

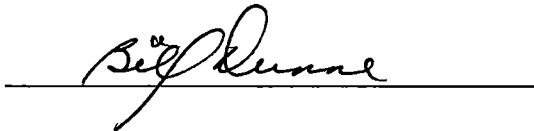
To the Graduate Council:

I am submitting herewith a thesis written by Joseph Christopher Hill entitled "Stratigraphy, Structure, and Tectonics of Part of the southern Appalachian Inner Piedmont near Marion, North Carolina." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geology.



Robert D. Hatcher, Jr. Major Professor

We have read this thesis and
recommend its acceptance:



Accepted for the Council:



Associate Vice Chancellor and
Dean of The Graduate School

**STRATIGRAPHY, STRUCTURE, AND TECTONICS OF PART
OF THE
SOUTHERN APPALACHIAN INNER PIEDMONT,
NEAR MARION, NORTH CAROLINA**

A THESIS
PRESENTED FOR THE
MASTER OF SCIENCE DEGREE
UNIVERSITY OF TENNESSEE, KNOXVILLE

Joseph C. Hill

August, 1999

This thesis is dedicated to the two
most important women in my life:

My wife:

Kristin Taylor Hill

My love, for the encouragement, the assistance, for everything.

This isn't enough.

and

My mother:

Lorene R. Hill

You always had faith. Thank you.

ACKNOWLEDGEMENTS

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ABSTRACT

This thesis presents the results of a field and laboratory study of the Marion East 7.5 minute quadrangle and the compilation, reconnaissance mapping, reinterpretation of contacts, and field checking of southern half of the published Marion West 7.5 minute quadrangle. The study area is located within the western Inner Piedmont approximately 50 km (35 mi.) east of Asheville, North Carolina. The Inner Piedmont is the Acadian metamorphic core of the southern Appalachians. A recognizable stratigraphy exists in the study area and in the Inner Piedmont, at least as far east as the Six Mile fault. This stratigraphy consists of the Tallulah Falls (Ashe) Formation unconformably overlain by the Poor Mountain Formation, both of which have been tectonically overridden by the Henderson Gneiss. No Grenville basement has been recognized in the study area. A minimum of three orogenic events have affected the study area: Taconic-Penobscott, Acadian, and Alleghanian. The study area has undergone at least 5 episodes of deformation and a single episode of prograde metamorphism. D_1 is thought to be Taconic; D_2 and D_3 are associated with the Acadian orogeny; and D_4 and D_5 are attributed to the Alleghanian orogeny. Peak metamorphism and penetrative deformation is associated with the D_2 event. Peak metamorphic conditions in the study area correspond to the first sillimanite zone, although most of the study area is at kyanite grade and only the southeast portion is at sillimanite grade. Metamorphic pressures and temperatures inferred from this study are 5-6.5 kb and 535-675 °C, respectively. Cooling curves were created using hornblende and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages. Results indicate that the peak D_2 event probably occurred between 378 and 386 Ma. To better understand the tectonics of the western Inner Piedmont, a tectonic model is presented to explain both orogen-parallel and orogen-oblique Acadian structures in the Inner Piedmont. The

model involves an oblique collisional event between the Inner Piedmont microcontinent and Laurentia followed by clockwise rotation of the Inner Piedmont before final accretion.

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Chapter I

Introduction

The Appalachian Inner Piedmont is a polydeformed and highly metamorphosed terrane composed of a stack of northwest- to west-vergent thrust sheets (Hatcher, 1993). In general, the dominant rock assemblages are pelitic schist, biotite gneiss, metagraywacke, granitic gneiss, amphibolite, and amphibole gneiss. Semiconcordant bodies of granitic rocks and ultramafic rocks are also present. Structurally, the Inner Piedmont is bounded on the northwest by the Brevard fault zone and on the southeast by the Central Piedmont suture (Fig. 1-1). Stratigraphic evidence, however, suggests that the northwest boundary of the tectonic province is located across the Brevard fault zone into the eastern Blue Ridge (Hatcher, 1972, 1978a, 1993; Hopson and Hatcher, 1988; Davis, 1993a).

The sediments that produced the rocks found in the Inner Piedmont have been interpreted to be Late Proterozoic to Early Cambrian rifted-margin and slope-rise type sequences deposited on probable oceanic basement subsequent to the rifting of Laurentia (Hatcher, 1987). Three separate orogenies, the Taconian-Penobscottian, Acadian, and Alleghanian, deformed and metamorphosed the rocks of the Inner Piedmont during the Ordovician, Devonian, and Pennsylvanian-Permian, respectively (Fig. 1-2). The Inner Piedmont is the Acadian metamorphic core of the southern Appalachians (Davis, 1993a; Hatcher, 1998a).

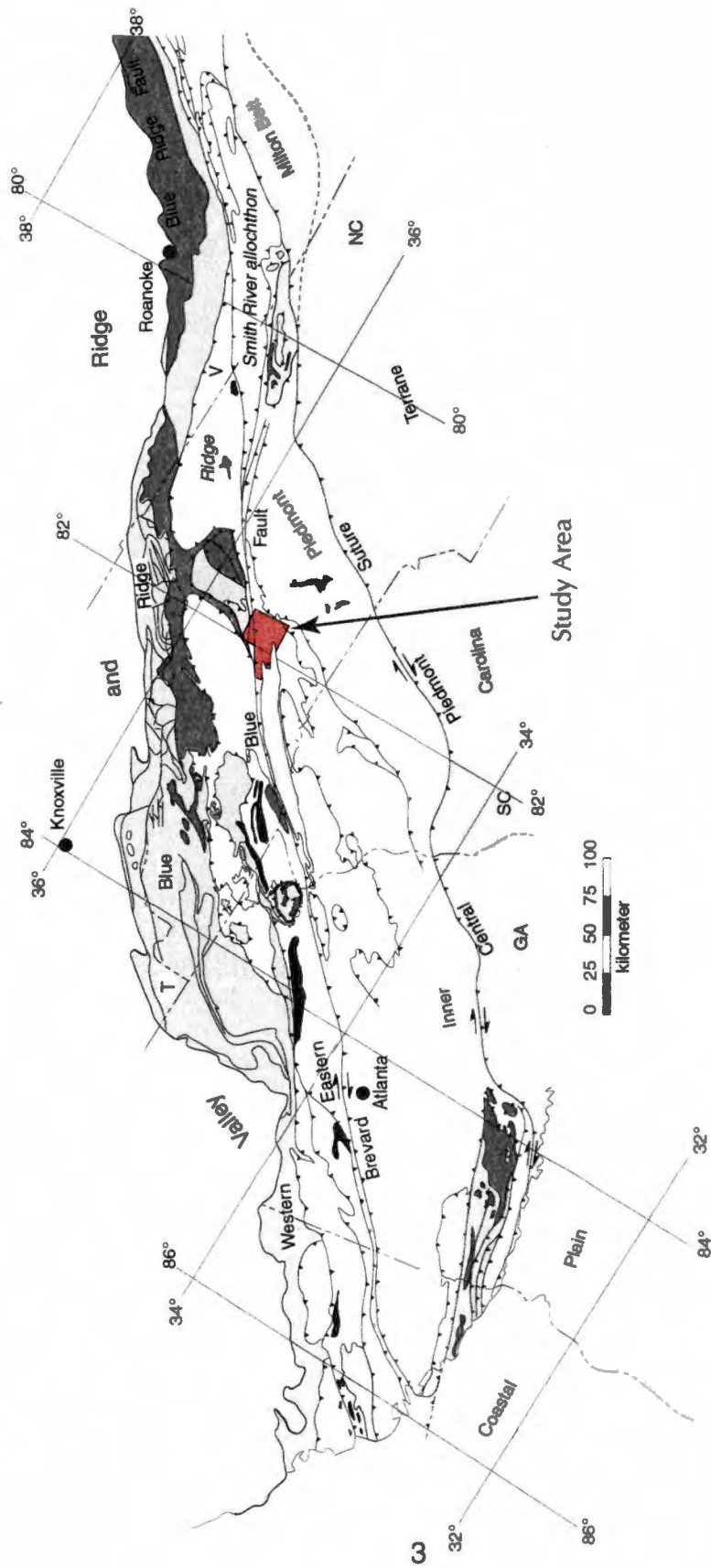
The focus of this study is the structural and stratigraphic relationships within the western Inner Piedmont primarily between the Henderson augen gneiss, Tallulah Falls Formation, and Poor Mountain Formation; and secondarily between the rocks of the

Figure 1-1.

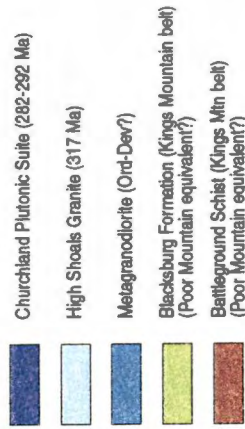
Regional geologic setting of the study area after Hatcher (1998b). (a) Tectonic map of the southern Appalachians with study area highlighted. (b) Geologic map of the Inner Piedmont with study area highlighted and (following page) explanation for geologic map of the northern half of the southern Appalachian Inner Piedmont (after Hatcher, 1998b).

Abbreviations: Mg= Morganton, NC; Hk= Hickory, NC; St= Statesville, NC; Hv= Henderson, NC; Sh= Shelby, NC; Gs= Gastonia, NC; Grv= Greenville, SC; An= Anderson, SC; Sp= Spartanburg, SC; Gav= Gainesville, GA; Gw= Greenwood, SC.

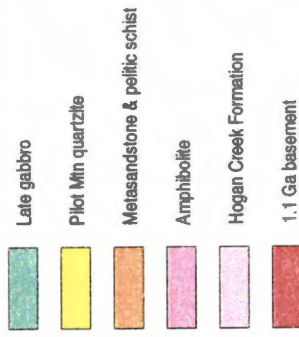
(a)



Kings Mountain Belt



Sauratown Mountains Window

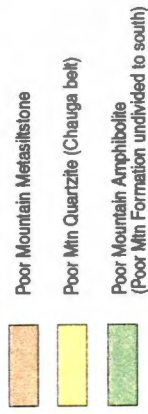


Inner Piedmont

Plutonic Rocks



Poor Mountain Formation



Mylonitic Rocks



Tallulah Falls Formation



Figure 1-2.

Timing of and possible related tectonic processes of orogenic events affecting the southern Appalachians. Modified from Hatcher (1998a).

	Ma.	Orogeny	Plate Tectonic Process
Jurassic	144		Rifting of Pangea
Triassic	208		
Permian	245 286		
Carb.	Pa 320	ALLEGHANIAN (325-265 Ma)	Continent-Continent Collision with Africa Formation of Pangea
	Miss 360		
Devonian	408	ACADIAN (410-360 Ma)	Subduction and Terrane Accretion
Silurian	438		
Ordovician	505	TACONIC (510-460 Ma)	A-Subduction Obduction Arc Collision and Accretion
Cambrian		PENOBSCOT	
	570		
Late Proterozoic	1000	AVALONIAN Virgilina (?) (575-620 Ma)	Subduction Volcanic Arc Generation
Middle Proterozoic		GRENVILLE (1.3 - 1.0 Ga)	Rifting of Rodinia Opening of the Iapetus Formation of Rodinia

Tallulah Falls Formation, the Brevard fault zone, and the Grandfather Mountain window.

The purpose is to provide raw data for an area that had not been studied in sufficient detail to provide clear stratigraphic and structural relationships. The ultimate objective, which is an outgrowth of the primary purpose of this study, is to better understand the tectonics of the western Inner Piedmont.

Regional Geology

Two accreted terranes make up the Piedmont and eastern Blue Ridge: the Piedmont terrane that consists of the Inner Piedmont, Chauga belt, and eastern Blue Ridge; and the Carolina exotic terrane east of the Central Piedmont suture (Fig. 1-1). King (1955) originally defined the Inner Piedmont in the Carolinas as the region of high-grade gneisses, schists, and mafic to ultramafic rocks between the Brevard and Kings Mountain belts. Adams (1926, 1933), Crickmay (1952), and Bentley and Neatherly (1970) all recognized similar lithologic assemblages in northern Georgia and central-eastern Alabama. Heyn (1984) and McConnell (1990) recognized and mapped the major subdivisions in the Tallulah Falls (Ashe) Formation southwest of the Sauratown Mountains window, the northeastern limit of the Inner Piedmont. The Piedmont disappears from view beneath the Coastal Plain of Alabama to the southwest.

Multiple episodes of deformation have been documented in the Inner Piedmont by Griffin (1974), Hopson and Hatcher (1988), Hatcher (1969, 1972, 1978a, 1989, 1993), Liu et al. (1991), Davis et al. (1990, 1991), Davis (1993a, 1993b), Davis and Tabor (1989), Edelman et al. (1987), Yanagihara (1994), and Curl (1998). Davis (1993a) concluded that at least five episodes of deformation had occurred: four of folding and at least one of faulting. The D_2 and D_3 events are thought to have occurred during a single continuous

event (Hopson and Hatcher, 1988; Liu, 1991; Davis, 1993a) and are associated with the major penetrative deformations in the Inner Piedmont.

Regional structural style is dominated by a stack of generally westward-vergent Type-F (ductile fold-related) thrust sheets. These sheets are thought to have formed by shearing of the common limb between tightly to isoclinally folded ductile antiform and synform pairs (Hatcher and Hooper, 1992) (Fig. 1-3). Cooling allowed these thrusts to evolve into Type-C (crystalline) thrusts, thus providing greater strength and permitting greater transport of the thrust sheets.

Goals

The primary goals of this study are:

- Construct a detailed geologic map and cross sections of the study area;
- Determine stratigraphic and structural relationships between lithologic units; and
- Describe metamorphic assemblages, the nature of metamorphism, and possible protoliths for rocks in the study area.

A secondary socioeconomic objective was to develop data useful in qualifying future potential land use and ground water issues. This included mapping of Quaternary alluvial deposits, economic deposits, and measurement of dominant bedrock fracture patterns.

Location of the Study Area

The study area (Fig. 1-1; Fig. 1-4) is located approximately 55 kilometers (35 miles) east of Asheville, North Carolina, in McDowell and Burke Counties, and is comprised of the Marion East quadrangle and approximately half of the Marion West quadrangle (field checked and compiled from Conley and Drummond, 1981) with a total area of

Figure 1-3.

Evolution of crystalline thrust sheets. Figures modified from Hatcher and Hooper (1992) and Hatcher (1999). (a) Type F ductile fold related thrust sheet. This type of sheet is formed in high temperature ductile environments from attenuation of a common limb between a synform and antiform. (b) Type T transitional sheet. This type of sheet is an intermediate step between end-members and is thought to form during the cooling stage after peak metamorphism. (c) Type C composite crystalline sheet. At this stage, the common limb is clearly severed. The rocks have cooled enough to gain sufficient rheologic strength that controls the shape and amount of displacement of the sheet.

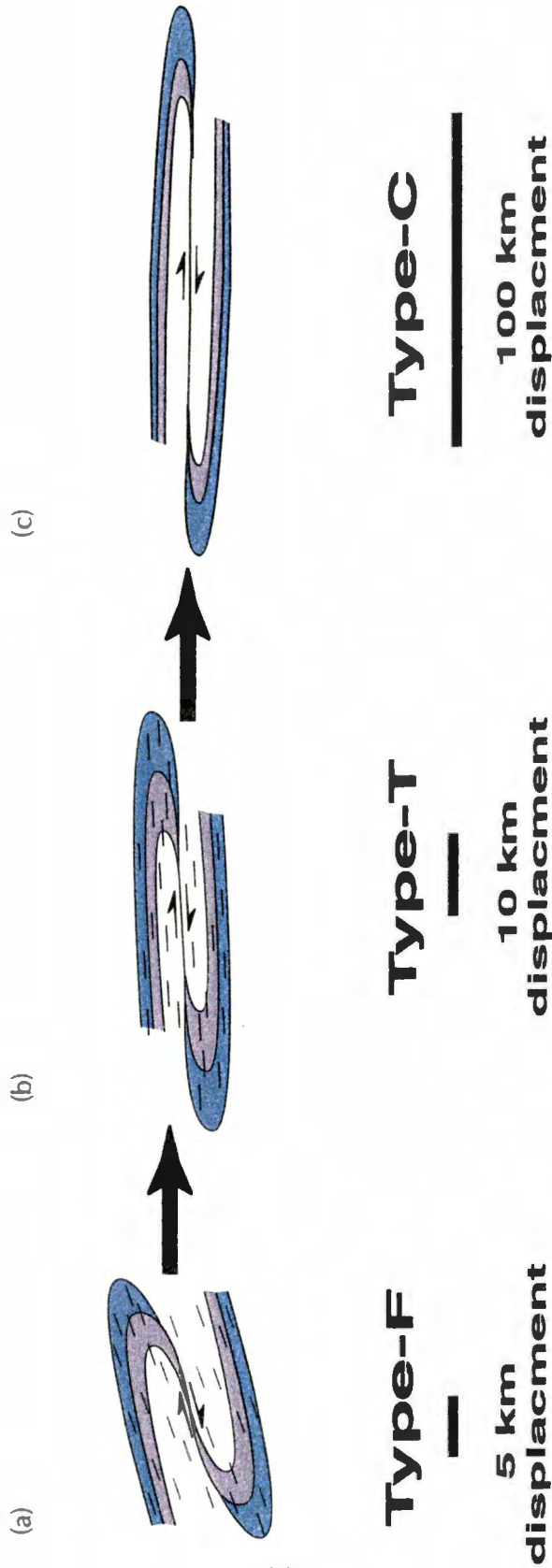
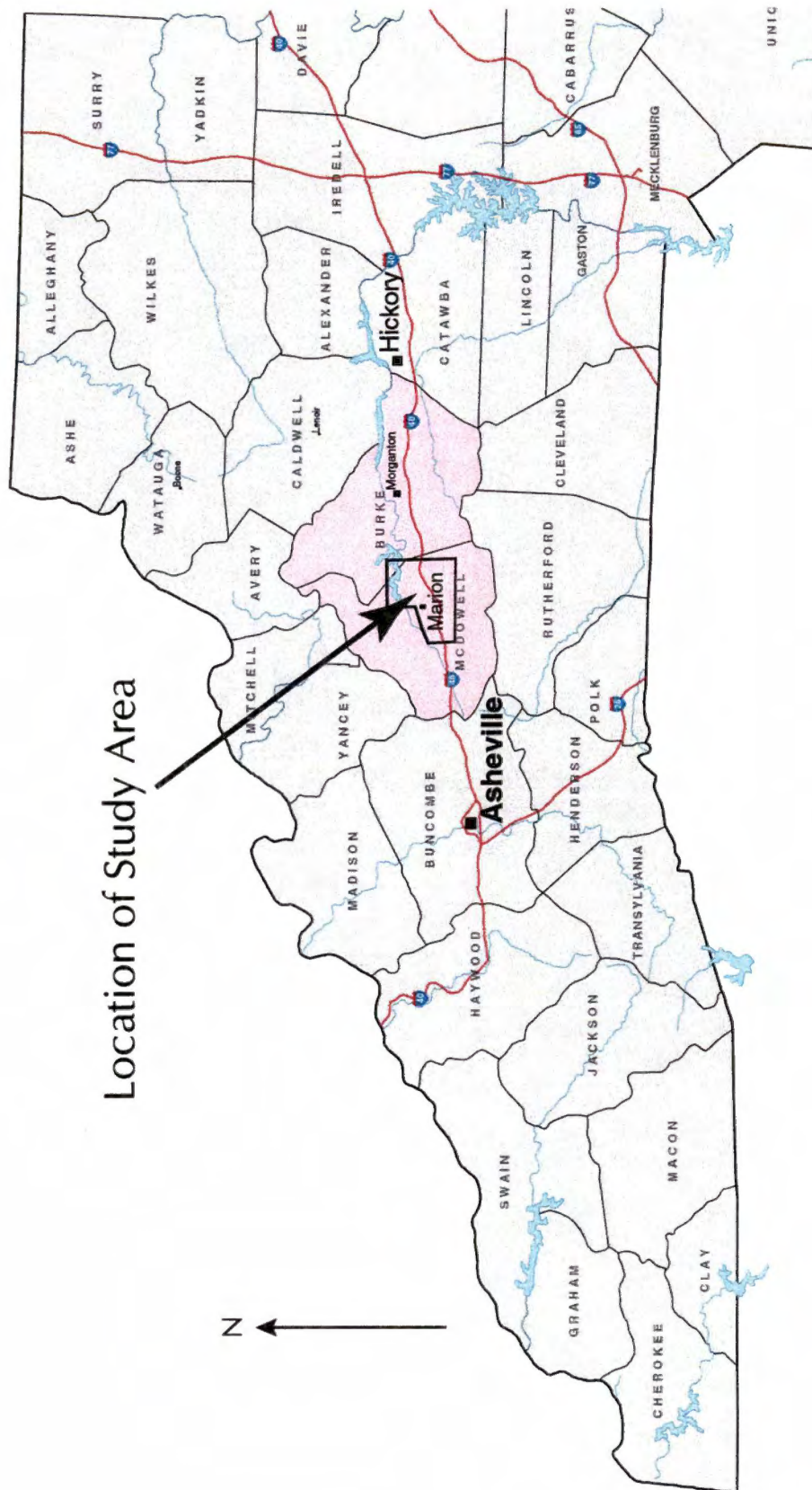


Figure 1-4.

Map of western North Carolina showing location of study area, political boundaries, interstate highways, selected cities, and major rivers and lakes. The counties in which the study area is located are highlighted and the study area is outlined.



approximately 230 km² (~90 mi²). The study area lies between 35° 37' 30" and 35° 45' north latitude and 81° 52' 30" and 82° 07' 30" west longitude, and is located almost completely within the Inner Piedmont geologic province. Only the northwest corner of the Marion East quadrangle lies within the Brevard fault zone and Grandfather Mountain window. Interstate 40 forms an E-W bisect across the study area.

Methodology

This study was conceived and implemented as two phases: 1) a field component, and 2) a laboratory component. Detailed mapping began in late January, 1997, and continued through July, 1997. A second field season began January, 1998, and ended July, 1998. Laboratory work was begun during the interval between the two field seasons and continued after completion of the mapping phase.

Mapping was done at the 1:12,000 scale and compiled at 1:24,000 scale using enlarged and standard USGS topographic base maps. Field work involved traverses, generally across regional strike, along all major streams, ridges, roads, and railroads. Additional area-specific traverses were undertaken and spaced closely enough to permit tracing of particular contacts. Structural measurements of dominant foliation, fold axial planes and plunge of hinges, mineral lineations, and fractures were collected at 1066 stations using a Brunton™ Model 5005LM Pocket Transit. In addition, "float" was identified and plotted on the map to help delimit contacts. Structural analyses were aided by use of GEORient stereographic projection software by Professor Rod Holcombe (Department of Earth Sciences, University of Queensland, Australia) and Stereonet software developed by R. W. Allmendinger (Cornell University).

Laboratory studies involved petrographic and microstructural analysis using a Leitz Orthoplan Pol™ polarizing microscope, and X-ray fluorescence analysis using an EG&G Ortec™ energy dispersive X-ray fluorescence spectrometer. Seventy-three oriented and nonoriented rock samples were collected, of which 47 were cut to make thin sections. Twenty-three representative thin sections were point counted for modal compositions of all major lithologic units.

Previous Studies

Arthur Keith (1904) first mapped in this area as part of the Asheville folio. Reconnaissance mapping and other studies were also done by Keith (1905, 1907), Conley and Drummond (1963, 1965, 1981), and Goldsmith et al. (1988). Previous mapping within close proximity and adjacent to this area was conducted by Hurley (1974), Whisonant (1979), McGill (1980), Davis (1993a), and Yanagihara (1994). Studies within the Inner Piedmont in similar lithologic terranes were conducted by Adams (1933), Crickmay (1952), Griffith (1967, 1969, 1974), Hatcher (1969, 1970, 1971), Heyn (1984), Lemmon (1973), Lemmon and Dunn (1973a, 1973b), and Bentley and Neathery (1970).

Chapter II

Stratigraphy and Lithostratigraphic Framework

Introduction

It has long been recognized that some type of stratigraphic order must be present within the Inner Piedmont. Recognition of that stratigraphy, however, has been limited to identification of similar rock units and generalities about their nature. Most studies have been content to describe the lithologic assemblages in the Inner Piedmont as a complex of medium- to high-grade ortho- and paragneisses intruded by pre-, syn- and post-kinematic plutons. Goldsmith et al. (1988) recognized two stratigraphic suites in the Inner Piedmont belt: a lower, mostly mafic suite of biotite gneiss and amphibolite, with layers of mica schist and granitoid gneiss, which is overlain by a metasedimentary sequence of biotite paragneiss and mica schist. Distinctive sequences have been recognized in the Inner Piedmont near the Sauratown Mountains (Heyn, 1988), in northwestern South Carolina (Hatcher, 1972, 1978a, 1989; Hatcher and Acker, 1984), in central South Carolina (Horkowitz, 1984; Willis, 1984), in the Columbus Promontory, North Carolina (Davis, 1993a, 1993b; Yanagihara, 1994), in the Alto allochthon in northeastern Georgia and northwestern South Carolina (Hatcher, 1978b; Hopson and Hatcher, 1988), adjacent to the Pine Mountain window in Georgia (Hooper and Hatcher, 1989), and southeast of the Brevard fault zone near Atlanta, Georgia (McConnell and Abrams, 1984). These stratigraphic sequences, although widely separated, have both similar lithologies and the same distinctive and traceable marker units that occur in the same position in the sequence (Hatcher, 1993). Intact and identical stratigraphic sequences that occur in the eastern Blue

Ridge, most notably around the Tallulah Falls dome, indicate they may be directly correlative with those found in the Inner Piedmont.

Previous stratigraphic studies have been limited to lithostratigraphic correlation (e.g., Davis 1993a; Yanagihara, 1994). Detailed mapping during this study provides a basis for correlation with the Chauga belt of Hatcher (1972) and across the Brevard fault zone with rocks of the Tallulah Falls (Ashe) Formation. Petrographic study reveals similar mineralogical compositions with those of the Chauga belt and the Tallulah Falls (Ashe) Formation.

Previous Work

Previous workers had recognized the Henderson Gneiss (Keith 1905, 1907; Reed and Bryant, 1964; Hadley and Nelson, 1971) but did little to describe the stratigraphy of the adjacent Inner Piedmont paragneisses, schists, and migmatite. Lemmon (1973) made the first significant contribution to delineation of Inner Piedmont stratigraphy dividing the Henderson Gneiss outcrop belt into three mappable units as part of his Sugarloaf Mountain group. Conley and Drummond (1975) described a similar stratigraphic package south of Lemmon's work, in Polk County, North Carolina, wherein they named the Tryon formation. Additionally, Conley and Drummond defined a sequence of migmatitic biotite gneiss, granitic gneiss, amphibolite, and amphibolite gneiss that they informally named the Mill Spring group.

Davis (1993a) combined the informal names of Lemmon (1973) and Conley and Drummond (1975) into a lithostratigraphic assemblage. Noting the similarity (acknowledged by Lemmon) of the Sugarloaf Mountain Group to rocks of the Poor Mountain Formation in South Carolina (Shufflebarger, 1961; Hatcher, 1969, 1970), Davis

concluded that the Sugarloaf Mountain Group, with the exception of the Sugarloaf Mountain granitic gneiss, was equivalent to the Poor Mountain Formation. Furthermore, Davis grouped the biotite gneiss and garnet-mica schist underlying the Sugarloaf Mountain group and the migmatitic gneiss and interlayered amphibolite of the Mill Spring group into the Mill Spring complex. Davis defined the stratigraphic framework as the Mill Spring complex, the Poor Mountain Formation, the Sugarloaf granitic gneiss, and the Henderson Gneiss. This study abandons usage of the informal name Mill Spring complex and alternatively suggests usage of Tallulah Falls (Ashe) Formation nomenclature based on subdivision of this sequence in the North Carolina Inner Piedmont identical to that in the Blue Ridge of northwestern South Carolina and northeast Georgia.

Description of Map Units

No confirmed Grenville basement has been recognized in the study area or the Inner Piedmont, except southwest of the Sauratown Mountain window (Heyn, 1984; McConnell et al., 1986). The rocks in the study area can be divided into five broad units: Henderson Gneiss, Tallulah Falls (Ashe) Formation, Poor Mountain Formation, Brevard fault zone rocks, and Grandfather Mountain Formation. These five units represent distinct mappable sequences in the study area. The Sugarloaf gneiss of Davis (1993a) is not recognized in the study area, although the granitoid gneiss in the southeast corner of the Marion East quadrangle is lithologically similar. Figure 2-1 shows the stratigraphic relationships within the study area. These relationships are thought to be applicable to the western Inner Piedmont, at least as far east as the Six Mile fault.

Figure 2-1.

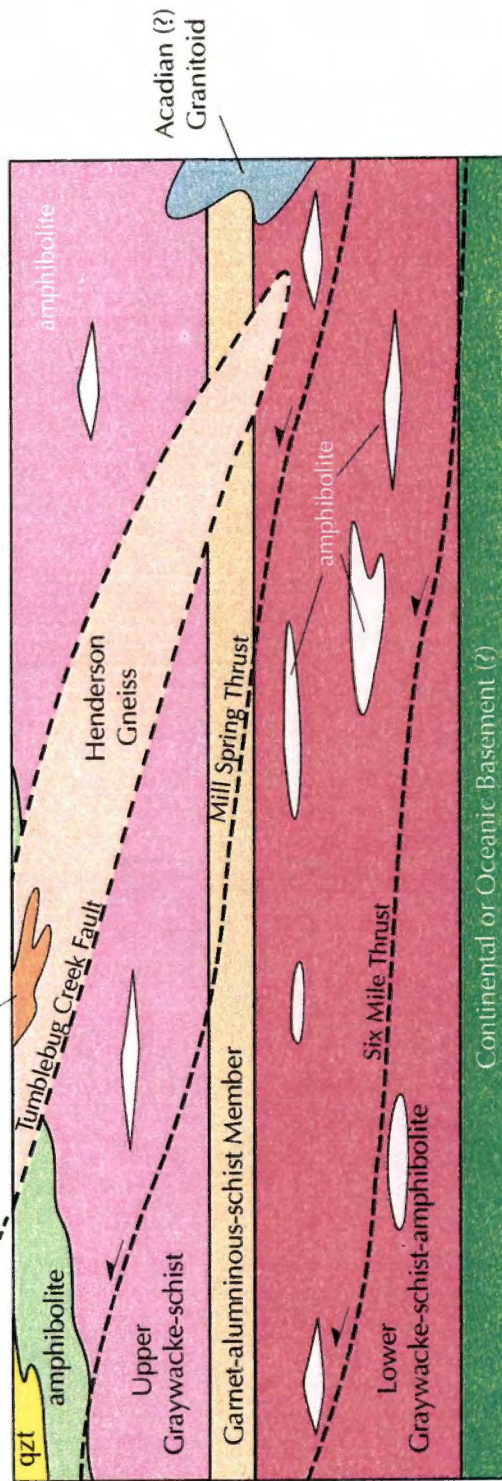
Generalized stratigraphy of the study area modified from Hatcher (1993). Similar stratigraphic relationships have been recognized in several localities in the Inner Piedmont.

Stratigraphy

509 Ma Henderson Augen Gneiss
Poor Mtn. Formation
Talullah Falls Formation
Basement (?)

20

423 and 428 Ma
Granite



Henderson Augen Gneiss

The Henderson Gneiss is a 509 Ma (Sinha et al., 1989) granitic to granodioritic augen gneiss that is confined to the Chauga belt southeast of the Brevard fault zone. The main body of the Henderson Gneiss extends from the study area in northwestern North Carolina to the Georgia-South Carolina border to the southwest. Outliers of Henderson Gneiss occur to the northeast of the main body as mapped herein (Plate I), Bryant and Reed (1970) and Goldsmith et al. (1988), suggesting transport from the northeast. Contact relationships in the study area indicate that the Henderson Gneiss was fault emplaced and is not intrusive (Chapter 3, this study). This interpretation is supported by previous studies (Davis et al., 1991; Liu, 1991; Liu et al., 1991; Davis, 1993a; Yanagihara, 1994).

The Henderson Gneiss is the structurally highest unit within the study area. The Henderson Gneiss is interpreted to be fault emplaced onto the rocks of the Chauga belt during early D₂ deformation (Chapter 3, this study), either from the east or northeast. Subsequent shearing to the southeast deformed the Henderson into a large map-scale sheath fold imbricated on the southwest end in South Carolina (Hill et al. 1998; Hatcher, 1999). Later deformation folded and transposed the fault contact obliterating earlier kinematic evidence. The Henderson Gneiss climbs stratigraphic section to the southwest from kyanite-grade Tallulah Falls Formation rocks in the study area to staurolite- and garnet-grade Poor Mountain Formation rocks in South Carolina (Fig. 1-1c).

The origin of the Henderson Gneiss is unclear and has been alternatively interpreted to be either sedimentary or igneous in origin (e.g., Hatcher, 1969). Based on its mineralogy, it is unlikely to have had a sedimentary protolith. Odom and Fullagar (1973) reported an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.703 indicating a lower crustal source. Sinha et al. (1989) suggested that the Henderson is one of many Late Cambrian-Early Ordovician

plutons that extend from Alabama to Delaware. This suite is based on age and geochemical correlation and includes the Occoquan (494 Ma), Melrose (515 Ma), and Leatherwood (516 Ma) plutons in Virginia; the Villa Rica gneiss (469 ± 13 Ma) in Georgia; and the Elkahatchee quartz diorite (509 Ma) in Alabama. Sinha et al. (1989) and Drake et al. (1989) suggested that these plutons are subduction related magmatic bodies along a paleo-continental margin.

In outcrop and hand sample, the Henderson Gneiss is a coarse- to medium-grained, light-gray augen gneiss (Fig. 2-2). It is typically well foliated and has an inequigranular granoblastic texture. Foliation is defined by lamellae of quartz and feldspar, and by preferred alignment of micas. Large, elongate feldspar porphyroclasts up to 2 cm in length are flattened into the dominant foliation. The porphyroclasts have a characteristic augen shape and serve as primary strain markers in the Henderson Gneiss. Weathering produces a distinctive light gray saprolite with white augen. Many times in the absence of good outcrop, the Henderson Gneiss may be recognized on the surface by the abundance of unweathered, flattened feldspar grains.

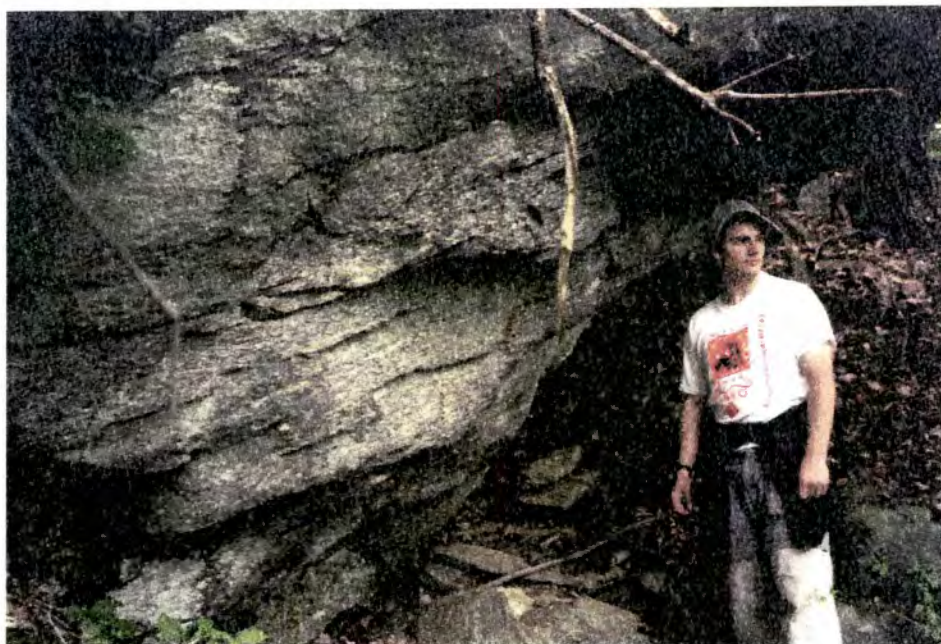
In the study area, petrographic work indicates that the Henderson Gneiss is composed primarily of plagioclase + quartz + K-feldspar + biotite $\pm$ muscovite $\pm$ epidote $\pm$ allanite $\pm$ sphene $\pm$ zircon $\pm$ garnet $\pm$ hornblende $\pm$ opaques. The porphyroclasts are microcline and/or plagioclase and commonly have a myrmekitic texture (Fig. 2-2). Plagioclase ($An_{20}-An_{30}$) is frequently twinned and contains small inclusions of zircon, quartz, and mica. Quartz is anhedral and is 0.1 to 2.0 mm in diameter. Biotite is euhedral, up to 4.0 mm in length, and has a distinct green-brown color in thin section. Muscovite occurs primarily in association with biotite. Bryant and Reed (1970) interpreted the micas to be late synkinematic to partly postkinematic. Table 2-1 summarizes modal

Figure 2-2.

Photographs and photomicrographs of Henderson Gneiss.

- (a) Typical outcrop exposure of Henderson Gneiss near the summit of Smith Mountain, Marion East quadrangle. Person in the foreground is approximately 1.8 meters tall.
- (b) Hand sample of Henderson Gneiss. Note the quarter for scale.
- (c) Photomicrograph of Henderson Gneiss from a sample taken on Smith Mountain, Marion East quadrangle, North Carolina. Field of view is approximately 4 mm.
- (d) Overlay showing dominant mineral constituents. B= biotite, K= K-feldspar, Q = quartz, F= feldspar. Field of view is approximately 4 mm.

