally occurring fracture planes. Changes in pore pressure resulting from impoundment are thought to be the triggering mechanism for the earthquakes [Talwani and Rastogi, 1979; Zoback, 1979; Talwani and others, 1980]. A major zone of brittle faulting is located along Wateree Creek several kilometers south of the Monticello Reservoir [Secor and others, 1981b; Simpson, 1981; see also Chapter II]. A hypothetical extension of the fault zone projects 1 to 2 kilometers west of the Virgil C. Summer nuclear station, on Monticello Reservoir, through the region of the most intense seismic activity. Because the estimation of the largest probable induced earthquake is critically dependent on whether the Wateree Creek fault zone is present in the area of seismic activity and on whether it has an orientation that would render it susceptible to reactivation, it is important to understand the structure of the rocks around the reservoir as thoroughly as possible. For this reason the writer undertook the preparation of a detailed geologic map of the Jenkinsville 7½' quadrangle which covers the region around the reservoir (Fig. 1, and Plate III). A general familiarity with the regional geology of the Appalachian Piedmont is assumed in this report. Some particularly relevant aspects of the regional geology are reviewed in the following section.

REGIONAL GEOLOGY

The Piedmont of the southern Appalachians can be subdivided into several distinctive northeast trending lithological belts (Fig. 13) of probable Paleozoic age [Crickmay, 1952; King, 1955; Overstreet and Bell, 1965a, 1965b; Hatcher, 1972]. The study area is located approximately 5 kilometers north of the boundary between the Charlotte and Carolina slate belts (Fig. 2).

The Carolina slate belt and the Charlotte belt consist of thick sequences of metasedimentary and metavolcanic rocks which are interpreted as having been deposited in an island arc environment during Proterozoic Z and early Cambrian time [Butler and Ragland, 1969; Seiders, 1978; Black, 1978, 1980; Whitney and others, 1978]. The Carolina slate belt and the Charlotte belt were subjected to greenschist and amphibolite facies regional metamorphism, respectively, during the main metamorphic event (M_1), which was probably Ordovician as is suggested by K-Ar studies of slates from the Carolina slate belt in North Carolina [Kish and others, 1979].

Several generations of plutonism and deformation have affected the country rocks of this region. The oldest intrusions range in age between

545 to 495 m.y. [Fullagar, 1971, 1981] and usually exhibit a metamorphic overprint produced by the M_1 event during the Ordovician. The second generation of intrusions range in age from 415 to 390 m.y. and are considered to have post dated the M_1 event. Several of the second generation plutons, however, were affected by an M_2 event which appears to be quite variable in intensity throughout the region [Fullagar, 1971; Fullagar and others, 1971; Butler and Fullagar, 1978; Kish and others, 1979]. The third generation of intrusions, which range in age between 320 and 280 m.y. [Fullagar, 1971; Fullagar and Butler, 1979; Fullagar, 1981], do not exhibit any metamorphic fabric and are therefore considered post metamorphic.

The youngest rocks to intrude the Charlotte and slate belts are the Late Triassic and/or Early Jurassic diabase dikes. These dikes, which are usually olivine tholeiites, are typically oriented N. 10° W. to N. 30° W. and are steeply dipping.

The nature of the Charlotte and Carolina slate belt boundary is a fundamentally important relationship in Piedmont geology and has been a long standing controversy. Thurmond and Whitney [1979] interpret a portion of the boundary in Georgia as an unconformity. Stromquist and Sundelius [1969] interpret the boundary as a fault. Elsewhere the boundary is regarded as a metamorphic gradient [Secor and Wagener, 1968; Overstreet and Bell, 1965a; Bourland and Farrar, 1980]. Peck [1981], south of the study area, considered the boundary as a metamorphic gradient representing a transition between a mafic basement complex (Charlotte belt) on which the slate belt arc was constructed and the lower part of that arc. A combination of the various suggested relationships may be involved along the boundary.

ROCK DESCRIPTIONS

Several rock units have been differentiated within the study area (Plate III). These include amphibolite (Єa), felsic gneiss (Єfgn), sillimanite schist (Єss), quartz monzonite (Sn), quartz diorite (Cd), quartz monzonite (Cw), and diabase dikes (Jd).

Amphibolite (Єa)

The amphibolite unit is found primarily within the southern portion of the study area (Fig. 2, and Plate III). The amphibolite in adjacent areas has been interpreted as metamorphic basaltic-andesitic flows by McCauley [1961] and Overstreet and Bell [1965a], with less mafic amphibolites interpreted as metasedimentary rocks and metatuffs [Overstreet and Bell, 1965a]. Bourland and Farrar [1980] interpret the amphibolites located to the immediate east of Jenkinsville to be of intrusive origin rather than of extrusive origin, based on its relationship with the surrounding country rock and its gabbroic texture. Amphibolites within the study area are interpreted as resulting from the metamorphism of mafic tuffs and/or flows because they are interlayered with metasedimentary rocks and because relict volcanic textures have locally been observed.

Numerous sheets of granitoid orthogneiss, ranging in size from several centimeters to several meters, intrude the amphibolite within the study area. These are too thin and numerous to be mapped separately from the amphibolite. Peck [1981] was able to delineate several thick sheets of orthogneiss within the amphibolite in the Little Mountain - Chapin area (Fig. 2, and Plate II).

Within the study area the amphibolites are generally fine to medium grained consisting of varying amounts of hornblende, plagioclase, sphene, and minor epidote, quartz, and opaque oxides (Table 4). The hornblendes

SAMPLE NUMBER	QUARTZ	HORNBLENDE	PLAGIOCLASE	BIOTITE	SPHENE	EPIDOTE	CHLORITE	WHITE MICA	OPAQUE	HEMATITE	K-FELDSPAR
6	O	X	X	-	X	X	O	O	O	O	-
15	O	X	X	-	X	O	-	-	-	-	-
25	O	X	X	O	X	X	-	-	X	O	O
28A	X	X	X	-	X	O	-	O	X	O	O
94	O	X	X	-	X	O	-	-	-	O	-
98A	O	X	X	-	X	X	-	O	O	O	-
148	X	X	X	-	X	X	-	-	X	-	-
158	X	X	X	X	X	O	-	O	X	O	-
163B	O	X	X	-	X	X	-	-	O	O	-
178	O	X	X	X	X	O	O	O	O	O	-
189	O	X	X	O	X	O	-	O	O	-	-

X = mineral present in amounts >1.0%

O = mineral present in amounts <1.0%

\- = mineral not present

Table 4. Metamorphic mineral assemblages for amphibolites (Ꞓa) south of the Winnsboro pluton (Cw)/amphibolite (Ꞓa) boundary in the Jenkinsville quadrangle.

are generally short and stubby euhedral to subhedral crystals, which have a preferred orientation, and comprise approximately 55 to 70% of the rock volume. Hornblende is pleochroic with x = yellow or yellow green; y = green or olive; a... z = dark blue green or dark olive green. The composition of the plagioclase, based on the Michel-Levy method, varies from An_{26} to An_{58} (oligoclase to labradorite) with an average composition of An_{34} (andesine). Plagioclases, which are usually short, subhedral crystals oriented subparallel to the foliation, comprise approximately 22 to 35% of the total volume of the rock. Sphene, which comprises 2 to 4% of the rock, occurs as isolated blebs commonly exhibiting its characteristic wedge shape crystal form. Minor minerals consist of epidote (3 to 7%), anhedral quartz (<1 to 2%), opaque oxides (<1 to 2%), potassium feldspar (<1%), biotite (<1%), and small amounts of apatite and zircon.

The small amphibolite units mapped within the quartz monzonite (Cw) are interpreted as enclaves of the amphibolite. The mineralogy of these enclaves generally agrees with that of the main body of amphibolite with a few minor differences (Table 5). The enclaves commonly exhibit a reduction of plagioclase and hornblende grain size as well as minor growth of pyroxenes in a few sites, a slight increase in the calcium content of plagioclase, and a general decrease in the amount of epidote.

Felsic Gneiss (Єfgn)

The felsic gneiss unit, which occurs in the extreme southeastern part of the study area (Fig. 2, and Plate III), consists of a fine to medium grained biotite-muscovite-quartzofeldspathic schist and gneiss with minor amounts of potassium feldspar, hornblende and opaque oxides. The dominant leucocratic minerals are quartz and muscovite, whereas [illegible] the primary mafic mineral.

SAMPLE NUMBER	QUARTZ	HORNBLENDE	PLAGIOCLASE	BIOTITE	SPHENE	EPIDOTE	CHLORITE	WHITE MICA	OPAQUE	HEMATITE	K-FELDSPAR	PYROXENE	OTHER
41	-	X	X	X	0	0	-	-	0	-	-	X	-
61	X	X	X	-	X	0	-	-	0	-	-	-	-
61A	X	X	X	-	X	0	-	-	0	-	-	-	-
70	X	X	X	-	X	0	-	0	0	-	-	-	-
102	X	X	X	-	X	X	-	0	0	0	-	-	-
108	X	X	X	X	-	X	0	-	X	-	-	-	-
246	-	X	X	0	-	-	-	0	X	0	0	X	-
341	0	X	X	-	X	0	-	-	0	-	-	-	-
342	0	X	X	-	X	-	-	-	0	-	-	0	-
496	0	X	X	-	X	-	-	-	-	-	-	-	-

X = mineral present in amounts >1.0%

0 = mineral present in amounts <1.0%

\- = mineral not present

Table 5. Metamorphic mineral assemblages for amphibolite (Єa) enclaves and xenoliths within the Winnsboro pluton (Cw) in the Jenkinsville quadrangle.

Field relationships between the felsic gneiss unit (Єfgn) and the amphibolite unit (Єa) suggest that they may be stratigraphically equivalent to one another. This interpretation is based on the observations that the contacts between the units are very transitional and gradational and the occurrences of minor amphibole rich layers, which vary in thickness from 0.5 to several meters, are intercalated within the felsic gneiss unit. Similar observations have been made by Peck [1981] in the Little Mountain and Chapin quadrangles to the south.

Sillimanite Schist (Єss)

The sillimanite schist occur in the central southeastern part of the study area (Plate III). The schists, which characteristically outcrop as small boulders and form several small resistant hilltops within the study area, are interpreted as enclaves within the Winnsboro pluton. Sillimanite occurrences have also been noted adjacent to this area by Wagener [1966, 1970], Secor and Wagener [1968], Farrar [1977], and Bourland and Farrar [1980]. The sillimanite schists are composed of approximately 32% accicular sillimanite, 40% potassium feldspar, 20% quartz, 8% muscovite and minor amounts of sphene and plagioclase.

Newberry Plutonic Complex (Sn)

The Silurian quartz monzonite, located in the northwestern corner of the study area (Fig. 2, and Plate III), is part of the extensive Newberry complex (Sn) extending west through Newberry County [Kesler, 1936; McCauley, 1961; Overstreet and Bell, 1965a, 1965b; Wagener, 1977a]. Outcrops of the pluton within the study area usually occur as a yellowish fine grained intensely weathered rock which can readily be distinguished from the reddish saprolite of the Winnsboro pluton (Cw) to the south and east. Unweathered exposures of this rock, found approximately 3 kilometers northwest of the study area within the Blair quarry and along nearby roads, outcrop as a massive fine grained light to medium grey colored rock. The Newberry plutonic complex also outcrops extensively in the adjacent Pomaria quadrangle (Fig. 2, and Plate IV), and a thorough petrographic description of it is presented in Chapter V. For purposes of the present study, modal analyses of two samples were used to determine the mineralogy of the pluton. These analyses plot in the quartz monzonite compositional field (Fig. 19). The mineralogy consists primarily of plagioclase, potassium feldspar, quartz, and biotite with accessory muscovite and opaque oxides (Table 6). The plagioclase, which has an An composition that ranges from An_{14} to An_{28} (oligoclase) is usually subhedral to anhedral. Associated with the plagioclase are minor occurrences of myrmekite with vermicular quartz. Subhedral to anhedral potassium feldspars and anhedral quartz, which exhibit undulatory extinction, are the remaining primary minerals that occur in the rock. The amount of biotite is usually three times more abundant than muscovite. Trace amounts of secondary epidote and chlorite also occur in the rock.