(a)



(b)



(c)



(d)

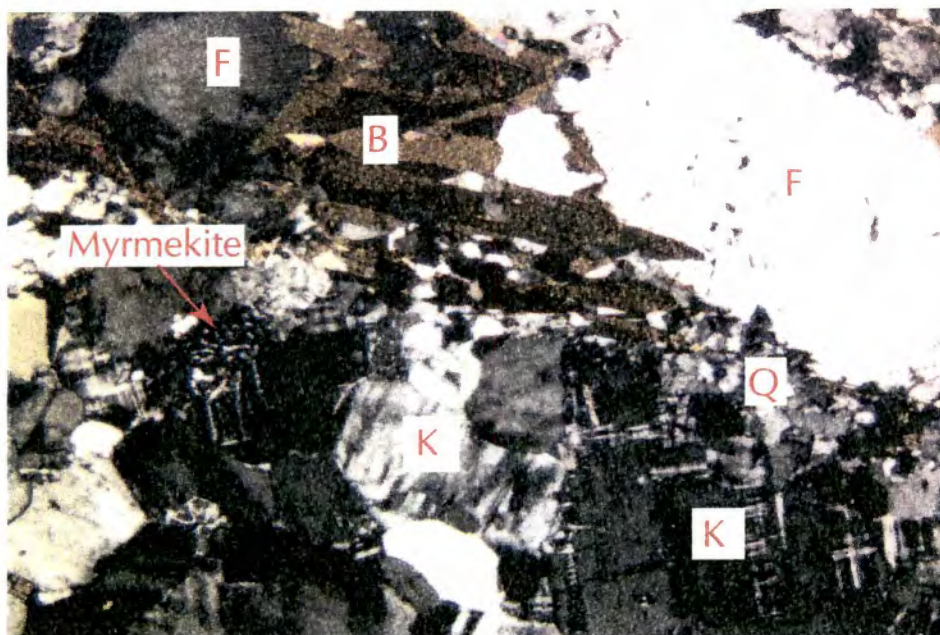


Table 2-1. Modal analyses of Henderson Gneiss determined by point counting. *Italic type indicates samples from this study.*
Bold italic typeface indicates data from Lemmon (1973). Abbreviations: Qtz=quartz, Bio=biotite, Musc=muscovite
Kspar=alkali feldspar, Plag=plagioclase, Zir=zircon, Aln=alanite, Gt=garnet, Hbl=hornblende, Opx=opaques.
Error indicated below each mineral calculated by using Van der Plas and Tobl (1965).

Sample	Qtz (1-2.5%)	Bio (1-3%)	Musc (1-3%)	Kspar (2-3%)	Plag (2-3%)	Epi/Clz (1-2.5%)	Zir (<1%)	Aln (<1%)	Gt (<1%)	Hbl (<1%)	Opx (<1%)	# Points Counted
ME125	26.17	15.39	2.4	11.52	40.46	1.75	---	---	0.55	---	1.75	1085
ME468	29.57	10.44	3.48	13.72	38.84	2.13	1.16	---	---	---	0.68	1035
ME580	24.37	13.83	5.64	16.75	35.18	4.23	---	---	---	---	---	1063
ME585	9.87	0.28	0.38	26.13	43.5	2.54	0.85	2.35	---	8.74	3.76	1064
<i>L4-15</i>	28.5	19.5	2.8	14.4	32.5	trace	yes	---	---	---	trace	
<i>K8-11</i>	22.4	10.2	0.6	32.3	32.8	trace	yes	---	trace	---	0.6	
<i>E3-2</i>	19.7	19	5.6	23.5	29.2	2.1	yes	yes	trace	---	trace	
<i>D4-1</i>	21.8	23.6	0.9	21.3	27.6	3	yes	---	---	---	trace	
<i>D5-3</i>	28.1	0.9	1.3	38.7	30.1	0.3	yes	---	---	---	0.6	
<i>J1-4</i>	21	14.4	4.7	23.5	34.5	1.1	yes	---	---	---	trace	
<i>J3-2</i>	12.2	23.2	---	15.6	41.5	5.4	yes	yes	---	---	0.2	
<i>C8-6</i>	17.8	10	2.8	32.2	35.5	1.2	yes	yes	---	---	0.4	
<i>F7-3</i>	28.3	14.7	0.1	22.8	33.3	0.3	yes	yes	---	---	0.4	

analyses of Henderson Gneiss thin sections from the study area and data compiled from Lemmon (1973). Figure 2-3 is a QAP diagram (after Streckeisen, 1976) of Henderson Gneiss samples from the study area and data from Lemmon (1973).

Poor Mountain Formation

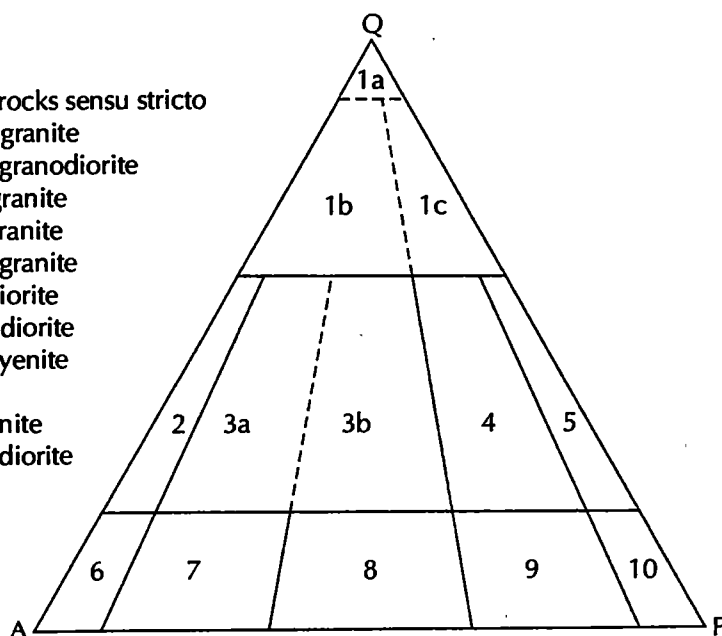
Hatcher (1969, 1970) defined the Poor Mountain Formation after the Poor Mountain sequence of Shufflebarger (1961). The type section of the Poor Mountain sequence was first described by Sloan (1908). The Poor Mountain Formation consists of three mappable units, two of which are observed in the study area. These units in ascending order are: (1) Brevard-Poor Mountain transitional unit; (2) Poor Mountain Amphibolite; and (3) Poor Mountain Quartzite. The Brevard-Poor Mountain transitional unit is not present in the study area. The Poor Mountain Formation has been traced as a continuous unit southwestward to the vicinity of Gainesville, Georgia (Hatcher, 1978b) and may continue into Alabama. Davis (1993a) noted that the Ropes Creek amphibolite is chemically very similar to the Poor Mountain Amphibolite. I have recognized the Poor Mountain Amphibolite northeast of study area continuing into and across the northwestern corner of the Glen Alpine quadrangle. The Poor Mountain Formation has been correlated with the Evington Group of Virginia (Brown, 1951; Espenshade, 1954) by Shufflebarger (1961). Wehr and Glover (1985) traced the Evington Group south from Virginia to North Carolina where they correlated it with the Alligator Back Formation of Rankin et al. (1973). Where observable, the contact between the Poor Mountain Formation and the underlying Tallulah Falls Formation is sharp. Yanagihara (1994) reported interleaving of the Poor Mountain and Tallulah Falls formations. I believe the sharp contact between the Tallulah Falls Formation and the overlying Poor Mountain Formation is due to transposition of

Figure 2-3.

Ternary QAP diagram of Henderson Gneiss samples listed in Table 2-2. (a) Classification of Streckeisen (1976). (b) Henderson Gneiss samples plotted on Streckeisen diagram. Q = quartz, A= alkali feldspar, and P = plagioclase.

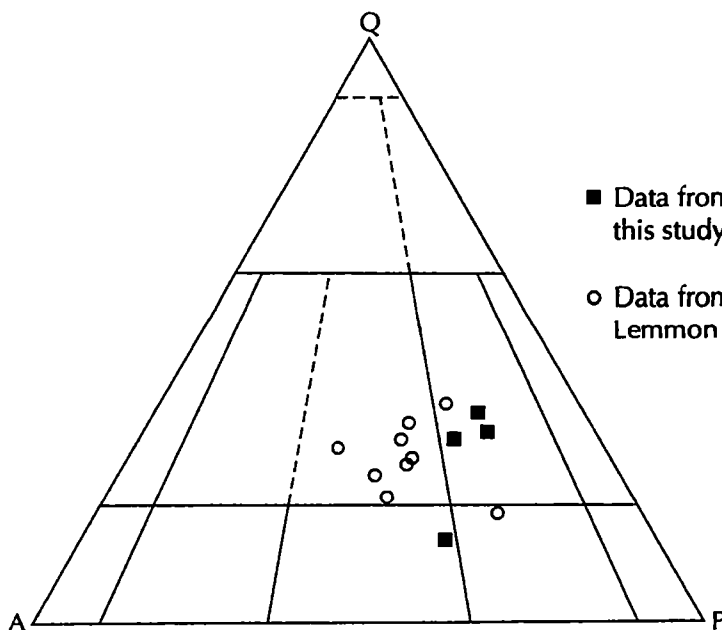
(a)

- 1a quartz rocks sensu stricto
- 1b quartz-granite
- 1c quartz-granodiorite
- 2 alkali granite
- 3a syenogranite
- 3b monzogranite
- 4 granodiorite
- 5 quartz-diorite
- 6 alkali syenite
- 7 syenite
- 8 monzonite
- 9 monzodiorite
- 10 diorite



(b)

- Data from this study
- Data from Lemmon (1973)



original (?) lithologic fabrics. Based on these observations and map patterns (Plate I), the contact is interpreted to be unconformable.

Quartzite member. The quartzite member is the uppermost unit of the Poor Mountain Formation recognized in the study area, although discontinuous marble bodies have been recognized to the southwest (e.g., Shufflebarger, 1961; Hatcher, 1970). In outcrop, the quartzite is massive to medium bedded and is light to medium gray (Fig. 2-4). A mineral lineation may be observable in places where the mica content is high. The quartzite holds up many of the highest ridges in the southeast portion of the study area.

The quartzite member is feldspathic, with total feldspar content ranging between 18.5 and 35.5 percent (Table 2-2). In general, the mineral assemblage is quartz + plagioclase + muscovite + biotite $\pm$ K-feldspar $\pm$ epidote/clinozoisite $\pm$ garnet $\pm$ opaques (Fig. 2-4). The quartzite member has been reported to be slightly calcareous (e.g., Hatcher, 1970). No carbonate was recognized during petrographic analysis, although massive bedded quartzite contains calcsilicate nodules that range from 1.5 cm to 3.0 cm across. The quartzite is medium- to fine-grained with an average grain size of approximately 0.1 mm and has a distinct granoblastic texture. Vein quartz grain size may reach 3.0 mm across. Muscovite can make up to 30 percent of the quartzite, making the quartzite appear schistose in places. Two generations of muscovite are observable in thin section as first reported by Yanagihara (1994): an earlier synmetamorphic phase that parallels the dominant foliation and a later randomly oriented fine-grained phase. Biotite occurs as small platy crystals averaging 0.4 mm in length parallel to the dominant foliation. Closer

Figure 2-4.

Photograph and photomicrograph of Poor Mountain Quartzite.

- (a) Typical exposure of thinly bedded Poor Mountain Quartzite exposed in a stream bed, in the Marion East quadrangle. Hammer is approximately 35 cm long.
- (b) Photomicrograph of Poor Mountain Quartzite from Higgins Mountain, Marion East quadrangle under crossed polars. Field of view is approximately 4 mm. Q= quartz, F= feldspar, M= muscovite, B= biotite, K= K-feldspar.

(a)



(b)

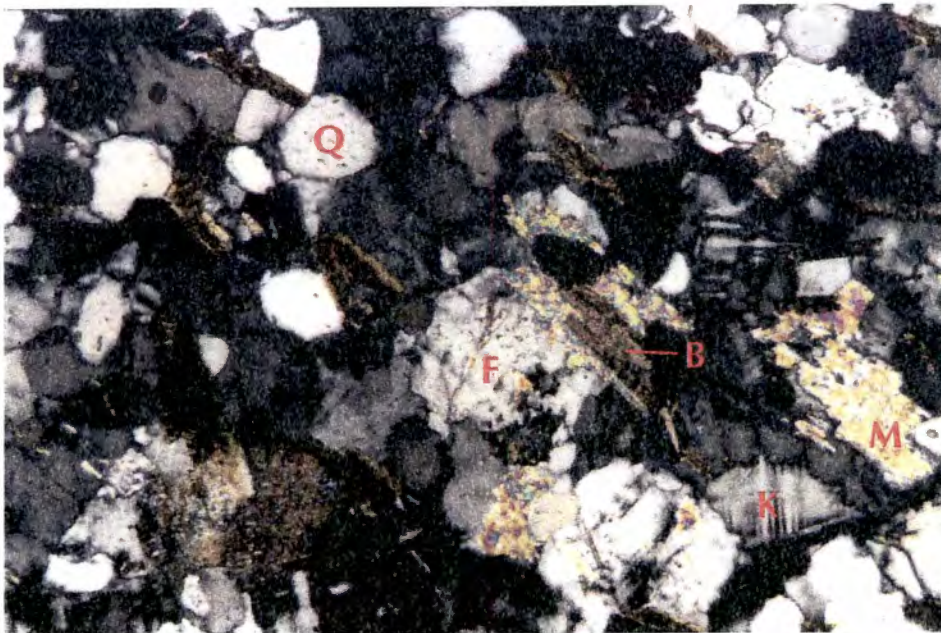


Table 2-2. Modal analyses of Poor Mountain Quartzite in the study area determined by point counting. Bold italic samples are compiled for comparison from Yanagihara (1994). See Table 2-1 for abbreviations and explanation of error calculations.

Sample	Qtz (1-2.5%)	Bio (1-3%)	Musc/Ser (1-3%)	Kspar (2-3%)	Plag (2-3%)	Epi/Clz (1-2.5%)	Zir (<1%)	Chl (<1%)	Gt (<1%)	Hbl (<1%)	Opq (<1%)	# Points Counted
ME3	45.93	7.14	12.26	7.32	25.98	trace	---	---	---	---	1.28	1113
ME28	47.62	6.29	7.73	5.57	28.93	1.35	---	---	0.36	---	2.17	1093
<i>Su410</i>	48.8	1.5	25	3.6	18.6	---	---	---	1.9	---	0.1	2448
<i>ShH40</i>	46.6	10.9	6	---	22.8	---	---	---	---	---	10.1	1044
<i>ShH1</i>	38.2	15.3	27.6	---	18.5	---	---	0.4	---	---	---	1038
<i>LL448</i>	57.3	3.6	6.9	---	29	0.9	---	---	---	---	1.6	1042

to the underlying amphibolite member, the quartzite may contain a significant amount of amphibole.

Figure 2-5 is a QFM ternary diagram of samples from Table 2-2. The samples plot either as a graywacke or as an arkose. Quartzite from South Carolina is often more of a true quartzite (Shufflebarger, 1961; Hatcher, 1970). Determination of the protolith for the Poor Mountain Quartzite involves several possibilities because of its diverse composition. It is tempting to interpret it to be a quartz-rich sand. An intriguing, alternate idea is that the Poor Mountain Formation may represent the metamorphosed equivalent of the top of an ophiolitic sequence that may have been obducted onto the Tallulah Falls Formation during the accretion of the Piedmont. If so, then the contact with the underlying Tallulah Falls Formation would be a fault.

Amphibolite member. Underlying the quartzite member is the amphibolite member (Fig. 2-6). The contact between the two is gradational. The Poor Mountain Amphibolite consists of laminated amphibolite and hornblende gneiss. The unit is generally medium- to fine-grained and possesses a strong mineral lineation defined principally by the preferred orientation of amphibole and subordinate biotite. The amphibolite member is black to dark gray, thin- to medium-bedded amphibolite with numerous felsic interlayers. Weathered amphibolite saprolite has a distinct reddish-brown to yellow-ochre color. Ultramafic rocks are conspicuously absent in the amphibolite member in the study area.

In general, hornblende and plagioclase (An_{25} - An_{35}) are the dominant minerals accounting for 58 to 85 percent of the total points counted (Table 2-3). For the amphibolite member, the mineral assemblage is hornblende + plagioclase + epidote $\pm$ quartz $\pm$ biotite $\pm$ allanite $\pm$ cummingtonite $\pm$ anthophyllite/gedrite $\pm$ chlorite $\pm$ zircon $\pm$

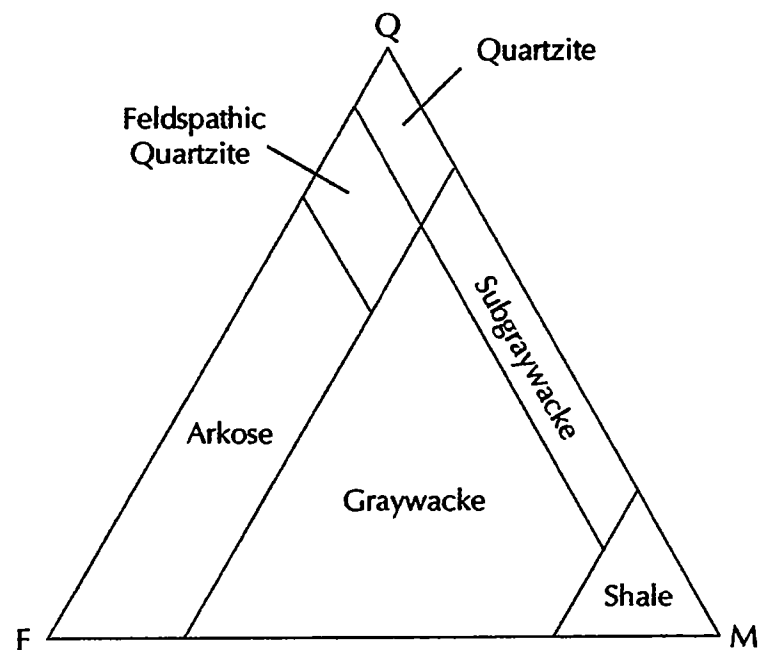
Figure 2-5.

Ternary QFM diagram of Poor Mountain Quartzite samples from Table 2-2.

(a) Classification of Pettijohn (1954).

(b) Plotted Poor Mountain Quartzite samples. Q= quartz, F= feldspar, and M= Mica.

(a)



(b)

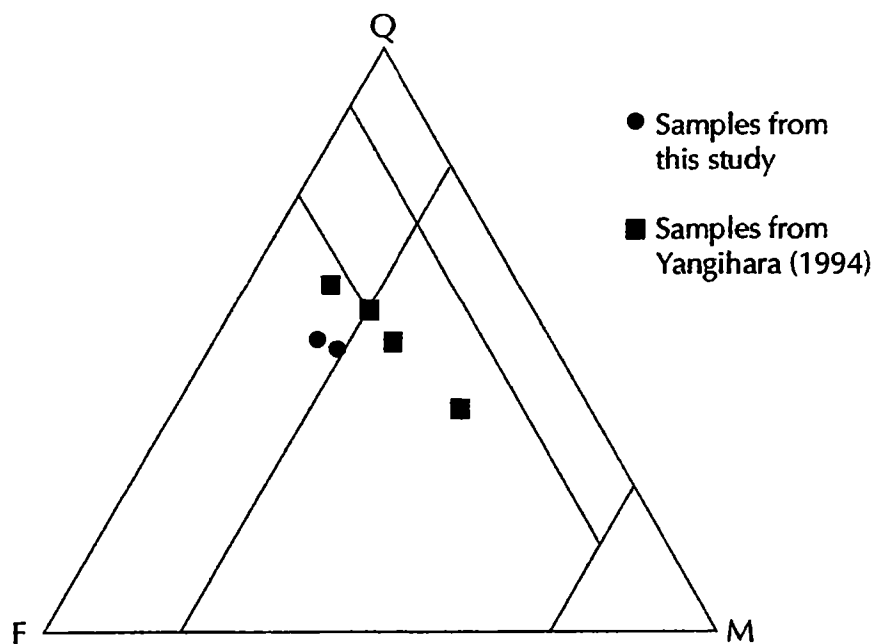


Figure 2-6.

Photograph and photomicrograph of Poor Mountain Amphibolite.

- (a) Typical Poor Mountain Amphibolite. Note the light colored quartzofeldspathic layers folded by D₂ generation folds. Sample courtesy of Robert D. Hatcher, Jr.
- (b) Photomicrograph of Poor Mountain Amphibolite from Higgins Mountain, Marion East quadrangle under crossed polars. Field of view is approximately 4 mm.

(a)



(b)

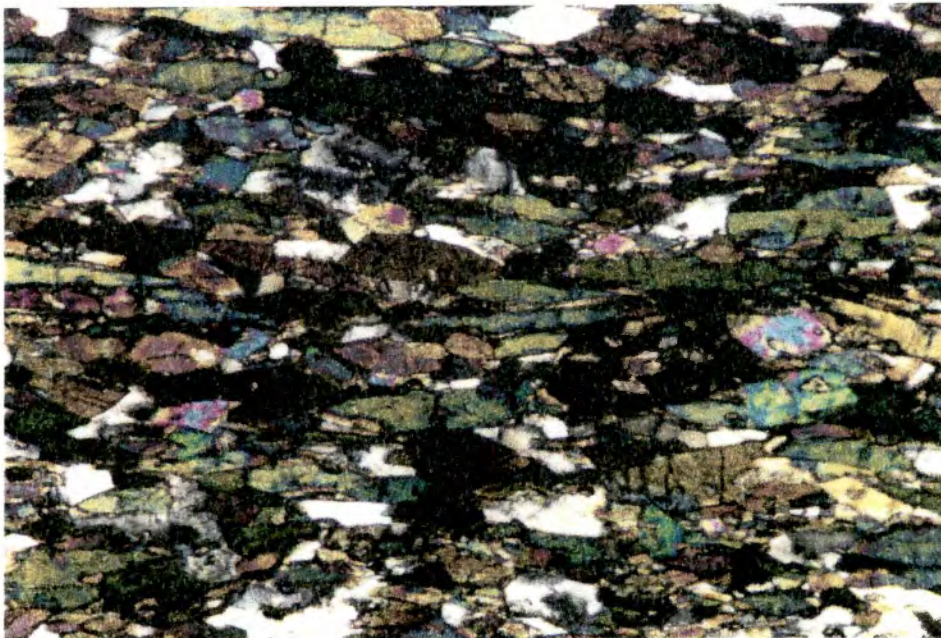


Table 2-3. Modal analyses of Poor Mountain Amphibolite in the study area determined by point counting. Bold italic samples are compiled for comparison from Yanagihara (1994). Abbreviations: Cum=cummingtonite, Anth=anthophyllite/gedrite, Allan=allanite. See Table 2-1 for more abbreviations and explanation of error calculations.

Sample	Hbl (1-2.5%)	Plag (1-2.5%)	Qtz (1-2.5%)	Epi/Clz (1-2.5%)	Bio (1-3%)	Cum (2-3%)	Anth (2-3%)	Chl (<1%)	Allan (<1%)	Gt (<1%)	Opq (<1%)	# Points Counted
ME11	26	33.06	14.08	0.94	21	0.5	2	1.5	---	0.93	trace	1064
ME 104	54.54	12.48	trace	25.42	---	5.6	1.96	trace	---	trace	trace	1074
ME376B	47.33	29.68	---	13.67	---	---	---	---	9.32	---	---	1105
ME378A	52.9	24.93	5.14	12.94	---	---	1.52	---	2.51	---	0.06	1051
ME 404	67.78	17.22	2.41	10.37	---	---	---	---	2.22	trace	trace	1080
Su148	46	15	3.2	2.1	31.8	---	---	---	---	---	---	1083
Su112	98.5	---	---	---	---	---	---	---	---	---	1.5	1024
LL526	47	11.2	1	35.4	---	---	---	0.1	---	---	1.5	1344
ShH20	37.6	40.2	4.2	14.2	0.2	---	---	---	---	trace	2.3	1043
ShH 272	43.1	39	17.7	0.2	---	---	---	---	---	---	---	150

garnet (Fig. 2-6). Ilmenite is the primary opaque mineral associated with the Poor Mountain Amphibolite, but is present only in trace amounts in thin sections point-counted for this study. Hornblende is the dominant amphibole, but cummingtonite and anthophyllite/gedrite also occur in amounts up to 5 percent. Hornblende varies in size from 0.5 to 4.0 mm with an average size of around 1.0 mm or less. Typically, hornblende occurs as slender prismatic to diamond-shaped crystals. It is euhedral to subhedral with a strong green or blue-green pleochroism. Biotite is commonly associated with hornblende, probably as an alteration product. Plagioclase occurs as small (0.1 to 0.8 mm) anhedral grains, which are commonly untwinned. It is commonly altered to saussurite. Epidote clinozoisite occurs as anhedral grains, sometimes with rims of allanite.

Quartzo-feldspathic interlayers are ubiquitous throughout the amphibolite member (Fig. 2-6). They range in thickness from a few millimeters to tens of centimeters. These interlayers are commonly continuous for tens of meters and may be complexly folded. The interlayers are composed primarily of plagioclase and epidote with minor amounts of quartz.

Tallulah Falls (Ashe) Formation

The Tallulah Falls Formation was first described by Hatcher (1971) for exposures in and around the Tallulah Falls dome in Rabun and Habersham Counties, Georgia. It is a stratigraphic package of quartzo-feldspathic gneisses and mica schists. The Tallulah Falls Formation rests unconformably on Grenville basement in and around the type locality (Hatcher, 1973, 1977). Rankin et al. (1989) interpreted the contact between the Tallulah Falls Formation and Wiley Gneiss as a fault. Liu (1991) stated the contact was faulted based on data from the ADCOH Project (Hopson et al., 1986), citing the interleaved nature

of the Wiley Gneiss and garnet- biotite schist. The Tallulah Falls Formation is thought to be equivalent of the Ashe Formation of Rankin (1970) and the Sandy Springs Group in Georgia (Hatcher, 1978a, 1989).

As originally defined, the Tallulah Falls Formation consisted of four members: a lower graywacke-pelitic schist-amphibolite member; a garnet-aluminous schist member; and an upper graywacke-pelitic schist member and its facies equivalent quartzite-schist member. The quartzite-schist member is observable only in the core of the Tallulah Falls dome. Hatcher (personal comm.) has reinterpreted the quartzite-schist as equivalent to rocks of the Great Smoky Group, thus making the contact between the quartzite-schist member and the upper graywacke-schist member a fault that exposes the Chattahoochee thrust sheet. In the study area, the Tallulah Falls Formation consists of the lower graywacke-pelitic schist-amphibolite member, overlain by the garnet-aluminous schist member, which is overlain by the upper graywacke-pelitic schist member.

Upper and lower graywacke-schist members. The upper and lower members of the Tallulah Falls Formation are lithologically identical except for the amount of amphibolite present. The upper unit is relatively amphibolite poor, whereas the lower unit is amphibolite rich. Amphibolite occurs as layers and boudins that vary in thickness from a meter or less to map-scale. The lower graywacke-schist member is also typically more migmatitic, although this may vary locally. Differentiation of units and stratigraphic position are difficult to determine in the field without identification of the garnet-aluminous schist member and detailed mapping to determine the relative abundance of amphibolite within each unit.

In outcrop, both units are light- to medium-gray and fine- to medium-grained (Fig. 2-7). Weathering produces a light brown to brownish-red saprolite. Foliation is defined by parallel alignment of micas and elongate quartz and plagioclase. Thickness of compositional layering varies from a few millimeters to several meters. Compositional layering reflects original bedding mineralogy although the original orientation of bedding has been obliterated by later transposition. Contacts between different lithologies are accentuated by metamorphic differentiation producing interlayered metagraywacke-biotite gneiss, and biotite schist. Layers with higher mica content are commonly coarser grained and darker in color. Localized minimum melt conditions can impart gneissic banding or a migmatitic texture to the rocks. Leucocratic granitoid and pegmatite are common in both the upper and lower graywacke-schist members. Amphibolite pods and layers are typically coarse-grained with hornblende, plagioclase (An_{25-35}), biotite, and quartz being the typical dominant mineral assemblage. Garnets may also be present in the amphibolite.

In hand sample and thin section, the upper graywacke-schist member is more commonly equigranular while the lower graywacke-schist member is typically inequigranular (Davis, 1993a). Although lithologically similar, both the upper and lower graywacke-pelitic schist members can show considerable mineralogic variation. In the study area, the mineral assemblage is plagioclase + biotite + muscovite/sericite + quartz + epidote/clinozoisite + opaques $\pm$ garnet $\pm$ K-feldspar $\pm$ zircon $\pm$ chlorite $\pm$ sphene (Table 2-4; Fig. 2-7).

Plagioclase (An_{20-35}) content varies from 28 to 60 percent. It occurs as subhedral crystals, commonly myrmekitic, up to 1.2 cm across. Inclusions in the larger plagioclase crystals show two preferred orientations roughly orthogonal to each other and at a high angle to the dominant foliation. Quartz is anhedral up to 1.0 cm across and commonly has a clear recrystallization texture. Muscovite and biotite occur as subhedral to euhedral crystals

Figure 2-7.

Photograph and photomicrograph of Tallulah Falls metagraywacke.

- (a) Typical exposure of Tallulah Falls metagraywacke. Exposure is on Jamison Mountain, Marion East quadrangle. Hammer is approximately 35 cm long.
- (b) Photomicrograph of Tallulah Falls metagraywacke from Grant Mountain Marion East and Marion West quadrangles. Field of view is approximately 4 mm.

(a)



(b)

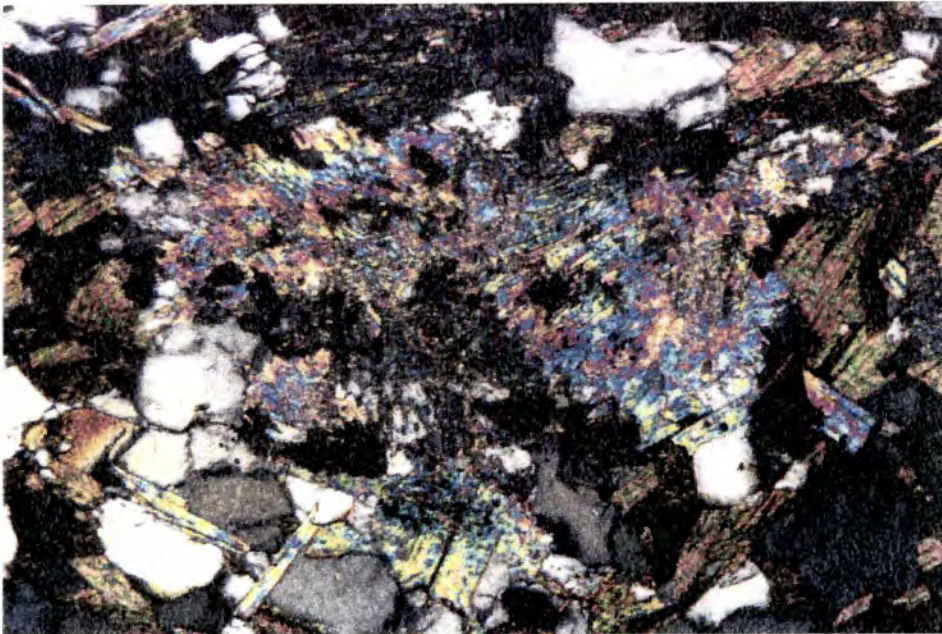


Table 2-4. Modal analyses of biotite gneiss-metagraywacke of the Tallulah Falls Formation in the study area determined by point counting. Bold italic samples are compiled for comparison from Davis (1993a). See Table 2-1 for abbreviations and explanation of error calculation.

Sample	Qtz (1-2.5%)	Bio (1-2.5%)	Musc/Ser (1-3%)	Kspar (2-3%)	Plag (2-3%)	Ep/Clz (1-2%)	Zir (<1%)	Chl (<1%)	Gt (<1%)	Hbl (<1%)	Opq (<1%)	# Points Counted
ME250A	26.64	20.76	6.14	0.52	37.02	5.36	1.64	---	0.87	---	1.04	1156
ME250B	17.57	23.42	26.35	---	26.53	2.38	trace	trace	1.65	---	1.28	1093
ME619yz	13.37	15.81	21.19	---	33.42	14.83	0.49	---	---	---	0.89	1227
ME657xz	23.3	18.3	4.93	---	41.4	10.93	---	---	0.27	---	0.9	1116
ME920A	20.2	13.28	26.39	0.45	33.67	3.64	0.27	1.09	0.45	---	0.55	1099
ME954xz	20.19	22.24	6.84	---	41.23	5.13	0.09	---	3.08	---	1.2	1169
ME981	23.14	5.3	10.25	---	36.4	22.26	---	---	0.35	---	2.3	1132
ME984	23.92	8.95	21.88	---	34.99	7.35	---	1.51	trace	---	1.33	1129
CM54	21.5	18.9	0.4	0.2	58.7	trace	no	no	trace	no	0.3	
CM379	30.2	10.8	3.2	13	42.1	no	no	no	no	no	0.7	
CM750	32.3	8.6	4.5	7.3	47.3	trace	no	trace	no	no	trace	

up to 1.0 cm or more in length. Sericite and epidote occur primarily as alteration products of plagioclase, although epidote may occur as a primary metamorphic mineral. Localized shear zones can impart a mylonitic texture to both the upper and lower graywacke-schist members. Amphibolite in the Tallulah Falls Formation is primarily composed of hornblende, plagioclase, and quartz. Figure 2-8 is a QFM ternary diagram of samples listed in Table 2-4.

Garnet-aluminous schist member. Stratigraphically, the garnet-aluminous schist member occurs below the upper graywacke-schist member and above the lower graywacke-schist-amphibolite member. It is arguably the most important rock unit in the study area. It not only serves as a stratigraphic marker, but because of its importance as a marker unit, also helps to define the structural relationships present in the study area.

In outcrop, the garnet-aluminous schist member closely resembles biotite schist of the metagraywacke-schist units. The garnet-aluminous schist unit, however, can be recognized by the abundance of pervasive garnets. The presence of ubiquitous garnet is the first indication of a lithologic change. Great care must be taken to verify the presence of kyanite and/or sillimanite, although this may not be possible at all outcrops. Pods of pelitic schist within the Tallulah Falls Formation may also contain numerous garnets. However, they do not contain an aluminous phase and are not traceable for more than a few meters. The garnet-aluminous schist member can show considerable lithologic variation, most often appearing as a garnetiferous-mica schist, but with increasing quartz content can approximate a garnet-rich quartzite. In fresh samples, the rock is a light to medium gray, medium- to coarse-grained schist. Weathered exposures are light tan to reddish tan, to purplish-red (Fig. 2-9). Outcrop patterns suggest that the garnet-aluminous

Figure 2-8.

Ternary QFM diagram of Tallulah Falls metagraywacke samples from Table 2-2.

(a) Classification of Pettijohn (1954).

(b) Plotted samples of Tallulah Falls metagraywacke. Q= quartz, F= feldspar, and M= mica.

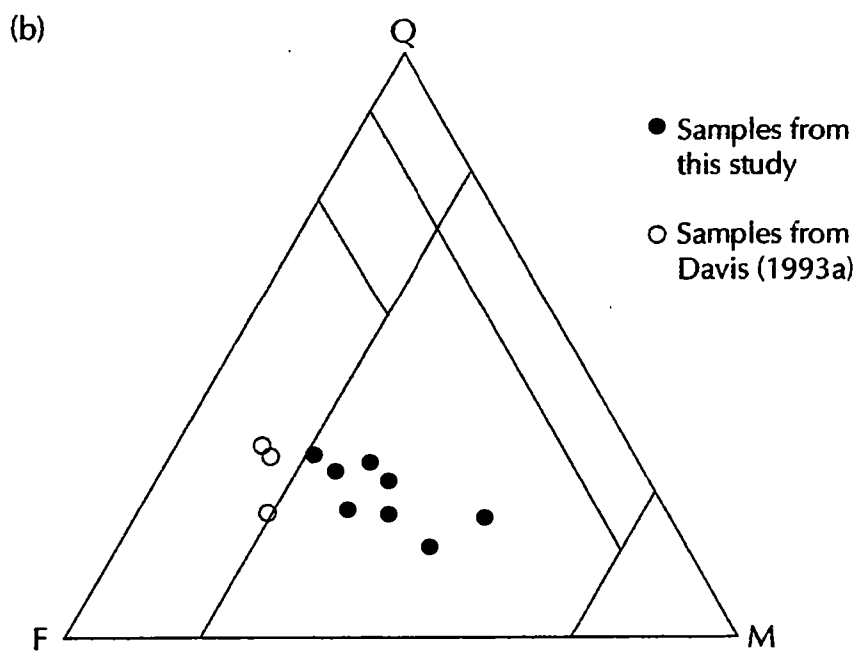
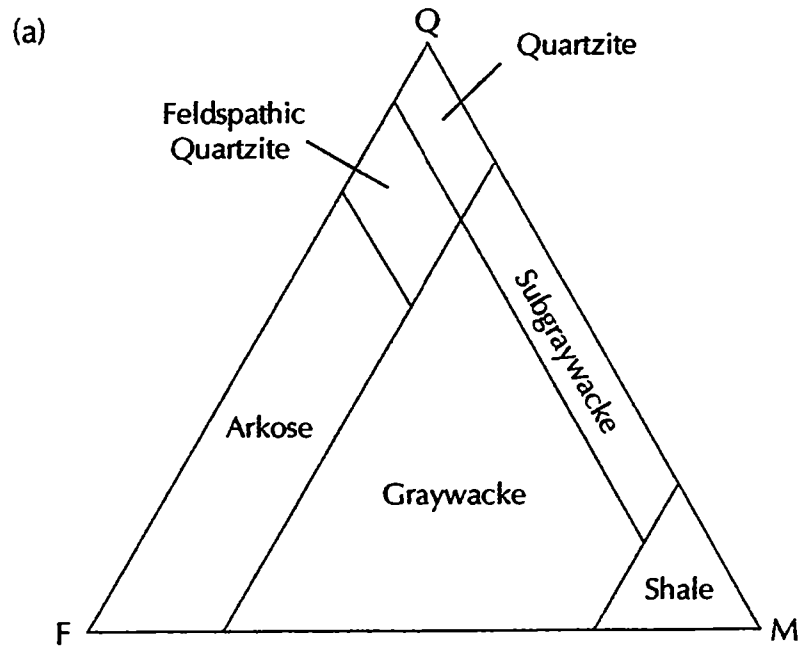


Figure 2-9.

Photograph and photomicrograph of garnet-aluminous schist of the Tallulah Falls Formation.

- (a) Hand sample of the garnet-aluminous schist member of the Tallulah Falls Formation. Sample is from the northeast side of Higgins Mountain, Marion East quadrangle. Arrows point to kyanite and garnets.
- (b) Photomicrograph of the garnet-aluminous schist member. Note the large kyanite crystals. Field of view is approximately 4 mm.

(a)



(b)



schist member is more susceptible to physical weathering than to chemical weathering, and therefore may be difficult to find in places typically thought to have excellent exposure such as stream beds. Thickness of the unit varies, but it is estimated to range between 20 and 100 meters.

In general, the garnet-aluminous schist is composed of muscovite + quartz + plagioclase + biotite + an aluminous phase + garnet + opaques $\pm$ epidote/clinozoisite $\pm$ chlorite $\pm$ tourmaline (Table 2-5). The aluminous phase total varies between 5.5 and 15 percent. Sillimanite was recognized only southeast of the Six Mile fault. It occurs predominantly as fibrolite but prismatic sillimanite up to 0.5 mm long was also recognized. Retrograde muscovite and sericite commonly replaces sillimanite. Kyanite appears as subhedral to euhedral crystals up to 7.0 mm long (Fig. 2-9). Larger kyanite crystals up to 3.5 cm long were collected in the field. Mica content, predominately muscovite, is generally between 32 and 45 percent. In the quartz-rich variety of the aluminous schist member, the micas are fine-grained euhedral crystals up to 1.0 mm long. In the more schistose variety, muscovite occurs as coarser grained euhedral crystals and augen up to 6.0 mm long. In both variations, biotite is much smaller than muscovite, only occasionally reaching 1.0 mm or more in length. Garnets are subhedral, commonly overgrown, range from 0.4 mm to 4.0 mm, and account for 6 to 10 percent of the total rock. They are usually inclusion rich and infrequently have an internal foliation rotated with respect to the dominant foliation. Quartz varies in relative abundance from 14 to 31 percent. Plagioclase content is generally between 8 and 19 percent. Both are inequigranular, subhedral, and vary in size from 0.1 mm to 1.5 mm. Epidote occurs as both primary and alteration minerals. Sericite occurs as an alteration product, primarily derived from feldspar. Chlorite is also present as an alteration product.

Table 2-5. Modal analyses of Talullah Falls aluminous-schist member in the study area determined by point counting. Abbreviations: Qtz = quartz; Plag = plagioclase; Musc = muscovite or sericite; Bio = biotite; Ky = kyanite; Sill = sillimanite; Gt = Garnet; Epd/Clz = Epidote/Clinzoisite; Opq = opaques; Chl = chlorite; Tour = tourmaline
See Table 2-1 for more abbreviations and explanation of error calculations.

Sample	Qtz (1-2.5%)	Plag (2-3%)	Musc (1-3%)	Bio (1-3%)	Ky (<1%)	Sill (<1%)	Gt (<1%)	Epd/Clz (1-2.5%)	Opq (<1%)	Chl (<1%)	Tour (<1%)	# Points Counted
ME 75	30.78	19.04	15.21	17.08	---	7.74	7.65	0.36	2.14	trace	---	1124
ME 658A	22.51	17.94	35.5	6.8	5.67	---	7.3	0.35	1.83	---	2.1	1093
ME 789	14.1	14.94	37.38	2.5	15.02	---	10.4	trace	trace	5.66	---	1078
ME 906	19.18	8.12	42.6	3.52	6.35	---	6.5	---	5.48	7.63	---	1022

Miscellaneous Rock Units

Phyllonitic schist and mylonite. Phyllonitic schist, phyllonite, blastomylonitic gneiss, and mylonite occur in a narrow belt associated with the Brevard fault zone. The phyllonitic schist occurs as a fine-grained gray to gray-green chlorite-sericite schist or phyllonite with interlayered metasilstone. Weathered samples are brown to brownish gray. The schists have a distinctive button appearance caused by a prominent S-C fabric that produces large muscovite "fish" up to 2 cm in diameter. Recrystallized quartz, plagioclase, epidote, and opaques ranging in size from 0.01 to 0.2 mm are common constituents. The phyllonitic schist frequently contains layers of mylonitic gneiss.

Bryant and Reed (1970) stated that the phyllonitic schist of the Brevard fault zone is mineralogically different from adjacent rocks of both the Inner Piedmont and Blue Ridge. They suggested that the rocks in the phyllonitic zone form an exotic tectonic slice derived from outside the Grandfather Mountain area. The presence of marble within the phyllonitic belt, however, suggests that the belt is the northern equivalent of the Chauga River Formation of Hatcher (1969).

Marble. Impure silicic marble was recognized in the Brevard fault zone. No thin sections were made of this unit. This same unit was recognized by Conrad (1960), Bryant and Reed (1970), and Conley and Drummond (1981) and the petrographic description of this unit is taken from their studies. The marble is light gray in outcrop with fresh surfaces frequently having a bluish color. Thickness of the marble varies from tens of centimeters to more than 30 m (Conrad, 1960). It is fine- to medium-grained and weakly foliated containing porphyroclasts of muscovite and biotite up to 5.0 mm long. The marble is interlayered with quartz-feldspar gneiss and biotite gneiss. Calcite occurs as inequigranular twinned

grains that vary in size from 0.25 to 1.0 mm in diameter. Carbonate content in the impure marble varies from 25 to 90 percent. MgCO_3 typically accounts for about 11 percent of the total carbonate. Plagioclase (An_{35}) and quartz occur as scattered anhedral grains interstitial to carbonate and in thin layers parallel to the dominant foliation. Generally, the composition of the marble is carbonate + quartz + plagioclase + muscovite + biotite + opaques $\pm$ apatite $\pm$ sphene.

Granitoid gneiss. Several granitoid gneiss bodies are present in the study area. They typically consist of a sheared inequigranular patchwork of anhedral plagioclase, microcline, quartz, biotite, muscovite, and opaques in various amounts. Foliation is defined by parallel alignment of micas. No thin sections of granitic gneiss were point-counted. Mica content is estimated to be less than 7 percent total in all samples examined. The granitic gneisses are medium- to fine-grained and light to medium gray. Most of the bodies are concordant to semiconcordant with the surrounding rocks, forming sharp contacts. Granitic gneisses weather to a gray to light-brown sand saprolite.

Ultramafic bodies. Several pods of ultramafic bodies are present within the study area, although not all are mappable. These bodies are usually medium- to fine-grained schists, although the largest, a body on the east side of Gibbs Mountain, is coarse grained. The ultramafic bodies are usually dark green-gray to black. They are composed primarily of amphibole, talc, chlorite, relict clinopyroxene, pyrophyllite (?), and serpentine.

Alluvium. Alluvium in the study area is found along all major and minor streams. It consists of unconsolidated stream deposits up to 2 meters thick. Generally, a lower

gravelly layer is overlain by a more sandy to clayey layer. The lower portion consists of well-rounded quartz pebbles from 1 cm to 50 cm in diameter in a sandy matrix. The upper layer is usually composed of finely layered, coarse- to fine-grained mixture of sand silt and clay.

Mineral and Economic Deposits

Two occurrences of tourmaline-bearing mica schist and tourmaline-bearing pegmatite material were noted in the study area. Tourmaline makes up approximately 10 to 20 percent of the observed rock volume for these occurrences. See Plate I for specific locations.

One active sand and gravel quarry is present within the study area and is located just north of Interstate 40 at Exit 85. The upper-graywacke-schist member of the Tallulah Falls Formation is being mined here. The Tallulah Falls Formation offers the best possibility for crushed stone production in the study area.

Kyanite occurs in the aluminous-schist member of the Tallulah Falls Formation in varying amounts. The economic occurrence of aluminum silicates in the study area is not likely. The aluminous-schist member makes up a small portion volumetrically of the study area. Aluminum silicate polymorphs were not found in any other rock unit.

Marble has never been mined in the study area. Conrad (1960) believed that occurrences in the study area may be potential quarry sites. He reported thickness of the marble unit from drill holes to be in excess of up to 130 feet. Impure marble was noted in this study but the economic value of such deposits are not thought to be economically viable.

Chapter III

Structural Relationships and Deformational History

Introduction

The western Inner Piedmont has undergone multiple episodes of both prograde metamorphism and ductile deformation. The rocks in the study area are middle- to upper-amphibolite metamorphic facies except where they have been affected by retrogressive metamorphism associated with the Brevard fault zone or local hydrothermal alteration. At least three separate orogenic events have affected the study area. The timing of deformational and metamorphic events is constrained between 535 Ma and 335 Ma by Rb-Sr ages of granitic gneisses and $^{40}\text{Ar}/^{39}\text{Ar}$ ages of hornblende, biotite, and muscovite within the Inner Piedmont (Harper and Fullagar, 1981; Dallmeyer, 1988). Multiple episodes of folding and faulting culminated with the last brittle movement corresponding to Alleghanian reactivation of the Brevard fault zone.

Davis (1993a) suggested a basic framework to explain the relationship between deformational events (D_1 to D_5) and metamorphism based on a thrust-wrench partitioned deformation that developed during the D_2 - D_3 deformational events. Davis (1993a) recognized that orogen-parallel and orogen-oblique structures in the Inner Piedmont could be explained by a single event of oblique collision. Both orogen-oblique and orogen-parallel structures had previously been recognized, but had been attributed to separate tectonic events (Reed and Bryant, 1964; Bryant and Reed, 1970; Griffin, 1971, 1974; Hatcher, 1972, 1977; Roper and Dunn, 1973; Stirewalt and Dunn, 1973; Bobyarchick et al., 1988). Tabor et al. (1990) argued for two separate episodes of movement. Davis

(1993a, 1993b) suggested that these structures formed coevally based on progressive change in orientation of mineral lineations and kinematic indicators. Table 3-1 is a summary of deformation and related structures from Davis (1993a).

Davis' model (Fig. 3-1) suggests that early southwest movement on the primordial Brevard fault was kinematically linked to the emplacement of west-directed and northwest-directed thrust sheets. In Davis' model, ductile thrust sheets were emplaced from the east and as the thrusts encountered the primordial Brevard fault, they were redirected southwest. He argued that northeast-southwest structures were related to orogen-parallel southwest-directed movement along the Brevard fault zone, and orogen-oblique east-west and west-northwest directed structures were related to emplacement of ductile thrust sheets during D_2 and D_3 . The basis of this argument is twofold. Lineation patterns are thought to be the pattern of ductile flow, and petrographic evidence that indicates sillimanite growth within the S_2 regional foliation occurred as a result of continuous reactions (Davis, 1993a).

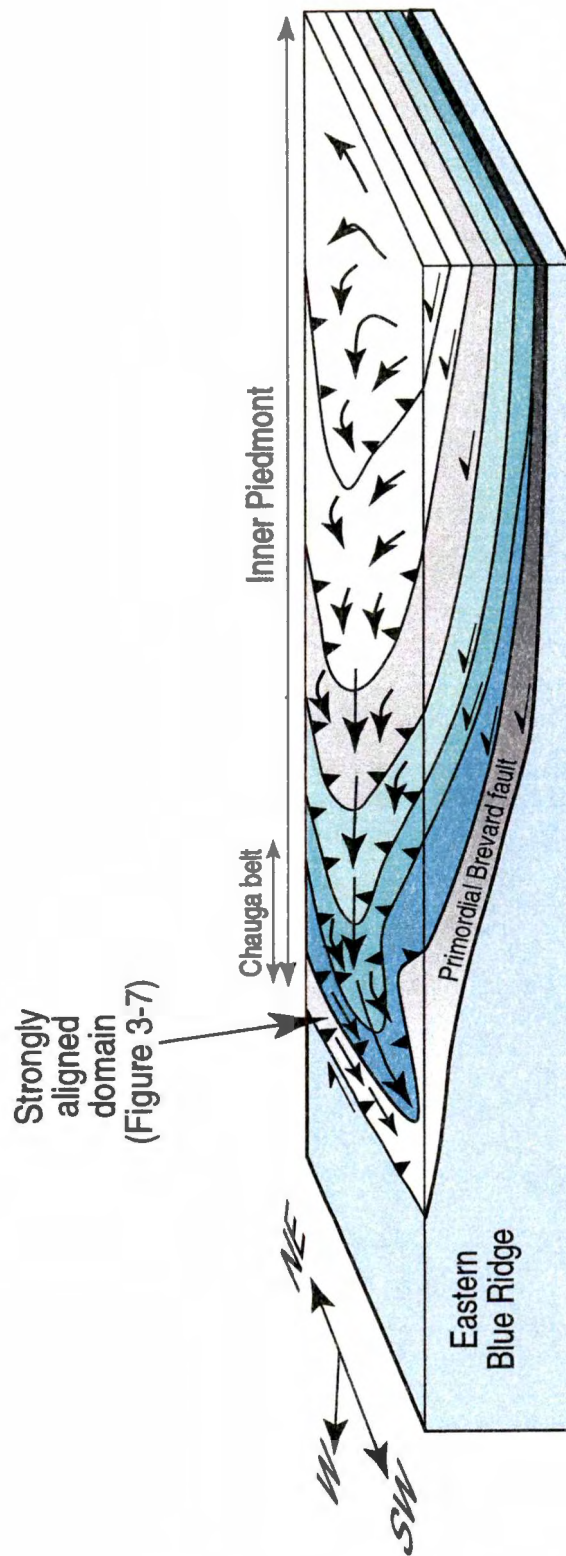
Based on recent work in the Inner Piedmont and adjacent Brevard fault zone near Marion, North Carolina, revisions are suggested to the framework presented by Davis (1993a). Map patterns reveal that previously unrecognized map-scale isoclinal folds predate the emplacement of the Henderson Gneiss. Furthermore, the outcrop pattern of the Henderson Gneiss has been related to a map-scale sheath fold that climbs stratigraphic section to the southwest (Hill et al., 1998). I believe that this relationship is a simple one relating early footwall deformation of the Chauga Belt/Brevard fault zone and a later phase of deformation in the lower section of the hanging wall(s) of imbricating blocks (e. g., Walhalla nappe, Six Mile nappe) during oblique collision. This model and its possible relationship to structures found in the study area and western Inner Piedmont will be discussed in greater detail in Chapter 5 of this study.

Table 3-1. Summary of deformational events and related structures. Data compiled from Davis (1993a).

	Folds		Fabrics	Faults
	Style	Orientation		
D ₁	small rootless, intrafolial, isoclinal to recumbent			
D _{2a}				Stumphouse Mtn. and Tumble Bug Creek faults, emplacement of the Henderson Gneiss
D _{2b}	Tight to isoclinal; recumbent to reclined	Variably oriented E- NE, west to northwest-vergent, northeast-trending	S ₂ foliation, L ₂ penetrative lineation	Walhalla nappe, Cedar Creek thrust
D ₃	Isolated, upright or inclined; deforms S ₂	Variably oriented NE to SE	S ₃ (indistinct)	Toccoa Falls-Shorts Mill fault, Alto allochthon, reactivation of Brevard fault, unnamed ductile strike-slip fault that cuts the Mill Spring thrust
D ₄	Upright broad, open to gentle	N to NE		
D ₅	Upright broad, open to gentle	NW		

Figure 3-1.

Crustal flow model for the western Inner Piedmont in North and South Carolina modified after Davis (1993b). Arrows represent approximate motion of the thrust sheets. In this model sheets began movement from the east toward the west-northwest and were then reoriented east-west and southwest as they encountered the Brevard fault zone.



Summary of Deformational Events and Associated Structures

Polyphase deformation has been recognized throughout the Inner Piedmont (e.g., Griffin, 1969a, 1969b, 1971; Hatcher, 1972, 1977, 1978a; Goldsmith, 1981; Horton et al., 1981; Hatcher and Acker, 1984; Hopson and Hatcher, 1988; Bobyarchick et al., 1988; Davis, 1993a). Some structural components, like the Brevard fault zone, were formed in one orogenic event and then reactivated during following events under different P-T conditions (e. g., Hatcher, 1972; Stirewalt and Dunn, 1973). Multiple reactivation of early structures complicates any effort to decipher the relative timing of deformational events. The need to place these deformational events in a relative time scale has led to numerical designations that vary among descriptions of various areas by different investigators. At least four generations are recognized in most areas of the Inner Piedmont (Horton and McConnell, 1991). The deformational events summarized here are thought to accurately represent the polyphase deformational events in the Chauga-Walhalla thrust complex.

A minimum of five deformational events have been recognized in the study area (Table 3-2). The D_1 event is associated with pre-peak metamorphism and is indistinct because of transposition associated with later events. The D_2 event is the most regionally pervasive event within the Inner Piedmont. Previous investigations (Davis, 1993a; Yanagihara, 1994; Curl, 1998) have subdivided the D_2 event into two sub-events: D_{2a} and D_{2b} . This usage is abandoned here because timelines associated with these sub-events have been invalidated by timing relationships revealed during this study. The D_3 event is a late syn- to post-peak metamorphic event that occurred prior to complete cooling of the rocks but under less ductile conditions than D_2 (Hopson and Hatcher, 1988; Davis, 1993a; Yanagihara, 1994; Curl, 1998). The D_2 and D_3 events are separated on the basis of both

Table 3-2. Revised summary of deformational events and related structures.

	Folds		Fabrics	Faults
	Style	Orientation		
D ₁	small rootless, intrafolial, isoclinal to recumbent			
D ₂	Tight to isoclinal; recumbent to reclined	Variably oriented E- NE, west to northwest-vergent, northeast-trending	Early isoclinal folding, emplacement of Henderson Gneiss, continued folding Brevard fault?, S ₂ foliation, L ₂ penetrative lineation	Tumble Bug Creek fault, emplacement of the Henderson Gneiss, Walhalla nappe (?)
D ₃	Isolated, upright or inclined; deforms S ₂	Variably NE to SE	S ₃ (indistinct)	Mill Spring fault, Six Mile fault, emplacement of thrust from east, Toccoa Falls, Shorts Mill fault, Alto allochthon, reactivation of Brevard fault
D ₄	Upright broad, open to gentle	N to NE		
D ₅	Upright broad, open to gentle	NW		

style of structures associated with each and their relative association with peak metamorphism. I suggest below that D_2 and D_3 are separate phases of a single event. The D_4 and D_5 events are both post-metamorphic, nonpenetrative (brittle?) events.

D₁ Deformation

Foliation

Evidence for an S_1 foliation was not obvious in the study area due to the penetrative nature of later deformational events. Amphibolite boudins within the Tallulah Falls Formation sometimes contain a foliation that is discordant with the dominant foliation. S_1 foliation has also been reported elsewhere in the Inner Piedmont as a weak axial planar foliation in the hinges of F_2 folds (Hopson and Hatcher, 1988; Davis, 1993a; Curl, 1998). Yanagihara (1994) interpreted compositional layering in the amphibolite member of the Poor Mountain Formation to be original layering because of the observed relationship between layer thickness and spatial relationship to the quartzite member. This idea is rejected here because of the overall parallelism between compositional layering, dominant foliation (S_2), and stratigraphic contacts.

Folds

The D_1 event is recognized by small rootless intrafolial folds and truncated folds within boudins, and occurred before the main phase of recrystallization (Davis, 1993a). Rootless intrafolial folds can be found in all stratigraphic units but are most observable in the layered rocks of the Poor Mountain and Tallulah Falls Formations (Fig 3-2).

Figure 3-2.

F_1 fold in the Tallulah Falls Formation.

(a) Rootless intrafolial F_1 fold in the graywacke-schist member of the Tallulah Falls Formation exposed on the northwest-side of Reedy Mountain.

(b) Same as (a) but with an overlay showing intrafolial fold and near parallelism of the F_1 fold axial surface with the dominant S_2 foliation.

The head of the rock hammer is approximately 18 cm long.

(a)



(b)



Similar structures have been recognized in the eastern Blue Ridge and elsewhere in the Inner Piedmont (e.g., Roper and Dunn, 1973; Stirewalt and Dunn, 1973; Hatcher, 1977; Hatcher and Butler, 1979; Goldsmith, 1981; Hopson and Hatcher, 1988). Evidence for D_1 in the study area is meager, but Davis (1993a), Yanagihara (1994), and Curl (1998) all reported D_1 structures within their respective study areas, indicating that the D_1 event was regionally extensive.

D₂ Deformation

Evidence indicates that the D_2 event was a polyphase event at or near peak metamorphic temperatures (Davis, 1993a). The D_2 event is pervasive and penetrative on all scales and is responsible for the development of the transposed regional S_2 foliation and the coplanar L_2 mineral stretching lineation. Multiple events are thought to be coincident with D_2 deformation. Therefore, D_2 is interpreted to be a protracted and progressive episode, in which heterogeneous and slightly diachronous deformation occurred as a continuum. Timing of this event is constrained to early to middle Paleozoic by the 509 Ma Rb-Sr age date on the Henderson Gneiss (Sinha et al., 1989) and a 438 Ma granitoid (Odom and Russell, 1975) that intruded the Henderson Gneiss, both of which have been deformed by the D_2 event. These ages correspond to the Acadian tectonothermal event for the southern Appalachians. Cooling curves for the emplacement of these sheets were constructed from muscovite and hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ closure data obtained by Dallmeyer (1988) (Chapter 4, this study). The data indicates an average cooling rate of 4.5° per million years. Assuming peak metamorphic temperature of 700°C , a simple calculation indicates that D_2 occurred around 382 Ma (Chapter 4, this study).

Foliation

The dominant planar feature in the study area is the S_2 foliation. The S_2 foliation is also the most pervasive fabric element in the southern Appalachian Piedmont and has been interpreted to be mylonitic. S_2 is roughly parallel to compositional layering. S_2 is thought to have developed as a C surface (Davis, 1993a: 1993b). The S_2 foliation is a composite foliation (Tobisch and Paterson, 1988) resulting from transposition of all earlier fabrics (Hatcher, 1990; Davis, 1993a). Based on asymmetric S-C fabrics, Davis (1993a) suggested that S_2 is a regionally extensive shear surface that developed by boundary parallel, noncoaxial flow.

One thousand sixty-six foliation measurements were made in the study area, with an additional 170 foliation measurements compiled from the Geologic Map and Mineral Resources Summary of the Northeast $\frac{1}{4}$ Marion Quadrangle map (Conley and Drummond, 1981). Equal area fabric diagrams and histograms of S_2 foliation are shown in Figure 3-3. The average strike for S_2 is N44E / 34SE and the calculated girdle is S38E / 85W with an β -axis of 052 / 5. Forty-eight percent of the measurements taken dip between 31 and 40 degrees, while almost 42 percent strike between N41E and N50E.

Folds

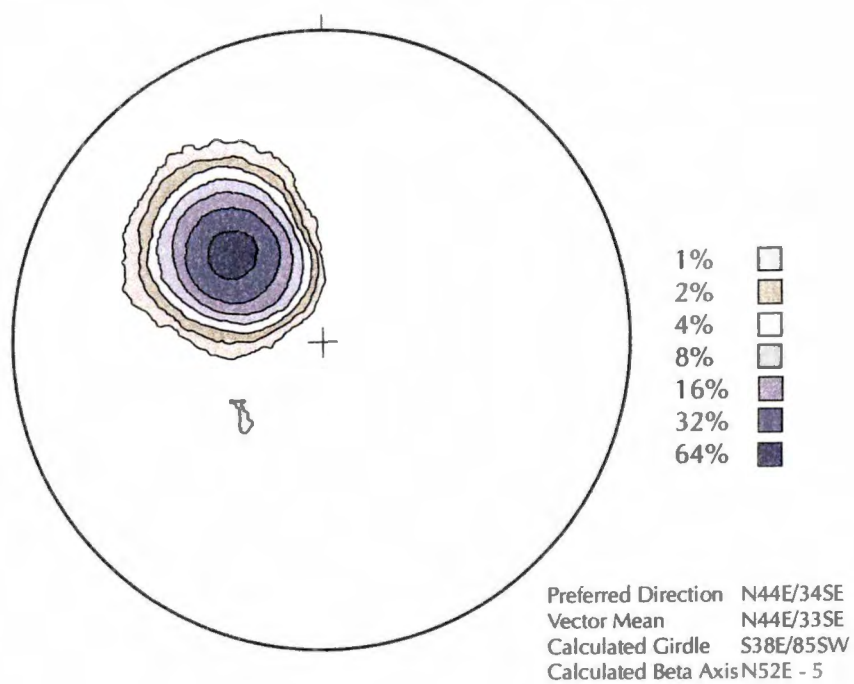
Map patterns (Plate I) of the garnet-aluminous schist member of the Tallulah Falls Formation define a map-scale fold pattern that predates the emplacement of the Henderson Gneiss. The garnet aluminous schist is truncated by the Tumblebug Creek fault in the study area and to the southwest (see Bream, 1999). These folds are orogen-parallel and axial planes are parallel to the strike of regional foliation. These folds are interpreted to be an early stage of folding and may explain truncation of isoclinal folds within the

Figure 3-3.

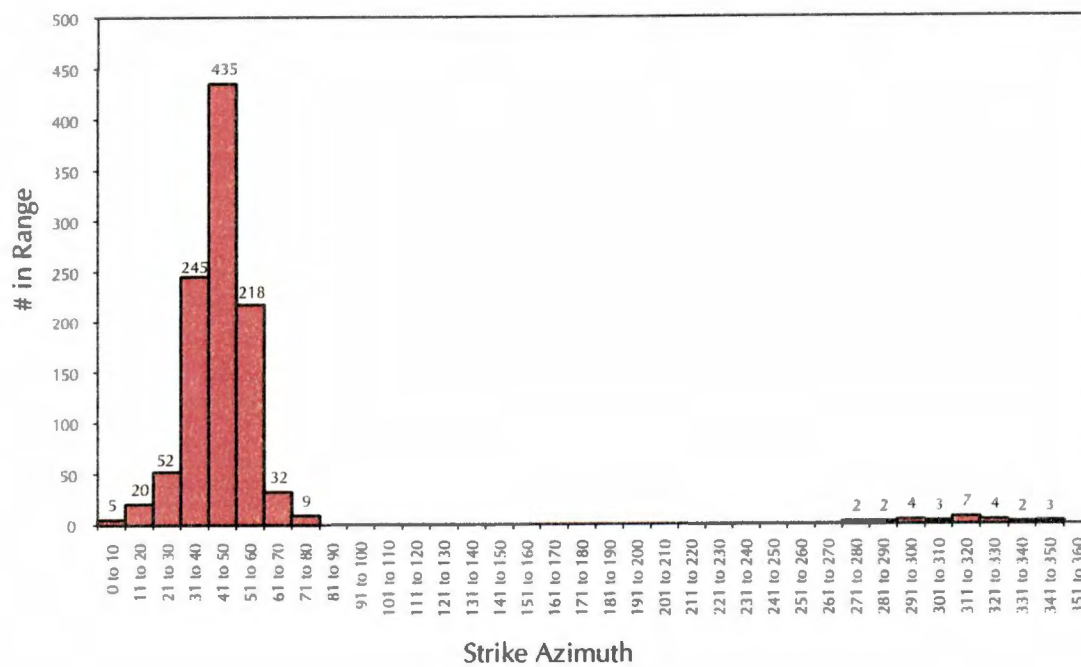
Fabric diagram and strike azimuth and dip magnitude histograms of 1041 measurements taken in the study area.

- (a) Lower hemisphere, equal area projection (intensity per 1% area) of contoured poles to S_2 . Note the bullseye pattern suggesting a dominant transposed foliation.
- (b) Histogram showing number of measurements within 10-degree intervals. Forty-two percent of the foliations strike between N41E and N50E and 86 percent strike between N31E and N60E.
- (c) Histogram showing number of dip measurements within 10-degree intervals. Seventy-seven percent of dip measurements are less than 40 degrees.

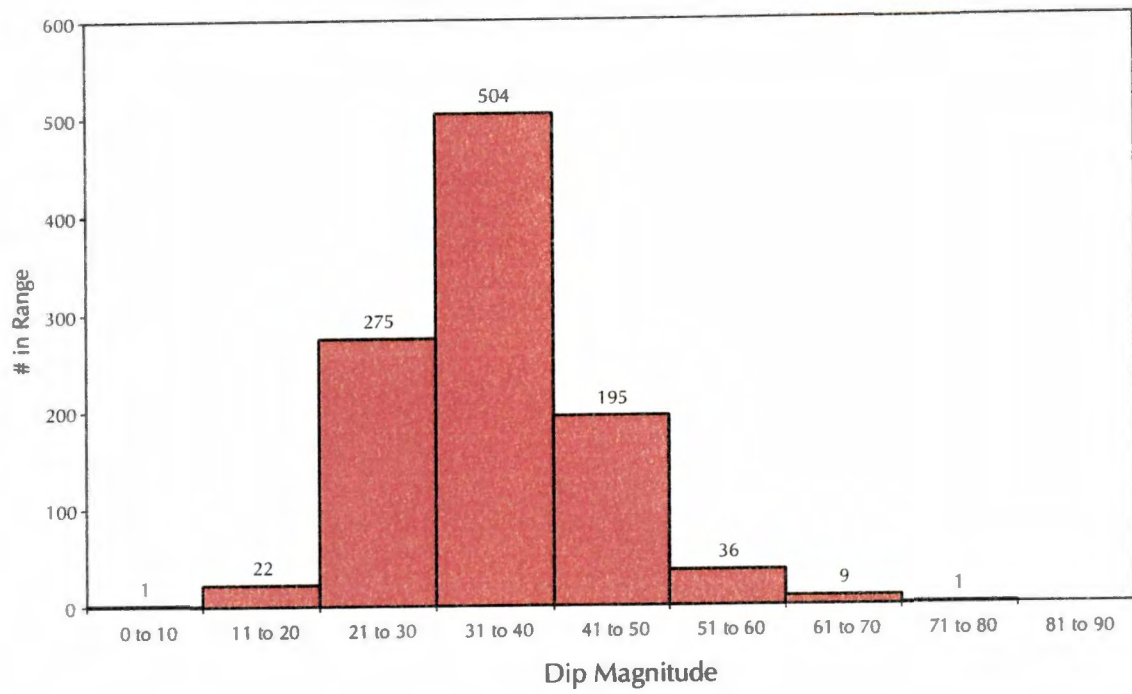
(a)



(b)



(c)



Poor Mountain Amphibolite against the Henderson Gneiss, as reported by Davis (1993a). A map-scale example of this early isoclinal folding is the Bob's Creek syncline. The Bob's Creek syncline is defined by the map pattern of the Poor Mountain Formation on Higgins Mountain in the southeast corner of the study area. This early synform is later openly folded again by a D_4 syncline, the Rockhouse Mountain syncline, which plunges shallowly to the northeast.

Outcrop-scale folds are characterized by tight, isoclinal folds that are recumbent to reclined and have axial planes approximately parallel to S_2 (Fig. 3-4). F_2 folds are northeast trending and have thickened hinges and attenuated limbs diagnostic of passive flow folds. Sheath folds have also been recognized at the outcrop scale within the study area. These sheath folds are thought to have formed under high simple shear by amplification and rotation of an initially cylindrical fold into the maximum extension (transport?) direction (Cobbold and Quinquis, 1980). Sheath folding seems to occur in all stratigraphic units and may be the dominant type of folding within the western Inner Piedmont. Fabric diagrams and histograms of all fold data collected are shown in Figure 3-5.

Recent recognition of the Henderson Gneiss as a map-scale sheath fold (Hill et al., 1998) that truncates earlier map-scale folds based on map patterns, clearly defines the order of early D_2 events. This is supported by the fact that Henderson Gneiss and surrounding rocks of the Tallulah Falls and Poor Mountain Formations share a common S_2 (?) foliation. The Henderson Gneiss must have been emplaced as a sheath fold after the initiation of the map-scale folding but syn- to post-development of the S_2 composite foliation. Northeast-trending folds that deform the Henderson Gneiss along its western edge (Vauchez and Brunel, 1988) indicate that isoclinal folding continued after emplacement. It should be pointed out that these events represent a continuation of a

Figure 3-4.

F₂ folds in the lower member of the Tallulah Falls Formation on the south side of Grant Mountain.

- (a) Folded leucocratic layer in the Tallulah Falls metagraywacke.
- (b) Photograph with overlay showing dominant S₂ foliation, trace of fold, and fold axes. Length of the hammer is approximately 28 cm.

(a)



(b)

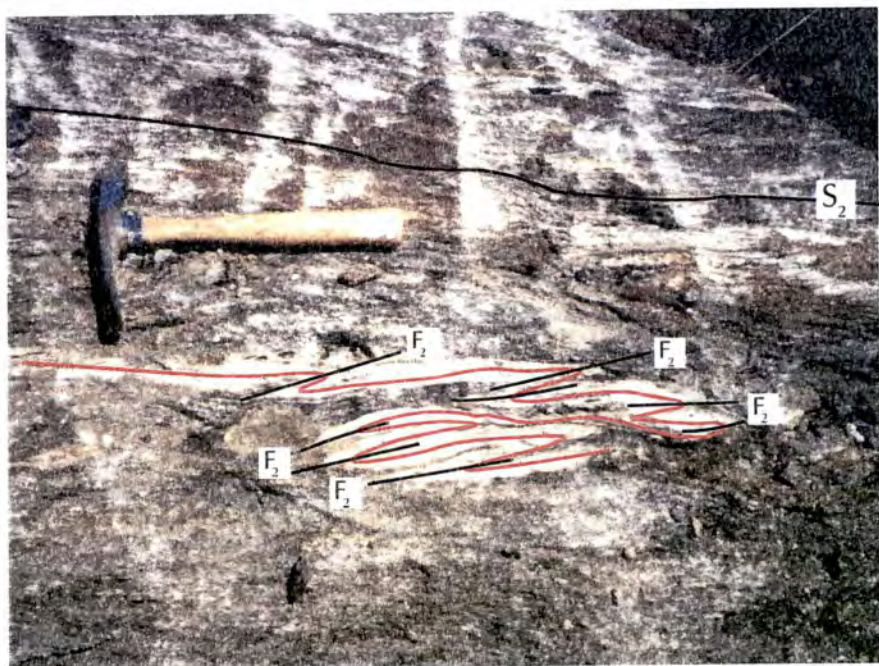
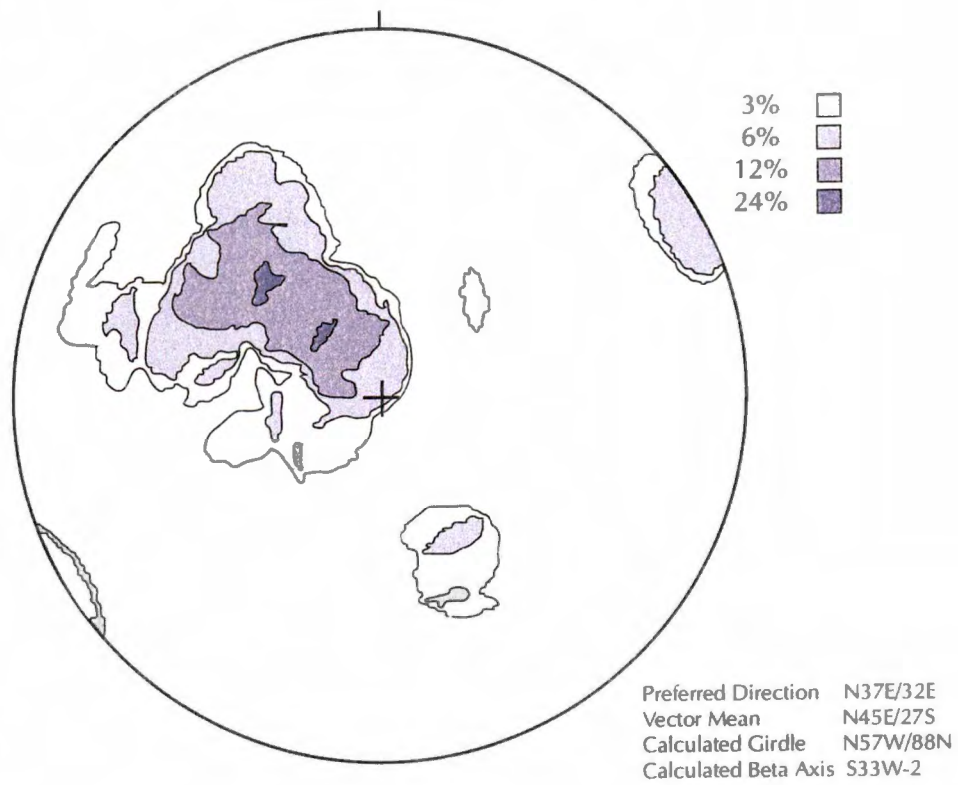


Figure 3-5.

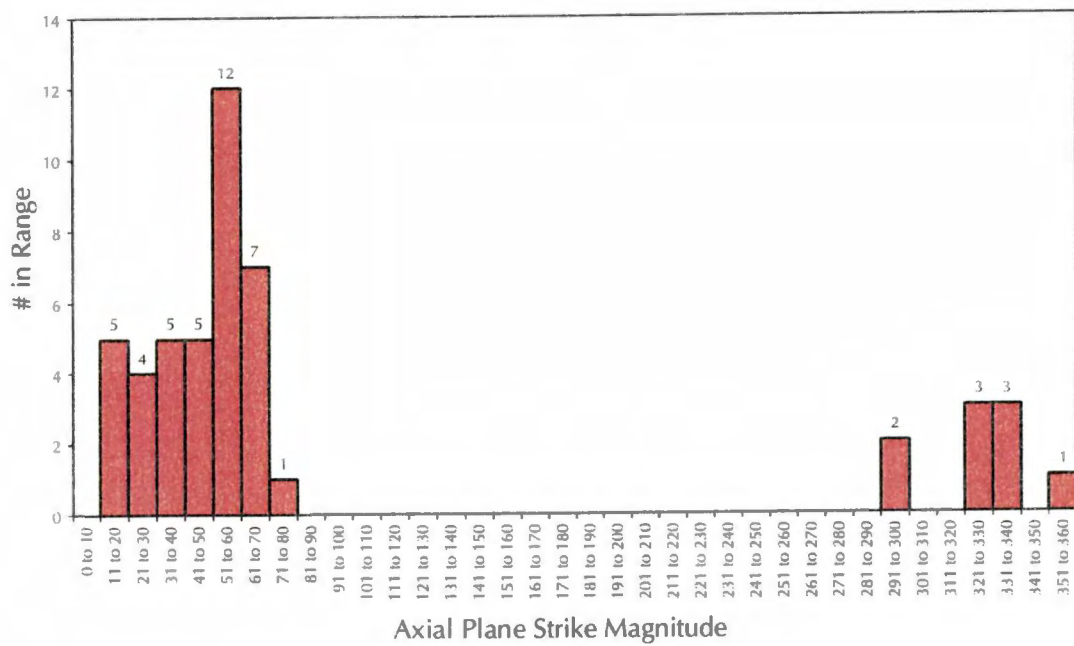
Fabric diagrams and histograms of 48 folds in the study area.

- (a) Lower hemisphere equal area projection (intensity per 1% area) of contoured poles to fold axial planes.
- (b) Histogram showing axial-plane strike magnitude of all fold measurements.
- (c) Lower hemisphere equal area projection of fold hinge-line plunge and trend for all folds measured in the study area.
- (d) Histogram showing trend magnitude of all fold measurements.