The Newberry pluton occasionally contains a distinct foliation manifested by an alignment of biotite. This weak foliation may be attributable to either flow or metamorphic phenomena.

Fullagar and Kish [1981] and Fullagar [1981] report a Rb-Sr whole-rock age determination for the Newberry pluton of 415 ± 9 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0.7024 ± 0.0003. This extremely low Sr^{87}/Sr^{86} initial ratio for the Newberry pluton suggests that the whole rock age is an emplacement age rather than an age of metamorphism.

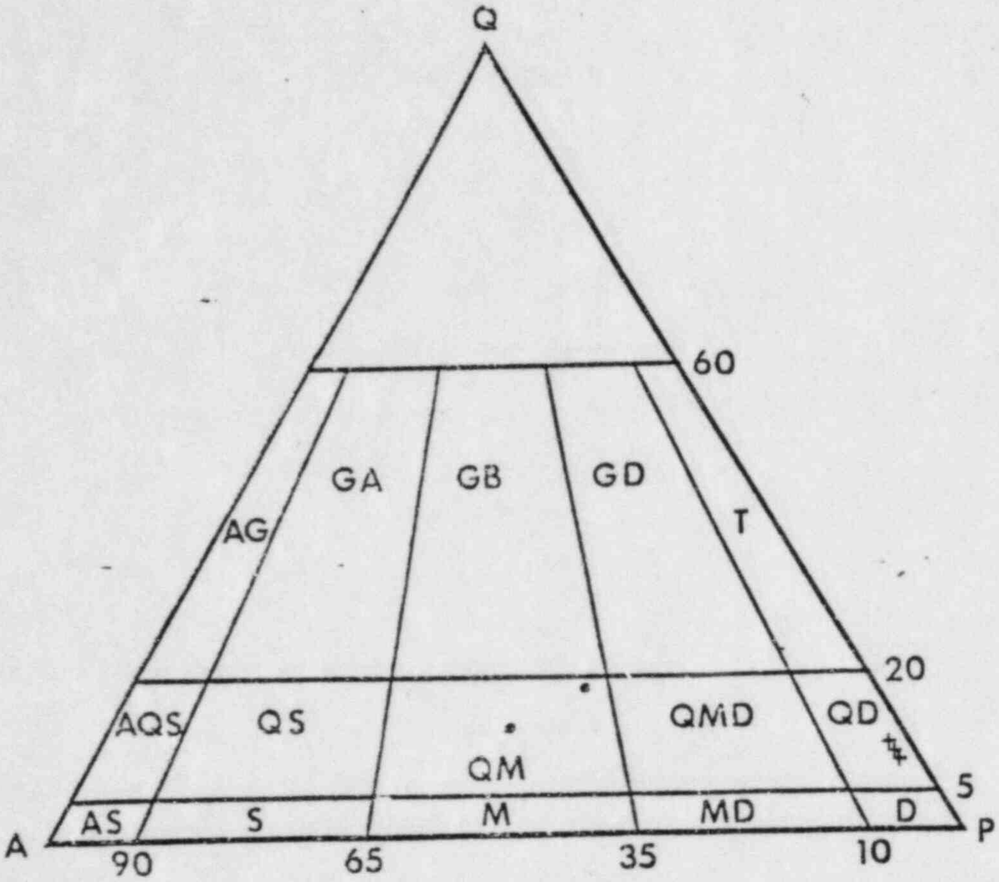

Figure 19. APQ diagram showing the modal variation for the Newberry pluton (Sn, •) and the quartz diorite (Cd, +). Diagram after Streckeisen [1967] where AG - alkali feldspar granite, AQS - alkali feldspar quartz syenite, AS - alkali feldspar syenite, GA and GB - Granite A field and B field, QS - quartz syenite, S - syenite, QM - quartz monzonite, M - monzonite, GD - granodiorite, QMD - quartz monzodiorite, MD - monzodiorite, T - tonalite, QD - quartz diorite and D - diorite. Modes were obtained by counting 1000 points each.

SAMPLE NUMBER	PLAGIOCLASE	K-FELDSPAR	QUARTZ	BIOTITE	HORNBLENDE	MUSCOVITE	CHLORITE	OPAQUE	SPHENE	EPIDOTE	HEMATITE	PYROXENE
						Cw						
16	42	29	12	6	10	-	-	tr	1	-	-	-
29	61	10	11	10	tr	3	tr	-	-	1	tr	-
33	42	27	16	11	tr	1	-	-	-	1	tr	-
36	40	33	17	1	4	4	tr	-	-	tr	tr	-
48	37	33	19	8	tr	1	tr	tr	tr	-	tr	-
52	41	32	16	6	tr	4	tr	tr	tr	tr	tr	-
325	40	31	17	2	8	-	-	tr	-	-	tr	-
						Cd						
249	56	1	7	18	15	-	tr	2	-	tr	tr	-
279	55	1	6	9	14	-	-	1	-	-	tr	15
422	48	1	5	18	7	-	-	4	-	-	tr	19
						Sn						
BQ	42	40	13	3	-	1	-	1	-	-	-	-
NEWB	39	30	18	2	-	1	-	-	-	-	-	-

Table 6. Modal mineralogical data for the Winnsboro pluton (Cw), quartz diorite (Cd), and the Newberry pluton (Sn) in the Jenkinsville quadrangle. Modes were obtained by counting 1000 points per thin section.

Quartz Diorite (Cd)

Several small bodies of hornblende quartz diorites (± pyroxene) are found within the southern half of the Winnsboro pluton (Cw, Plate III). The rocks are generally dark colored fine to medium grained with a ramifying network of net veins composed generally of quartz and feldspar. In one location the quartz diorite has been forcefully intruded by an apophysis of the Winnsboro pluton. This is interpreted to indicate that the quartz diorite may range in age from pre- to syn- plutonic emplacement. Associations of quartz diorite with granitoid plutons have also been observed in other localities in South Carolina [Overstreet and Bell, 1965a; Secor and Snoke, 1978].

Modal analyses were calculated on several samples to determine the mineralogy of the rock. The mineralogy consists primarily of plagioclase, quartz, biotite, hornblende, pyroxene, and minor accessory minerals (Table 6). The rocks generally have an equigranular igneous texture. The plagioclase, which has a composition that ranges from An_{38} to An_{48} (andesine), forms medium grained anhedral to subhedral grains, which occasionally are zoned. The pyroxene (clinopyroxene) is usually identified by its cleavage and the fact that it is colorless in thin sections. The biotite has a yellow (x) to brown (z) pleochroism. Hornblende occurs as subhedral to anhedral crystals and exhibits pleochroism with x = yellow or olive, y = green or olive, and z = darker olive or green. The opaque oxides occur as small blebs generally associated with the biotite and hornblende. Quartz generally has undulatory extinction and an interstitial growth form. Minor accessory minerals include epidote, hematite, and chlorite. The modal analyses plot well into the quartz diorite compositional field (Fig. 19).

Winnsboro Plutonic Complex (Cw)

The Carboniferous pluton is apparently an extension of the Winnsboro plutonic complex in the east [Wagener, 1970, 1977a] and extends through the middle and north parts of the study area (Fig. 2, and Plates III and IV). Detailed and reconnaissance mapping of the Winnsboro pluton complex has been conducted by Kesler [1936]; Wagener [1966, 1968, 1970, 1973, and 1977a]; Secor and Wagener [1968]; Farrar and Becker [1977]; and Bourland and Farrar [1980]. Detailed petrographic analyses were done by Wagener [1973] and Farrar and Becker [1976]. Further mapping and petrography of the pluton within the study area were done by South Carolina Electric and Gas Company [1977] in conjunction with the building of Monticello Reservoir and the Virgil C. Summer nuclear station.

The quartz monzonite usually consists of medium to coarse grained megacrystic potassium feldspar with variable amounts of biotite, hornblende, and quartz. The Winnsboro pluton also occurs as a homogeneous fine to medium grained rock.

Modal analyses of several thin sections and stained rock slabs were studied to determine the petrography and possible variations within the pluton. Modal analysis was done by counting 1000 points per thin section and slab. The results of the modal analysis are represented in Figure 20. The rocks plot mostly below the 20% quartz line which separates the monzogranites (>20% quartz) from quartz monzonites (<20% quartz). The mineralogy of the quartz monzonite consists primarily of plagioclase, potassium feldspar, quartz, biotite, hornblende, and minor amounts of accessory minerals such as muscovite, sphene, epidote, hematite, chlorite, and opaque oxides (Table 6). The plagioclase crystals, which have a composition that varies from An_{27} to An_{32} (oligoclase), generally are

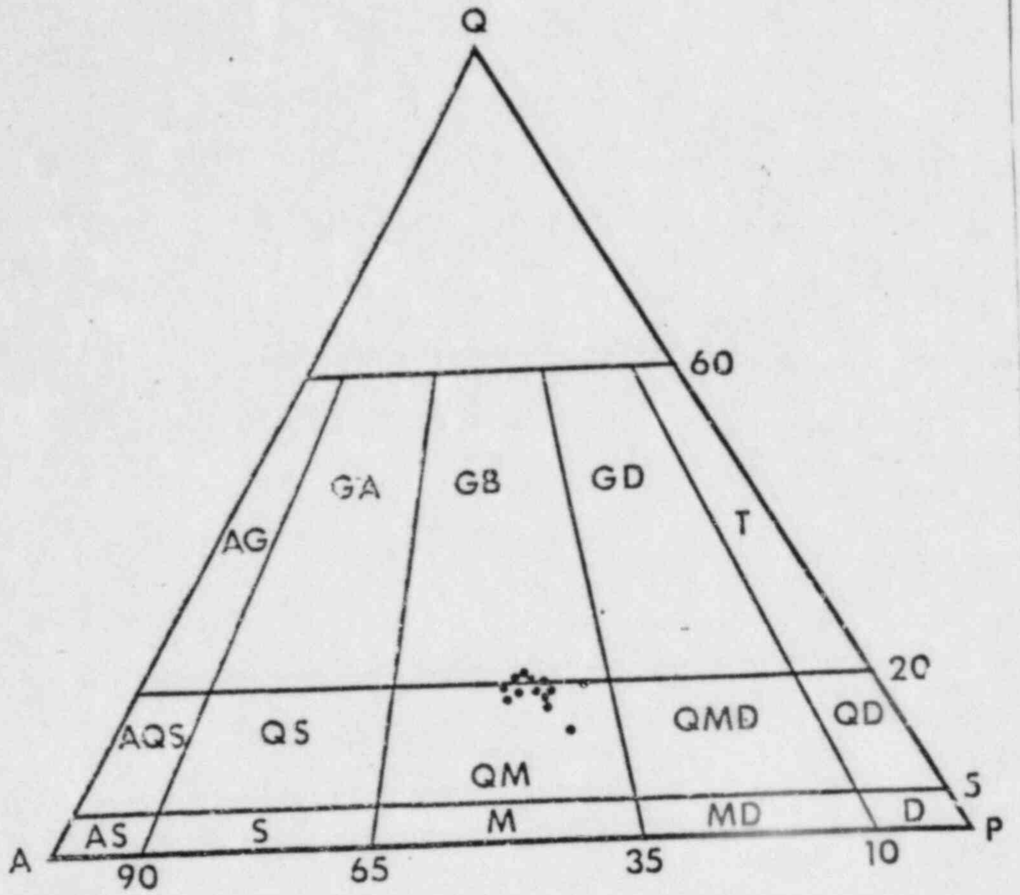

Figure 20. APQ diagram showing the modal variation within the Winnsboro pluton (Cw) for seven thin sections and six stained slabs from the Jenkinsville quadrangle. Modes were obtained by counting 1000 points each.

subhedral to anhedral. Some of the plagioclase crystals exhibit normal oscillatory zoning with cores of a more calcic composition grading outward to a more sodic composition. Plagioclase crystals also exhibit sausseritization forming epidote and sericite. Microcline, commonly perthitic, is generally a subhedral megacrystic mineral with an average length of 0.3 to 1.1 cm long. Several crystals have been observed to be greater than 2 cm long, but this is very rare. The quartz is commonly rutilated and exhibits undulatory extinction. Biotite is pleochroic yellow to dark brown or olive brown. Hornblende, generally subhedral, is pleochroic with x = yellow orange or yellow brown, y = olive, and z = dark green or green. Minor amounts of accessory minerals such as muscovite are also present.