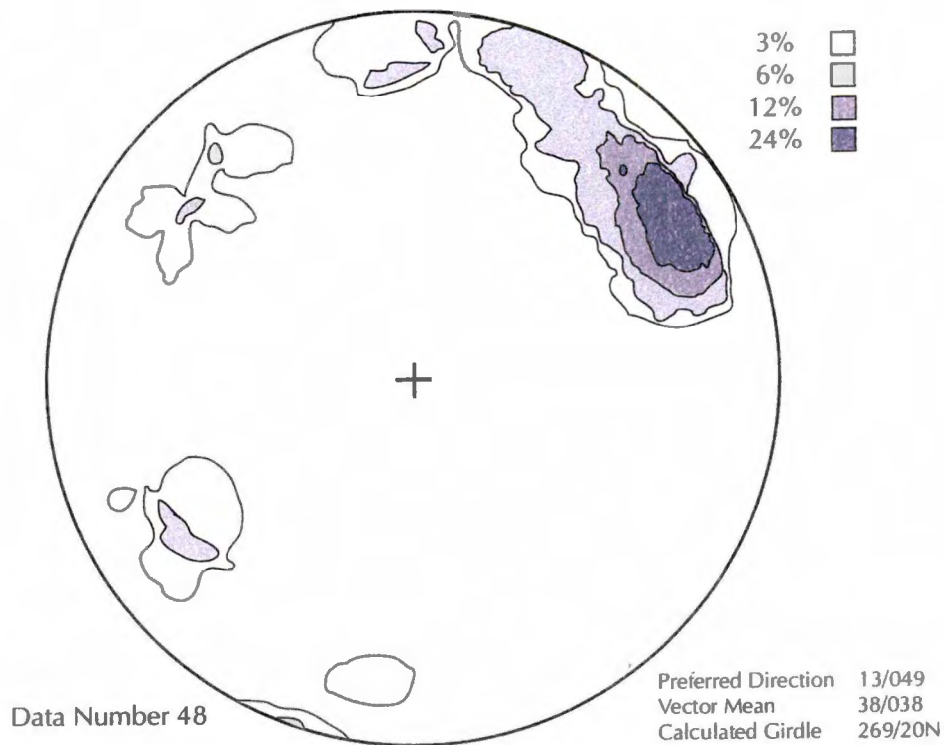
(a)



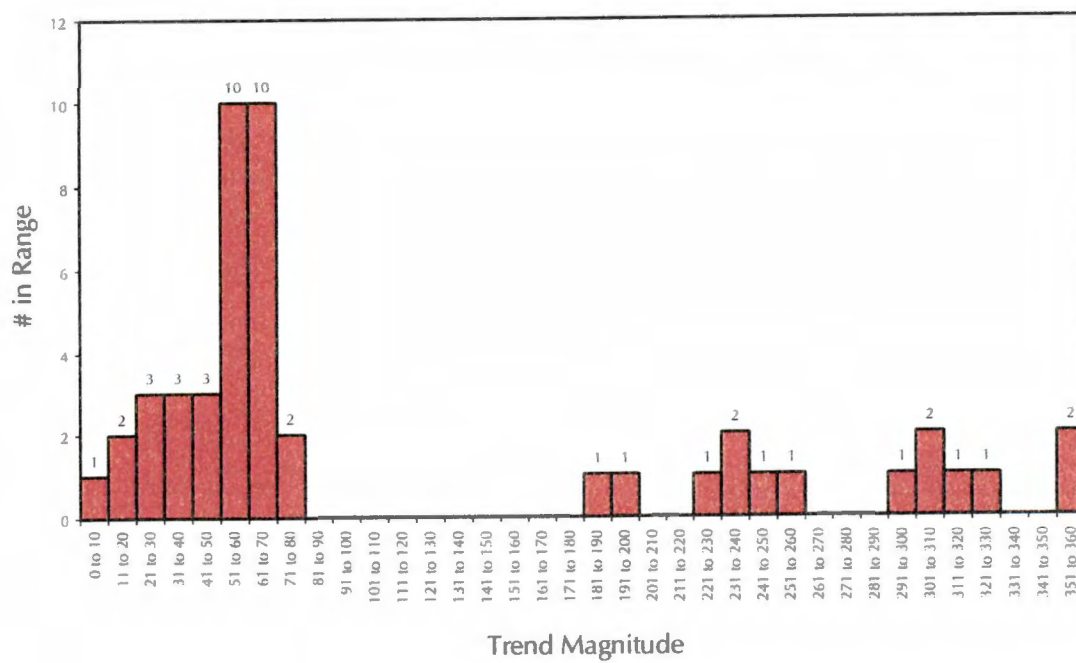
(b)



(c)



(d)



series of events that cannot be separated or separately discerned. This pattern is consistent with the early phase of deformation of a footwall undergoing oblique collision, which is characterized by stretching lineations subparallel to the orogen and development of isoclinal and sheath folds (Ellis and Watkinson, 1987).

The Henderson Gneiss climbs stratigraphic section from its base in North Carolina to its termination southwest in South Carolina (Fig. 1-1c). Map-scale structure on the northeast termination of the Henderson Gneiss indicates that the Henderson Gneiss trends obliquely across earlier structure. At the southeast termination, the Henderson Gneiss and the Poor Mountain Amphibolite reveal a complex, interfolded map pattern that is best explained by a map-scale sheath fold. Shear-sense indicators, mostly S-C fabrics, asymmetrical folds, σ -type, and δ -type feldspar porphyroclasts, indicate relative movement toward the southwest. Mineral stretching lineations predominantly trend northeast-southwest subparallel to the orogen.

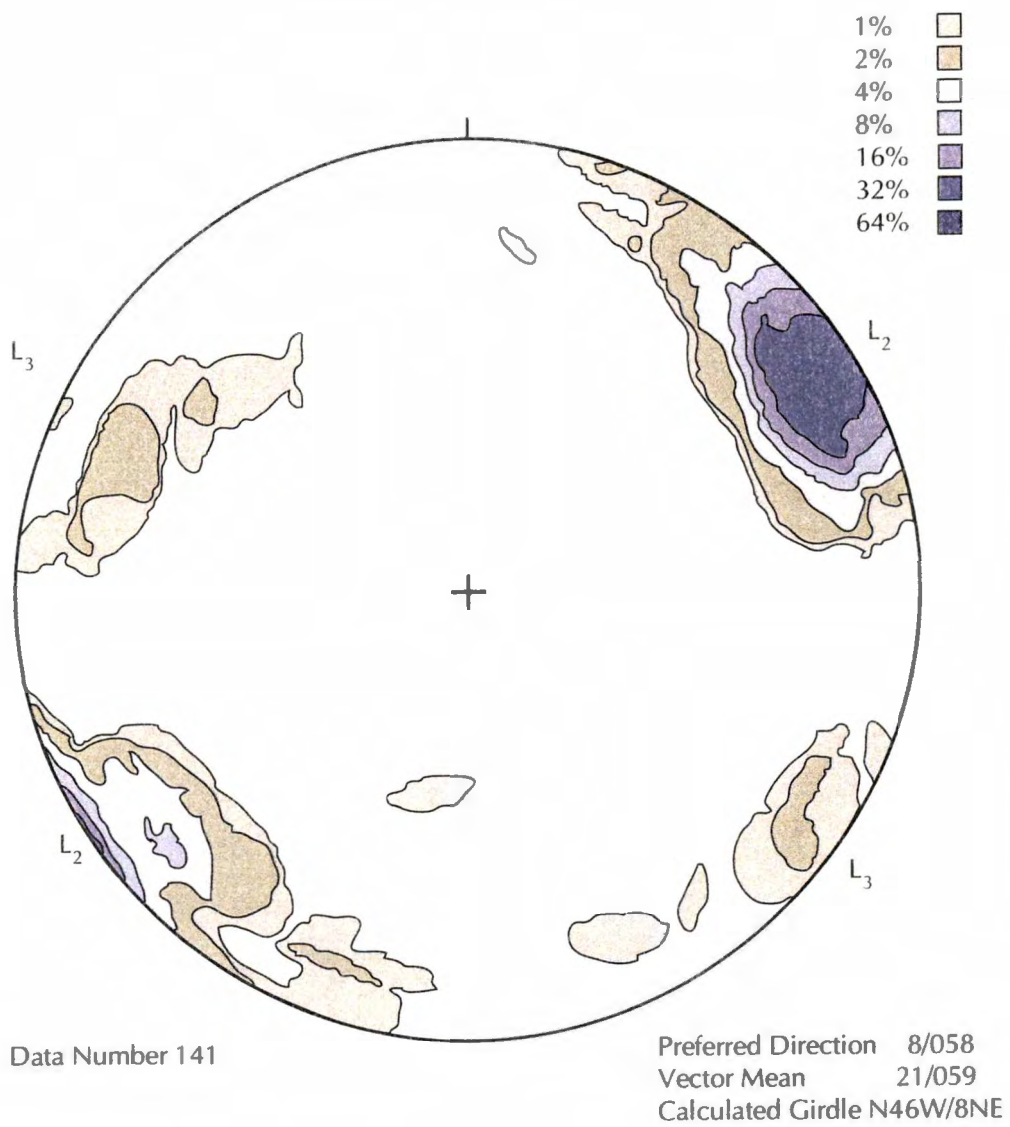
Lineations

Mineral lineations (Fig. 3-6) associated with the D₂ metamorphic peak are the dominant linear feature within the study area. L₂ lineations are defined by elongate minerals such as amphibole and biotite in rocks of the Poor Mountain and Tallulah Falls Formations and by elongate feldspar porphyroclasts in the Henderson Gneiss. L₂ lineations trend northeast-southwest and have shallow plunge. L₂ lineations are parallel to subparallel to the strike of the dominant foliation and lie within the plane of S₂. The attitudes of L₂ lineations are generally coincident with shear-sense indicators and have been interpreted to be mineral stretching lineations (Davis, 1993a). True movement direction, however, is parallel only to the lineation that lies within the C-surface of a shear

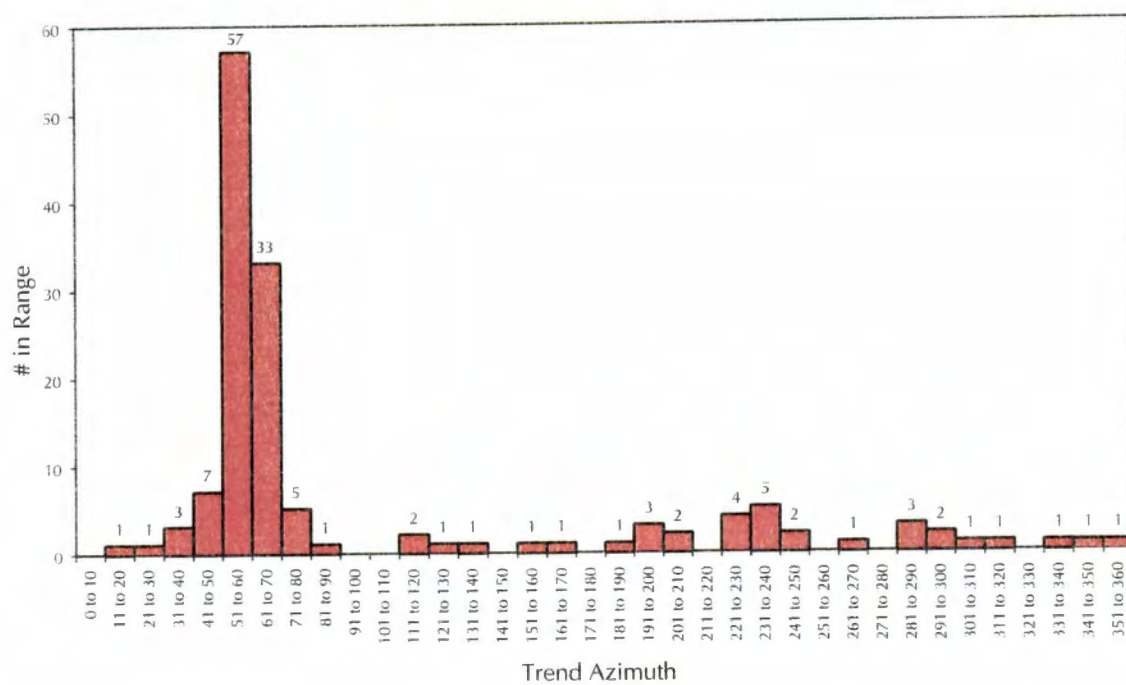
Figure 3-6.

Fabric diagram and histograms of all lineation data collected in the study area.

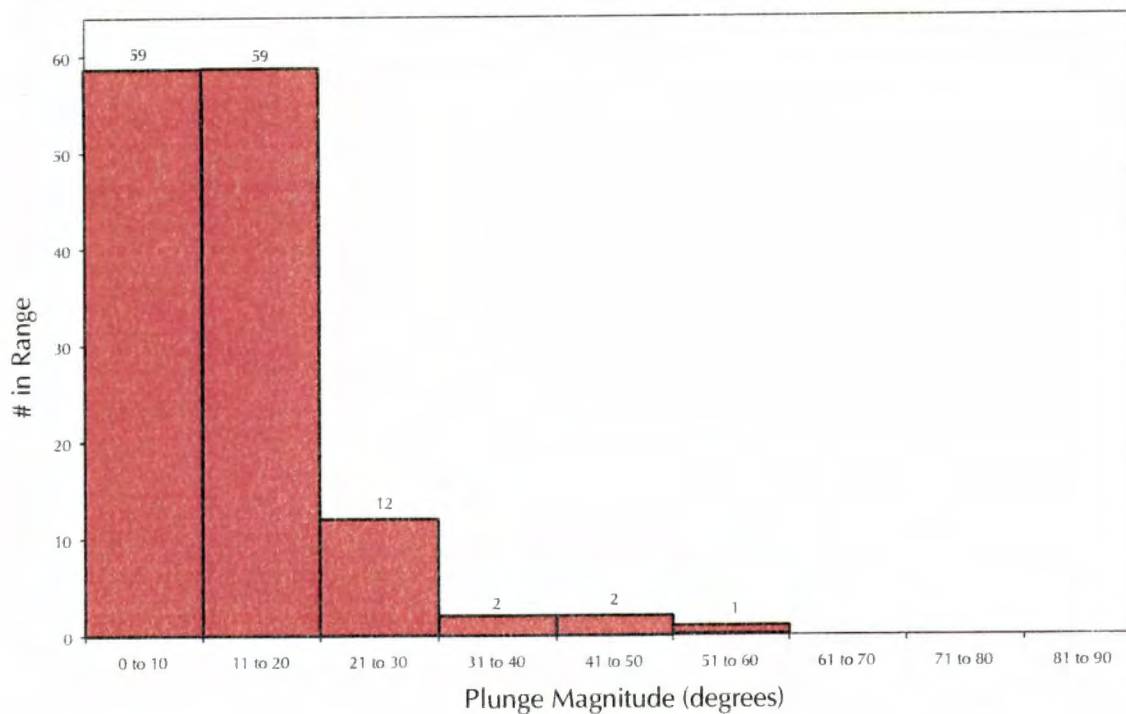
- (a) Contoured poles (intensity per 1% area) to foliation for all lineation data. Note two distinct sets. Calculated girdle for L_2 lineations lies within the plane of S_2 .
- (b) Histogram showing trend magnitude of lineation data. Sixty-four percent of the data strike between N51E and N70E.
- (c) Histogram showing plunge magnitude of lineation data. Eighty-four percent of lineation in the study are plunge less than 20 degrees.



(b)



(c)



plane (Lin and Williams, 1992). F_2 fold hinge lines are usually parallel to subparallel to the L_2 lineation. This relationship may be alternatively interpreted as an intersection lineation between axial planar foliation and earlier (S_1 ?) compositional layering but cannot then be related to kinematics or transport. I believe that these lineations are mineral stretching lineations that do indicate transport direction, but care must be taken to verify this interpretation with independent kinematic indicators.

Faults

Davis (1993a) attributed most ductile faulting to the D_2 event (Table 3-1). The Tumblebug Creek fault is an early D_2 fault that emplaced the Henderson Gneiss (Fig. 3-7). The timing of emplacement is somewhat nebulous. It is clear that the Henderson must have been emplaced after the initiation of the map-scale D_2 folding event defined by the aluminous schist member of the Tallulah Falls Formation, but before cessation of that event. Also, the direction of emplacement is unclear. Hatcher (personal comm.) advocates emplacement from the east and subsequent shearing and sheath folding to the southwest. The tectonic model discussed below favors emplacement from the northeast, possibly contemporaneously with, or as the result of, the development of the sheath folding. Map patterns in the study area and the Charlotte 1° X 2° sheet (Goldsmith et al., 1988) also support emplacement from the northeast. Isolated elongate bodies of Henderson Gneiss disconnected from the primary body occur along strike to the northeast in the strongly aligned zone of the Inner Piedmont. Emplacement of the Walhalla nappe probably occurred during D_2 , perhaps as a crustal scale sheath fold. The Brevard fault probably formed as a ductile strike-slip fault during the later stages of D_2 , although there may have been a component of dip-slip coeval with strike-slip deformation.

Figure 3-7.

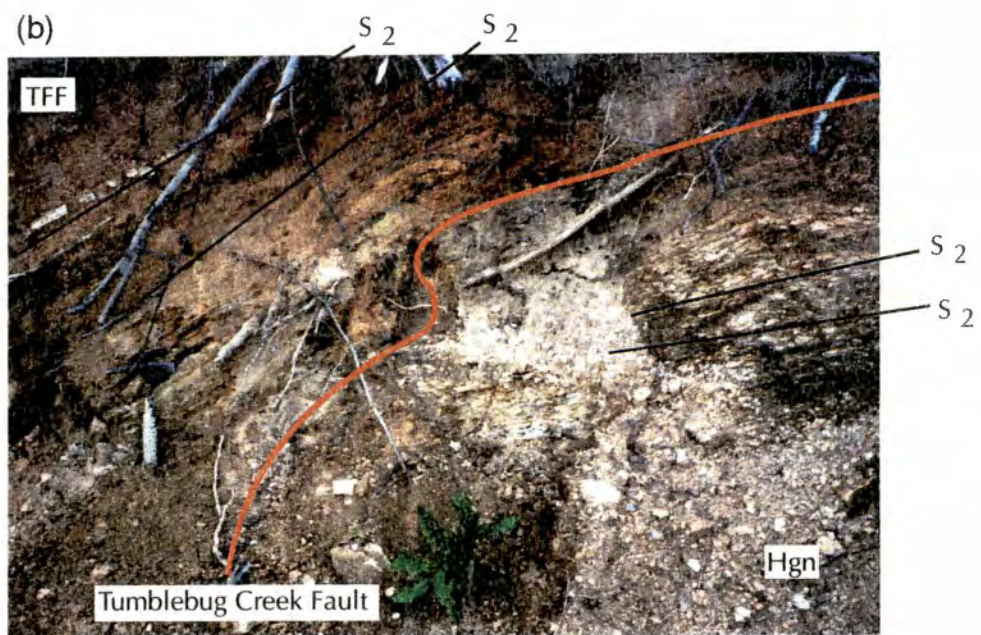
Tumblebug Creek fault.

- (a) Tumblebug Creek fault between the Tallulah Falls Formation (TFF) and the Henderson Gneiss (Hgn) near the summit of Gibbs Mountain.
- (b) Overlay showing the trace of the Tumblebug Creek fault and dominant S_2 foliation. Note the difference between the orientation of S_2 in the Henderson Gneiss and the Tallulah Falls Formation.

(a)



(b)



D₃ Deformation

The D₃ event is a syn- to post-peak metamorphic event (Davis, 1993a). D₃ is separated from the D₂ event on the basis of structural style. The D₃ event is interpreted to be a post-peak metamorphic event during which most thrust sheets were emplaced. Dallmeyer (1988) reported hornblende closure ages between 335 and 360 Ma for the Inner Piedmont in South Carolina and northeast Georgia and suggested this age to be the age of uplift and emplacement of thrust sheets. Hornblende closure temperature is approximately 500° C. The temperature in the rocks must have dropped near or through this temperature during the transformation of Type-F thrust sheets into Type-T or -C sheets. Using cooling rates determined from hornblende and muscovite ⁴⁰Ar/³⁹Ar ages, the time between the occurrence of the peak temperature and the hornblende closure temperature was determined to be approximately 44 million years (Chapter 4, this study). Assuming minimum displacement of the Six Mile thrust sheet to be the distance between the western edge of the Alto allochthon and the trace of the Six Mile thrust, a distance of approximately 35 kilometers, emplacement rates were calculated to be around 0.8 kilometers per million years.

Foliation

Davis (1993a), Yanagihara (1994), and Curl (1998) reported a weakly developed axial-planar foliation associated with F₃ folding, but none was observed in the study area. Measured foliations show a marked discordance with observed structure (e.g., the attitudes of the Six Mile fault and Bob's Creek syncline). Measured foliations are thought to be related to D₂ deformation. An alternative interpretation is that the dominant foliation in the

study area may be an S_3 foliation and structures such as the Six Mile fault are late S_2 structures. This explanation does not coincide with available kinematic evidence.

Folds

D_3 is primarily recognized by development of mesoscale F_3 folds (Fig. 3-8). F_3 folds are generally asymmetric and northwest vergent. F_3 folds have vertical to gently inclined axial planes, and deform and reorient F_2 folds and fabrics. F_3 folds maintain constant thickness in both the limbs and hinges, suggesting that these are flexural-slip folds. The style of these folds indicates that F_3 folds were formed under less ductile conditions than F_2 , where rheologic or structural anisotropy controlled the style of folding. F_3 folds probably formed because of semiductile shortening during the early stages of thrust sheet emplacement. Locally developed chevron (crenulation) folds are also attributed to D_3 deformation (Fig. 3-9). These folds are observed only in schistose pelitic units in the study area and are primarily confined to the garnet-aluminous schist along the trace of the Six Mile fault. Most models of kink folding involve flexural slip between layers, indicating lower temperature and pressures during deformation. This supports fault emplacement of thrust sheets during D_3 deformation and not D_{2b} as suggested by Davis (1993a).

Lineations

A second set of lineations has been recognized in the study area and has been interpreted as L_3 lineations. This set trends west-northwest and has shallow plunge that is variably oriented northwest or southeast (Fig. 3-6). This lineation represents approximately 10 percent of all mineral lineations measured within the study area. Although statistically significant, the number of lineations does not allow for determination of their nature, other

Figure 3-8.

F_3 folds within the study area located on the northeast shore of Lake James near Black Bear Cove.

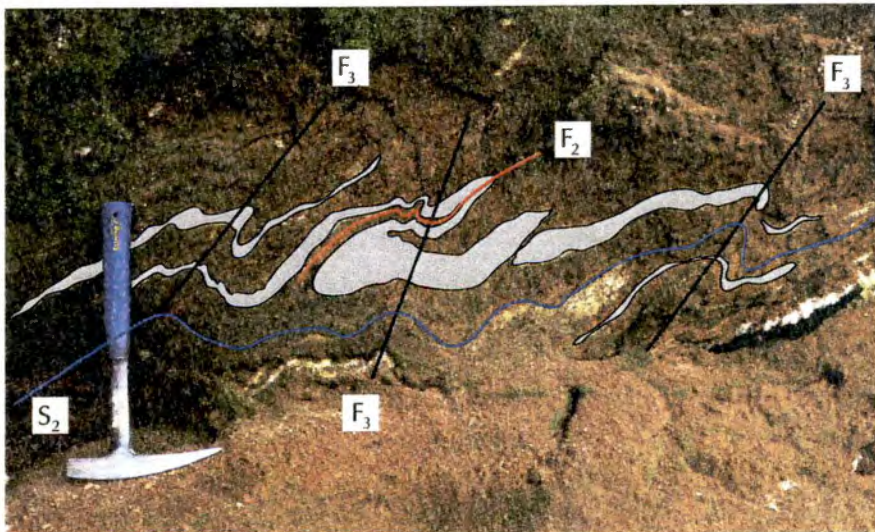
- (a) Folded leucocratic layer in saprolite of the Tallulah Falls Formation.
- (b) Overlay outlining the refolded F_2 fold (red). Black lines indicate the orientation of F_3 fold axial planes. Vergence is to the northwest (right).
- (c) Upright, northwest vergent F_3 folds.
- (d) Overlay outlining F_3 fold axial surfaces (black lines).

The hammer is approximately 35 cm long.

(a)



(b)



(c)



(d)



Figure 3-9.

Crenulations in the sillimanite schist.

- (a) F_3 crenulations developed in sillimanite schist.
- (b) Overlay with hinge lines and crenulations highlighted.

(a)



(b)



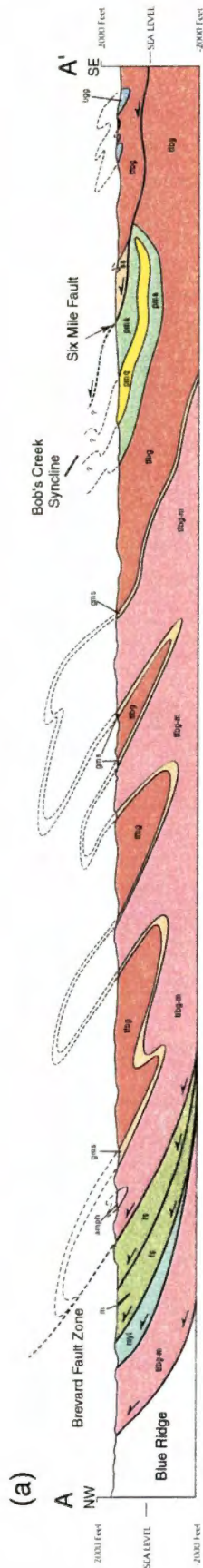
than recognition as a later developed set. This later set of lineations may be related to the later overthrusting of the Six Mile thrust sheet. It is possible that these lineations are related to an unresolved structure in the study area.

Faults

D₃ deformation is interpreted to be caused by emplacement of semiductile thrust sheets. Davis had previously interpreted the emplacement of most of these sheets to have occurred during D₂. It is clear, however, from the nature of deformation associated with D₃ events that most faults (e.g., Mill Spring, Six Mile) are D₃ structures. Attitudes of faults in the western Inner Piedmont do not coincide with measured foliations. Faults are shallow (~15°) dipping and are folded by broad open folds. The dominant foliation (S₂) generally dips 10° to 15° greater than the calculated attitudes of major D₃ structures. This discrepancy can be explained if one set of structures evolved at a different time and under different P-T conditions than the other. I think the S₂ foliation developed earlier than the map-scale structure. The relationship between D₂ and D₃ structures and variance to previous interpretations will be discussed in Chapter 5 in greater detail. Faults associated with D₃ deformation (previously interpreted as associated with D_{2b} by Davis, 1993a) in the western Inner Piedmont are the Sugarloaf Mountain, Shingle Hollow, Six Mile, and Mill Spring faults. Only the Tumblebug Creek and Six Mile faults were recognized in the field area. It is not clear whether or not the Sugarloaf Mountain thrust continues into the study area coplanar with the trace of the Tumble Bug Creek fault, tipping out in an anticline in the Tallulah Falls Formation. Cross section A-A' (Plate III, Fig. 3-10) shows the inferred attitude of the Six Mile fault. The Six Mile fault is a tightly folded, relatively planar

Figure 3-10.

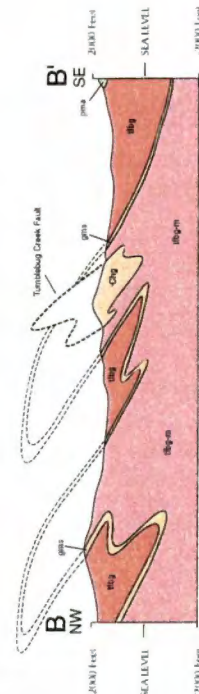
Cross sections A-A' (a) and B-B' (b) constructed in the Marion East quadrangle. See Plate I for cross section locations.



Explanation

Chg	Henderson Gneiss	gr	Granitic gneiss
psa	Poor Mountain Amphibolite	ul	ultramafic rocks
psq	Poor Mountain Quartzite	my	mylonite
psa	Poor Mountain Amphibolite	fs	schistose mylonite and phyllonite
tlg	Tallulah Falls biotite gneiss/metagraywacke	ma	marble
tlg	Tallulah Falls biotite gneiss/metagraywacke	ss	Tallulah Falls garnet mica schist or sillimanite schist
tlg	Tallulah Falls biotite gneiss/metagraywacke	tlg	Tallulah Falls magnesian biotite gneiss and metagraywacke
tlg	Tallulah Falls biotite gneiss/metagraywacke	tlg	Amphibolite within the Tallulah Falls Formation
tlg	Tallulah Falls biotite gneiss/metagraywacke	tlg	Biotite granitic gneiss within the Tallulah Falls Formation

(b)



structure that dips gently (12-19°) to the southeast. The Six Mile fault emplaces a hanging-wall antiform of Tallulah Falls Formation over the synformal footwall Rockhouse Mountain syncline. D₃ faults are believed to have occurred as ductile Type-F thrust sheets evolved into Type-C thrust sheets (Hatcher and Hooper, 1992). As early ductile fold-related sheets cooled, they gained greater mechanical strength and evolved into Type-T (transitional) (Hatcher, 1999) and then into Type-C (crystalline) sheets, thus allowing for greater transport displacement (Fig. 1-3). Interpretation that the above-mentioned faults are D₃ structures is based on the inference that a substantial amount of time is needed for adiabatic cooling to transform Type-F sheets into Type-C sheets. Also, there is a strong discordance between measured foliations in the study area and the attitude (both from map patterns and three-point determination) of the Six Mile fault. Cross sections by Davis (1993a) and Yanagihara (1994) also showed similar relationships.

D₄ and D₅ Deformation

D₄ and D₅ deformations are late brittle overprints and are probably associated with the Alleghanian orogenic event. F₄ folding produces broad open folds (Fig. 3-11) that warp D₂ to D₃ structures. The Rockhouse Mountain syncline (Plate I) is the only map-scale F₄ fold recognized within the study area. The Rockhouse Mountain syncline folds the Bob's Creek syncline into a gentle, upright, open fold. The Rockhouse Mountain syncline plunges gently to the northeast and ends in a culmination just southwest of the study area in the Glenwood quadrangle (Bream, 1999). F₅ folding occurs as upright northwest-trending open folds, which refold D₄ structures creating map-scale type-1 (dome and basin of Ramsay, 1967) interference patterns with the Inner Piedmont. This pattern was recognized to the southwest by Hopson and Hatcher (1988) and Liu (1991). D₄ and D₅ are

Figure 3-11.

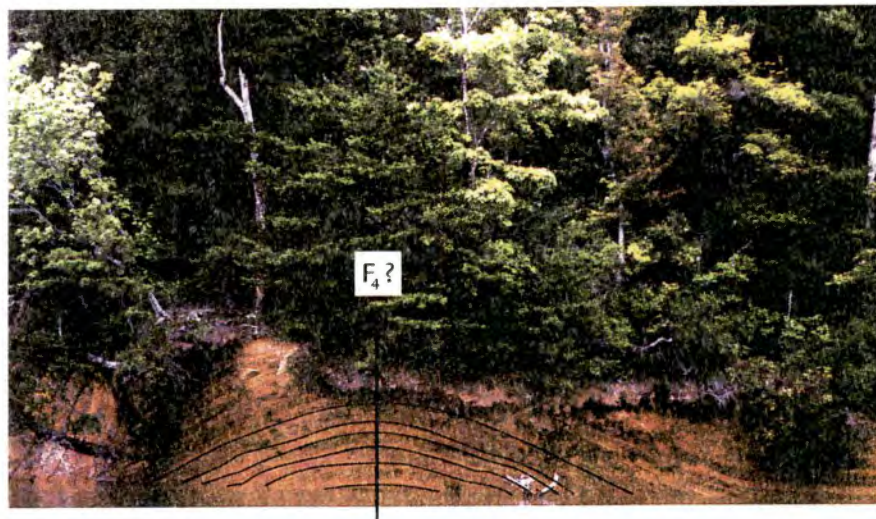
F_4 folds along the shore of Lake James.

- (a) F_4 fold in the study area exposed along the northwest shore of Lake James, just east of Big Island.
- (b) Overlay with foliations superimposed for clarity.

(a)



(b)



also associated with late brittle faulting observed elsewhere in the Inner Piedmont (Garihan et al., 1993; Curl, 1998). Two sets of fractures are also attributed to D_4 and D_5 deformation (Fig. 3-12). These fractures are generally planar in nature, with small aperture. No regular pattern was noted but fractures are ubiquitous in the study area. No systematic study of jointing was undertaken in the study area other than taking all available measurements.

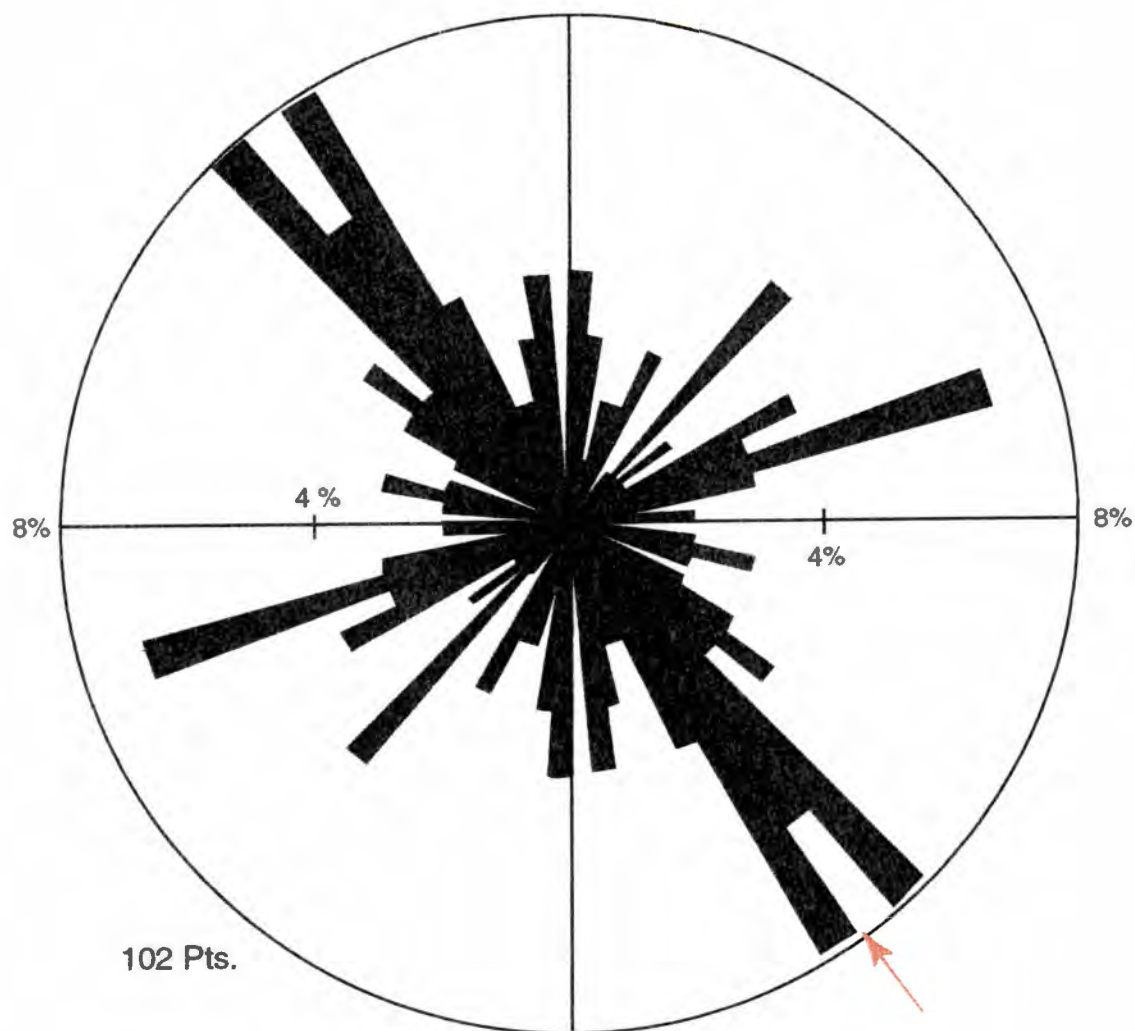
Cross Section Construction and Interpretation

Two cross sections (Plate III, Fig. 3-10) A-A' and B-B' were constructed approximately perpendicular to strike in the study area. Construction of both sections was based primarily on field data and map patterns. Down-plunge projection of map-scale structures was based on map patterns and comparison to dominant (D_2) outcrop-scale structures. All reasonable methods were employed to rigorously constrain both structural interpolation and interpretation; some latitude, however, was taken based on field observations.

The two most important observations concerning the cross sections are the contrasting characteristics of the Tumblebug Creek and Six Mile faults, and the nature of the Tallulah Falls garnet-aluminous schist member. The Tumblebug Creek fault is shown as a map-scale sheath fold consistent with regional observations. This fault is refolded and somewhat transposed into the S_2 foliation. The Six Mile fault is shallowly dipping, almost planar in character, and is refolded. The planar nature of this fault was determined from the map pattern of the Poor Mountain Formation, obtaining three-point solutions for various segments of the fault trace and surrounding units. The map pattern of the garnet-aluminous schist member defines map-scale folding. The nature of this folding has

Figure 3-12.

Rose diagram showing distribution of 102 joints measured within the study area. The sector size is 5° and the circle is equal to 8 percent maximum. Note there are three dominant sets NW-SE, NE-SW, and N-S. The red arrow is the vector mean of all measurements.



Sector Size	5 °
Vector Mean	S38E
Circular Variance	.36
Circular Std. Deviation	54 °
Maximum	7.9%

significant implications on interpretation of structural relationships both regionally and in the study area. These folds are early D_2 tight to isoclinal folds that have been transposed into the dominant foliation. Style of the folds was determined by map pattern and comparison to mesoscale early F_2 folds.

Chapter IV

Metamorphism

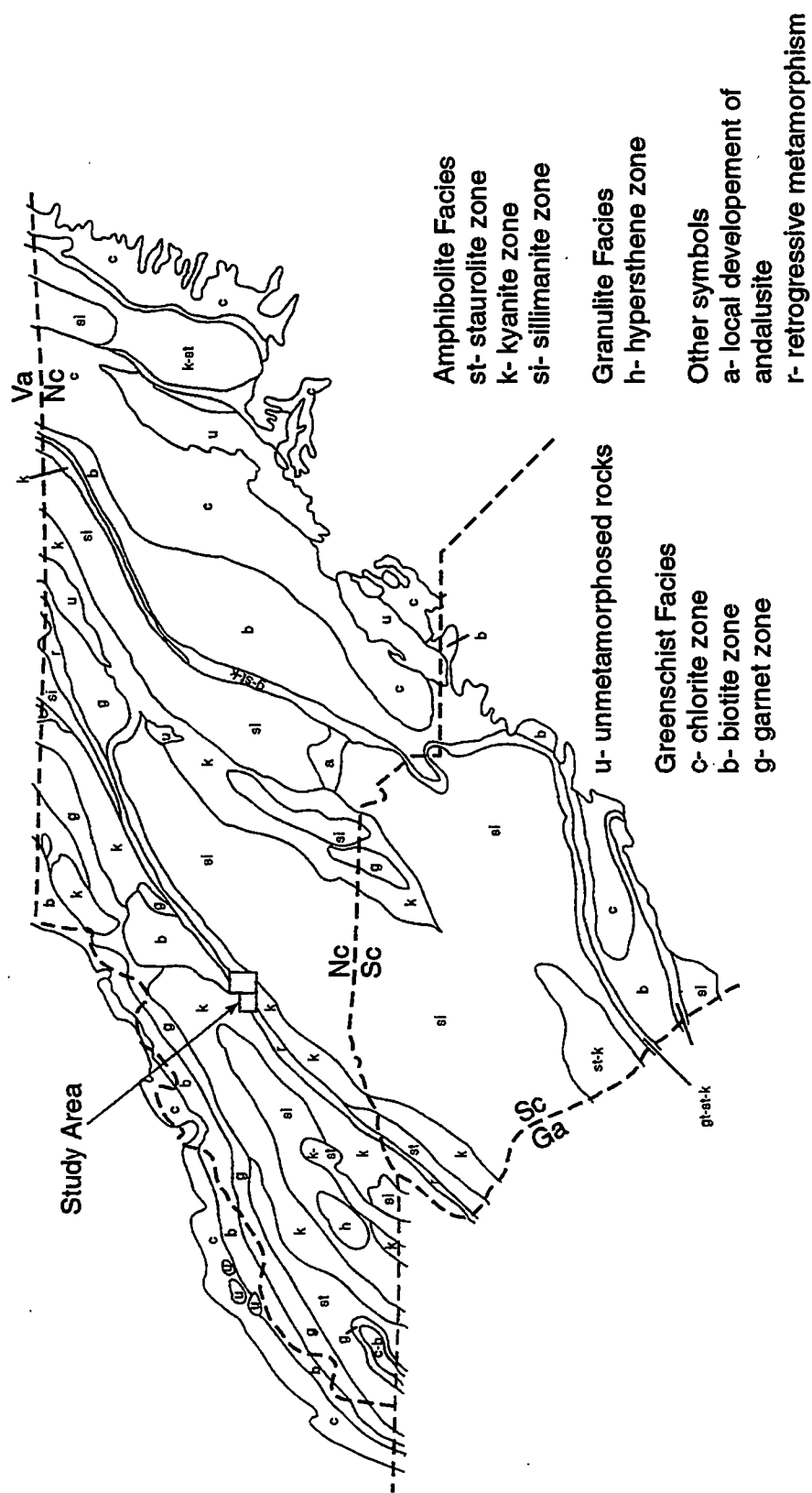
Introduction

The Inner Piedmont is a fault-bounded stack of thrust sheets that seems to contain metamorphic complexes of different tectonic affinities (Horton and McConnell, 1991). This stack of thrust sheets is characterized by an inverted pattern of metamorphic zones in that higher-grade rocks physically overlie rocks of lower grade, although Goldsmith (1981) stated that the overall pattern of foliation in the Inner Piedmont defines an asymmetrical synform. This structural pattern is inversely mirrored by the antiformal metamorphic grade (Fig. 4-1). The core of the Inner Piedmont is a vast terrane of sillimanite-muscovite (first sillimanite zone) grade rocks, although the presence of migmatite indicates minimum melt conditions for pelites was achieved. On the flanks, the metamorphic grade decreases to garnet-staurolite or kyanite on the northwest (Butler, 1991) and staurolite-kyanite on the southeast (Horton and McConnell, 1991).

Timing of peak metamorphism in the Inner Piedmont remains ambiguous. Early episodes of deformation are constrained by the 509 Ma Rb-Sr age of the Henderson Gneiss (Sinha et al., 1989) and later, 429 ± 22 Ma deformed granitic intrusions into it (Odom and Russell, 1975). Deformed granitic gneisses having Rb-Sr whole rock ages of 460 to 420 Ma are widespread in the Inner Piedmont (Butler, 1991). The 460 ± 9 Ma (Harper and Fullagar, 1981) Call pluton in the northwestern Inner Piedmont contains northwest-vergent, tight-to-isoclinal, gently inclined folds indicative of the D_2 deformational event described in Chapter 3 herein (Butler, 1991). Hornblende closure ages from Dallmeyer (1988)

Figure 4-1.

Metamorphic isograd map of the Carolinas modified from Butler (1991). Isograds are based on first appearance of index minerals.



require peak metamorphism to have occurred before 355 Ma. An attempt to better delimit the timing of peak metamorphism is undertaken later in this chapter.

Metamorphism in the Study Area

A single prograde metamorphic event has been recognized in the study area and throughout the Inner Piedmont (e.g., Davis 1993a, 1993b; Yanagihara, 1994; Curl, 1998). Metamorphism in the Inner Piedmont can be best explained as classic Barrovian-type regional metamorphism. Metamorphic peak has been determined to be at or below the first sillimanite isograd, corresponding to upper-amphibolite facies metamorphism (Davis, 1993b). Peak metamorphism is associated with the Acadian D₂ deformational event. Metamorphic conditions in the study area were determined using mineral assemblages in pelitic and psammitic units that represent the majority of rocks found in the study area.

Davis (1993b) determined P-T conditions for the Chauga belt in the Columbus Promontory area to be 535° to 690° C with corresponding pressures ranging from 3 to 6 kb. He related these values to post-metamorphic peak conditions based on retrograde reaction textures involving the consumption of garnet and muscovite. Temperatures were determined from Fe-Mg exchange reactions between biotite and garnet. Pressures were calculated using both the GASP (Ghent and Stout, 1981) and GPMB (Hodges and Crowley, 1985) geobarometers. Schumann (1988) using garnet-biotite geothermometry determined temperatures for the Alto allochthon and adjacent Chauga belt to be 616°-720° C $\pm$ 50° and 516°-647° C $\pm$ 50°, respectively. Using muscovite-K-feldspar geothermometry, Schumann obtained temperatures of 641°-663° C for the Alto allochthon and 628° C for the Chauga belt.

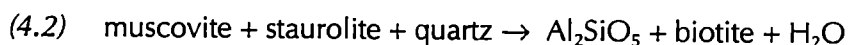
Mineral assemblages in the study area agree with the P-T conditions determined by Davis (1993a) and Schumann (1988). Although no geothermometry or geobarometry was done for this study, an attempt is made below to quantify P-T conditions in the study area based on petrographic analysis of thin sections. An ideational P-T-t time path was also constructed based on inferred P-T conditions.

Mineral Assemblages, Possible Reaction Relationships, and P-T Conditions

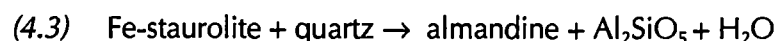
Pelitic units in the study area contain the assemblage quartz + plagioclase + muscovite + biotite + garnet. Psammitic units in the study area contain the assemblage quartz + plagioclase + muscovite + biotite + garnet $\pm$ epidote $\pm$ K-feldspar. The pelitic assemblage is characteristic of both the kyanite and sillimanite Barrovian zones (Yardley, 1993) with the notable absence of staurolite. The absence of staurolite is extremely important to this study and may be accounted for in two simple ways. First, the presence of staurolite in Barrovian metamorphic terranes indicates a "true pelite" because staurolite grows in a range of Al-rich, Ca-poor pelitic rocks but only rarely in other lithologies (Yardley, 1993). The absence of staurolite in the study area may indicate that the bulk composition of the rocks was unsuitable for staurolite to form, relegating the rocks to psammities or semi-pelites. This agrees well with the metagraywacke nomenclature adopted in this study. A second possibility for the absence of staurolite is that all staurolite was consumed in the following metamorphic reactions:



and/or



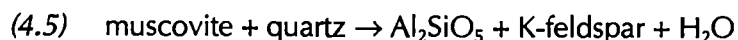
and/or



and/or



If it is assumed that staurolite is absent in the rocks of the study area because it was the limiting factor in reactions 4.1, 4.2, 4.3, and 4.4, the reaction 4.1 may be used as a lower temperature boundary condition in a P-T diagram. Reaction 4.1 marks the first appearance of kyanite in low aluminum pelites and the upper limit of the staurolite stability field. The upper temperature boundary for metamorphism in the study area must lie below the second sillimanite zone characterized by the reaction:



first because K-feldspar is not present in all pelitic samples (Table 2-4, 2-5) and secondly because the metamorphic grade in the Inner Piedmont does not rise above the first sillimanite zone (Butler, 1991). This boundary may further be delimited by the minimum melt conditions for granitic rocks given by the reaction:

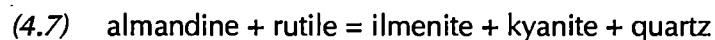


Migmatitic rocks are sparse in the field area and are restricted to localized zones, usually within the lower graywacke-schist member of the Tallulah Falls Formation. Rocks to the southeast of the Six Mile fault (Plate I) are more migmatitic than those of the lower thrust sheet. From this observation, I believe that temperatures needed for migmatization were not reached in most of the study area, and that local migmatization was facilitated by the occurrence of an excess fluid phase.

Pressure indicators among metamorphic reactions in pelites are relatively few, while temperature indicators are numerous. An upper pressure limit for the petrogenic grid

may be obtained by observing the nature of the Ti-oxide phase present in the pelites.

Bohlen et al. (1983) calculated an equilibrium curve for the reaction:



that lies within the stability field of kyanite and separates higher pressure kyanite-garnet schists containing rutile from lower pressure varieties with ilmenite (Yardley, 1993).

Ilmenite is the primary opaque phase observed in petrographic analysis of thin sections from the study area. Therefore, the maximum pressure experienced by rocks in the study area must be below the divariant line bounding this reaction.

A second, but more controversial pressure indicator is given by stability of Al_2SiO_5 minerals (e.g., Richardson et al., 1969; Holdaway, 1971; Salje, 1986). Fibrolitic sillimanite seems to have a higher stability field than prismatic sillimanite (Fig. 4-2). The presence of only fibrolitic sillimanite in parts of the study area while Davis (1993a) recognized prismatic sillimanite suggests the study area was metamorphosed at slightly higher pressures. This pressure would have been enough to form kyanite instead of sillimanite in the study area but must not have been enough to form rutile instead of ilmenite. Using fibrolite, Richardson et al. (1969) placed the invariant point for aluminum silicates approximately 100° C and 2 kb higher than that of Holdaway (1971), who used prismatic sillimanite. A study by Salje (1986) concluded that the andalusite-sillimanite boundary may be displaced by as much as 200° C higher for the fibrolitic variety of sillimanite as opposed to the prismatic variety (Spear, 1993). The reason for this difference is not clearly understood.

A simple model for interpreting P-T conditions in pelitic rocks based on the intersection of reactions 4.2 and 4.5 with the Al_2SiO_5 phase boundary curves was presented by Charmichael (1978; Fig. 4-3). Rocks in the study area correspond to upper

Figure 4-2.

P-T diagram illustrating the possible stability fields of aluminum silicate polymorphs. Green lines are experimental determinations from Richardson et al. (1969) using fibrolitic sillimanite. Red lines are from Holdaway (1971), which is the standard aluminum silicate triple point diagram using prismatic sillimanite. Curves s1, s2, and s3 are equilibrium curves between andalusite and naturally occurring varieties of prismatic sillimanite and F is the equilibrium curve between fibrolitic sillimanite and andalusite (Salje, 1986). Diagram modified from Yardley (1993).

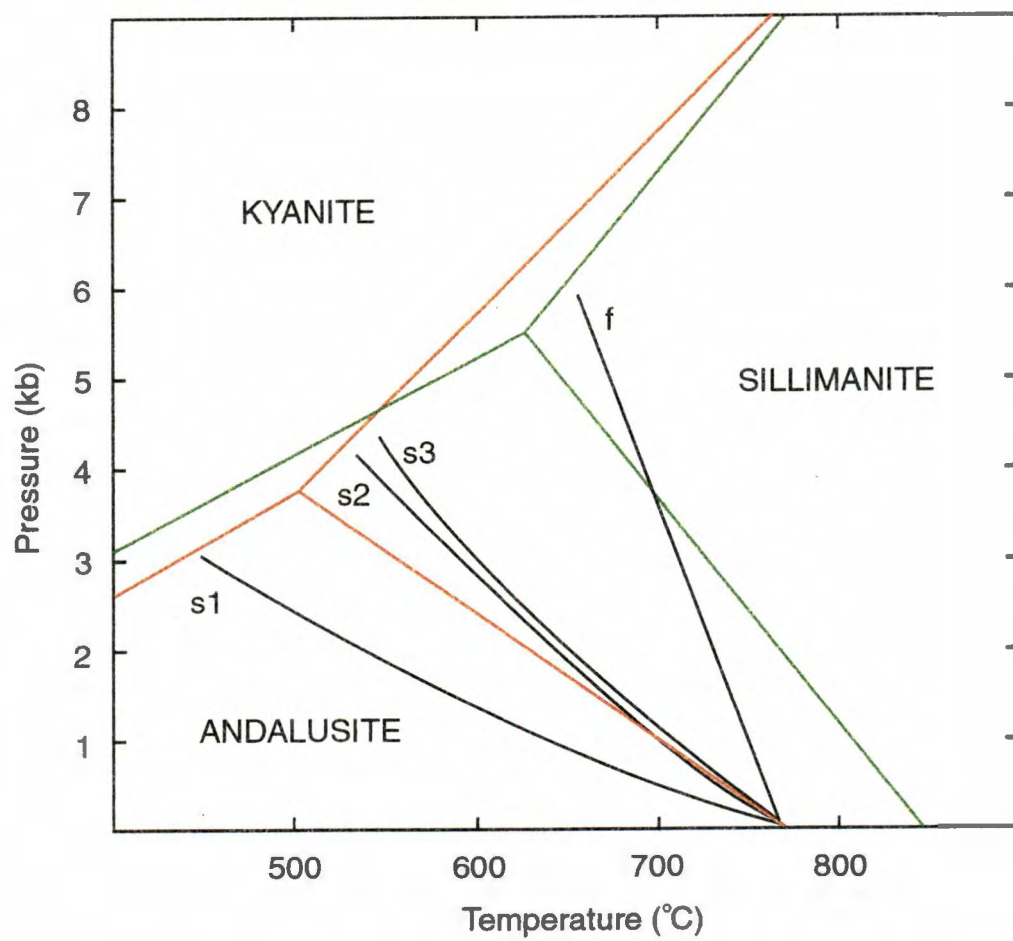
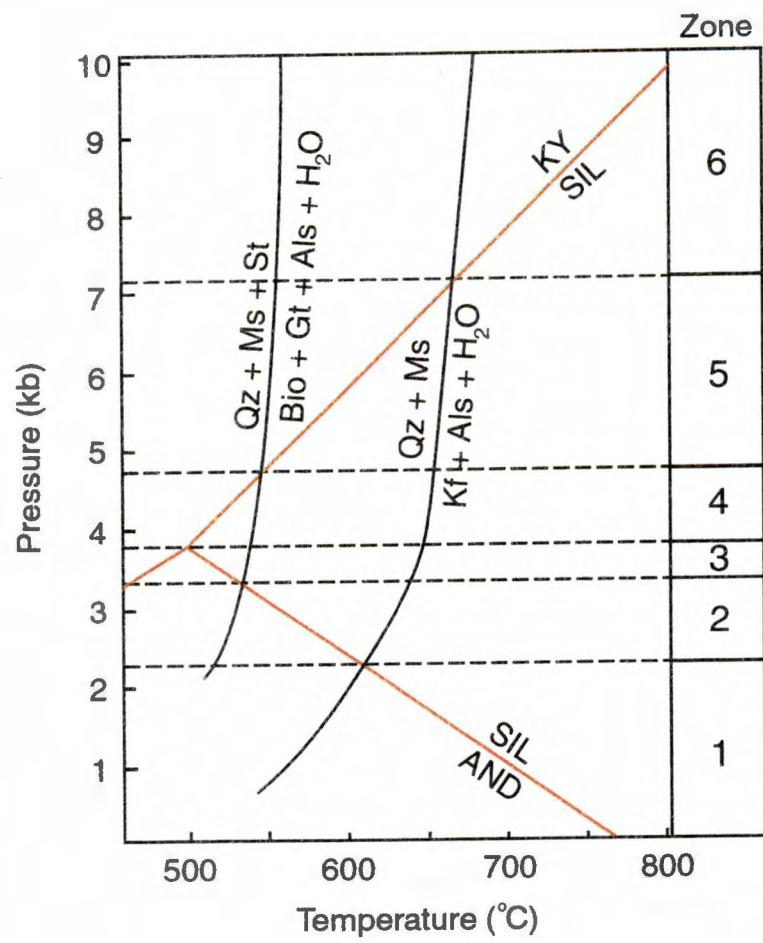


Figure 4-3.

Charmichael (1978) model for interpreting P-T conditions based on the intersection of aluminum silicate phase boundaries with reactions 4.2 and 4.4. Rocks within the study area are interpreted to correspond with Zones 4 and 5. Abbreviations: Als= aluminum silicate; AND = Andalusite; Bio = biotite; Gt = garnet; Kf = K-feldspar; KY = kyanite; Ms= muscovite; Qz = quartz; SIL=sillimanite; St = staurolite.



part of Zone 4 and/or the lower portion of Zone 5. In both zones, kyanite is produced by reaction 4.2. In Zone 5, kyanite is produced but sillimanite is the stable phase by the temperature at which muscovite breakdown is reached. If the aluminum silicate invariant point is shifted as suggested by Richardson et al. (1969; Fig. 4-4), then kyanite would remain the stable aluminum silicate polymorph for a larger portion of the interpreted P-T conditions. Figure 4-4 shows maximum inferred metamorphic conditions from this study.

Using $^{40}\text{Ar}/^{39}\text{Ar}$ Ages to Determine Cooling Rates, Rates of Thrust Sheet Emplacement and Timing of Peak Metamorphism

It can be reasonably inferred that peak metamorphic P-T conditions were somewhat greater than those calculated by Davis (1993a). In an effort to better delimit timing of deformational events, cooling curves were created using hornblende and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained by Dallmeyer (1988; Table 4-1) and are shown in Figure 4-5. Assuming cooling rates remained constant after peak metamorphism, estimates of the timing of peak metamorphism (D_2) were calculated.

Some samples were discarded for reasons described by Dallmeyer (1988). Biotite ages were not used because Dallmeyer stated these data are not reliable. Harrison et al. (1985) determined closure temperatures for biotite of 280° to 320° C. Muscovite closure temperatures are around 350° C (Dallmeyer, 1988). Therefore, biotite samples should record ages younger than those recorded by muscovite samples. Because biotite samples consistently recorded ages older than muscovite samples, Dallmeyer concluded that excess argon contamination was likely. Harrison (1981) determined that igneous hornblende closure temperatures ranged between 578° and 490° C. The lowest temperature recorded

Figure 4-4.

Petrogenic grid for pelitic metasedimentary rocks with $P=P_{H_2O}$ modified from Yardley (1993). Rose colored area is the interpreted P-T conditions for the study area. Red lines are the aluminous silicate equilibrium curves after Holdaway (1971). Green lines are aluminum silicate equilibrium curves from Richardson et al. (1969) using fibrolitic sillimanite. Light gray area represents the approximate conditions of the biotite isograd. Light green area represents the approximate conditions for the garnet isograd. Rectangular area outlined by the dashed line is the P-T range reported by Davis (1993a). Data sources for the curves are as follows: (1) Kerrick (1968); (2) Bohlen et al. (1983); (3) Yardley (1981); (4) Luth et al. (1964); (5) & (6) Thompson (1982). Note that curve (6) is for H_2O absent conditions; (7) Chatterjee and Johannes (1974); (8) Albee (1965), Hess (1969). Abbreviations: Ab = albite; Alm = almandine; Als = aluminum silicate; Bio = biotite; Ch = chlorite; Ilm = ilmenite; Kf = K-feldspar; Ky = kyanite; Ms = muscovite; Pyp = pyrophyllite; Qz = quartz; Rt = rutile; St = staurolite.

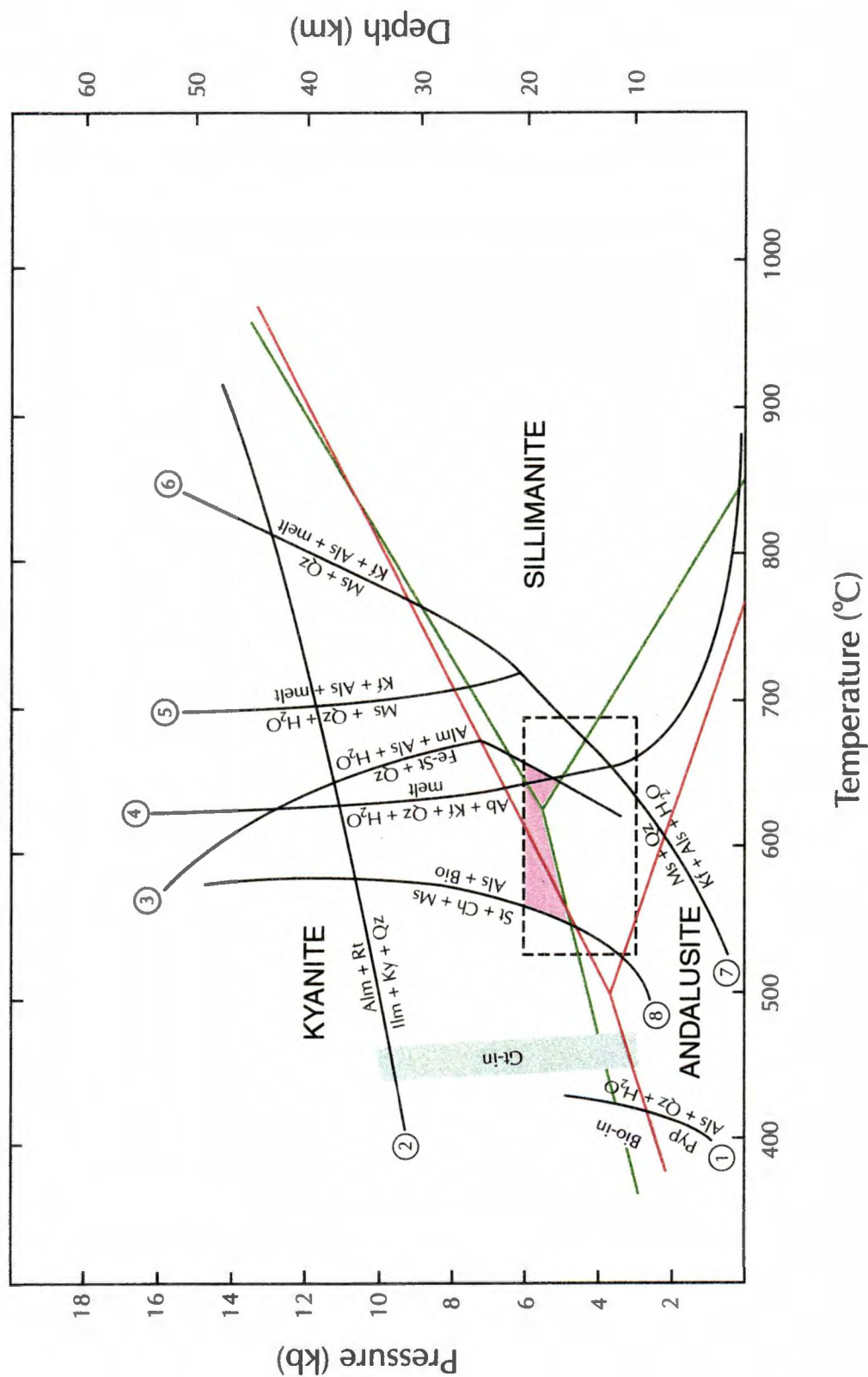


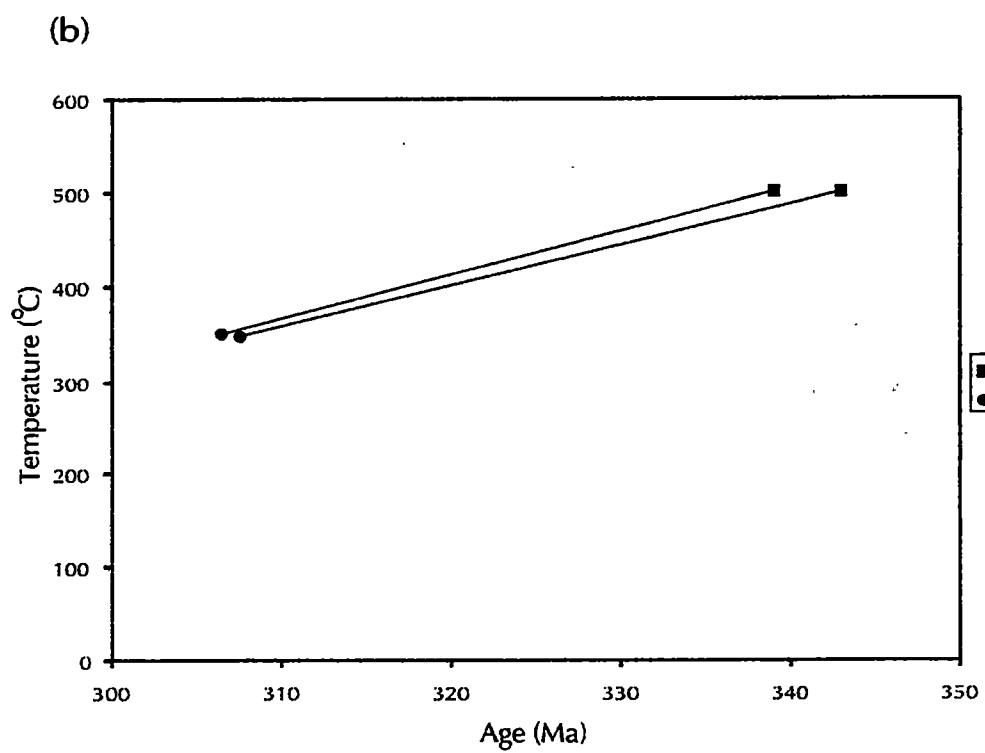
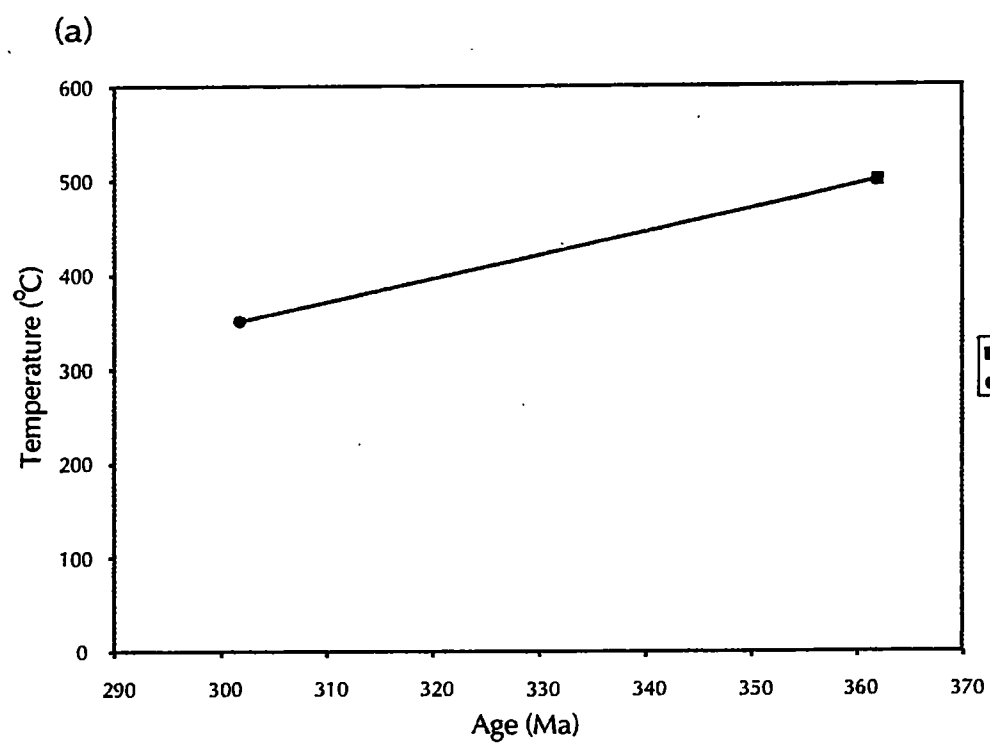
Table 4-1. Hornblende-muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ ages used to construct cooling curves in Figure 4-5. Data from Dallmeyer (1988).

Sample #	Hornblende Age (Ma)	Error (Ma)	Muscovite Age (Ma)	Error (Ma)	Locality
1	324.5	3.7			Chauga- Walhalla
2	324.9	4.6			Chauga- Walhalla
3	331.3	3.5			Chauga- Walhalla
6			308.1	1.3	Chauga- Walhalla
7			306.9	2.7	Chauga- Walhalla
8	322.5	4.2			Chauga- Walhalla
10	341.1	6.5			Chauga- Walhalla
12	361.9	4.2	301.7	1.1	Chauga- Walhalla
13	337.1	3.1			Chauga- Walhalla
16	334.3	4.2			Chauga- Walhalla
18			309.6	0.9	Alto allochthon
19	358.4	6.4			Alto allochthon
20	350.1	4.7	305.9	1.5	Alto allochthon
21	344.5	4.6			Alto allochthon
24	343	4.1	307.6	1.9	Alto allochthon
25	339.1	3.4	306.4	1.3	Alto allochthon
27A	349.3	3.8			Alto allochthon
28B			311.2	2.4	Alto allochthon
29			311.9	2.4	Alto allochthon
31			308.1	1.1	Alto allochthon
33			317.7	1.7	Chattahoochee thrust sheet
34	324	4.4			Chattahoochee thrust sheet
35	321.8	5			Chattahoochee thrust sheet
36			311.1	1.2	Chattahoochee thrust sheet
37	328	4.5			Chattahoochee thrust sheet
38	329.1	3.5			Chattahoochee thrust sheet
39			312.7	1.6	Chattahoochee thrust sheet

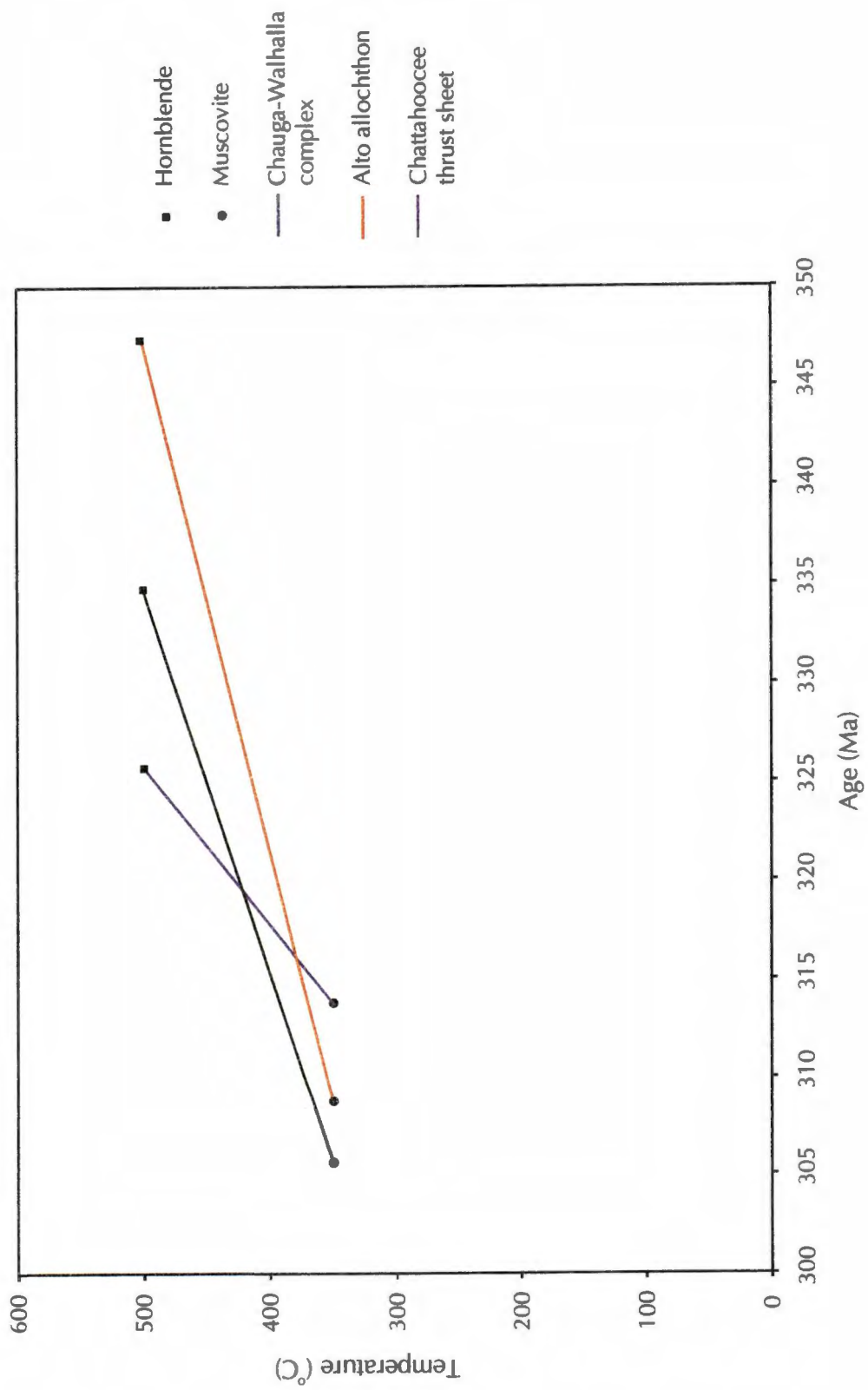
Figure 4-5.

$^{40}\text{Ar}/^{39}\text{Ar}$ cooling curves.

- (a) $^{40}\text{Ar}/^{39}\text{Ar}$ cooling curve for sample 12 (Table 4-1; Dallmeyer, 1988).
- (b) $^{40}\text{Ar}/^{39}\text{Ar}$ cooling curves for samples 24 and 25 (Table 4-1; Dallmeyer, 1988).
- (c) Average $^{40}\text{Ar}/^{39}\text{Ar}$ cooling curve for all samples from the Chauga belt and Alto allochthon (Six Mile thrust sheet) (Table 4-1; Dallmeyer, 1988).



(c)



by Davis (1993a; 1993b) is 535° C. A hornblende closure temperature of 500° C was used to construct the cooling curves. A temperature of 500° C is sufficiently below the lowest temperature reported by Davis that any error in calculations made by Davis is unlikely to affect the validity of this choice.

It would be most advantageous to construct cooling curves obtained from $^{40}\text{Ar}/^{39}\text{Ar}$ analysis of both hornblende and muscovite from the same sample. Unfortunately, only three samples from the data of Dallmeyer (1988) fit the criteria: two from the Alto allochthon (Six-Mile thrust sheet) and one from the Chauga belt (Fig. 4-5). The sample from the Chauga belt yielded a cooling rate of 2.5° C per million years. The validity of this sample is questionable because the age dates for hornblende and muscovite are the oldest and youngest, respectively, for all samples collected by Dallmeyer in the Chauga belt. The two samples from the Alto allochthon yielded cooling rates of 4.2° C and 4.6° C per million years. The cooling rate for all samples from the Chauga belt is 5.2° C per million years, roughly twice the single sample determination. I believe this to be a more reasonable cooling rate for the Chauga belt. The average cooling rate for all samples from the Alto allochthon is 3.9° C per million years. This value is 8 percent to 15 percent lower than single sample calculations. The samples from the Chattahoochee thrust sheet gave a cooling rate of 12.6° C per million years. This rate is abnormally high and I believe it to have no geologic significance. Only extremely rapid uplift and thrust emplacement would account for this abnormal thermal gradient. No other evidence suggests that this occurred. Regardless of calculated values, relative cooling rate values indicate that the Chattahoochee thrust sheet cooled faster than the Chauga belt, which cooled more rapidly than the Alto allochthon (Six-Mile thrust sheet). The relative cooling rates mimic the emplacement order of these thrust sheets.

Average cooling rates for all samples from the Chauga belt and Alto allochthon was determined to be 4.5° C per million years (Fig. 4-5). Assuming peak metamorphic temperature of 700° C, a rough determination of the time interval between the D₂ and D₃ events was calculated. This yields a time interval of 44 million years. Adding this to the average age of hornblende closure (338 ± 4.4 Ma.), peak temperature during D₂ occurred around 378 to 386 million years ago. This age date fits well within the timing of the Acadian orogen.

P-T-t Paths

The ultimate goal of metamorphic petrology is to delimit metamorphic events in P-T-t space. The problem is exacerbated by the knowledge that metamorphic conditions observable in the field represent a "frozen" moment in time. Multiple episodes of metamorphism may be observable (as in the study area) in the form of inherited mineral relics or retrograde metamorphic minerals. In this section, a P-T-t path is presented, but, it is well to recognize that this path is one of many that may be applicable.