Several Rb-Sr and K-Ar mineral and mineral-whole rock ages obtained from the quartz monzonite in the foundation rock of the Virgil C. Summer nuclear station have been determined. These dates range from 309 to 286 m.y. and probably reflect a time of cooling rather than an age of pluton emplacement [South Carolina Electric and Gas Company, 1977; Fullagar and Kish, 1981]. A Rb-Sr whole-rock age of 295 ± 4 m.y. and an initial Sr^{87}/Sr^{86} ratio of 0.7047 ± 0.0004 have been determined for the Winnsboro pluton east of the present study area [Fullagar and Butler, 1979; Fullagar, 1981].

The U. S. Geological Survey drilled two boreholes, Monticello #1 and #2, into areas of induced seismicity west of Monticello Reservoir (Fig. 2) in order to determine in situ pore pressures and stresses [Zoback, 1979; Zoback and Hickman, in press]. The Monticello #1 core (1.1 km deep) is relatively free of inclusions whereas 15 to 20% of the total volume of the Monticello #2 core (1.2 km deep) consisted of enclaves and xenoliths of gneiss and amphibolite (Fig. 3) which are mostly concentrated in the top 330 meters [Secor and others, in press].

Throughout the main body of the pluton, numerous xenoliths and enclaves occur which are in various stages of assimilation. The most persistent xenoliths are the mafic-rich country rock (amphibolite). This is probably due to the fact that the felsic gneiss country rock contains a relatively high proportion of low melting temperature constituents so that xenoliths of these rocks would be more likely to disintegrate. The xenoliths vary in size from 1 cm to several meters in length. Many of the xenoliths carry a foliation (S_1) which is usually parallel to the elongation of the xenolith. This suggests that the shape of the inclusions could be controlled by the S_0 or S_1 foliation. Since the quartz monzonite commonly outcrops as loose boulders, measurements were not taken on the orientation of many of the xenoliths found within these boulders. A few measurements obtained from the more reliable outcrops indicated that the direction of elongation of the xenoliths was often parallel or subparallel to the contact of the pluton. Schlieren features or protoclastic foliations were seen in several places and are very common where abundant xenoliths occur. These are generally biotite-rich and occasionally contain hornblende. There are probably more large enclaves within the Winnsboro pluton which were not detected during mapping owing to lack of exposure. Subsurface distribution of large enclaves within the Winnsboro pluton as well as compositional variations within the quartz monzonite could account for the irregular character of the magnetic field over the pluton (Fig. 4).

The boundary between the Winnsboro plutonic complex (Cw) and the Newberry plutonic complex (Sn) is approximate. It is based primarily on the changes in color between the Winnsboro (red) and Newberry (yellow) saprolite. In the streams this contact is also manifested by the last occurrence of the Carboniferous pluton boulders. Examination of the rocks on either side of the contact reveals no exposures which show xenoliths of one within the other. The small enclave of the Newberry plutonic complex (Sn) within the Winnsboro plutonic complex (Fig. 2, and Plate III) was mapped primarily on the observations of saprolite color changes and grain size variations.

The southern boundary between the Winnsboro plutonic complex (Cw) and the amphibolite (Ga) is based primarily on the first occurrences of quartz monzonite boulders and saprolite. These boulders, which consist of the medium to coarse grained megacrystic quartz monzonite, usually contain abundant xenoliths of the amphibolite. The xenoliths, which vary in size and shape, are occasionally agmatized and highly disrupted. The agmatites were formed as a result of either the injection of magma into the relatively rigid country rock or the engulfing of country rock by the magma.

Physical conditions of pluton emplacement are very difficult to determine based on field relationships and the lack of geochemical data. Sinha and Merz [1976] suggest a depth of emplacement, for the Winnsboro complex to the east, around 12 to 14 km at 700 to 800°C. Since the contact metamorphic effects in the amphibolite are very difficult to differentiate from the regional metamorphic effects, a contact aureole has not been delineated. Farrar and Becker [1976] and Farrar [1977] also report similar observations for the Winnsboro complex in the east.

Diabase Dikes (Jd)

Numerous diabase dikes are intruded into the study area (Fig. 2, and Plate III). The trends of these range from N.30°W. to N.15°W. with an average of approximately N.20°W. The average dips of the dikes are vertical to near vertical. Thicknesses vary from 0.1 meters to 10 meters with an average of 1 meter. Diabase is best exposed in streams where they occur as boulder trains or as in-situ blocks. Columnar cooling joints are normal and parallel to the trend of the dike walls, which increases the susceptibility of the dike to weathering. With progressive weathering, the boulders are reduced in size to rounded to subangular boulders surrounded by clays.

Modal analyses of seven diabase dikes were used to determine the mineralogy of the rock. The diabase, generally a fine to medium grained rock with an ophitic to subophitic texture, consists primarily of plagioclase, olivine, and clinopyroxene with minor amounts of opaque oxides, serpentine, and chlorite (Table 7). The plagioclase, which occurs as randomly oriented euhedral stellate crystals, has an An composition averaging An_{59} (labradorite). The clinopyroxene occurs as colorless to pale green or brown anhedral crystals which were identified as an augite. The augite is commonly altered to a chlorite and sometimes to opaque oxides. Olivine occurs as colorless euhedral to subhedral crystals which commonly have serpentine-filled fractures. The major accessory mineral is euhedral to subhedral titanomagnetite.

A ternary plot of the total volume percent of plagioclase, pyroxene, and olivine is shown in Figure 21. Wiegand and Ragland [1979] characterize the diabase dikes of eastern North America, based on calculating the norms, into three main groups: the olivine normative tholeiite, the low TiO_2 quartz normative tholeiite, and the high TiO_2 quartz normative tholeiite. A plot of modal analysis can show a correspondence to either the olivine or quartz tholeiites, although it cannot distinguish between the three groups. These seven dikes fall well into the olivine tholeiite composition.

A paleomagnetic study of dikes in the study area and adjacent areas of the central Piedmont has recently been completed by Dooley and Smith [1981]. Briefly, Dooley and Smith obtained an average pole position which agrees with other well established Late Triassic - Early Jurassic pole positions

SAMPLE NUMBER	PLAGIOCLASE	OLIVINE	PYROXENE	OPAQUE	CHLORITE	SERPENTINE	HEMATITE
				Jd			
5	67	18	12	2	tr	tr	tr
22	62	17	18	2	tr	tr	-
71	64	17	15	3	1	tr	tr
88	50	20	27	2	1	tr	-
115	57	13	27	1	1	tr	-
199	61	24	13	tr	tr	tr	tr

Table 7. Modal data for six diabase dikes (Jd) in the Jenkinsville quadrangle. Modes were obtained by counting 1000 points per thin section.

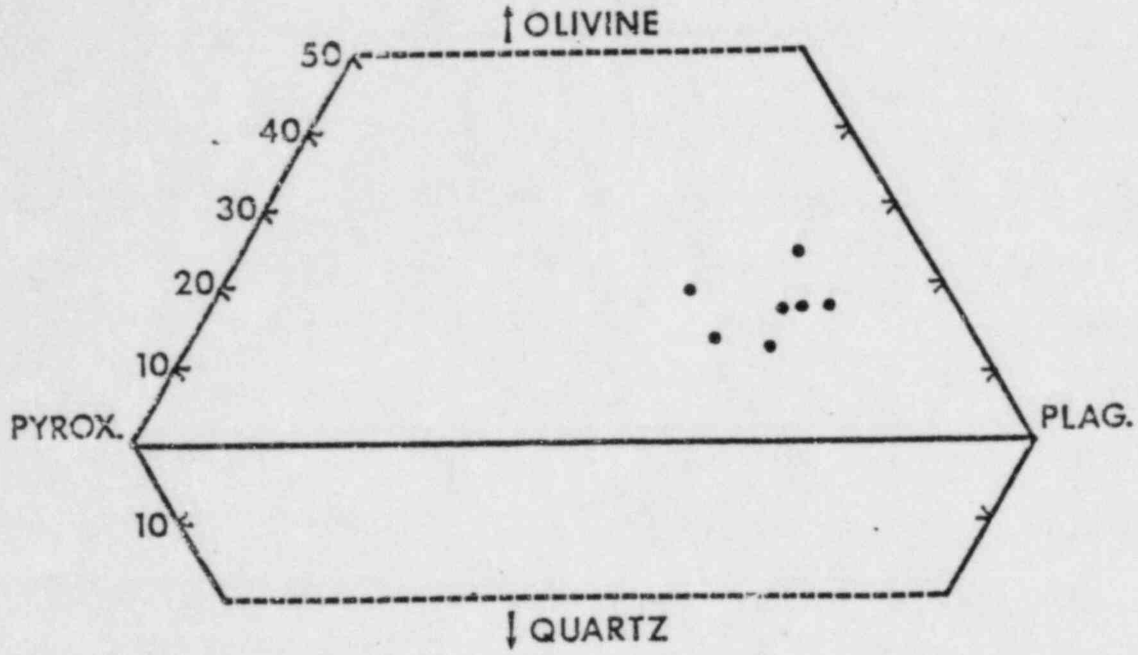

Figure 21. An olivine-plagioclase-pyroxene-quartz diagram showing the modal variation of seven diabase dikes from the Jenkinsville quadrangle. Modes were obtained by counting 1000 points each.

from North America [see deBoer, 1967; Watts, 1975; Smith and Noltimier, 1979; Sutter and Smith, 1979; Bell and others, 1980]. Conventional single analysis whole-rock K-Ar apparent age determinations for several of the dikes have ages which range from 207 to 180 m.y. [Robert E. Dooley, 1981, personal communication], which agree with the paleomagnetic results.

REGIONAL RELATIONSHIPS AND DISCUSSION

Rocks within the Carolina slate belt and the Charlotte belt have been subjected to at least two deformational episodes. The timing of the oldest and strongest deformational event (D_1) is not well constrained although it apparently predates the emplacement of the 415 to 390 m.y. series of plutons within the Charlotte belt [Fullagar, 1971, 1981]. This is based on the observation that xenoliths which carry the S_1 fabric are found within the 415 m.y. Newberry pluton, suggesting that D_1 occurred prior to 415 m.y. ago. Kish and others [1979] suggest that the age of metamorphism was probably Ordovician based on whole-rock K-Ar studies of slates from the Carolina slate belt in North Carolina. The D_1 event was accompanied by greenschist facies metamorphism in the Carolina salte belt and amphibolite facies metamorphism within the Charlotte belt. The D_1 event also produced the major penetrative metamorphic foliation (S_1) as well as the Chapin synclinorium, a major large-scale fold (F_1), to the south [Peck, 1981; Secor and others, in press]. The amphibolites and felsic gneiss units within the study area are located on the northern limb of the Chapin synclinorium. The axis of the synclinorium trends N.75°E. The S_1 foliation usually contains a strong elongation, L_1, which generally plunges to the northeast, parallel to the axis of the synclinorium.

A second deformational event (D_2) also affected the area during the middle to late Paleozoic time. Bourland and Farrar [1980] describe the D_2 event as forming a variable series of mesoscopic and macroscopic F_2 folds which are generally coaxial with the L_1 elongation lineations [Peck, 1981]. Poles to S_1 from the study area and the Chapin - Little Mountain area are shown in Figures 5a, 17, 18, and 22 and indicate that S_1 has been refolded during the D_2 event. Peck [1981] reports abundant occurrences of F_2 folds in the Little Mountain - Chapin area. A few F_2 folds have been recognized within amphibolite xenoliths within the Winnsboro pluton in the study area, indicating that the time of F_2 folding at least in part predated the time of emplacement of the Winnsboro pluton (295 m.y.).

The intrusion of the Winnsboro pluton (Cw) within the study area apparently only caused local deformation limited to the immediate vicinity of the pluton. Rb-Sr whole-rock age determinations of 295 ± 4 m.y. [Fullagar and Butler, 1979; Fullagar, 1981] for the Winnsboro pluton in the east and 309 to 286 m.y. for the pluton in the study area [South Carolina Electric and Gas Company, 1977; Fullagar and Kish, 1981] provide an upper (younger) age bracket for the deformational events (D_1, D_2) preceding the pluton emplacement.

Two periods of brittle faulting have affected the area south of the study area [Peck, 1981; Simpson, 1981]. The oldest set of faults are typically east-west trending and usually contain brecciated and silicified country rocks. The amount of displacement is unknown although the faults can be traced for several kilometers. The age of these silicified faults is thought to be of late Paleozoic or early Mesozoic age because they cut Carboniferous rocks in the Kiokee belt of South Carolina and are themselves cut by early Jurassic dikes [Secor and Snoke, 1978; Secor and others, in press].

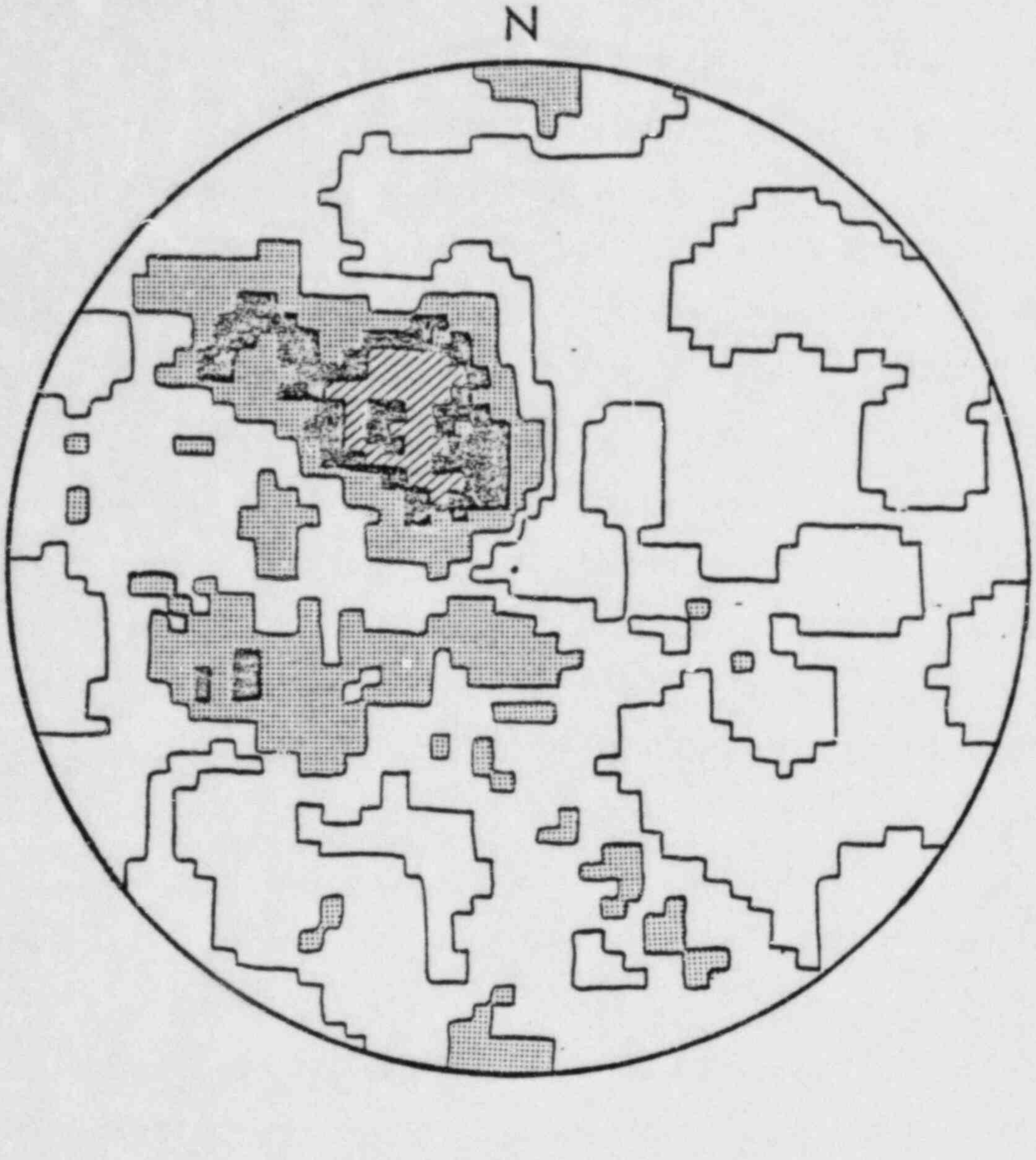

Figure 22. Lower hemisphere, equal-area projection of poles to 138 S_1 foliation planes from the Jenkinsville quadrangle. Contours: 2, 4, 6, 8 and 11%.

Younger north-south trending high angle reverse faults offset the older east-west trending silicified faults. The north-south trending Wateree Creek fault zone, south of the study area (Fig. 2, and Plate I), has been the subject of a detailed study by Simpson [1981]. The fault is characterized as a high angle reverse fault which 1) offsets the stratigraphy, the axis of the Chapin synclinorium, and the east-west trending silicified faults, and 2) has a dip slip displacement of approximately 1700 meters. The interaction of a Jurassic diabase dike with the Wateree Creek fault zone was also studied [Simpson, 1981] to determine a possible constraint on the timing of the last fault movement. Backhoe trenching and detailed magnetometer traverses across the dike and fault zone suggest that the faulting occurred prior to the diabase dike emplacement (early Jurassic). The Summers Branch fault zone to the west (Fig. 2, and Plates I and II) appears to be similar to the Wateree Creek fault zone based primarily on the offset of stratigraphic contacts [Peck, 1981].

Within the study area, numerous outcrops that exhibit fracturing and zeolite mineralization have been observed. These fractures are commonly variable in length, displacement, and orientation. Two sets of steeply dipping zeolite filled fractures were discovered during the excavation of the Virgil C. Summer nuclear plant. These fracture sets, which were oriented N.28°E. and N.60°W., have undergone oblique slip displacement ranging from several centimeters to a few meters. Numerous fractures with zeolite mineralization, have also been observed in the quarry, east of Monticello Reservoir (Fig. 1) and at the Parr Shoals spillway. Monticello #2 had several zones which exhibited fracturing along with zeolite and carbonate mineralization (Fig. 3). A K-Ar age of 45 ± 5 m.y. has been determined from zeolites along fractures at the nuclear excavation site and is interpreted as a minimum age of movement along the fractures [South Carolina Electric and Gas Company, 1977; Wagener, 1977b]. These occurrences of zeolite filled fractures are interpreted as a Mesozoic deformational event [Privett, 1973, 1974, 1977; Brown and Gilbert, 1977; Butler, 1977; Ragland, 1977; Wagener, 1977b].

Zoback and Hickman [in press] conducted a study on possible mechanisms for induced seismicity caused by impoundment of Monticello Reservoir. Examinations of in situ properties in the Monticello #1 and #2 wells revealed that the earthquakes are resulting from high horizontal stresses which cause thrust type fault motion on naturally existing fracture planes and that the changes in fluid pressure act as a triggering mechanism. Talwani and Rastogi [1979] report a mechanism of pore pressure diffusion which reduces the effective strength in highly stressed rocks and triggers failure.

CONCLUSIONS

This study was undertaken because there was concern that the Wateree Creek fault zone and the induced seismic activity at Monticello Reservoir might pose a threat to the safe operation of the Virgil C. Summer nuclear station. The induced seismicity around the Monticello Reservoir appears to be occurring within the Winnsboro plutonic complex, based on observations of geophysical and geological investigations. The Winnsboro pluton includes variable amounts and distributions of xenoliths and enclaves of country rock. Based on borehole examinations, it is suspected that the irregular character of the magnetic field over the pluton indicates that several subsurface inhomogeneities exist around the area of high seismic activity. Stress measurements within the Monticello #2 borehole indicate that only the top few hundred meters of rock are critically stressed [Zoback and Hickman, in press]. The greatest principal stress is horizontal and thrust type fault motion is thought to be occurring on the naturally existing fracture planes. The numerous and diversely oriented fractures and enclaves within the Winnsboro pluton probably control the seismic activity around Monticello Reservoir. It is unlikely that a steeply dipping to vertical fault, such as the Wateree Creek fault, would be reactivated by the horizontal orientation of the greatest principal stress as observed in Monticello #2.

The boundary between the Winnsboro plutonic complex and the adjacent country rock is an intrusive contact with a narrow zone (300 meters to 1 kilometer) of migmatitic rock between the two units. The boundary does not appear to be offset and is regarded as coherent across the study area. Therefore there is no evidence that the Wateree Creek fault zone is present within the study area. Fault breccia, located within Chapin quadrangle approximately eight kilometers south of the Virgil C. Summer nuclear station, is the northernmost control point of the Wateree Creek fault zone.

It is concluded that it is unlikely that a large magnitude local earthquake will occur in response to the pore pressure and stress changes related to the impoundment of Monticello Reservoir. This conclusion is based primarily on the absence of any through going faults and the small volume of critically stressed rock near the surface in the seismically active region.

CHAPTER V

THE BEDROCK GEOLOGY OF THE POMARIA 7½' QUADRANGLE, SOUTH CAROLINA

INTRODUCTION

The Pomaria 7½' quadrangle is located about sixty-five kilometers northwest of Columbia, South Carolina. It lies entirely within the Charlotte belt, a linear belt of amphibolite-facies metamorphic rocks containing numerous igneous plutons extending southwest-northeast across central South Carolina (Fig. 13). The southern edge of the quadrangle is approximately six kilometers north of the Charlotte belt - Carolina slate belt boundary (Fig. 2).