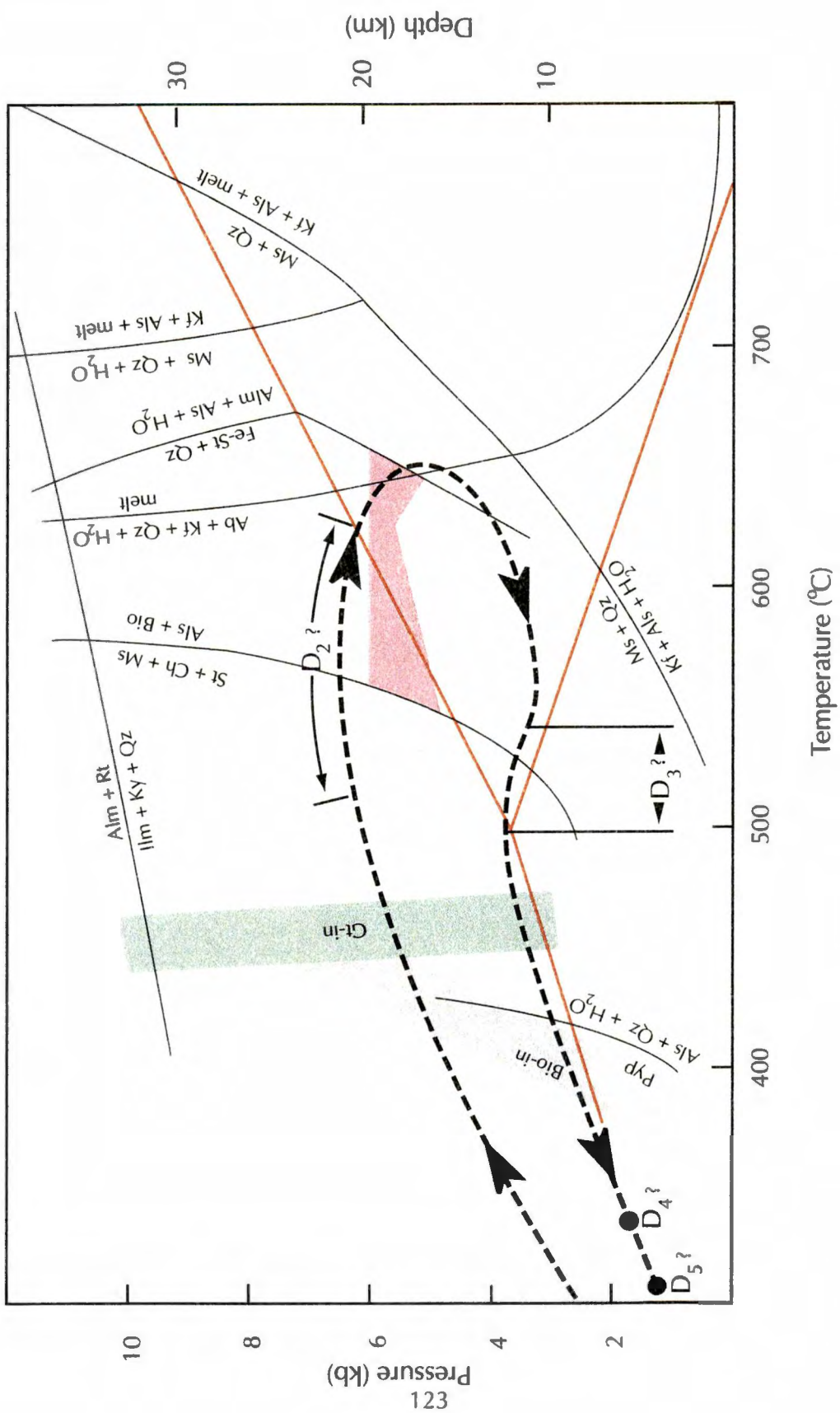
It is impossible to accurately represent the path that a group of rocks underwent to reach their current state of metamorphism. A number of assumptions must be made based on all available data. The P-T-t path here is based on a homogenous crustal thickening model consistent with the compressional tectonic regime for the Inner Piedmont. This model requires a clockwise P-T loop (Spear, 1993). It assumes temperature increases during a period of time before the onset of erosion allows pressure to decrease. It is intuitively obvious that the maximum pressure does not necessarily coincide with maximum temperature in compressional tectonics. The metamorphic mineral assemblage commonly referred to as the "peak metamorphic assemblage" forms at or near the

maximum temperature and is the assemblage most likely to be preserved in the rocks (Spear, 1993).

The simple P-T-t path (Fig. 4-6) is an idealized depiction of a possible path. This uncertainty must be kept in mind when interpreting the significance of this loop. It is undoubtedly an oversimplification of what actually occurred and does not take into account complications such as lateral variability in initial thermal structure, differential uplift rates, and nonconductive heat transfer mechanisms such as metamorphic fluids.

Figure 4-6.

P-T-t grid with inferred metamorphic path for the study area. The heating portion of the path is consistent with large-scale down-folding that would accompany homogenous crustal thickening (Spear, 1993). Note that the penetrative D_2 event is interpreted to be near-peak pressures. The D_3 event is marked by a local increase in pressure during the retrograde portion of the P-T-t path. This increase is attributed to stacking of thrust sheets as the whole Inner Piedmont is being uplifted. The D_4 and D_5 events are placed near the end of the retrograde portion of the path. These events are thought to be related to the Alleghanian orogeny. It is important to note that at the onset of the Alleghanian event, the crust still contained significant amount of residual heat from the Acadian event.



Chapter V

Tectonic Overview and Oblique Convergence Model for the Western Inner Piedmont

Introduction

The history of the southern Appalachians is an epic involving one or more Wilson Cycles (Hatcher, 1989). At least four orogenic events are preserved in the rocks of the southern Appalachians. Although the current state of knowledge is adequate to decipher the relative timing of these events, much debate continues. The southern Appalachians are only now undergoing the first cycle of intensive geologic and geophysical study (Hatcher, 1989). Much work remains to be done and the tectonic synthesis presented herein is knowingly inadequate. It is beyond the scope of this chapter to discuss in detail the tectonic history of the southern Appalachians. My intention here is to provide sufficient knowledge to familiarize readers with the tectonic framework of the southern Appalachians, and thus be able to discuss a tectonic model for the study area.

Tectonic Overview

The oldest rocks observed in the southern Appalachians are of Middle Proterozoic age (1.3 to 1.0 Ga). Our understanding of the Grenvillian history of Laurentia is limited. Lack of detailed studies as well as intense Paleozoic overprinting have obscured and complicated the events of 1.3 Ga to 1.0 Ga. Correlation of Precambrian orogenic belts that were once continuous suggests that the Grenville event created a Late Proterozoic supercontinent centered on Laurentia, called Rodinia. Hoffman (1991) stated that the

continents adjacent to northern, western, southern, and eastern Laurentia during the Late Proterozoic were Siberia, Australia-Antarctica, southern Africa, and Amazonia-Baltica, respectively. This supercontinent underwent rifting and breakup from 780 Ma to 600 Ma (Williams and Hiscott, 1987; Hoffman, 1989).

On the eastern margin of Laurentia, this breakup was a two-stage protracted episode of continental rifting (Badger and Sinha, 1988). The comparison of the Crossnore and Catoctin mafic sequences indicates that 100 to 150 m.y. separates the older Crossnore plutonic suite and the Catoctin formation (Badger and Sinha, 1988). The Crossnore plutonic sequence marks the earliest stage of rifting that began around 680-710 Ma (Odom and Fullagar, 1984). The age of the Catoctin volcanics determined from Sr isotopes is 570 ± 36 Ma. Sedimentological arguments (Lukert and Clark, 1981) suggest that the Crossnore plutonic suite was intruded, uplifted, and eroded prior to the eruption of the Catoctin volcanics, thus supporting the age data. Simpson and Sundberg (1987) stated that no major unconformity separates the Catoctin Formation from the overlying, Early Cambrian Chilhowee Group. Since the lower Chilhowee marks the transition from rifting to passive margin (Thomas, 1991), the age of the Catoctin Formation is coincident with the opening of the Iapetus ocean.

The Taconic orogen is estimated to have occurred 510 to 460 Ma in the southern Appalachians (Butler, 1991). Evidence for this event in the southern Appalachians is abundant. It produced major thrusts and penetrative deformation resulting in multiple foliations and passive to flexural-flow folds on all scales (Hatcher, 1989). The Taconic suture (Allatoona-Hayesville-Gossan Lead- fault) separates Grenville basement and cover sequences to the west from overthrust Laurentian slope and rise sedimentary sequences to the east. Several rifted Grenville age microcontinental blocks (e.g., Toxaway Gneiss,

Baltimore Gneiss domes) were reaccreted to Laurentia during the Taconic. Abundant Taconian-Penobscottian plutons present throughout the southern Appalachians are a result of a westward-dipping subduction zone during the collision of an island arc.

The Acadian orogen was the result of the accretion of Inner Piedmont and Carolina terrane to Laurentia during the closing of the Iapetus ocean. The Acadian orogeny is the most important tectonic event in the study area. Evidence for the Acadian event (e.g., Davis 1993a, 1993b; Dennis and Wright, 1997) in the southern Appalachians is not as abundant as for the Taconic. Remnants of a Silurian-Devonian sedimentary sequence are preserved in the Talladega belt of Alabama, but are heavily overprinted by Alleghanian deformation (Osberg et al., 1989). Widespread deformed granitic gneisses within the Inner Piedmont have Rb-Sr ages of 430 to 380 Ma (Osberg et al., 1989). The Acadian orogeny occurred 410-360 Ma.

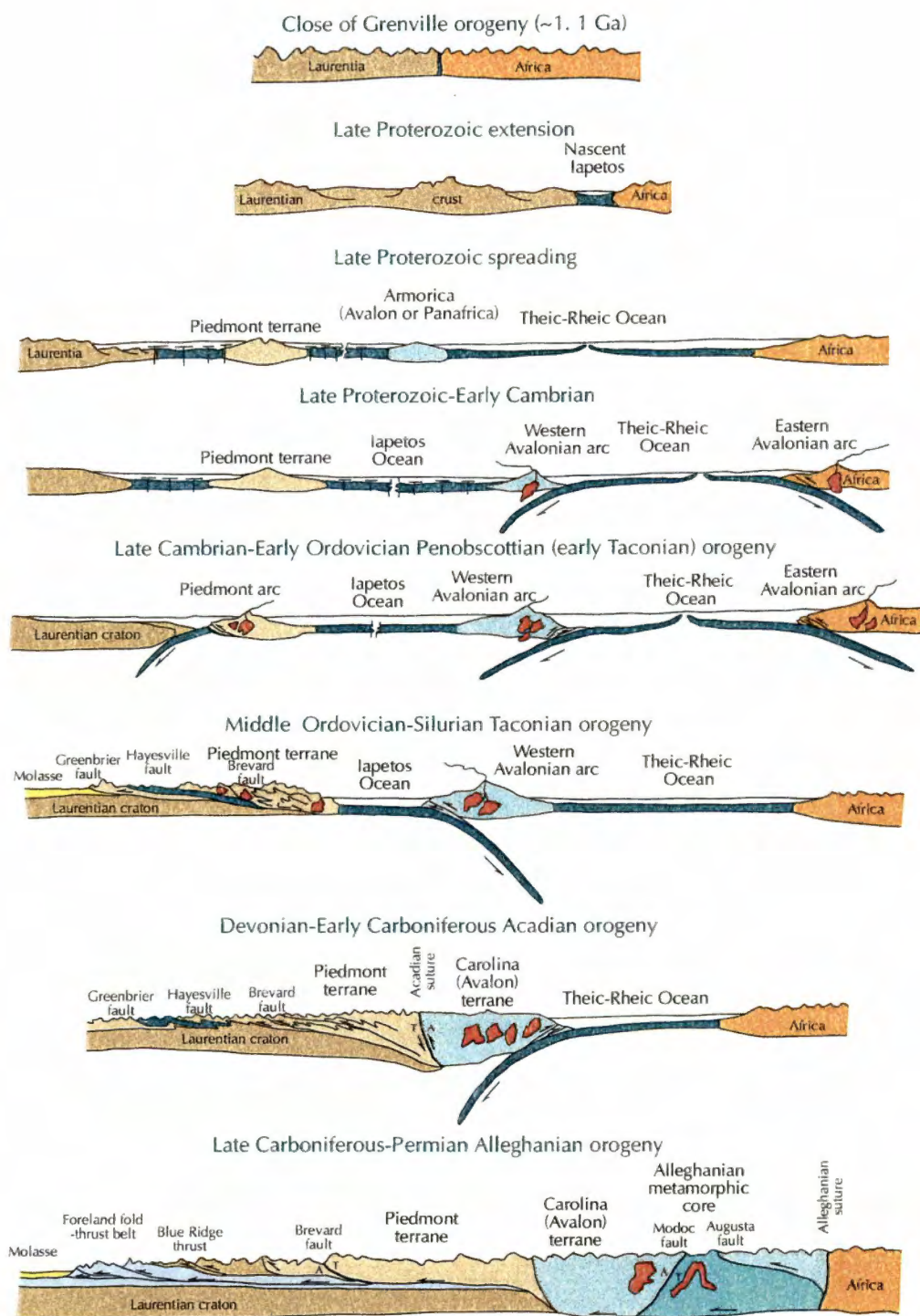
The Alleghanian orogeny represents the termination of the Appalachian Wilson cycle with the closing of the Theic-Rheic ocean. The timing of the Alleghanian event is constrained by Rb-Sr whole-rock ages on Alleghanian plutons to be 325 to 265 Ma (Butler, 1991). Continent-continent collision between Laurentia and Gondwana resulted in the development of the Appalachian Mountains. Figure 5-1 shows one possible scenario for the late Precambrian-Paleozoic orogenic events affecting the eastern margin of Laurentia.

Oblique Convergence Model

Structural patterns within the Inner Piedmont are best explained by an oblique collision tectonic model, but the nature of deformation within the Inner Piedmont does not allow for a unique solution. Davis (1993a) first used an oblique convergence model to

Figure 5-1.

Tectonic development of the southern Appalachians (from Hatcher, 1987).



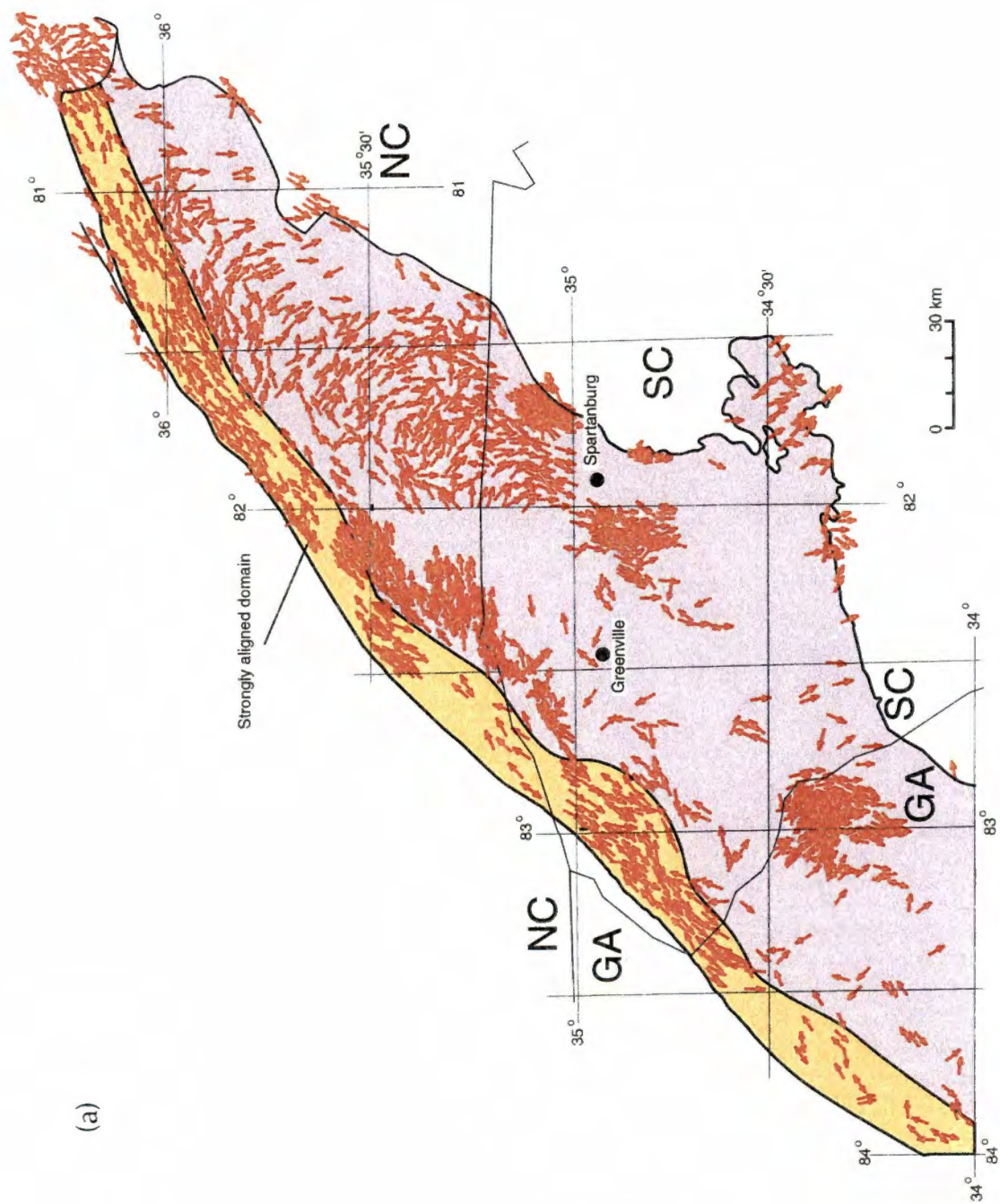
explain the pattern of deformation within the Inner Piedmont. His model was based on a crustal flow pattern. Building on this model, Hatcher (1998a) postulated that the Inner Piedmont moved as a coherent ductile mass involving initial north to northwest transport in the east (root zone), east-west in the internal parts of the Inner Piedmont, and finally southwest-directed transport in the western Inner Piedmont (Fig. 5-2). The change in transport direction was attributed to buttressing of the ductile Inner Piedmont against the primordial Brevard fault zone. In the model presented herein, an argument is made for a two-stage oblique collisional event during the Acadian orogeny based on map and kinematic patterns within the southern Appalachian Inner Piedmont. This model differs from Davis' and Hatcher's significantly in kinematics and timing relationships within the Inner Piedmont.

Shackleton and Ries (1984) stated that post-collisional movements are responsible for most observed structures in orogenic belts. Although there is much validity to that assertion, it is undoubtedly an oversimplification. It can be stated unequivocally that deformation must happen as collision is occurring. Ellis and Watkinson (1987) stated that early-formed structures are emplaced and preserved within the major footwall during underthrusting or subduction and later-formed structures represent hanging-wall deformation. Many collisional orogens do exhibit two distinct deformational phases caused by a single collisional event (Dewey, 1982; Laubscher and Bernoulli, 1982; Duncan, 1984; Merle and Brun, 1984; Brun et al., 1985; Ellis, 1986; Watkinson and Ellis, 1987). Oldow et al. (1990) stated that oblique plate convergence is the driving force for synchronous development of contractional and strike-slip fault systems. Resolving oblique convergence into components parallel and normal to the plate boundary has been used to explain longitudinal transport of terranes along continental margins in many forearc and

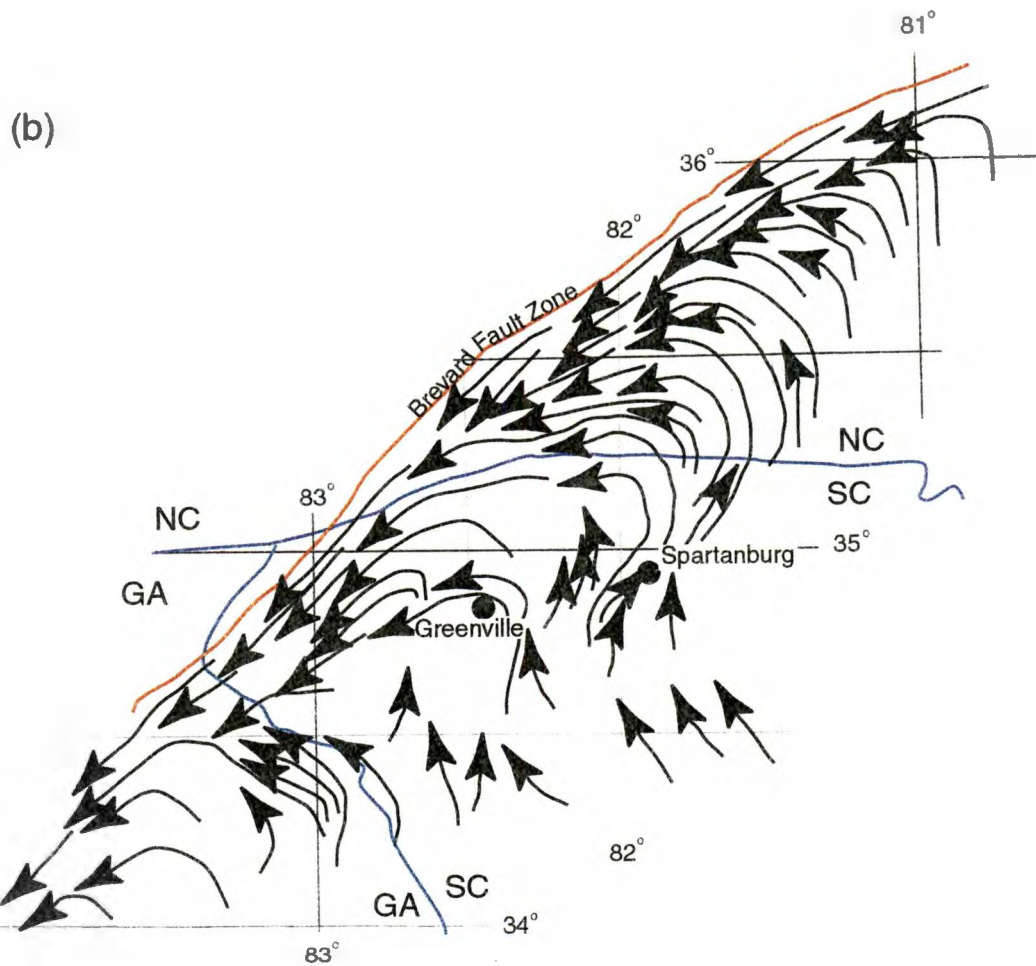
Figure 5-2.

Lineation data and ductile flow model for the Inner Piedmont.

- (a) Lineation map of the western Inner Piedmont by Hatcher (1998b). Note that the study area is located in the strongly aligned zone.
- (b) Interpretive flow model for the western Inner Piedmont by Hatcher (1999) based on lineation patterns in part (a).



(a)



arc regions (Beck, 1976; Walcott, 1978; Hamilton, 1979; Jarrard, 1986). Ellis and Watkinson (1987) demonstrated that orogen-parallel deformation of the footwall reflects relative plate motion and later deformation in the hanging wall would reflect isostatically driven emergence normal to the orogen during the imbrication process (Fig. 5-3). In their model, orogen-parallel extension is seen as preservation of oblique plate convergence. Footwall deformation reflects relative plate motion, while hanging-wall deformation is independent of relative plate convergence. In this model, later-forming structures tend to be progressively more disharmonic and develop syn- or post-metamorphic peak (Ellis and Watkinson, 1987).

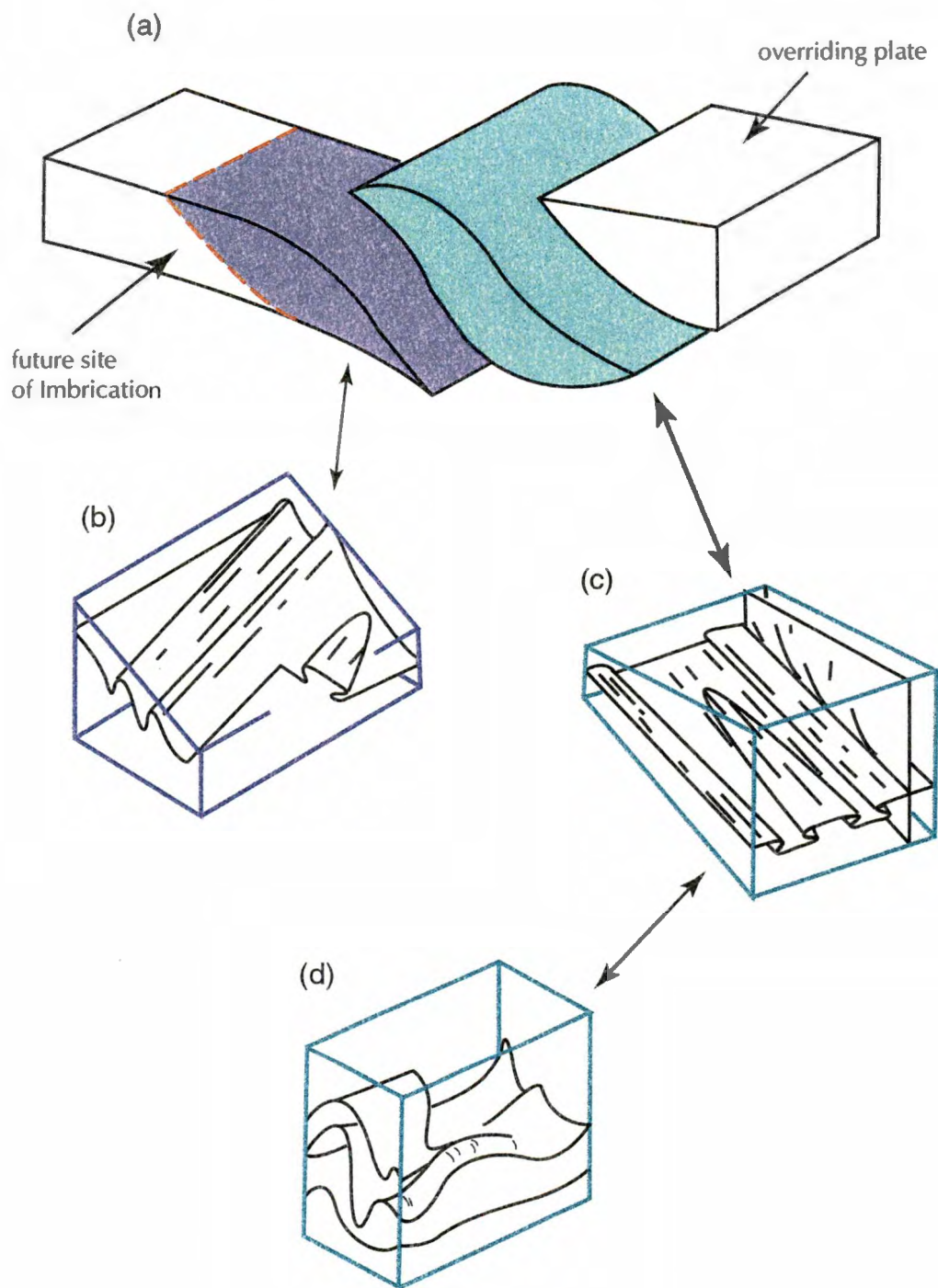
Watkinson and Cobbold (1981) clearly demonstrated that earlier fabrics and structures strongly influence the nature and style of later deformational events. It is therefore feasible that first-phase and second-phase structures may have similar orientations although different structural styles. In the Ellis and Watkinson (1987) model older first-phase structures that develop in the footwall during oblique collision are associated with mineral stretching lineations and significant ductile extension subparallel to cylindrical and sheath fold axes and the orogen length. The second phase starts with subduction or underthrusting migrating toward the foreland. As the thrust sheets begin the imbrication process, the footwall is incorporated into the major hanging wall. Consequently, first-phase structures are developed within the footwall, while second-phase structures are developed contemporaneously in the hanging wall. First-phase structures develop parallel to the orogen and later deformation in the hanging wall reflects isostatically driven emergence normal to the orogen.

This relationship is indicative of the fundamental kinematic transition that occurs during the imbrication process (i.e. emplacement of orogen-normal thrusts). These

Figure 5-3.

Structures associated with oblique subduction, imbrication, and isostatic emergence after Ellis and Watkinson (1987).

- (a) Schematic showing possible plate interaction.
- (b) Footwall deformation reflecting high, noncoaxial strain. This is characterized by development of cylindrical, isoclinal folds, sheath folds, and stretching lineations parallel to subparallel to orogen length.
- (c) Hanging wall deformation reflecting orogen-normal structural development driven by isostatic emergence of the crust.
- (d) Disharmonic structures developed later in the higher section of the hanging wall (see Figure 5.4).



kinematics are in agreement with seismic deformation at modern obliquely convergent margins (Fitch, 1972). Furthermore, structures along obliquely convergent margins (e.g., the San Andreas fault, Beck, 1986) reflect normal and oblique components of convergence (Stein and King, 1984). Strain under such conditions is high because of the duration of deformation and is most likely noncoaxial.

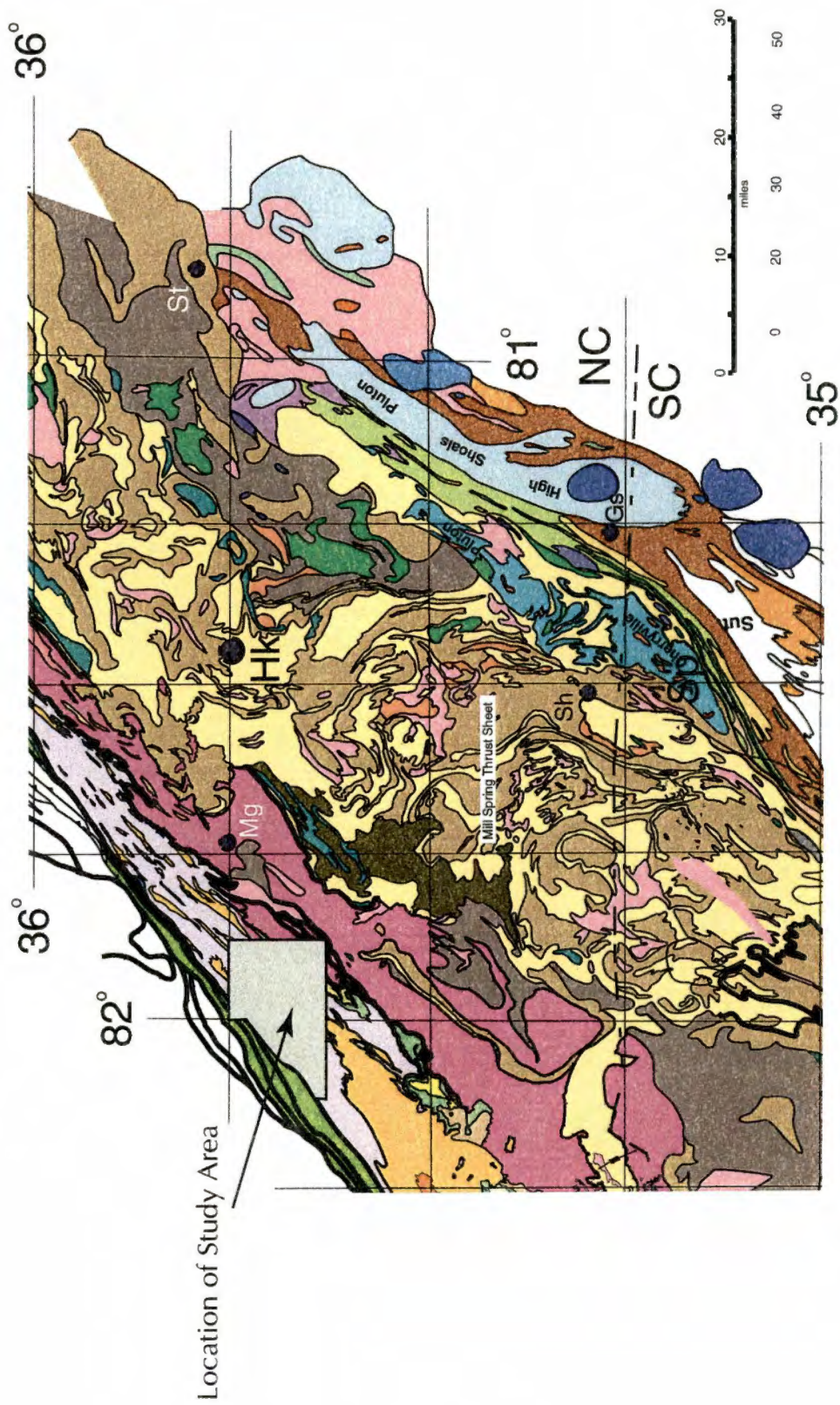
Application to the Inner Piedmont

The basis of a two-phase oblique collision model is based on similar relationships as described by Ellis and Watkinson (1987). The Inner Piedmont contains a zone of strongly aligned orogen-parallel mineral stretching lineations along its western margin. These lineations are parallel to subparallel to hinge lines of early D_2 isoclinal folds defined by the garnet-aluminous schist member of the Tallulah Falls Formation and to the sheath fold axes in the Henderson Gneiss. The emplacement direction of the Henderson Gneiss body indicates southeast-directed extension. Both the lineation and structural patterns are consistent with first-phase deformation as described in the model above.

The structural pattern exhibited in the Inner Piedmont is also comparable to the Ellis and Watkinson model (Fig. 1-1). The Inner Piedmont is a stack of west-vergent thrust sheets (Griffin, 1974; Horton and McConnell, 1991). Each thrust may be thought of as an imbricating block as described in the model above. Ellis and Watkinson (1987) maintained that late deformation in the higher levels of the hanging wall becomes progressively more disharmonic. These structures are thought to reflect vertical maximum strain and shape of the footwall. The map pattern in and around Shelby, North Carolina shows a very complicated and disharmonic pattern (Fig. 5-4). This area contains the highest-grade thrust sheets that are thought to represent lower sections of the crust. As

Figure 5-4.

Map of a portion of the Inner Piedmont (modified from Hatcher, 1998b) showing complex, disharmonic fold pattern in the Mill Spring thrust sheet. Note the location of the study area. Refer to Figure 1-1 for location within the Inner Piedmont. Hk= Hickory, N.C.; Mg = Morganton, N.C.; Sh= Shelby, N.C.; Sp= Spartanburg, S.C.



these late thrust sheets were emplaced, their structural style may have been controlled by earlier-formed structures in the underlying thrust sheets. The map pattern may also be partially explained by reorientation of fold hinge lines. This area was chosen as an example because it is one of the few areas within the eastern Inner Piedmont that has been mapped in detail.

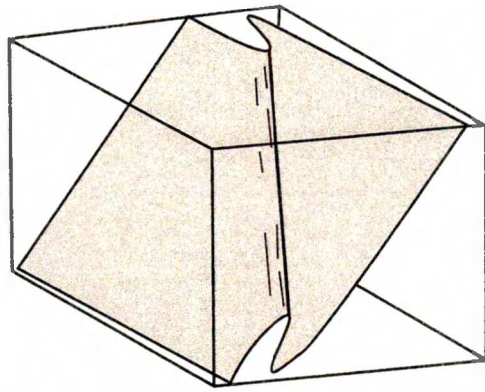
The application of a two-phase oblique collision tectonic model developed out of a need to explain certain inconsistencies with the flow model of Davis (1993a) and Hatcher (1998). First, this study demonstrates that the rocks on either side of the Brevard fault zone are the same. As such, the rocks on either side of the Brevard fault zone should have been under similar P-T conditions during deformation. Hatcher (personal comm., 1999) believes the lineation pattern in the Inner Piedmont (Fig. 5-2) is a ductile flow pattern. The counterclockwise rotation that this pattern shows is attributed to buttressing against the "primordial" Brevard fault zone (Davis, 1993a). If the rocks on either side of the Brevard fault zone are the same as concluded in this study, there is no clear reason for the buttressing effect. Goldsmith (1981) constructed a similar map showing lineation patterns in the Inner Piedmont. He described the majority of the lineations as fold hinge lines. The pattern of lineations in the Inner Piedmont may thus be explained by rotation of fold hinges into parallelism with direction of thrusting as described by Hobbs et al. (1976; Fig 5-5). The strongly northeast-southwest aligned zone of mineral stretching lineations, orogen-parallel cylindrical and sheath folds southeast of the Brevard fault zone represents footwall deformation attributed to southeast-directed oblique collision. The east-west and north-south portions of the lineation pattern may be explained by subsequent clockwise rotation of the Inner Piedmont block, and hence redirected thrusting, as it was being accreted to Laurentia. This requires that thrust plane lineations be younger than the

Figure 5-5.

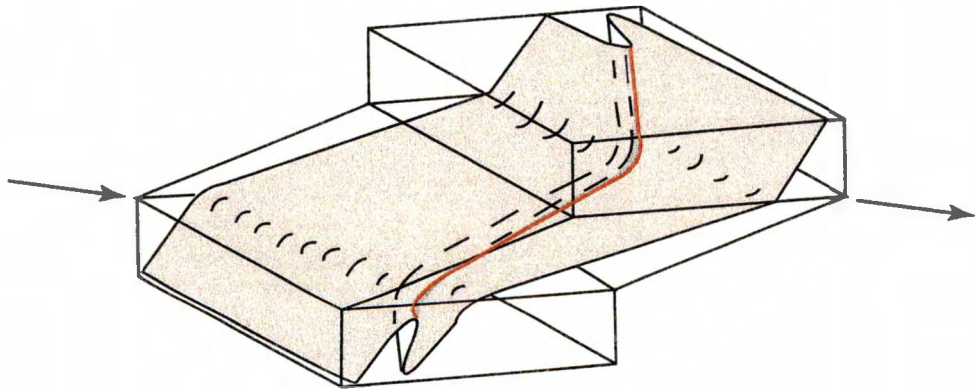
Diagram showing how early folds may be reoriented by shearing within a zone of intense deformation after Hobbs et al. (1976).

- (a) Orientation of original fold. Note that the hinge line is not parallel to the direction of thrusting.
- (b) Orientation of fold (hinge-line in red) after thrusting. The thrusting is assumed to be achieved by ductile deformation only and is concentrated within a narrow shear zone. Strain is assumed to be simple shear. Note that the principal axis of extension is not parallel to thrust direction. As shear is increased, both the principal axis of extension and the fold hinge-line will rotate toward parallelism with the direction of transport as indicated by the arrows.

(a)



(b)



internal lineations, and that the lineations become younger eastward in the Inner Piedmont. This remains to be shown. Also, the lineations are penetrative and are not related to brittle deformation.

Secondly, the presence of the lower-grade Chauga belt rocks is limited to the area just southeast of the Brevard fault zone. This can be explained by imbrication of the Chauga-Walhalla thrust complex onto the Chattahoochee thrust sheet as proposed in the model described above. If the deposition of the Chauga River-Poor Mountain Formations was limited to a single basin, then subsequent faulting through the basin would account for the limited spatial distribution. Relative timing of thrust emplacement as discussed above also supports the two-phase faulting model. If the emplacement of the Chauga-Walhalla complex involved initial dextral strike-slip motion associated with southeast-directed crustal-scale sheath folding, the low-grade nature of the Chauga belt may be explained by uplift of the belt by the same thrusting and sheath folding event that emplaced the Henderson Gneiss.