The mapping of this quadrangle was undertaken as part of a project to complete detailed geologic maps of four quadrangles surrounding Monticello Reservoir in western Fairfield County (Fig. 2). This lake is the site of one of the most thoroughly documented cases of induced seismicity in the eastern United States [Talwani, 1979; Talwani and others, 1978; Talwani and others, 1980]. The purpose of the project is to provide the geologic data necessary to understand the cause of the tremors. Although a number of other geologic studies have been made in the area [McCauley, 1961; Wagener, 1977; South Carolina Electric and Gas Company, 1977], this is the first attempt to complete a detailed geologic map of the quadrangle.

REGIONAL GEOLOGY

The Piedmont of South Carolina is divided into several lithologic belts [King, 1955; Hatcher, 1972]. The Charlotte belt, within which the study area is located, is a belt of amphibolite facies metasedimentary and felsic to mafic metavolcanic rocks. A number of pre- to post-metamorphic plutons intrude these metamorphic rocks. The Charlotte belt is interpreted to be part of a magmatic arc active during Proterozoic Z and Cambrian times [Butler and Ragland, 1969; Whitney and others, 1978]. Regional magnetic and gravity highs over the area have been interpreted as indications that the Charlotte belt and much of the Carolina slate belt are underlain by mafic crust [Hatcher and Zietz, 1980].

The rocks to the south in the Carolina slate belt are greenschist facies metasedimentary and felsic to intermediate metavolcanic rocks which can be divided into mappable stratigraphic units. Peck [1981] described the slate belt units found to the south of the study area in the Chapin and Little Mountain quadrangles (see Chapter III). The metasedimentary and metavolcanic rocks have been locally intruded by igneous rocks of various ages, although these intrusions are less abundant than in the Charlotte belt. The rocks of the slate belt were deposited during the Proterozoic Z and Cambrian time, as indicated by geochronological studies [Carpenter and others, 1978] and recently confirmed by the discovery of numerous Middle Cambrian trilobites by University of South Carolina graduate student Sara Samson near the Clouds Creek pluton in the Batesburg quadrangle [Samson and others, 1982]. Metamorphism in the Carolina slate belt was probably roughly contemporaneous with that in the Charlotte belt. Whole-rock K-Ar studies in the slate belt of North Carolina indicated a probable early Ordovician age for this episode of regional metamorphism [Kish and others, 1979].

Three different generations of igneous activity have been defined within the Charlotte and Carolina slate belts [Fullagar, 1971; Fullagar, 1981]. Members of all three groups occur in the study area. The first predates the main metamorphic event and is represented by the granitic gneiss unit (Єggn) in the Little Mountain quadrangle and the granitic orthogneiss within the felsic gneiss unit (Єfgn) in the present study area. These carry the S_1 foliation. A zircon age of 550 m.y. [James Wright, personal cummunication, 1982] has been determined for the Єggn unit in the Chapin quadrangle southeast of the study area. Previous Rb-Sr dating by Fullagar [1971] had placed the group in the age range of 545-495 m.y. The second generation is the 415 to 385 m.y.-old group of plutons. In the study area it is represented by the 415 m.y.-old Newberry granite (Sn) [Fullagar, 1981]. These postdate the main metamorphic event and do not contain a penetrative deformation fabric. The final episode of igneous activity is a group of 320 to 280 m.y.-old plutons, which are represented by the Winnsboro pluton (Cw) and possibly the Pomaria granite (Cp). These do not exhibit signs of penetrative deformation and are considered to be post-metamorphic in age. This group probably includes a quartz syenite body discovered near the Pomaria quadrangle - Newberry East quadrangle boundary.

All of the above units are cut by a number of northwest trending diabase dikes. These are the youngest rocks present, and are of probable Late Triassic - Early Jurassic age.

ROCK DESCRIPTIONS

Six rock units have been identified within the Pomaria quadrangle, two metamorphic and four igneous. These are amphibolite (Єa) and felsic gneiss (Єfgn), both Cambrian in age; Newberry granite (Sn), Silurian in age; the Winnsboro pluton (Cw), Carboniferous; Pomaria granite (Cp), possibly Carboniferous; and diabase dikes (Jd), Jurassic or Triassic in age. A description of each follows.

Amphibolite (6a)

The amphibolite unit is limited to the southeastern portion of the study area with the exception of a few lenses within the felsic gneiss unit (6fgn) (Fig. 2, and Plate IV). It includes both amphibolite and hornblende gneisses with occasional biotite paragneiss or granitic orthogneiss layers too thin to be mapped separately. A foliation is generally well defined in the rock, though in a few locations the amphibolite is massive, with no distinct mineral orientation at either the megascopic or microscopic level. The well foliated amphibolites interlayered with paragneisses are interpreted to be metamorphosed mafic tuffs. Some of the massive amphibolites may be metamorphosed mafic flows or mafic intrusive rocks. One sample of massive amphibolite (number 4903 in Table 1) contained considerable amounts of pyroxene, which otherwise is limited to contact aureoles of the granites. Bourland and Farrar [1980] interpreted some of the amphibolites near the Winnsboro plutonic complex to the east of the study area to be of intrusive origin.

Hornblende is the predominant mineral present in the amphibolites, comprising from 50-75% of the rock. The crystals are subhedral to anhedral, prismatic in habit, pleochroic with x = pale green to yellow green, y = olive green to brown, and z = dark blue green to dark green.

Plagioclase usually occurs in short, unzoned, subhedral crystals with no apparent orientation with respect to foliation. Using the Michel-Lévy method, plagioclase compositions were determined to range from An_{28} (oligoclase) to An_{65} (labradorite). Most values fell in the range from An_{35} to An_{40} (andesine). Plagioclase generally makes up from 15 to 30% of the rock.

Anhedral quartz is present in amounts ranging up to 8% of the rock volume, although it more commonly comprises only 2-4% of the total. Quartz

SAMPLE NUMBER	QUARTZ	HORNBLENDE	PLAGIOCLASE	SPHENE	BIOTITE	MUSCOVITE	K-FELDSPAR	EPIDOTE	GARNET	CHLORITE	OPAQUES	PYROXENE
0601	X	X	X	X	X	T	0	X	0	X	X	0
1804	X	X	X	X	X	0	0	X	0	0	X	0
2001	X	X	X	0	0	0	0	X	0	0	X	0
2605	X	X	X	0	X	0	0	X	0	0	X	X
4903	X	X	X	0	0	0	X	X	0	0	T	X
5906	X	X	X	T	X	0	X	X	0	X	X	0
6704	X	X	X	X	0	0	0	X	0	X	X	0
6809	X	X	X	0	T	0	0	0	0	0	X	0
7003	X	X	X	X	T	0	0	X	0	T	X	0
7004	X	X	X	0	X	0	0	X	X	0	X	0

X = mineral present in amounts greater than 1%

T = mineral present in amounts less than 1%

0 = mineral not present

Table 8. Metamorphic mineral assemblages for amphibolites (Ga) from the Pomaria quadrangle.

nearly always exhibits moderate undulose extinction as the result of strain.

Epidote is present in nearly all the amphibolites, occurring in small subhedral grains. Often it is congregated in small aggregates. The amphibolite contains up to 7% of this mineral.

Garnet is present in only a few of the samples. It occurs as large, highly fractured crystals which show considerable alteration around the rims, with associated growth of plagioclase, quartz, and chlorite. Inclusions are common but appear to lack a preferred orientation. Garnet was not reported as occurring in amphibolites in the Jenkinsville quadrangle [Smith, 1982] or the Little Mountain quadrangle [Peck, 1981], although in all other respects these are very similar compositionally to amphibolites in the Pomaria quadrangle. From its occurrence garnet is interpreted to be metastable during the last episode of deformation.

Other components of the amphibolite include sphene (0-3%), biotite (0-2%), secondary chlorite (0-3%), opaque oxides (trace-4%), potassium feldspar (0-trace), and trace amounts of muscovite, apatite, zircon, and pyrite.

Amphibolite which occurs as xenoliths within the Winnsboro pluton and within approximately 100 meters of the granite-country rock contact show signs of contact metamorphism. Minerals show a large reduction in grain size and quartz has recrystallized into polygonal, relatively unstrained subgrains. Clinopyroxene, diopsidic in composition, appears with a corresponding decrease in the amount of epidote present.

Felsic Gneiss (Єfgn)

The felsic gneiss unit is composed of two main rock types - biotite paragneiss and granitic orthogneiss, with minor amounts of amphibolite and hornblende gneiss. These are often interlayered, with biotite paragneiss predominating in the southern portion of the quadrangle, and granitic orthogneiss becoming more common northward. This interlayering of thin sheets of each rock type along with the generally poor exposure prevent mapping these as separate units. The petrography of the paragneiss and orthogneiss will be discussed individually, however.

This unit is essentially the equivalent of the Charlotte belt gneiss unit of Wagener [1973], McCauley [1961], and South Carolina Electric and Gas Company [1977]. The only difference is that the amphibolite has been separated out as a separate unit whenever possible.

Biotite paragneiss. The biotite paragneiss always carries a distinct foliation defined by alignment of biotite and muscovite. Strike of the paragneiss is quite consistent over the southern portion of the study area, averaging about N.70°E.

Felsic stringers and pods parallel to foliation occur frequently within the paragneiss. These are granitic in nature, being composed almost entirely of quartz, plagioclase, and some potassium feldspar. It is unknown whether these are related to synmetamorphic differentiation or the intrusion of the granitic orthogneiss.

The biotite paragneiss is highly variable in composition, ranging from a hornblende-biotite gneiss to a muscovite schist. Although biotite was present in all samples, the amount varied from 2-25% of the rock volume. It is pleochroic, from light brown to dark brown or green-brown.

Plagioclase is generally the most abundant mineral present. As in the amphibolite, it occurs as short subhedral crystals with no apparent preferred orientation. Michel-Lévy determinations of composition yielded an average value of An_{34} (andesine).

Quartz occurs in subhedral grains which exhibit undulose extinction. In general, it is more abundant in the paragneiss than in the amphibolite, comprising as much as 15% of some samples. It is considerably more abundant in the granitic stringers and pods occurring within the paragneiss.

Muscovite is found in most but not all samples of the paragneiss. It is exceptionally abundant in a small area in the southwestern corner of the quadrangle, from near Taylors Crossroads eastward for about three kilometers. In portions of this area the rock is a muscovite schist, with that mineral comprising nearly 50% of the rock. Protolith composition must have been more aluminous in this area. Elsewhere, muscovite totals less than 10%.

Other minerals occasionally present in the paragneiss include hornblende, potassium feldspar, sphene, and epidote. Opaque oxides in minor amounts are found in all samples.

In the large enclave of the felsic gneiss unit in the western part of the study area (Plate IV), the biotite paragneiss shows signs of contact metamorphism from the surrounding Newberry granite. A high-grade assemblage of biotite, quartz, plagioclase, garnet, sillimanite, green spinel, and opaques is present. Garnet crystals are euhedral and contain many large inclusions. The sillimanite and spinel occur within what appear to be outlines of crystals which have been totally altered. This rock is part of a band of slightly higher grade rocks which stretch east-west across the quadrangle. This band will be discussed in more detail at a later point.

<u>Granitic orthogneiss</u>. The granitic orthogneiss is found throughout the felsic gneiss unit but is most abundant in the northern part. It is interlayered with biotite paragneiss and some amphibolite. It occurs as concordant sheets of granitic material which exhibit sharp, well defined contacts with the other rock types.

The orthogneiss is composed primarily of quartz, plagioclase, and potassium feldspar. Common accessory minerals include muscovite, biotite, and opaque oxides, with minor amounts of epidote, garnet, zircon, and secondary chlorite (Table 9).

The foliation in the rock is defined by elongated quartz grains. Large quartz grains present in the original rock have become elongated during deformation, recrystallizing into less strained subgrains. These elongated quartz aggregates distinguish the orthogneiss from the flow-foliated portions of the Pomaria granite.

Potassium feldspar is usually more abundant than plagioclase. Both occur as subhedral crystals with no apparent orientation with respect to foliation. Plagioclase is often highly altered and in places only the outline of the former crystal remains. The potassium feldspar is in the form of microcline. As in the amphibolite, accessory garnets are altered along fractures and do not appear to be completely stable under terminal metamorphic conditions.

Newberry Granite (Sn)

The Newberry granite is widespread over the northern portion of the study area. It is an extensive plutonic complex, extending from west of Newberry eastward for some 30 kilometers into the Salem Crossroads and Jenkinsville quadrangles. The Newberry has apparently been intruded as a number of sheets, partly concordant to concordant with the foliation in the area. These vary considerably in thickness, upwards from a few meters. This, along with the extensive weathering of the granite, prevents a very accurate representation of the outcrop pattern on the geologic map of the quadrangle. It is certain that even in the areas shown as all Newberry

SAMPLE NUMBER	QUARTZ	HORNBLENDE	PLAGIOCLASE	K-FELDSPAR	BIOTITE	MUSCOVITE	SPHENE	EPIDOTE	GARNET	CHLORITE	OPAQUES	
0305	X	O	X	T	X	X	O	T	O	O	X	
1001	X	O	X	O	X	X	O	O	X	O	X	
1101	X	O	X	O	X	X	O	O	O	O	X	
1802	X	O	X	O	X	X	O	O	X	X	X	BIOTITE
4101	X	O	X	O	X	O	O	O	O	O	X	PARAGNEISS
6602	X	O	X	O	X	X	O	O	O	O	X	
3502	X	X	X	X	X	O	X	X	O	X	X	
6604	X	X	X	O	X	O	X	X	O	O	X	
1801	X	O	X	X	X	X	O	X	O	X	X	
2301	X	O	X	X	X	X	O	O	O	O	X	
6007	X	O	X	X	X	X	O	O	O	O	X	GRANITIC ORTHOGNEISS
6301	X	O	X	X	O	X	O	O	O	O	X	
6802	X	O	X	X	O	O	O	X	T	O	X	

X = mineral present in amounts greater than 1%

T = mineral present in amounts less than 1%

O = mineral not present

Table 9. Metamorphic mineral assemblages for biotite paragneiss and granitic orthogneiss within the felsic gneiss unit (Єfgn) of the Pomaria quadrangle.

granite there are enclaves of metamorphic rock that have not been recognized because of sparse exposure and extensive weathering.

The Newberry granite is a generally quite homogeneous, fine- to medium-grained rock which compositionally lies near the quartz monzonite-monzogranite boundary on the APQ diagram (see Figure 23). It is composed primarily of quartz, plagioclase, potassium feldspar, and biotite. Minor amounts of muscovite and opaques are generally present, with traces of epidote, sphene, and zircon. Hornblende was not observed in thin section, although it was present in a hand sample taken from a boulder near the western edge of the Pomaria quadrangle just north of South Carolina highway 34.

Five thin sections were point counted to determine mineral percentages. The results of the point counts are shown in Table 10. In all cases plagioclase was the most abundant mineral, comprising between 34 and 44% of the rock volume. It occurs as subhedral crystals, with larger grains often showing extensively sericitized cores. Zoning is also prevalent in the larger crystals, with calcic cores and more soda-rich rims. Average plagioclase composition fell in the oligoclase range (An_{24}).

Potassium feldspar was always the second most abundant mineral present, with 29 to 40% of total volume. It occurs as subhedral microcline crystals. Quartz totaled between 13 and 24% of the rock. Most samples fell in the range of 19 to 20% quartz. This mineral occurs as small anhedral grains which show at most slight undulose extinction. The only other major mineral present was biotite, with 3 to 8% total. Distinct orientation of biotite crystals was evident in only one sample, number 0403, which was collected from a thin (less than 1 meter thick) sheet of granite within amphibolite. This preferred orientation probably is the result of flow during emplacement.

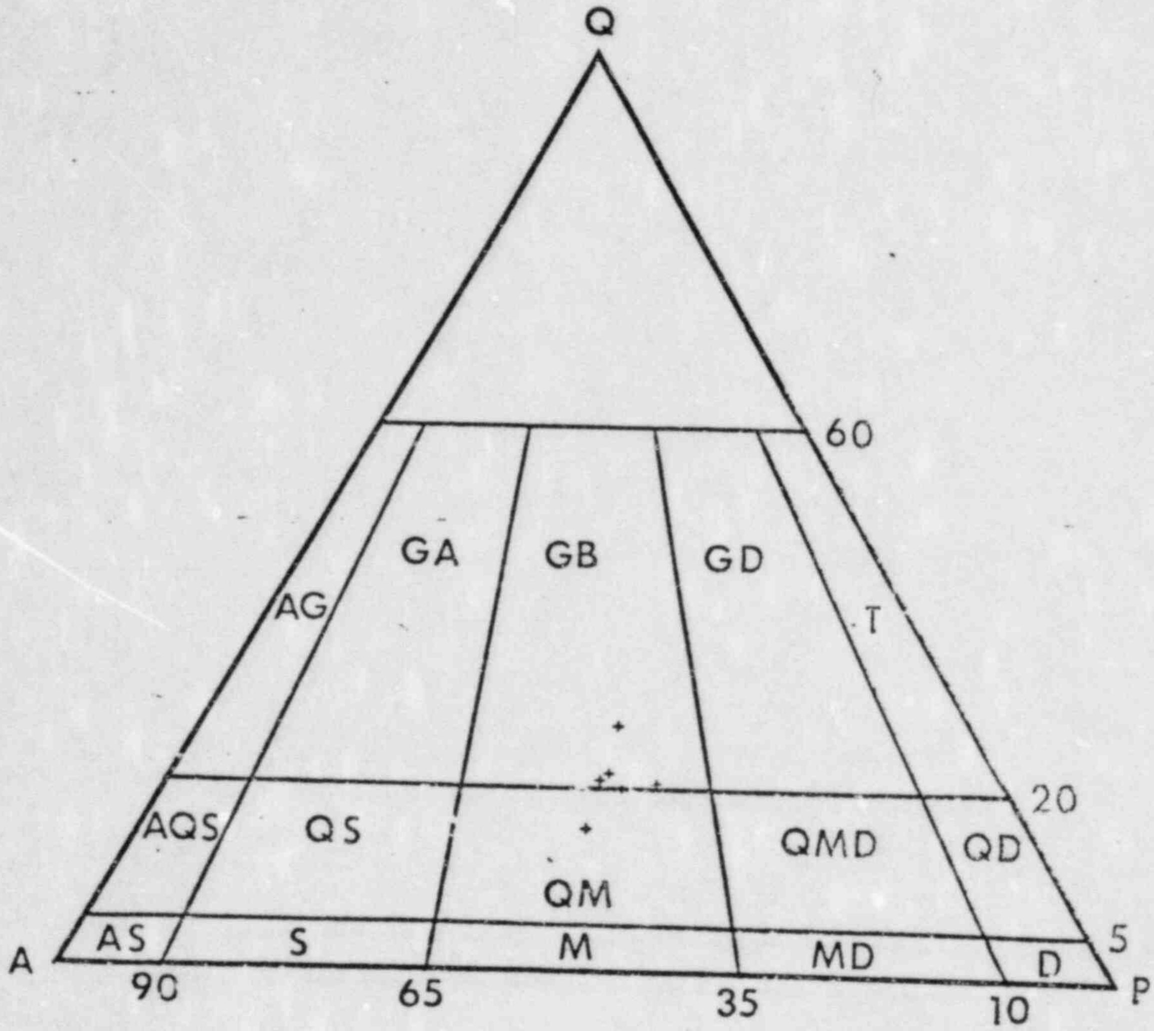

Figure 23. APQ diagram showing the modal variation for the Newberry pluton (+) in the Pomaria quadrangle. Diagram after Streckeisen [1967].

SAMPLE NUMBER	QUARTZ	PLAGIOCLASE	K-FELDSPAR	BIOTITE	MUSCOVITE	OPAQUES	EPIDOTE	HORNBLENDE	SPHENE	GARNET	NUMBER OF POINTS
					NEWBERRY GRANITE						
BL-1	19	42	33	4	1	1	T	0	0	0	1000
WS-1	20	38	34	5	1	2	0	0	T	0	1000
2905	20	44	31	4	1	T	0	0	0	0	700
0403	19	37	34	7	2	1	0	0	0	0	600
0901	24	34	29	8	2	2	1	0	T	0	1000
BQ*	13	42	40	3	1	1	0	0	0	0	1000
					POMARIA GRANITE						
6203A	42	28	28	T	1	1	0	0	0	T	1000
6203B	32	39	27	0	1	1	0	0	0	0	1000
6203	27	24	46	T	0	3	0	0	T	0	700
					WINNSBORO GRANITE						
3303	14	44	22	12	T	3	1	4	0	0	1000
4101	16	53	5	25	T	1	0	0	0	0	1000
4601	20	44	17	13	2	4	0	0	0	0	1000

*From Smith [1982].

Table 10. Modal mineralogical data for the Newberry, Pomaria and Winnsboro plutons in the Pomaria quadrangle. Modes were obtained by counting thin sections, with the numbers of points indicated in the table.

The Newberry pluton as a whole does not show any evidence of deformation. There is an indistinct compositional layering noted at Lone Star Industries' Blair quarry (in the Blair quadrangle), but this is nonuniform over any distance and certainly does not represent a throughgoing fabric. Fullagar [1981] reports a Silurian Rb-Sr whole rock age of 415 ± 9 m.y. for this granite. The initial $^{87}Sr/^{86}Rb$ ratio of .7024 is extremely low and implies a lower crustal origin [Fullagar, 1971].

The Newberry granite is distinct from the Winnsboro and Pomaria igneous bodies in several ways. It is generally finer-grained, in most cases has a higher muscovite content, and contains a few xenoliths. Many of the "xenoliths" in the Blair quarry are mafic mineral clots composed almost entirely of biotite. Pitcher [1979] suggests clots of this nature are the result of re-equilibration between liquid and crystal fractions during ascent and emplacement. This results in the removal of the mafic constituents into the dark clots which then settle out.

The Newberry, like the Winnsboro, seems to have at least two distinct facies distinguished by differences in grain-sizes. There are areas in which the grain-size of the Newberry is noticeably larger, just as there are locations where a fine-grained phase of the Winnsboro exists. Speer, Becker, and Farrar [1980] contend that in many cases intrusive contacts exist between the different facies of the Winnsboro plutonic complex and this may also be the case with the older Newberry granite.

Winnsboro Plutonic Complex (Cw)

The Winnsboro pluton is found in the central section of the study area (Fig. 2, and Plate IV). It is apparently the same pluton which extends from the Winnsboro area westward into the Jenkinsville quadrangle as mapped by

Smith [1981]. Extensive work has been done on this complex by a number of workers, including Wagener [1970, 1973, 1977], Farrar [1977], Farrar and Becker [1977], and South Carolina Electric and Gas Company [1977].