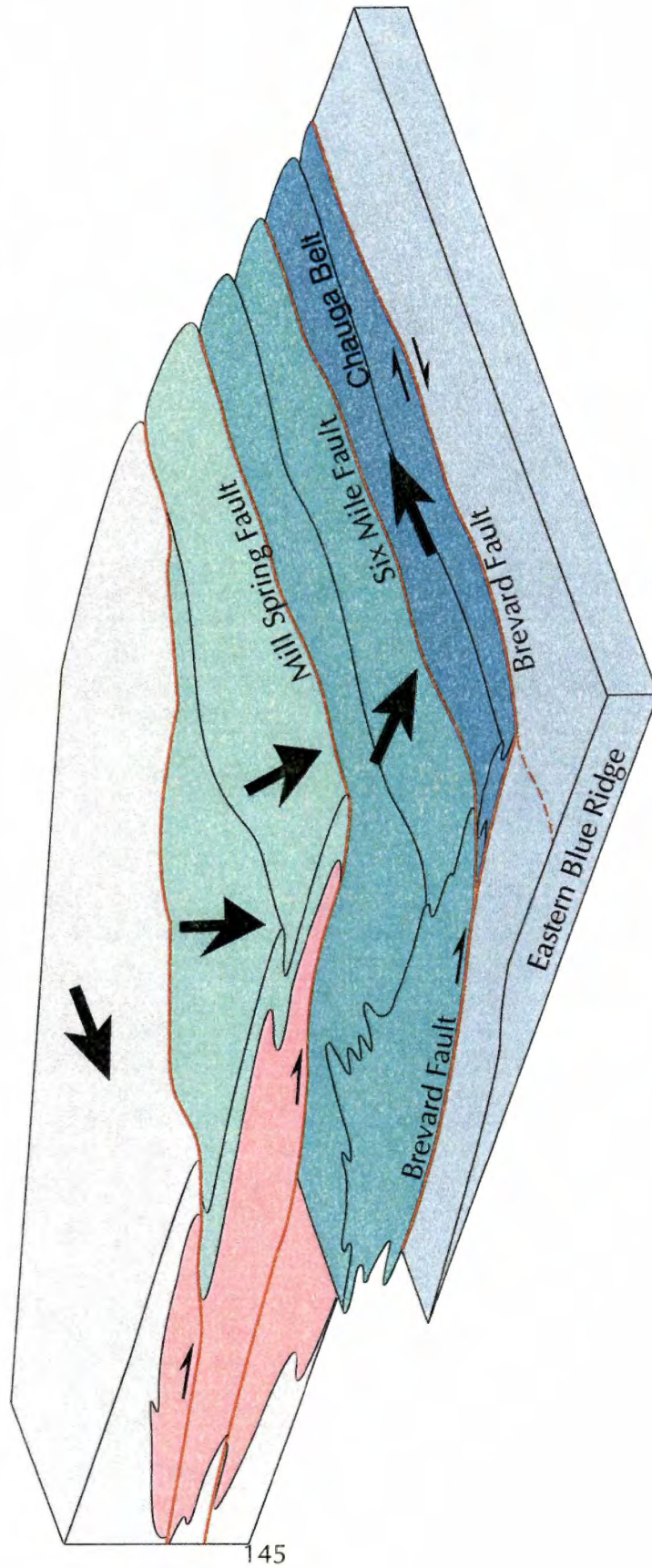
Figure 5-6 illustrates how the model discussed above may apply to the Inner Piedmont. Initial collision occurred somewhere to the northeast forming the Brevard fault as a dextral strike-slip fault. Early first-phase structures (orogen-parallel cylindrical and sheath folds) developed at this time. The Henderson Gneiss was also emplaced almost simultaneously to the southwest. The Walhalla nappe may have been emplaced as a crustal scale sheath fold during this first-phase of deformation. As the Inner Piedmont block rotated clockwise, the Brevard developed components of both strike-slip and dip-slip. The Walhalla, Six Mile, and Mill Spring (along with other undifferentiated) nappes began initial westward movement as Type-F sheets. Timing of the D_2 event is feasibly concurrent with this stage. As deformation progressed into D_3 time, evolution of Type-F

sheets into Type-T or Type-C occurred and north- to northwest-directed thrusting became the dominant deformation. Ensuing rotation of the Inner Piedmont block caused the north to northwest lineation pattern of Figure 3-7 as the Inner Piedmont terrane was incorporated to Laurentia. Later Alleghanian collision would have caused the D₄ and D₅ events (Curl, 1998).

Figure 5-6.

Oblique convergence model. Black arrows indicate the direction of emplacement of thrust sheets. Note that the Brevard fault is shown as both a strike-slip and dip-slip fault. Also, note that the Chauga belt has the form of a map-scale sheath fold. In this model thrust sheets young eastward.

NE



Chapter VI

Conclusions

1. A recognizable stratigraphy exists in the western Inner Piedmont, at least as far east as the Six Mile fault. This stratigraphy consists of the Tallulah Falls Formation overlain unconformably by the Poor Mountain Formation, both of which are tectonically overridden by the Henderson Gneiss.
2. Five deformational events are recognized in the study area. Evidence for the D_1 event is sparse in the study area. D_1 is most likely with the Taconic (or earlier?) deformational event. D_2 is associated with peak, penetrative deformation and transpositional events. Emplacement of the Henderson Gneiss postdates the earliest D_2 deformational event in the study area. Emplacement of thrust sheets are D_3 events. D_4 and D_5 are associated with the Alleghanian orogen.
3. A single prograde metamorphic event has been recognized within the study area. Based on pelitic mineral assemblages, peak P-T conditions in the study area are interpreted to be between 550° C and 685° C, with corresponding pressures between 5 and 6.5 kb. This corresponds to kyanite and/or first sillimanite zone metamorphic grade.

4. Peak deformation and metamorphism are associated with the Acadian orogeny.

Tentative dates constructed from hornblende-muscovite cooling curves suggest peak metamorphism to have occurred around 382 m.y.a.

5. The structural pattern evident in the Inner Piedmont may be explained by an oblique collisional event between the Inner Piedmont microcontinent and Laurentia during the Acadian orogeny.

6. Stratigraphic correlation across the Brevard fault indicates that the portion of the Eastern Blue Ridge up to the Chattahoochee fault is tectonically related to the western Inner Piedmont.

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APPENDIX
STRUCTURAL DATA

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 1	N60E / 28SE	12 / 060			
ME 2	N45E / 26SE	13 / 040			
ME 3	N65E / 40SE	24 / 055			
ME 4	N53E / 25SE	09 / 065			
ME 5	N43E / 53SE	05 / 050			
ME 6	N68E / 21SE	19 / 061			
ME 7	N57E / 39SE	10 / 060			
ME 8	N57E / 39SE	15 / 070			
ME 9	N56E / 26SE	09 / 060			
ME 10	N40E / 20SE	14 / 061			
ME 11	N44E / 17SE	09 / 055			
ME 12	N51E / 23SE	06 / 059			
ME 13	N50E / 20SE	07 / 061			
ME 14	N43E / 26SE				
ME 15	N48E / 23SE				
ME 16	N43E / 27SE	08 / 058			
ME 17	N53E / 27SE	09 / 059			
ME 18	N44E / 37SE	11 / 054			
ME 19	N41E / 23SE	09 / 050			
ME 20	N51E / 43SE	09 / 062			
ME 21	N31E / 37SE	07 / 062			
ME 22	N17E / 51SE				
ME 23	N56E / 17SE	04 / 066			
ME 24	N52E / 30SE	09 / 058			
ME 25	N58E / 34SE	04 / 064			
ME 26	N31E / 29SE				
ME 27	N51E / 26SE	10 / 057			
ME 28	N53E / 20SE	09 / 055			
ME 29	N49E / 33SE				
ME 30	N56E / 24SE				
ME 31	N44E / 24SE	04 / 054			
ME 32	N47E / 26SE				
ME 33	N61E / 24SE				
ME 34	N54E / 26SE				
ME 35	N19E / 30NW				
ME 36	N45E / 29SE	04 / 067			
ME 37	N48E / 23SE				
ME 38	N43E / 27SE				
ME 39	N56E / 36SE	03 / 064			
ME 40	N58E / 23SE	13 / 060			
ME 41	N57E / 29SE				
ME 42	N58E / 31SE	14 / 060			
ME 43	N63E / 34SE	09 / 060			
ME 44	N57E / 38SE	09 / 063			
ME 45	N58E / 32SE				
ME 46	N53E / 37SE				
ME 47	N50E / 27SE				
ME 48	N57E / 31SE	16 / 058	16 / 238 13 / 258	N68E / 39NW N74E / 58NW	
ME 49	N55E / 34SE				
ME 50	N56E / 23SE	11 / 065			

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 51	N54E / 24SE				
ME 52	N58E / 28SE				
ME 53	N56E / 26SE	22 / 053			
ME 54	N56E / 36SE				
ME 55	N53E / 24SE				
ME 56	N48E / 23SE				
ME 57	N44E / 36SE				
ME 58	N47E / 37SE				
ME 59	N57E / 37SE				
ME 60	N54E / 47SE				
ME 61	N55E / 41SE				
ME 62	N59E / 41SE				
ME 63	N47E / 32SE				
ME 64	N47E / 34SE				
ME 65	N51E / 24SE	08 / 064			
ME 66	N56E / 26SE				
ME 67	N51E / 27SE	16 / 060			
ME 68	N48E / 24SE				
ME 69	N45E / 31SE	14 / 062			
ME 70	N46E / 34SE				
ME 71	N48E / 41SE				
ME 72	N50E / 41SE				
ME 73	N50E / 40SE				
ME 74	N37E / 17SE				
ME 75	N44W / 41SW				
ME 76	N53E / 25SE				
ME 77	N51E / 31SE	12 / 061	32 / 075	N61E / 56SE N40E / 44SE	
ME 78	N56E / 29SE				
ME 79	N33E / 31SE				
ME 80	N53E / 34SE				
ME 81	N57E / 35SE				
ME 82	N49E / 27SE	13 / 060			
ME 83	N47E / 34SE				
ME 84	N56E / 41SE				
ME 85	N54E / 43NW				
ME 86	N46E / 22SE	10 / 058			
ME 87	N43E / 34SE				
ME 88	N51E / 30SE				
ME 89	N63E / 33SE				
ME 90	N44E / 12SE				
ME 91	N40E / 31SE				
ME 92	N53E / 32SE				
ME 93	N47E / 29SE				
ME 94	N46E / 41SE				
ME 95	N43E / 38SE				
ME 96	N50E / 34SE				
ME 97	N48E / 29SE				
ME 98	N47E / 27SE				
ME 99	N44E / 38SE				
ME 100	N20E / 40SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 101	N41E / 22SE				
ME 102	N26E / 51SE				
ME 103	N43E / 31SE				
ME 104	N63E / 28SE				
ME 105	N63E / 17SE				
ME 106	N43E / 46SE				
ME 107	N23E / 57SE				
ME 108	N53E / 28SE	05 / 050			
ME 109	N59E / 24SE				
ME 110	N54E / 36SE				
ME 111	N54E / 27SE				
ME 112	N27E / 24SE				
ME 113	N49E / 31SE	09 / 057			
ME 114	N39E / 37SE				
ME 115	N54E / 34SE				
ME 116	N53E / 24SE				
ME 117	N57E / 37SE				
ME 118	N59E / 36SE	12 / 060			
ME 119	N44E / 26SE		28 / 054	N44E / 31SE	
ME 120	N44E / 37SE				
ME 121	N50E / 27SE				
ME 122	N31E / 36SE				
ME 123	N44E / 41SE				
ME 124	N53E / 33SE				
ME 125	N55E / 28SE				
ME 126	N44E / 34SE				
ME 127	N50E / 25SE				
ME 128	N32E / 42SE				
ME 129	N44E / 27SE				
ME 130	N43E / 31SE				
ME 131	N34E / 32SE				
ME 132	N34E / 11SE				
ME 133	N42E / 22SE				
ME 134	N25E / 36SE				
ME 135	N29E / 35SE				
ME 136	N44E / 37SE				
ME 137	N53E / 31SE		17 / 065	N65E / 19SE	
ME 138	N41E / 29SE				
ME 139	N43E / 24SE				
ME 140	N41E / 30SE				
ME 141	N44E / 33SE				
ME 142	N51E / 24SE	17 / 234			
ME 143	N50E / 23SE				
ME 144	N53E / 24SE				
ME 145	N56E / 24SE				
ME 146	N38E / 24SE				
ME 147	N55E / 30SE				
ME 148	N48E / 41SE				
ME 149	N50E / 26SE				
ME 150	N50E / 32SE				
ME 151	N50E / 36SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 152	N47E / 24SE				
ME 153	N57W / 21SW				
ME 154	N46E / 28SE				
ME 155	N57E / 26SE				
ME 156	N59E / 42SE				
ME 157	N62E / 51SE				
ME 158	N55E / 32SE				
ME 159	N47E / 31SE				
ME 160	N53E / 24SE				
ME 161	N36E / 34SE				
ME 162	N32E / 24SE				
ME 163	N32E / 40SE				
ME 164	N50E / 36SE				
ME 165	N44E / 34SE				
ME 166	N53E / 32SE				
ME 167	N38E / 41SE				
ME 168	N47E / 29SE				
ME 169	N40E / 33SE				
ME 170	N42E / 29SE				
ME 171	N38E / 31SE				
ME 172	N60E / 44SE				
ME 173	N30E / 36SE				
ME 174	N43E / 39SE				
ME 175	N40E / 31SE				
ME 176	N41E / 27SE				
ME 177	N39E / 36SE				
ME 178	N33E / 26SE				
ME 179	N48E / 32SE	11 / 060			
ME 180	N47E / 26SE				
ME 181	N33E / 41SE				
ME 182	N31E / 41SE				
ME 183	N41E / 24SE				
ME 184	N34E / 39SE				
ME 185	N41E / 37SE				
ME 186	N33E / 27SE				
ME 187	N48E / 37SE				
ME 188	N53E / 42SE				
ME 189	N38E / 49SE				
ME 190	N37E / 42SE				
ME 191	N54E / 34SE	14 / 058			
ME 192	N49E / 29SE				
ME 193	N54E / 41SE				
ME 194	N51E / 38SE				
ME 195	N47E / 31SE				
ME 196	N49E / 41SE	13 / 056	13 / 054		
ME 197	N34E / 26SE				
ME 198	N33E / 44SE				
ME 199	N44E / 41SE				
ME 200	N38E / 34SE				
ME 201	N39E / 43SE				
ME 202	N37E / 42SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 203	N36E / 41SE				
ME 204	N36E / 44SE				
ME 205	N41E / 32SE				
ME 206	N44E / 26SE				
ME 207	N40E / 29SE				
ME 208	N37E / 34SE				
ME 209	N41E / 44SE				
ME 210	N43E / 31SE				
ME 211	N51E / 41SE				
ME 212	N38E / 40SE				
ME 213	N42W / 44SW				
ME 214	N42E / 32SE				
ME 215	N46E / 40SE		12 / 071 31 / 040	N57E / 30SE N61E / 43SE N15E / 44SE N37E / 46SE	
ME 216	N47E / 46SE				
ME 217	N46E / 27SE				
ME 218	N39E / 31SE				
ME 219	N46E / 36SE				
ME 220	N41E / 32SE				
ME 221	N47E / 42SE				
ME 222	N39E / 37SE				
ME 223	N41E / 32SE				
ME 224	N43E / 27SE				
ME 225	N25E / 36SE				
ME 226	N23E / 35SE				
ME 227	N17E / 36SE	12 / 061		N43E / 25SE	
ME 228	N21E / 39SE				
ME 229	N31E / 24SE				
ME 230	N36E / 27SE				
ME 231	N75E / 37SE		14 / 061	N51E / 24SE	
ME 232	N68E / 32SE				
ME 233	N70E / 24SE				
ME 234	N66E / 34SE				
ME 235	N33E / 36SE				
ME 236	N37E / 29SE				
ME 237	N37E / 42SE			N37E / 35SE	
ME 238	N31E / 37SE				
ME 239	N24E / 32SE				
ME 240	N36E / 34SE				
ME 241	N41E / 44SE				
ME 242	N37E / 42SE				
ME 243	N34E / 37SE				
ME 244	N41E / 39SE				
ME 245	N43E / 37SE				
ME 246	N34E / 42SE				
ME 247	N30E / 32SE				
ME 248	N36E / 34SE				
ME 249	N44E / 27SE				
ME 250	N64E / 44SE	13 / 062			
ME 251	N52E / 43SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 252	N59E / 37SE				
ME 253	N54E / 24SE				
ME 254	N27E / 24SE				
ME 255	N44E / 31SE				
ME 256	N47E / 27SE				
ME 257	N64E / 48SE				
ME 258	N59E / 37SE				
ME 259	N55E / 28SE				
ME 260	N44E / 29SE				
ME 261	N48E / 32SE				
ME 262	N53E / 33SE				
ME 263	N59E / 38SE				
ME 264	N60E / 35SE				
ME 265	N52E / 33SE				
ME 266	N48E / 32SE				
ME 267	N54E / 43SE				
ME 268	N55E / 38SE				
ME 269	N49E / 46SE				
ME 270	N53E / 34SE			N48E / 38SE	
ME 271	N50E / 41SE				
ME 272	N22E / 42SE				
ME 273	N42E / 32SE				
ME 274	N49E / 31SE				
ME 275	N50E / 26SE				
ME 276	N40E / 38SE				
ME 277	N43E / 34SE				
ME 278	N46E / 32SE				
ME 279	N43E / 35SE				
ME 280	N46E / 43SE				
ME 281	N47E / 44SE				
ME 282	N41E / 36SE		14 / 310 17 / 057	N60W / 16NE N57E / 84SE	
ME 283	N43E / 37SE				
ME 284	N45E / 31SE				
ME 285	N46E / 30SE				
ME 286	N51E / 33SE				
ME 287	N44E / 34SE				
ME 288	N47E / 31SE				
ME 289	N38E / 27SE				
ME 290	N53E / 31SE				
ME 291	N42E / 37SE				
ME 292	N52E / 35SE				
ME 293	N51E / 33SE			N48E / 26SE	
ME 294	N53E / 33SE				
ME 295	N48E / 34SE				
ME 296	N43E / 36SE				
ME 297	N41E / 33SE				
ME 298	N53E / 27SE				
ME 299	N44E / 31SE				
ME 300	N52E / 30SE				
ME 301	N48E / 32SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 302	N44E / 36SE				
ME 303	N42E / 33SE				
ME 304	N57E / 49SE				
ME 305	N50E / 27SE				
ME 306	N61E / 30SE				
ME 307	N47E / 41SE				
ME 308	N57E / 19SE				
ME 309	N39E / 34SE				
ME 310	N31E / 32SE				
ME 311	N33E / 27SE	14 / 061			
ME 312	N34E / 30SE				
ME 313	N38E / 46SE				
ME 314	N28E / 32SE				
ME 315	N30E / 27SE				
ME 316	N33E / 29SE				
ME 317	N50W / 36SW		19 / 227		
ME 318	N36E / 32SE				
ME 319	N45E / 51SE				
ME 320	N43E / 31SE				
ME 321	N41E / 27SE				
ME 322	N51E / 42SE				
ME 323	N41E / 34SE				
ME 324	N40E / 43SE				
ME 325	N35E / 47SE	11 / 062			
ME 326	N37E / 38SE				
ME 327	N42E / 44SE				
ME 328	N46E / 32SE				
ME 329	N43E / 25SE				
ME 330	N41E / 39SE				
ME 331	N34E / 24SE				
ME 332	N37E / 30SE				
ME 333	N46E / 24SE				
ME 334	N52E / 34SE				
ME 335	N52E / 44SE				
ME 336	N50E / 43SE				
ME 337	N37E / 27SE				
ME 338	N43E / 35SE				
ME 339	N39E / 23SE				
ME 340	N31E / 27SE				
ME 341	N43E / 31SE				
ME 342	N41E / 30SE				
ME 343	N57E / 37SE		21 / 062 33 / 237	N37E / 45SE N60E / 9SE	
ME 344	N27E / 47SE				
ME 345	N40E / 36SE				
ME 346	N37E / 33SE				
ME 347	N36E / 27SE	09 / 057			
ME 348	N35E / 34SE				
ME 349	N33E / 27SE				
ME 350	N42E / 27SE				
ME 351	N44E / 36SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 352	N46E / 37SE				
ME 353	N47E / 28SE				
ME 354	N48E / 32SE				
ME 355	N44E / 41SE	12 / 090			
ME 356	N39W / 27NE				
ME 357	N50E / 25SE				
ME 358	N47E / 29SE				
ME 359	N30E / 70SE		13 / 060	N53E / 60SE	
ME 360	N37E / 33SE				
ME 361	N37E / 22SE				
ME 362	N35E / 22SE	08 / 054		N57E / 9SE	
ME 363	N21E / 32SE				
ME 364	N40E / 22SE				
ME 365	N37E / 22SE	13 / 070			
ME 366	N10W / 24NE				
ME 367	N5E / 22SE				
ME 368	N21E / 24SE				
ME 369	N20E / 31SE				
ME 370	N54E / 17SE				
ME 371	N17E / 31SE	11 / 046			
ME 372	N37E / 24SE				
ME 373	N44E / 31SE	17 / 057			
ME 374	N35E / 29SE		14 / 060	N57E / 21SE	
ME 375	N44E / 28SE				
ME 376	N51E / 44SE				
ME 377	N55E / 47SE	14 / 064			
ME 378	N44E / 21SE				
ME 379	N54E / 17NW				
ME 380	N55E / 46SE				
ME 381	N41E / 42SE				
ME 382	N37E / 54SE				
ME 383	N38E / 30SE				
ME 384	N37E / 26SE				
ME 385	N46E / 29SE				
ME 386	N71E / 30SE				
ME 387	N55E / 31SE				
ME 388	N24E / 36NW	28 / 315			
ME 389	N60E / 43NW	36 / 307	34 / 303	N63E / 44NW	
ME 390	N17E / 24NW	23 / 298			
ME 391	N56E / 37SE				
ME 392	N46E / 29NW				
ME 393	N53E / 68SE				
ME 394	N37E / 24SE				
ME 395	N33E / 30SE				
ME 396	N42E / 33SE	09 / 058			
ME 397	N43E / 27SE	07 / 057			
ME 398	N39E / 33SE				
ME 399	N40E / 67SE				
ME 400	N48E / 20SE				
ME 401	N54E / 49SE				
ME 402	N52E / 24SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 403	N60E / 57NW	05 / 241			
ME 404	N50E / 36SE				
ME 405	N48E / 38SE				
ME 406	N28E / 54SE				
ME 407	N60E / 44SE				
ME 408	N57E / 19SE				
ME 409	N10E / 46SE				
ME 410	N44E / 27NW				
ME 411	N62E / 21SE				
ME 412	N24E / 26SE				
ME 413	N47E / 32SE				
ME 414	N57E / 36SE				
ME 415	N47W / 31SW				
ME 416	N36E / 24SE				
ME 417	N39E / 34SE				
ME 418	N14E / 27SE				
ME 419	N41W / 39NE				
ME 420	N60W / 27NE				
ME 421	N33E / 37SE		15 / 050	N17E / 17SE	
ME 422	N41E / 23SE	11 / 343			
ME 423	N33E / 31SE				
ME 424	N41E / 37SE				
ME 425	N46E / 36SE				
ME 426	N51E / 33SE				
ME 427	N46E / 44SE				
ME 428	N47E / 30SE				
ME 429	N44E / 41SE				
ME 430	N17E / 49SE		26 / 035 25 / 067	N36W / 37SW N57E / 44SE	
ME 431	N54E / 34SE				
ME 432	N35E / 29SE				
ME 433	N31E / 24SE	12 / 056	14 / 037		
ME 434	N40E / 24SE	13 / 061			
ME 435	N37E / 44SE				
ME 436	N30E / 34SE				
ME 437	N38E / 37SE				
ME 438	N46E / 31SE				
ME 439	N27E / 36SE	21 / 071			
ME 440	N29E / 27SE				
ME 441	N32E / 28SE				
ME 442	N44E / 41SE	11 / 057			
ME 443	N37E / 29SE				
ME 444	N31E / 38SE				
ME 445	N36E / 43SE				
ME 446	N44E / 40SE				
ME 447	N46E / 54SE				
ME 448	N44E / 41SE				
ME 449	N48E / 51SE				
ME 450	N27W / 27NE	07 / 235			
ME 451	N53W / 34NE				
ME 452	N83W / 54NE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 453	N63W / 23NE				
ME 454	N63E / 49SE				
ME 455	N50E / 36SE				
ME 456	N44E / 36SE				
ME 457	N44E / 33SE				
ME 458	N17E / 42SE				
ME 459	N57E / 40SE				
ME 460	N51E / 37SE				
ME 461	N43E / 40SE				
ME 462	N47E / 27SE				
ME 463	N41E / 37SE		28 / 320		
ME 464	N38E / 27SE				
ME 465	N57E / 56SE				
ME 466	N47E / 34SE				
ME 467	N54E / 37SE	05 / 061			
ME 468	N54E / 45SE				
ME 469	N47E / 51SE				
ME 470	N44E / 32SE				
ME 471	N51E / 37SE	18 / 285			N74E / 69NW N10W / 87NE
ME 472	N32E / 17SE				
ME 473	N27E / 42SE				
ME 474	N49E / 31SE				
ME 475	N47E / 24SE				
ME 476	N43E / 22SE				
ME 477	N56E / 39SE				
ME 478	N57E / 27NW				
ME 479	N47E / 37SE				
ME 480	N47E / 34SE				
ME 481	N34E / 44SE				
ME 482	N41E / 27SE				
ME 483	N54E / 29NW				
ME 484	N51E / 36SE				
ME 485	N57E / 41SE				
ME 486	N47E / 42SE				
ME 487	N54E / 44SE				
ME 488	N46E / 54SE				
ME 489	N41E / 37SE				
ME 490	N37E / 43SE				
ME 491	N37E / 34SE				
ME 492	N41E / 43SE				
ME 493	N52E / 46SE				
ME 494	N44E / 34SE				
ME 495	N34E / 34SE				
ME 496	N45E / 41SE				
ME 497	N44E / 46SE				
ME 498	N44E / 34SE				
ME 499	N37E / 29SE				
ME 500	N41E / 38SE				N45E / 68NW N40W / 67SW
ME 501	N33E / 41SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 502	N48E / 46SE				
ME 503	N39E / 33SE				
ME 504	N37E / 46SE				N77E / 86SE N / 81NE
ME 505	N41E / 29SE				
ME 506	N41E / 34SE				
ME 507	N39E / 32SE				
ME 508	N44E / 34SE				
ME 509	N41E / 32SE				
ME 510	N37E / 30SE				
ME 511	N27E / 29SE				N74E / 65NW
ME 512	N46E / 33SE				
ME 513	N44E / 35SE				
ME 514	N47E / 41SE				
ME 515	N41E / 29SE				N61E / V N47E / 61NW
ME 516	N42E / 26SE				
ME 517	N37E / 31SE				
ME 518	N48E / 32SE				
ME 519	N42E / 33SE				
ME 520	N37E / 44SE				N55W / 77SW
ME 521	N41E / 36SE				
ME 522	N38E / 47SE				
ME 523	N42E / 27SE				
ME 524	N41E / 37SE				
ME 525	N17E / 29SE				
ME 526	N30E / 34SE				
ME 527	N36E / 38SE				
ME 528	N34E / 36SE				
ME 529	N46E / 34SE				N73E / 57NE
ME 530	N54E / 46SE				
ME 531	N33E / 36SE				
ME 532	N41E / 44SE				
ME 533	N46E / 43SE				
ME 534	N41E / 36SE				
ME 535	N46E / 42SE				
ME 536	N46E / 47SE				
ME 537	N53E / 43SE				
ME 538	N43E / 33SE				
ME 539	N41E / 44SE				
ME 540	N45E / 41SE				
ME 541	N39E / 36SE				
ME 542	N41E / 31SE				
ME 543	N38E / 32SE				
ME 544	N40E / 31SE				
ME 545	N41E / 37SE				
ME 546	N39E / 29SE				N47W / 66SW
ME 547	N49E / 34SE				
ME 548	N44E / 31SE				
ME 549	N42E / 39SE				
ME 550	N46E / 41SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 551	N47W / 32NE				
ME 552	N39E / 28SE				N30E / 47SE
ME 553	N41E / 29SE				N65E / 81NW
					N31W / 77NE
ME 554	N17E / 27SE		11 / 057	N57E / 54SE	N44E / 67NW
					N71E / 57NW
ME 555	N27E / 29SE				N61E / 84SE
ME 556	N39E / 34SE				
ME 557	N41E / 31SE				
ME 558	N43E / 32SE				
ME 559	N37E / 39SE	14 / 059			
ME 560	N31E / 34SE				
ME 561	N27E / 41SE				
ME 562	N34E / 26SE				
ME 563	N40E / 29SE				
ME 564	N60E / 24SE				
ME 565	N37E / 33SE				
ME 566	N46E / 27SE				
ME 567	N44E / 36SE				
ME 568	N27E / 36SE				
ME 569	N44E / 27SE				N51E / 78SE
					N7E / V
					N27W / 74NE
ME 570	N40E / 25SE				
ME 571	N44E / 34SE				
ME 572	N40E / 29SE				
ME 573	N47E / 50SE				
ME 574	N20W / 17NE				
ME 575	N42E / 19NE				
ME 576	N44E / 19NE	04 / 057			N7W / V
					N70E / 81NE
					N57W / 64NE
ME 577	N46E / 34SE				
ME 578	N48E / 33SE				
ME 579	N42E / 44SE				
ME 580	N45E / 36SE				
ME 581	N43E / 31SE				
ME 582	N46E / 41SE				
ME 583	N52E / 38SE				
ME 584	N46E / 32SE				
ME 585	N37E / 43SE				
ME 586	N55E / 24SE	03 / 285			N10E / 77SE
					N76E / 65NW
ME 587	N47E / 31SE				
ME 588	N44E / 28SE				N41W / 58SW
ME 589	N42E / 29SE				
ME 590	N50E / 37SE				
ME 591	N40E / 35SE				
ME 592	N46E / 30SE				
ME 593	N53E / 31SE				
ME 594	N44E / 37SE				N63E / V

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 595	N42E / 27SE				
ME 596	N41E / 31SE				
ME 597	N50E / 39SE				
ME 598	N47E / 36SE				
ME 599	N39E / 31SE				N20W / 76NE N56W / 58NE
ME 600	N41E / 33SE				
ME 601	N37E / 26SE				
ME 602	N36E / 33SE				
ME 603	N52E / 31SE			N53E / 41SE	
ME 604	N55E / 34SE	09 / 057			N75W / 82SE N17E / 67NW
ME 605	N47E / 30SE				
ME 606	N41E / 36SE				
ME 607	N53E / 36SW				N-S / V E-W / V
ME 608	N17E / 36SE				
ME 609	N57E / 33SE				
ME 610	N48E / 39SE				N72E / 54NW
ME 611	N41E / 26SE				
ME 612	N40E / 36SE				
ME 613	N41E / 44SE				
ME 614	N36E / 29SE				
ME 615	N56E / 38SE				
ME 616	N77W / 38SW				
ME 617	N50E / 32SE	09 / 055			N23E / 70NW N77W / V
ME 618	N57E / 24SE	09 / 270			N22E / 64NW N30W / V N35W / 74NE
ME 619	N58E / 23SE				
ME 620	N51E / 31SE				N14E / 84NW N33W / V
ME 621	N47E / 23SE		21 / 330 19 / 297	N30W / V N60W / 24SW	N74E / 75NW N33W / 82NE N5W / 79SW N39E / V
ME 622	N51E / 37SE				
ME 623	N46E / 30SE				
ME 624	N56E / 41SE				
ME 625	N62E / 63SE	17 / 288			
ME 626	N58E / 38SE				
ME 627	N64E / 29SE	11 / 136	13 / 186	N5W / 33NE	
ME 628	N53E / 34SE	07 / 120			
ME 629	N53E / 41SE				
ME 630	N47E / 41SE				
ME 631	N48E / 31SE				N79E / 74NW N28E / 74SE
ME 632	N52E / 34SE		21 / 191	upright	N54W / 61SW N42E / 86SE N3E / 64NW