The Winnsboro has been determined to be of Carboniferous age as the result of Rb-Sr and K-Ar dating [South Carolina Electric and Gas Company, 1977; Fullagar, 1981; Fullagar and Kish, 1981]. These dates range from 309 to 286 m.y., thus placing the Winnsboro in the group of 300 million year old postmetamorphic plutons. There is no evidence of deformation within the granite body, although a weak fabric defined by alignment of tabular potassium feldspar crystals has been observed near the contact with surrounding country rocks. In these areas xenoliths are also aligned parallel to subparallel with the contact. These features are probably the result of flow during emplacement.

Outcrop of this unit is very sparse due to extensive weathering. Unweathered material has been found in only a few streams in the western portion of the quadrangle where the pluton is highly charged with xenoliths. Elsewhere, only a few residual boulders remain. The streams in the area, however, form a distinctive drainage pattern by which the extent of the pluton can be approximated. Stream valleys are very wide and the sides have a gentle slope. The pluton is also very well defined on the aeroradiation map (Fig. 24), where it shows as a distinct radiation high. The body is not as well defined on the aeromagnetic map (Fig. 4). This may be due to the large number of xenoliths and enclaves present. Drilling near the site of the V. C. Summer nuclear station revealed significant amounts of gneiss and amphibolite present at depth [South Carolina Electric and Gas Company, 1977].

The most striking feature of the Winnsboro pluton is the abundance of xenoliths, especially near the contact with surrounding metamorphic rocks.

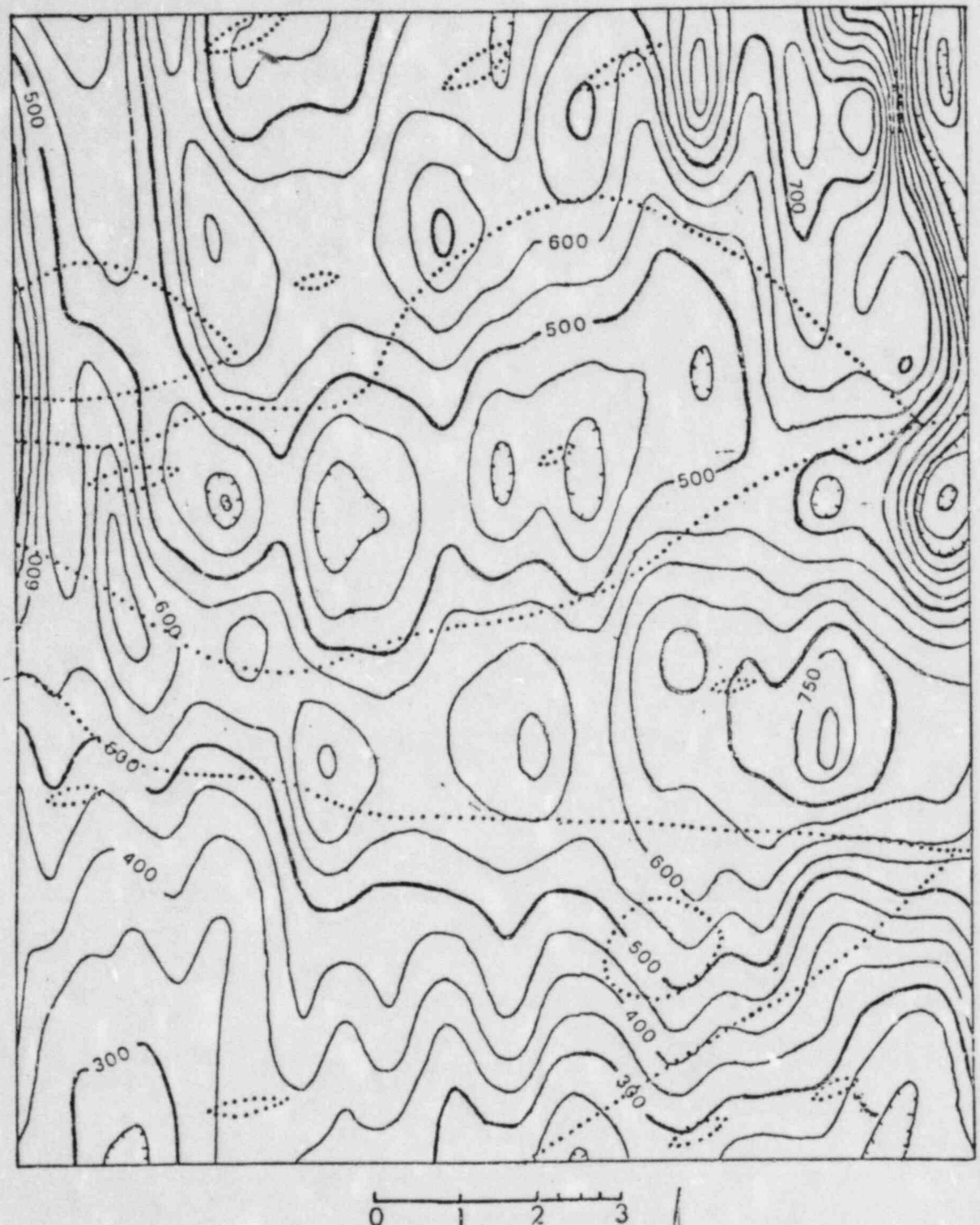

Figure 24. Aeroradiation map of the Pomaria quadrangle. Contour interval is 50 counts per second. From the U. S. Geological Survey [1978]. Dotted lines are geological contacts from Plate IV.

In contrast with the Newberry granite, the Winnsboro does not exhibit sharp contacts with surrounding rocks, but rather seems to have been injected along fractures and joints. The mapped contact was based upon the last appearance of significant amounts of the medium-grained granitic material within the country rock. As one traverses inward into the pluton, the number of xenoliths decrease, although a number of xenoliths and enclaves were observed well into the interior portion of the body.

Compositionally, the pluton generally falls into the quartz monzonite or monzogranite field on the APQ diagram [Wagener, 1973; Smith, 1982]. Modal analyses taken on three thin sections produced a wide scattering of points on the diagram (see Figure 25). Upon staining of the rock slabs for potassium feldspar, it was shown that distribution of the feldspars is very uneven. Potassium feldspar percentage in the slabs was estimated to be considerably higher than that in the thin sections, and thus the points in the figure are misleading. Due to the uneven potassium feldspar distribution, a larger number of point counts are needed to accurately determine the composition of this plutonic complex.

The major minerals present in the Winnsboro are plagioclase, potassium feldspar, quartz, and biotite. Common accessories are muscovite and opaque oxides, with occasional epidote and hornblende.

Plagioclase is the most abundant occurring mineral. Crystals are generally subhedral, highly zoned, and often exhibit considerable alteration and sericitization within the cores. Average composition was determined to fall within the oligoclase range. Quartz is present as anhedral, relatively unstrained grains. Myrmekitic intergrowth with potassium feldspar is common. The potassium feldspar occurs in the form of anhedral to subhedral microcline, with the larger crystals most often showing the distinct crystal faces.

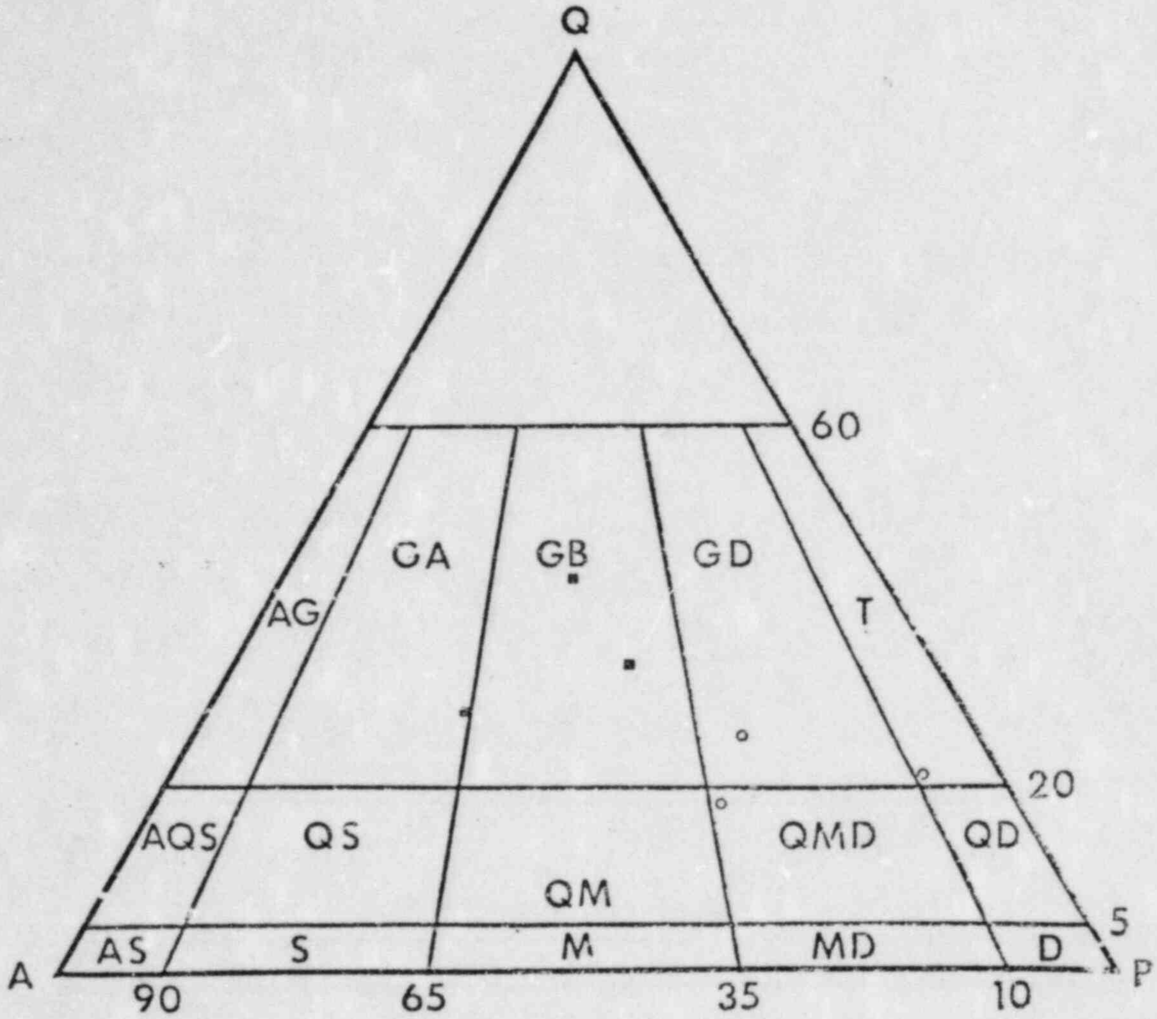

Figure 25. APQ diagram showing the modal variation for the Winnsboro pluton (o) and the Pomaria pluton (▪) in the Pomaria quadrangle. Diagram after Streckeisen [1967].

Biotite is quite common in the rock, comprising as much as 25 percent of some samples. The high percentages shown in Table 10 are thought to be the result of contamination due to the assimilation of country rock during emplacement. All three thin sections analyzed come from areas with significant amounts of xenoliths present. In weathered material taken from areas where few or no xenoliths were observed, biotite appeared to be significantly less abundant.

Hornblende is present in one of the thin sections and was noted in several hand samples. This mineral has been identified in a number of the postmetamorphic plutons of the southern Piedmont [Speer, Becker, and Farrar, 1980]. Within the Winnsboro pluton its distribution appears to be quite uneven. In the case of the Bald Rock batholith in northern South Carolina, van Gelder and McSween [1981] suggest the presence of hornblende is due to the assimilation of mafic country rocks. This may possibly be the case with the Winnsboro as well, as within the study area hornblende was observed only where the granite contained xenoliths.

Pomaria Granite (Cp)

The Pomaria granite is a small, roughly circular body centered near the town of Pomaria. Primary exposure is at an abandoned quarry just north of U. S. highway 176. The only other exposure is a few boulders within the town itself. Excellent constraint on the extent of the granite to the south is provided by exposures of biotite paragneiss on U. S. 176 and the road leading to the quarry.

The granite is assumed to be postmetamorphic due to the occurrence of undeformed material within it. Most of the rock, however, carries a weak to strong fabric, presumably related to flow during emplacement. The granite clearly intrudes surrounding country rocks as is shown by the presence of xenoliths. Although interpreted here as Carboniferous in age, no dating on this body has yet been performed. It is presumed to be Carboniferous solely on the basis of lack of deformation throughout the body.

The Pomaria granite is extremely inhomogenous as the results of point counting show in Table 10 and the APQ diagram in Figure 25. Large variations in both composition and grain-size occur over very short distances. Within any one sample, however, the granite is relatively equigranular. The average composition plots well into the granite B field owing to the high quartz content, in one case 42% of the rock. The other major minerals present are plagioclase and potassium feldspar. The results of staining for potassium content as well as the point counts indicated large variations in the amounts of potassium feldspar and plagioclase present. Both of these minerals occur in generally subhedral crystals. Myrmekite is common. One unusual feature of the rock is the near absence of biotite. It is quite leucocratic, with no more than 3% dark minerals, mostly opaques. Other minerals present include muscovite and traces of sphene and garnet. The garnet was observed in only one sample which was taken from an area where xenoliths were abundant. It is unclear whether the garnet is the result of contamination or was an original component of the granite.

Other Rock Types

Several diabase dikes cross the study area. These have an orientation from about N.15°W. to N.30°W. and are steeply dipping to vertical. Paleomagnetic study of a number of dikes in the central South Carolina Piedmont by R. E. Dooley and W. A. Smith [1982] indicated a Late Triassic and/or Early Jurassic age. Compositionally, the diabase dikes are olivine tholeiites.

A quartz syenite has recently been discovered just to the west of the boundary between the Pomaria and Newberry East quadrangles in the area south of Keitts Crossroads. It is possible that the body extends slightly into the study area. The quartz syenite is unfoliated and contains numerous xenoliths of varying composition. Minerals present in the rock include potassium feldspar, quartz in myrmekite, plagioclase, orthopyroxene, clinopyroxene, opaque oxides, and secondary hornblende. This composition indicates a very hot, dry magma. Further work needs to be done on this body to determine its extent and relationships with surrounding rocks.

The only other rock types present in the study area are numerous postmetamorphic aplite and pegmatite dikes which occur in all the different units.

STRUCTURAL GEOLOGY

With the complex geology in the Charlotte belt, it is difficult to determine the deformational history of the area. In addition, the lack of exposure limits the amount of structural data available. One foliation (S_1) is observed in the metamorphic rocks. It is quite consistent in orientation over the extreme southern portion of the quadrangle but becomes more variable as the granites are approached. This foliation is the result of the earliest recognizable deformational episode (D_1). Timing of D_1 must be Silurian or older, as the 415 m.y.-old Newberry pluton contains rotated xenoliths which carry the S_1 foliation. The D_1 deformational event also produced tight to isoclinal F_1 folds with axial planes parallel to foliation. These F_1 folds have been observed in the biotite paragneiss in many parts of the quadrangle.

In several locations the S_1 foliation has been disrupted by F_2 folds. The axial planes of the F_2 folds are nearly perpendicular to the S_1 foliation.

Figure 26 is a plot of poles to S_1 foliation in the Pomaria quadrangle showing the folding of S_1. Rotated xenoliths within the Winnsboro pluton have been observed to contain F_2 folds. As the Winnsboro is undeformed, the D_2 deformational event forming the folds must be older than the 300 m.y.-old granite.

Faulting in the area of study is limited to small ductile offsets, although a number of brittle faults have been discovered to the south in both the Little Mountain and Chapin quadrangles. One of these is the north-south Summers Branch fault mapped by Peck [1981]. If projected several more kilometers to the north, it would extend into the southeastern corner of the Pomaria quadrangle. However, no evidence for the existence of this fault in the study area has been found. A diabase dike of probable Late Triassic or Early Jurassic age has been found to cut across the north-south Wateree Creek fault zone in the Chapin quadrangle [Secor and others, 1981]. This indicates that most of the movement on the fault occurred prior to about 190 m.y. ago.

In the metamorphic rocks to the north of the Winnsboro pluton, the metamorphic grade seems to be slightly higher than in the rocks to the south. Sillimanite is present in some rocks, and the schistosity common in the paragneiss to the south of the granites is no longer present. This schistosity returns to the rocks as one progresses northward into the Blair quadrangle. Overall composition of the metamorphic rocks remains fairly constant. Possibly the additional heat brought in by the granites could be responsible for the higher grade. Certainly both the Winnsboro and Newberry plutons contact metamorphosed surrounding country rocks. The sillimanite has been found only in the immediate vicinity of the granites. Pyroxene is also found in the contact aureoles.

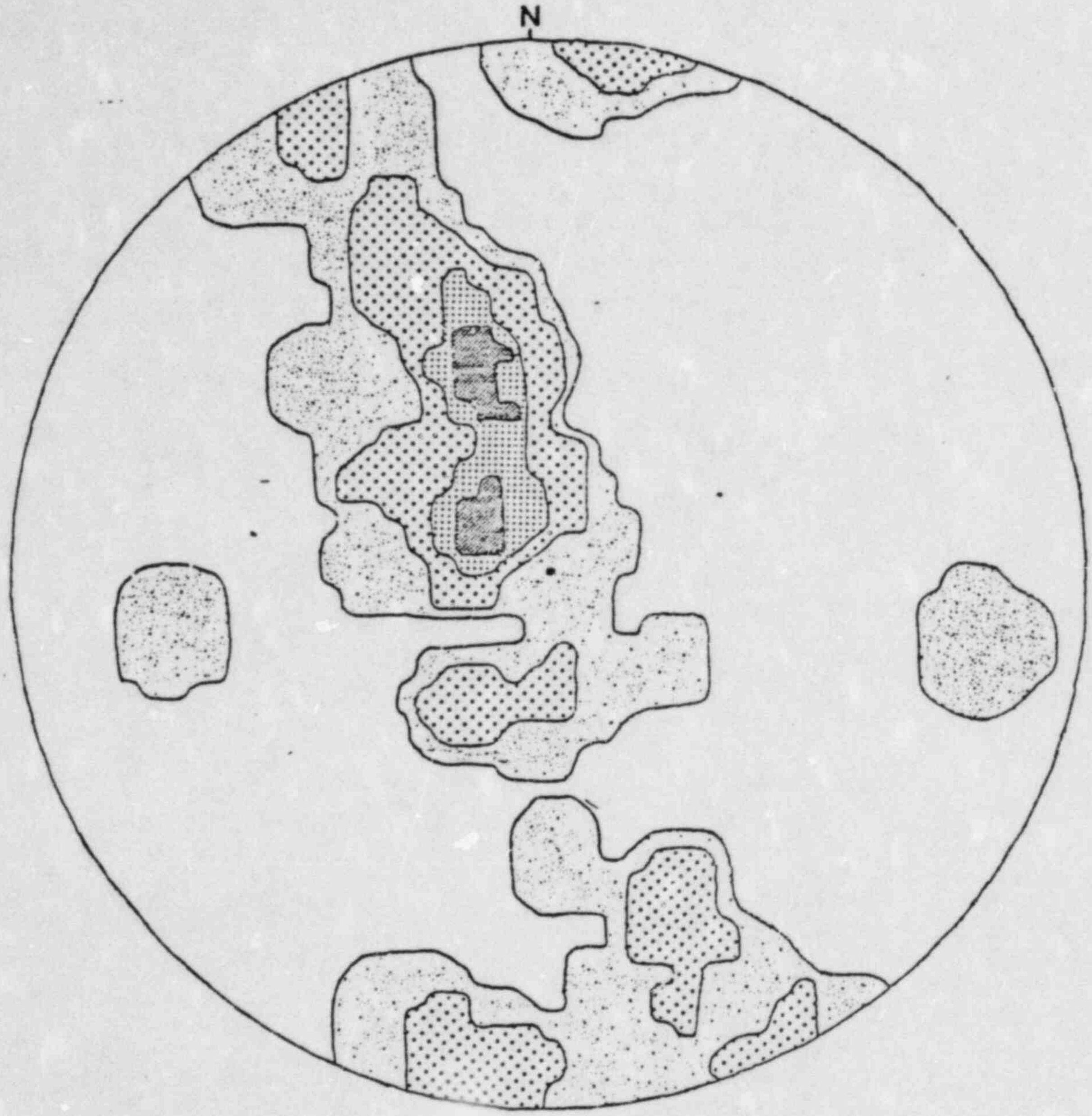

Figure 26. Lower hemisphere, equal-area projection of poles to 97 S_1 foliation planes measured in the Pomaria quadrangle. Contours: 1, 3, 9 and 15%.

Another possibility is that this area forms the core of an antiformal structure. The increased burial depth along with the additional heat of the granites might easily be enough to slightly increase the metamorphic grade. Rocks to the north in the Blair quadrangle closely resemble the paragneiss, orthogneiss, and amphibolite in the Pomaria quadrangle. Strike once again becomes consistent, with dips to the southeast. If this is an antiform, the northern limb of the structure would be overturned.

CONCLUSIONS

The Pomaria 7½' quadrangle is located within the high-grade metamorphic region known as the Charlotte belt. Six mappable rock units, two of them metamorphic and four igneous, occur in the study area. Contacts between units are largely approximate and in the case of the contact between the main amphibolite unit (Єa) and the felsic gneiss unit (Єfgn) it may be gradational. Three distinct episodes of igneous activity occur in the study area. Granitic rocks are considerably more abundant than originally believed. The Winnsboro pluton stretches east-west across the quadrangle while a large part of the northern third of the study area is underlain by Newberry granite.

The study area has experienced at least two phases of deformation. The earliest and strongest produced the amphibolite facies metamorphism and the S_1 foliation. The second produced F_2 folding but no overprinting cleavage or foliation. The time of the deformational events is somewhat constrained by the dated igneous rocks present.

Several problems remain to be solved in the area. One is the determination of whether the amphibolite facies metamorphic rocks of the Charlotte belt are in any part correlative with the greenschist facies metamorphic rocks of the Carolina slate belt. Although McCauley [1961] concluded from geochemical studies that the rocks in the two belts are not correlative, further work of this type needs to be done. Another area of needed study is the dating and mapping of the quartz syenite on the western border of the quadrangle. Recent field work revealed that this body is of mappable size. Rocks of this type elsewhere in the Piedmont are often associated with mafic plutons and more detailed mapping in the Newberry East quadrangle could determine if this is the case here as well. Age dating also needs to be done on the small Pomaria granite to see if it is a member of the post-metamorphic group of plutons.

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