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 633	N53E / 26SE	12 / 161			N6W / 79SW N35W / V
ME 634	N47E / 26SE				
ME 635	N48E / 27SE				
ME 636	N54E / 32SE				
ME 637	N48E / 31SE				
ME 638	N52E / 29SE				
ME 639	N47E / 27SE				
ME 640	N44E / 26SE	24 / 071			N41W / 38NE
ME 641	N51E / 29SE				
ME 642	N51E / 28SE				
ME 643	N59E / 34SE				
ME 644	N47E / 31SE				
ME 645	N44E / 37SE				
ME 646	N43E / 24SE				
ME 647	N46E / 27SE				
ME 648	N50E / 37SE				
ME 649	N45E / 33SE				
ME 650	N44E / 31SE				
ME 651	N43E / 35SE				
ME 652	N47E / 32SE				
ME 653	N56E / 22SE				
ME 654	N49E / 29SE				
ME 655	N54E / 31SE				
ME 656	N53E / 21SE				
ME 657	N49E / 26SE	21 / 061			N44E / 71NW N10E / 77NW
ME 658	N62E / 41SE				
ME 659	N61E / 46SE				
ME 660	N54E / 37SE				
ME 661	N57E / 33SE				
ME 662	N76E / 34SE				
ME 663	N48E / 34SE				
ME 664	N47E / 39SE				
ME 665	N37E / 27SE				
ME 666	N38E / 31SE				
ME 667	N46E / 47SE	09 / 058			N40W / V
ME 668	N44E / 57SE				
ME 669	N74E / 39SE				
ME 670	N54E / 46SE				
ME 671	N52E / 41SE				
ME 672	N53E / 37SE				
ME 673	N51E / 31SE				
ME 674	N41E / 36SE				
ME 675	N58E / 37SE				
ME 676	N52E / 27SE				N12W / V N40W / V N70W / 77SW
ME 677	N31E / 42SE				
ME 678	N42E / 34SE				
ME 679	N51E / 32SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 680	N47E / 24SE	11 / 057			N4E / 65NW N9W / V N37W / V
ME 681	N48E / 31SE				
ME 682	N47E / 33SE				N41W / 63SW
ME 683	N50E / 38SE				N46W / V
ME 684	N47E / 31SE				E-W / V N27W / V
ME 685	N46E / 32SE				
ME 686	N42E / 37SE				
ME 687	N52E / 37SE				
ME 688	N47E / 42SE				
ME 689	N37E / 33SE				
ME 690	N49E / 36SE				
ME 691	N32E / 47SE				
ME 692	N48E / 43SE				
ME 693	N33E / 38SE				N26W / V N14W / V
ME 694	N39E / 46SE				N42W / 76SW
ME 695	N47E / 33SE				N45W / 76SW N29W / 81SW
ME 696	N39E / 27SE	14 / 296			
ME 697	N36E / 41SE				
ME 698	N39E / 52SE				
ME 699	N26E / 48SE				
ME 700	N37E / 34SE				
ME 701	N39E / 32SE				
ME 702	N71E / 29SE				
ME 703	N38E / 34SE				
ME 704	N44E / 40SE				N17W / 67NE N30W / V
ME 705	N56E / 31SE				
ME 706	N48E / 36SE				
ME 707	N43E / 37SE				
ME 708	N39E / 34SE				
ME 709	N47E / 34SE				
ME 710	N35E / 24SE				
ME 711	N34E / 31SE				
ME 712	N44E / 27SE				
ME 713	N40E / 32SE				
ME 714	N41E / 36SE				
ME 715	N41E / 36SE				
ME 716	N46E / 42SE				
ME 717	N51E / 32SE				
ME 718	N33E / 42SE				
ME 719	N54E / 37SE				
ME 720	N43E / 30SE				
ME 721	N40E / 34SE				
ME 722	N41E / 34SE				
ME 723	N41E / 39SE				
ME 724	N44E / 30SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 725	N48E / 42SE				
ME 726	N51E / 49SE				
ME 727	N48E / 31SE				
ME 728	N37E / 32SE				
ME 729	N50E / 37SE				
ME 730	N52E / 37SE		07 / 062	N62E / 28NW	
ME 731	N51E / 41SE				
ME 732	N47E / 33SE				
ME 733	N37E / 31SE				
ME 734	N43E / 34SE				
ME 735	N44E / 36SE				
ME 736	N35E / 33SE				
ME 737	N34E / 31SE				
ME 738	N36E / 31SE				
ME 739	N58E / 37SE				
ME 740	N51E / 36SE				
ME 741	N47E / 31SE				
ME 742	N44E / 38SE				
ME 743	N49E / 37SE				
ME 744	N52E / 38SE				
ME 745	N41E / 36SE				
ME 746	N39E / 33SE				
ME 747	N22E / 44SE				
ME 748	N29E / 43SE	016 / 064			
ME 749	N36E / 41SE				N80W / 63SW N50W / 62NE
ME 750	N33E / 29SE				
ME 751	N36E / 39SE				
ME 752	N31E / 33SE				
ME 753	N35E / 33SE				
ME 754	N40E / 36SE				
ME 755	N43E / 27SE				
ME 756	N39E / 31SE				
ME 757	N37E / 31SE				
ME 758	N44E / 46SE	07 / 054	19 / 030	N30E / 44SE	
ME 759	N39E / 30SE	11 / 059			
ME 760	N39E / 36SE				
ME 761	N48E / 36SE				
ME 762	N39E / 22SE				
ME 763	N31E / 34SE				
ME 764	N39E / 33SE				
ME 765	N36E / 31SE				
ME 766	N36E / 34SE				
ME 767	N41E / 35SE				
ME 768	N50E / 31SE				
ME 769	N46E / 33SE				
ME 770	N33E / 32SE				
ME 771	N47E / 41SE				
ME 772	N44E / 32SE				
ME 773	N46E / 44SE				
ME 774	N49E / 36SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 775	N46E / 36SE				
ME 776	N43E / 29SE				
ME 777	N27E / 40SE				
ME 778	N31E / 41SE				
ME 779	N43E / 37SE				
ME 780	N44E / 32SE				
ME 781	N44W / 37NE				N20E / 37NW N44E / 62NW
ME 782	N43E / 33SE				
ME 783	N44E / 47SE				
ME 784	N50E / 36SE				
ME 785	N50E / 42SE				
ME 786	N24E / 44SE				
ME 787	N42E / 34SE				
ME 788	N50E / 41SE				
ME 789	N51E / 36SE				
ME 790	N36E / 26SE				
ME 791	N41E / 36SE				
ME 792	N40E / 41SE				
ME 793	N47E / 39SE				
ME 794	N46E / 39SE				N35W / 80SW
ME 795	N45E / 43SE				
ME 796	N45E / 33SE	11 / 057			
ME 797	N32E / 41SE				
ME 798	N40E / 49SE	21 / 066			
ME 799	N36E / 39SE				
ME 800	N39E / 33SE				
ME 801	N32E / 44SE				
ME 802	N30E / 42SE				N6W / V N70E / V N32W / V N70W/V N50W / V
ME 803	N37E / 40SE				
ME 804	N32E / 42SE				
ME 805	N35E / 41SE	14 / 059			
ME 806	N33E / 38SE				N35W / V N75W / 70SW N73E / 77SE
ME 807	N40E / 33SE				
ME 808	N35E / 36SE				
ME 809	N31E / 34SE				
ME 810	N27E / 32SE	16 / 060			
ME 811	N33E / 42SE				
ME 812	N39E / 37SE				
ME 813	N33E / 34SE				
ME 814	N35E / 39SE				
ME 815	N33E / 40SE				
ME 816	N31E / 30SE				
ME 817	N28E / 37SE				
ME 818	N36E / 32SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 819	N36E / 34SE				
ME 820	N46E / 36SE				
ME 821	N49E / 33SE	11 / 061			
ME 822	N46E / 33SE				
ME 823	N41E / 27SE	08 / 057			
ME 824	N32E / 54SE	14 / 047			
		42 / 333			
ME 825	N44E / 34SE	09 / 057			
ME 826	N44E / 34SE				
ME 827	N42E / 34SE				
ME 828	N38E / 42SE				
ME 829	N41E / 37SE				
ME 830	N39E / 32SE				
ME 831	N36E / 39SE				
ME 832	N41E / 34SE				
ME 833	N40E / 33SE				
ME 834	N37E / 36SE				
ME 835	N46E / 33SE				
ME 836	N43E / 36SE				
ME 837	N41E / 30SE				
ME 838	N43E / 33SE				
ME 839	N41E / 31SE				
ME 840	N38E / 31SE				
ME 841	N40E / 36SE				
ME 842	N35W / 30NE				N50W / 52SW
ME 843	N38W / 32NE				
ME 844	N44E / 46SE				
ME 845	N30W / 44NE				
ME 846	N31E / 36SE				
ME 847	N26E / 31SE				
ME 848	N54E / 31SE				
ME 849	N74E / 52SE				
ME 850	N52E / 41SE				
ME 851	N50E / 52SE				
ME 852	N52E / 29SE				
ME 853	N52E / 31SE				
ME 854	N42E / 28SE				
ME 855	N41E / 30SE				
ME 856	N44E / 32SE				
ME 857	N42E / 30SE				
ME 858	N37E / 32SE				
ME 859	N40E / 37SE				
ME 860	N40E / 32SE				
ME 861	N40E / 37SE				
ME 862	N39E / 31SE				
ME 863	N40E / 37SE				
ME 864	N36E / 34SE				
ME 865	N34E / 52SE				
ME 866	N36E / 44SE				
ME 867	N46E / 34SE				
ME 868	N59E / 34SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 869	N44E / 38SE				
ME 870	N54E / 34SE				N35W / V N60W / V
ME 871	N39E / 33SE				
ME 872	N43E / 32SE				N70E / 45SE
ME 873	N42E / 32SE				
ME 874	N40E / 29SE				
ME 875	N50E / 32SE				
ME 876	N50E / 44SE				
ME 877	N47E / 42SE				
ME 878	N50E / 39SE	09 / 062			N40W / 82SW N60E / V N20W / V
ME 879	N52E / 34SE				
ME 880	N48E / 34SE				
ME 881	N54E / 33SE				
ME 882	N48E / 44SE				
ME 883	N46E / 36SE				
ME 884	N40E / 27SE				
ME 885	N62E / 39SE				
ME 886	N40E / 31SE				
ME 887	N42E / 36SE				
ME 888	N44E / 32SE				
ME 889	N43E / 32SE	11 / 062			
ME 890	N44E / 41SE				
ME 891	N39E / 33SE				
ME 892	N42E / 46SE				
ME 893	N40W / 39NE				
ME 894	N17W / 20NE				N30E / 67SE
ME 895	N44E / 36SE				N16W / V
ME 896	N47E / 32SE	13 / 051	11 / 044	N54E / 9SE	
ME 897	N40E / 30SE	13 / 060			
ME 898	N42E / 30SE				
ME 899	N44E / 36SE				
ME 900	N43E / 34SE				
ME 901	N41E / 37SE				
ME 902	N51E / 47SE	05 / 063			N33W / V N62W / V N83E / V
ME 903	N44E / 33SE				
ME 904	N42E / 36SE				
ME 905	N42E / 36SE				N30W / V N80W / V N55E / V
ME 906	N44E / 34SE				
ME 907	N47E / 34SE				
ME 908	N46E / 35SE				
ME 909	N52E / 37SE				
ME 910	N44E / 33SE				
ME 911	N23E / 28SE				
ME 912	N56E / 32SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 913	N57E / 20SE				
ME 914	N49E / 28SE				
ME 915	N75W / 54SW				
ME 916	N64W / 27SW				
ME 917	N41E / 60SE				
ME 918	N35E / 37SE				
ME 919	N54E / 46SE				
ME 920	N36E / 32SE				
ME 921	N44E / 34SE				
ME 922	N40E / 44SE				
ME 923	N44E / 43SE				
ME 924	N44E / 40SE				
ME 925	N54E / 43SE	16 / 058			
ME 926	N44E / 46SE	14 / 060			
ME 927	N53E / 29SE				
ME 928	N41E / 52SE		26 / 000	N20E / 44SE	
ME 929	N46E / 31SE				
ME 930	N47E / 31SE				
ME 931	N24E / 14SE				
ME 932	N44E / 34SE	07 / 059			
ME 933	N44E / 21SE				
ME 934	N41E / 33SE				
ME 935	N41E / 26SE				
ME 936	N43E / 23SE N20E / 70SE fault		09 / 023	N14E / 56SE N40E / 44SE N11W / V N19E / V N22E / 73SE	
ME 937	N69W / 54SW				
ME 938	N42E / 35SE				
ME 939	N40E / 22SE				
ME 940	N61E / 72SE				
ME 941	N44E / 33SE				
ME 942	N27E / 41SE				
ME 943	N10E / 62SE N14E / 28SE fault				
ME 944	N84W / 64S				
ME 945	N19E / 59SE		11 / 354 / 355	09 N20W / 15NE N27W / 32NE N11E / 68SE	
ME 946	N49E / 22SE				
ME 947	N18E / 21SE				
ME 948	N14E / 22SE				
ME 949	N54E / 24SE				
ME 950	N47E / 26SE				
ME 951	N52E / 41SE				
ME 952	N54E / 23SE				
ME 953	N36E / 41SE				
ME 954	N13W / 20SW				
ME 955	N49E / 36SE				
ME 956	N41E / 32SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 957	N48E / 34SE				
ME 958	N57E / 36SE				
ME 959	N21E / 30SE				
ME 960	N51E / 44SE				
ME 961	N44E / 41SE				
ME 962	N56E / 41SE				
ME 963	N30E / 32SE				
ME 964	N29E / 35SE				
ME 965	N37E / 29SE	09 / 051			
ME 966	N40E / 29SE				
ME 967	N17E / 27SE				
ME 968	N26E / 29SE			N21E / 53SE	
ME 969	N29E / 31SE				
ME 970	N36E / 35SE				
ME 971	N28E / 36SE				
ME 972	N34E / 29SE	09 / 054			
ME 973	N36E / 42SE	14 / 056			
ME 974	N37E / 34SE				
ME 975	N34E / 48SE				
ME 976	N36E / 32SE				
ME 977	N39E / 49SE				
ME 978	N61E / 30SE				
ME 979	N54E / 33SE	22 / 152			
ME 980	N51E / 46SE				
ME 981	N38E / 52SE				
ME 982	N41E / 32SE				
ME 983	N51E / 57SE		14 / 205	N52E / 84NW	
ME 984	N44E / 62SE	11 / 039	13 / 074	N57E / 59SE	
ME 985	N57E / 32NW				
ME 986	N61E / 41SE				
ME 987	N40E / 47SE				
ME 988	N60E / 42SE	17 / 016			
ME 989	N10E / 27SE				
ME 990	N53E / 50SE				
ME 991	N53E / 45SE				
ME 992	N48E / 35SE				
ME 993	N65E / 60SE				
ME 994	N46E / 44SE				
ME 995	N56E / 45SE	05 / 201			
ME 996	N52 / 62SE				
ME 997	N53E / 31SE				
ME 998	N69E / 31SE				
ME 999	N36E / 40SE				
ME 1000	N24E / 52SE				
ME 1001	N42E / 49SE				
ME 1002	N76E / 50SE				
ME 1003	N45E / 27SE				
ME 1004	N44E / 52SE				
ME 1005	N35E / 51SE				
ME 1006	N61E / 38SE				
ME 1007	N38E / 24SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
ME 1008	N51E / 46SE				
ME 1009	N56E / 60SE				
ME 1010	N48E / 50SE				
ME 1011	N51E / 38SE				
ME 1012	N43E / 39SE				
ME 1013	N8E / 27SE				
ME 1014	N69E / 49SE				
ME 1015	N41E / 35SE	15 / 068			
ME 1016	N17E / 45SE				
ME 1017	N44E / 44SE				
ME 1018	N56E / 35SE				
ME 1019	N30E / 38SE				
ME 1020	N61E / 34SE				
ME 1021	N79E / 43SE				
ME 1022	N53E / 57SE				
ME 1023	N46E / 50SE	22 / 071			
ME 1024	N50E / 28SE				
ME 1025	N36E / 45SE				
ME 1026	N24E / 22SE				
ME 1027	N46E / 26SE				
ME 1028	N45E / 24SE				
ME 1029	N60E / 31SE				
ME 1030	N57E / 21SE				
ME 1031	N63E / 45SE				
ME 1032	N50E / 37SE				
ME 1033	N54E / 29SE				
ME 1034	N50E / 47SE				
ME 1035	N70E / 24SE				
ME 1036	N54E / 55SE				
ME 1037	N71E / 53SE				
ME 1038	N67E / 45SE	045 / 185			
ME 1039	N55E / 36SE				
ME 1040	N51E / 44SE				
ME 1041	N49E / 51SE				
MW 1	N39E / 31SE				
MW 2	N52E / 32SE				
MW 3	N62E / 42SE				
MW 4	N59E / 52SE				
MW 5	N42E / 34SE				
MW 6	N29E / 37SE				
MW 7	N31W / 26NE				
MW 8	N68E / 18SE				
MW 9	N37E / 20E				
MW 10	N36E / 25SE				
MW 11	N33E / 23SE				
MW 12	N38E / 25SE				
MW 13	N39E / 29SE				
MW 14	N26E / 27SE				
MW 15	N41E / 28SE				
MW 16	N36E / 19SE				
MW 17	N41E / 21SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
MW 18	N24E / 20SE				
MW 19	N20E / 28SE				
MW 20	N74E / 26SE				
MW 21	N65W / 56SW				
MW 22	N36E / 31SE				
MW 23	N39E / 16SE				
MWc 24	N35E / 45NW				
MWc 25	N46E / 55SE				
MWc 26	N36E / 70NW				
MWc 27	N38E / 50NW				
MWc 28	N51E / 30NW				
MWc 29	N51E / 20NE				
MWc 30	N61E / 31SE	?? / 237			
MWc 31	N36E / 31SE				
MWc 32	N61E / 60SE				
MWc 33	N58E / 25SE				
MWc 34	N11E / 40SE				
MWc 35	N59E / 55NW				
MWc 36	N30E / 50NW	20 / 225			
MWc 37	N49E / 53NW				
MWc 38	N33E / 31SE				
MWc 39	N28E / 35SE	?? / 037 11 / 237			
MWc 40	N36E / 35SE				
MWc 41	N26E / 20SE				
MWc 42	N9E / 31SE				
MWc 43	N88W / 45SW				
MWc 44	N42E / 12SE				
MWc 45	N31E / 19SE				
MWc 46	N21E / 40SE				
MWc 47	N76E / 45SE	?? / 232			
MWc 48	N23E / 50SE				
MWc 49	N31E / 70SE				
MWc 50	N38E / 25SE				
MWc 51	N45E / 20SE				
MWc 52	N49E / 60SE				
MWc 53	N46E / 35SE				
MWc 54	N25W / ??				
MWc 55	N21E / 39SE				
MWc 56	N55E / 30SE	?? / 210			
MWc 57	N37E / 20NW				
MWc 58	N63E / 50NE				
MWc 59	N77E / 34SE				
MWc 60	N70E / 25SE	60 / 198			
MWc 61	N62E / 65SE				
MWc 62	N69E / 10SE				
MWc 63	N46E / 40SE				
MWc 64	N47E / 30SE				
MWc 65	N47E / 45SE				
MWc 66	N75E / 45SE				
MWc 67	N45E / 26SE	?? / 057			

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
MWc 68	N35E / 25SE				
MWc 69	N2E / 31SE				
MWc 70	N31E / 40SE				
MWc 71	N33E / 30SE				
MWc 72	N21E / 58SE				
MWc 73	N43E / 45SE				
MWc 74	N71E / 34SE				
MWc 75	N21E / 35SE				
MWc 76	N53E / 50SE	05 / 41 10 / 228			
MWc 77	N9W / 20NE				
MWc 78	N10W / 35NE	?? / 027			
MWc 79	N50E / 25SE				
MWc 80	N35E / 45SE				
MWc 81	N03W / 30NE				
MWc 82	N53E / 15SE				
MWc 83	N78E / 15SE				
MWc 84	N53E / 51NW				
MWc 85	N10E / ??SE				
MWc 86	N71E / 20SE				
MWc 87	N39E / 36SE				
MWc 88	N2E / 31SE				
MWc 89	N76E / 24NW				
MWc 90	N61E / 42SE	?? / 116			
MWc 91	N52E / 21SE				
MWc 92	N82E / 40SE				
MWc 93	N60E / 37SE				
MWc 94	N40E / 48SE				
MWc 95	N46E / 25SE				
MWc 96	N38E / 20SE				
MWc 97	N89E / 10SE	?? / 221			
MWc 98	N68E / 10SE				
MWc 99	N27E / 50SE				
MWc 100	N30E / 45SE				
MWc 101	N18W / 70SW				
MWc 102	N6W / 57SW				
MWc 103	N12E / 41SE	?? / 51			
MWc 104	N25E / 16SE				
MWc 105	N16E / 50SE				
MWc 106	N19E / 35SE				
MWc 107	N42E / 55SE				
MWc 108	N37E / 51SE				
MWc 109	N52E / 40SE				
MWc 110	N73E / 31SE				
MWc 111	N74E / 21SE	31 / 360			
MWc 112	N38E / 59SE				
MWc 113	N12E / 34SE				
MWc 114	N54E / 65SE				
MWc 115	N81E / 31SE				
MWc 116	N87W / 36SW	29 / 246			
MWc 117	N03E / 15SE				

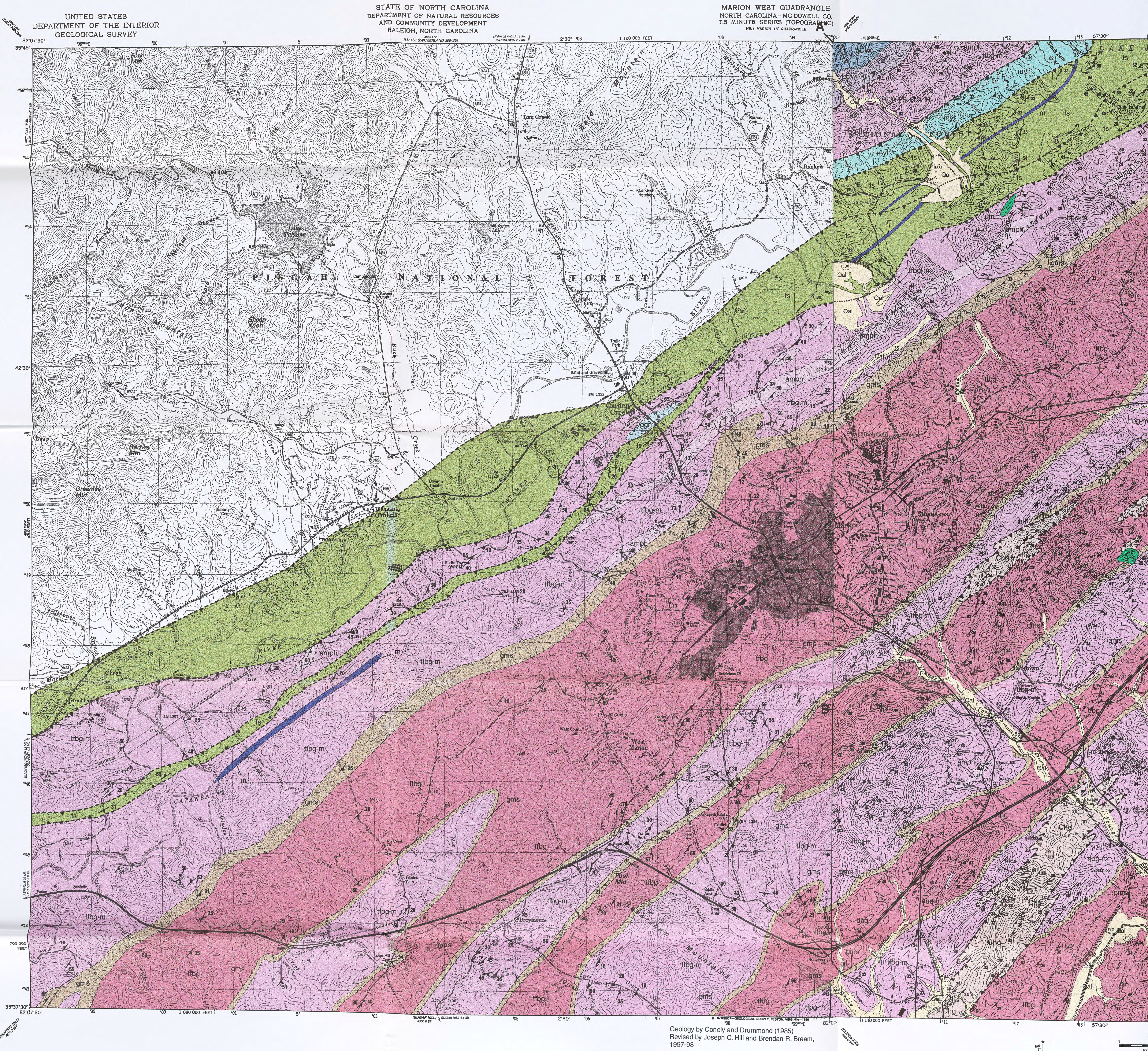
Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
MWc 118	N34E / 13NW				
MWc 119	N87W / 29SW				
MWc 120	N81E / 51SE				
MWc 121	N82W / 21SW				
MWc 122	N13E / 73NW				
MWc 123	N29E / 8SW				
MWc 124	N11W / 17NE				
MWc 125	N23E / 12SE				
MWc 126	N53W / 60NE				
MWc 127	N34E / 34SE				
MWc 128	N27E / 36SE				
MWc 129	N22E / 60SE				
MWc 130	N38E / 55SE				
MWc 131	N27E / 30SE				
MWc 132	N69E / 50SE				
MWc 133	N48E / 40SE				
MWc 134	N45E / 43NE				
MWc 135	N26E / 16SE				
MWc 136	N17E / 18SE				
MWc 137	N48E / 24SE	21 / 061			
MWc 138	N42E / 50SE				
MWc 139	N68E / 22SE	14 / 196			
MWc 140	N26E / 50SE	07 / 193			
MWc 141	N34E / 65SE				
MWc 142	N62W / 24NE	?? / 074			
MWc 143	N50E / 46SE				
MWc 144	N17E / 45SE	?? / 063			
MWc 145	N51E / 12SE	04 / 224			
MWc 146	N70E / 35SE	10 / 072			
MWc 147	N88E / 30SE	?? / 126			
MWc 148	N03 / 30SE				
MWc 149	N07E / 22SE				
MWc 150	N28E / 61SE				
MWc 151	N23E / 50SE				
MWc 152	N30E / 55SE				
MWc 153	N41E / 31SE				
MWc 154	N29E / 36SE				
MWc 155	N73E / 40SE				
MWc 156	N28E / 20SE				
MWc 157	N81W / 40SW				
MWc 158	N25E / 65SE				
MWc 159	N55E / V				
MWc 160	N32E / 30SE				
MWc 161	N51E / 10SE				
MWc 162	N84E / 22SE	15 / 045			
MWc 163	N61E / 15SE	22 / 051			
MWc 164	N71E / 15SE				
MWc 165	N65E / 29SE				
MWc 166	N21E / 18SE				
MWc 167	N33E / 31SE				
MWc 168	N55E / 41SE				

Station Number	Foliation: Strike/Dip	Lineation: Plunge/Trend	Folds: Plunge/Trend	Axial Plane	Joints: Strike/Dip
MWc 169	N51E / 40SE				
MWc 170	N32E / 21SE				

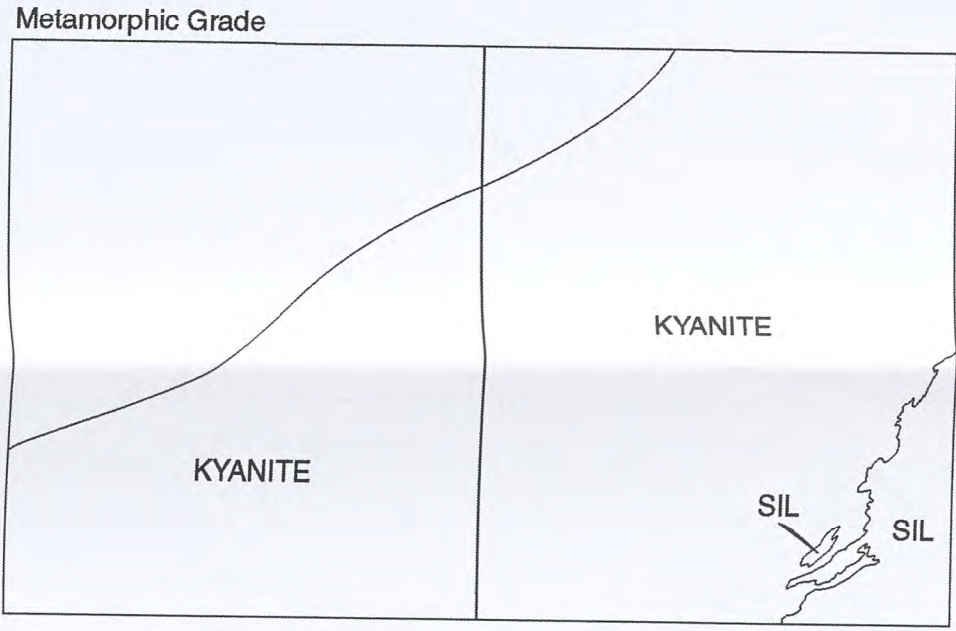
Vita

Joseph Christopher Hill was born to Earl W. and Lorene R. Hill in Oak Ridge, Tennessee on April 11, 1969. He is the youngest of eight children. Joe grew up on his family's farm near the Clinch River just outside Clinton, Tennessee. He graduated from Anderson County High School in June, 1987. Joe enrolled as an engineering student at the University of Tennessee the following Fall. During an on again off again pursuit of an engineering degree, Joe joined the University of Tennessee Men's Lacrosse Team in the Fall of 1989. He was team captain and a starting midfielder/crease attackman from 1990 to 1994 and a member of two Southeastern Lacrosse Conference championship teams in 1993 and 1994. In 1995, Joe decided to also pursue a degree in Geology and found his calling. He graduated with a B.S. in geology in 1996 and entered graduate school that Fall. Joe was married September 5, 1998 to Kristin Leigh Taylor, a beautiful brunette from Conyers, Georgia who's love of animals and the outdoors eclipsed his own. Joe is now in pursuit of a Ph.D. degree in Structural Geology at the University of Missouri-Columbia and a good fishing boat. Joe hates to refer to himself in the third person.

Plate I- Geologic Map of the Study Area



Explanation



Qal Quaternary alluvial deposits

Unconsolidated stream deposits. Generally consist of a lower portion of well rounded quartz pebbles in sandy to clayey matrix overlain by an upper layer of laminated sand and clay mixture. May be interlayered instead of graded.

Chg Henderson Gneiss

Granitic to granodioritic, medium- to fine-grained, light-gray to gray augen gneiss. Augen are K-feldspar up to 3 cm across. Matrix is composed primarily of inequigranular plagioclase (An₂₅-An₃₅), quartz, K-feldspar, biotite, muscovite, and epidote.

Poor Mountain Formation

pmq Poor Mountain Quartzite

Medium- to fine-grained, massive to thinly bedded, light- to medium-gray feldspathic quartzite. May contain calcisilicate nodules up to 3 cm across. Composed of equigranular quartz, plagioclase, muscovite, biotite with subsidiary K-feldspar, epidote, and garnets.

pma Poor Mountain Amphibolite

Laminated, black to dark-gray, thin- to medium-bedded hornblende gneiss. Weathered samples have a distinct yellow-ochre color. Dominant minerals are hornblende and plagioclase (An₂₅-An₃₅).

Tallulah Falls Formation

tfbg Tallulah Falls biotite gneiss/metagraywacke

Medium- to dark gray, medium- to fine-grained, with compositional layering that varies from 10 to 120 cm thick. Composed of equigranular plagioclase, quartz, biotite, muscovite, and epidote. Biotite gneiss may include layers of biotite schist that range from several cm to a m or more in thickness.

gms **ss** Tallulah Falls garnet mica schist or sillimanite schist

Light- to dark-gray, porphyroblastic, muscovite-biotite-garnet-kyanite (or sillimanite) schist. Garnet porphyroblasts up to 4 mm in diameter. Variable amounts of microcline, plagioclase, and quartz may be present.

tfbg-m Tallulah Falls migmatitic biotite gneiss and metagraywacke

Generally similar to the upper biotite gneiss/metagraywacke unit. May be more inequigranular in texture. Difficult to distinguish in the field. The presence of abundance of amphibolite (described below) is the major lithologic difference from upper unit.

amph Amphibolite within the Tallulah Falls Formation

Greenish-black to black, medium- to coarse-grained amphibole gneiss. Locally garnetiferous. Composed of amphibole and plagioclase. It is, as a general rule, coarser grained than Poor Mountain Amphibolite.

bgg Biotite granitic gneiss within the Tallulah Falls Formation

Light- to medium-gray, medium- to coarse-grained, equigranular quartz-feldspar gneiss. Composed primarily of quartz, plagioclase, biotite, and muscovite. Usually shows a slight to strong foliation.

Miscellaneous Rock Units

gg Granitic gneiss

Weakly foliated, light-gray, equigranular quartz monzonite gneiss. Composed of K-feldspar, plagioclase, quartz, biotite, and muscovite.

um ultramafic rocks

Small bodies and pods of medium- to fine-grained, dark green-gray to black talc schists.

Brevard Fault Zone

myl mylonite

Massive to bedded, gray to dark-gray banded mylonites.

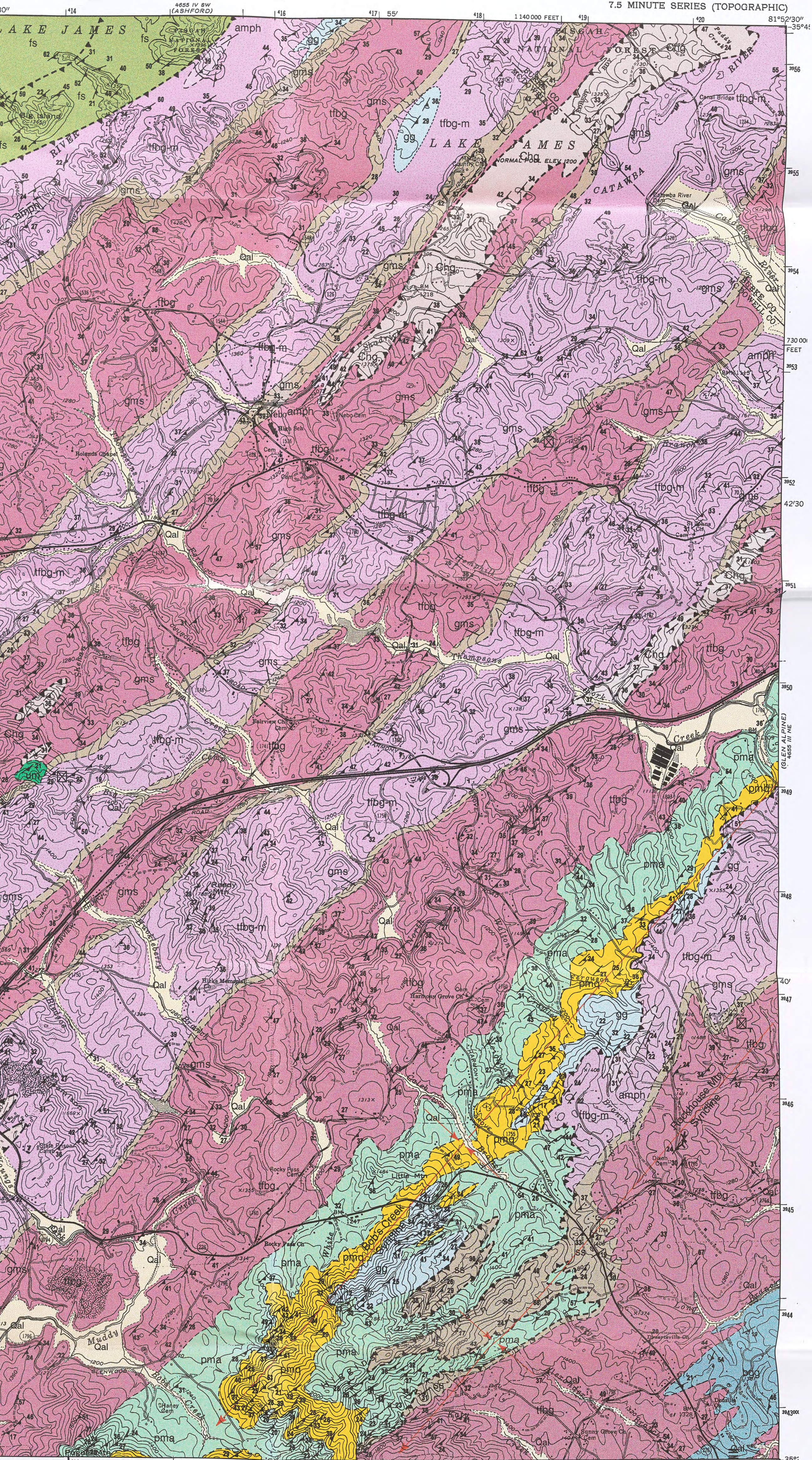
fs schistose mylonite and phyllonite

Greenish-gray, muscovite button schists and interlayered mylonites. Composed primarily of equigranular muscovite in a matrix of quartz, feldspar, chlorite, and biotite. Muscovite "fish" may be up to 2 cm across.

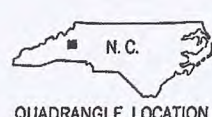
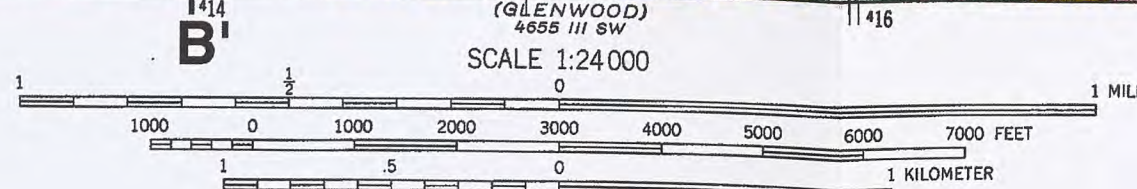
m marble

Fine- to medium grained, light- to medium-gray, siliceous marble.

MARION EAST QUADRANGLE
NORTH CAROLINA
7.5 MINUTE SERIES (TOPOGRAPHIC)



Geology by Joseph C. Hill, 1997-98



MARION EAST, NC
35081-F8-TF-024
1993

Blue Ridge

pCwmg mica gneiss (Ashe ?)

Mica gneiss, to augen gneiss, light-gray, well foliated, medium- to fine-grained, well-rodged and lineated, inequigranular. Composed of quartz, plagioclase, muscovite, microcline, opaques, various amounts of sericite altered from muscovite and feldspar, and chlorite altered from biotite. Weathers to light-tan saprolite and pinkish clay soil (Conley and Drummond, 1985).

Wilson Creek Gneiss

pCwq quartz monzonite

Light silvery-gray, equigranular, medium- to fine-grained. Composed of quartz, muscovite, and plagioclase with minor chlorite and epidote.

Strike and dip of dominant foliation

Trend and plunge of mineral lineation

Trend and plunge of mesoscopic antiform

Trend and plunge of mesoscopic synform

Thrust fault: solid where exact, dashed where approximate, dotted where inferred

Lithologic contact: solid where exact, dashed where approximate, dotted where inferred

crushed stone and sand

building stone and crushed stone

Tourmaline occurrence

Plate II- Station Map

UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

STATE OF NORTH CAROLINA
DEPARTMENT OF NATURAL RESOURCES
AND COMMUNITY DEVELOPMENT
RALEIGH, NORTH CAROLINA

MARION WEST QUADRANGLE
NORTH CAROLINA—MC DOWELL CO.
7.5 MINUTE SERIES (TOPOGRAPHIC)
NE 4 MARION 15' QUADRANGLE



Mapped, edited, and published by the Geological Survey
Control by USGS, NOS/NOAA, and State of North Carolina agencies
Topography by photogrammetric methods from aerial photographs
taken 1978. Field checked 1978. Map edited 1985
Projection and 10,000-foot grid ticks: North Carolina coordinate
system (Lambert conformal conic)
1000-meter Universal Transverse Mercator grid, zone 17
1927 North American Datum
To place on the predicted North American Datum 1983
move the projection lines 9 meters south and
14 meters west as shown by dashed corner ticks
Red tint indicates area in which only landmark buildings are shown
There may be private inholdings within the boundaries of
the National or State reservations shown on this map

UTM GRID AND 1985 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

SCALE 1:24 000
1 000 000 FEET
1 KILOMETER
CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U.S. GEOLOGICAL SURVEY, RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST



QUADRANGLE LOCATION

ROAD CLASSIFICATION
Primary highway, hard surface
Secondary highway, hard surface
Unimproved road
Interstate Route
U.S. Route
State Route

MARION WEST, N.C.
NE 4 MARION 15' QUADRANGLE
35082-F1-TF-024

1985

DMA 4555 II NE—SERIES Y842

LE
CO.
HIC



N. C.
DOLZ

UTM GRID AND 1995 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET

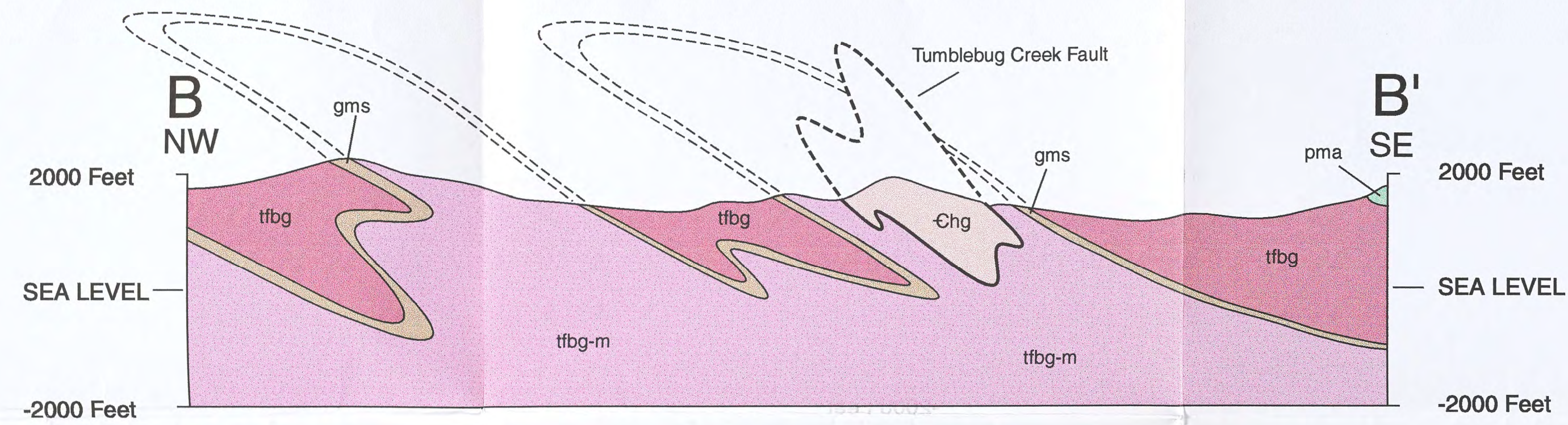
SCALE 1:24,000
CONTOUR INTERVAL 40 FEET
DOTTED LINES REPRESENT 20 FOOT CONTOURS
NATIONAL GEODETIC VERTICAL DATUM OF 1929



MARION EAST, NC
35081-F8-TF-024

1993

Plate III- Cross Sections



Explanation

Chg Henderson Gneiss

Poor Mountain Formation

pmq Poor Mountain quartzite

pma Poor Mountain amphibolite

Tallulah Falls Formation

tfbg Tallulah Falls biotite gneiss/metagraywacke

gms ss Tallulah Falls garnet mica schist or sillimanite schist

tfbg-m Tallulah Falls migmatitic biotite gneiss and metagraywacke

bgg Biotite granitic gneiss within the Tallulah Falls Formation

amph Amphibolite within the Tallulah Falls Formation

Brevard Fault Zone

myl mylonite

fs schistose mylonite and phyllonite

m marble

Scale:

0 1000 2000 3000 4000

No Vertical Exaggeration

