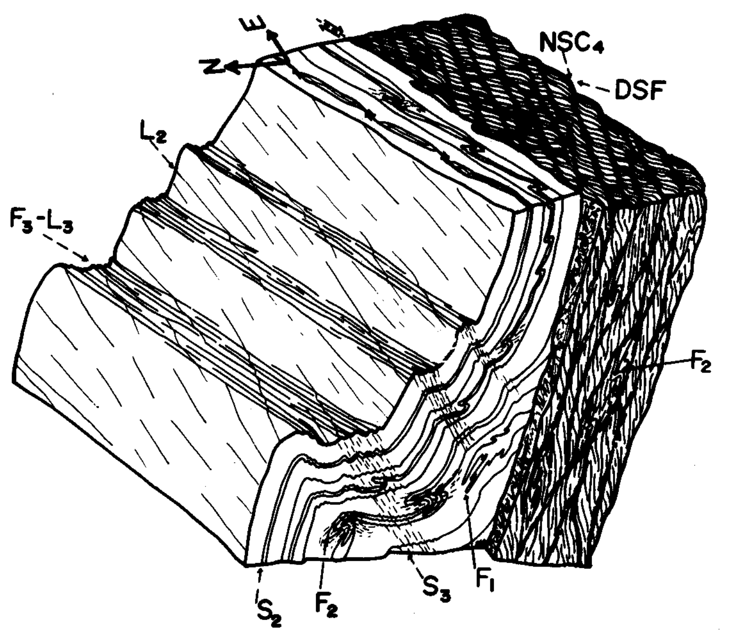
Anatomy of the Alleghanian orogeny as seen from the Piedmont of South Carolina and Georgia

edited by
Donald T. Secor, Jr.



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November 14-15, 1987

CAROLINA GEOLOGICAL SOCIETY
FIELD TRIP GUIDEBOOK

November 14-15, 1987

ANATOMY OF THE ALLEGHANIAN OROGENY AS SEEN FROM THE PIEDMONT OF SOUTH CAROLINA AND GEORGIA

(with a field trip guide on the bedrock geology of the Clark Hill Lake area)

Edited by

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Front cover: sketch showing the fabric elements of early and late Paleozoic age as observed in the Clark Hill Lake area, by Harmon D. Maher

Copies of this guidebook can be obtained from
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Columbia, South Carolina 29210

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FOREWORD

October, 1978 was the last time that the Carolina Geological Society met to examine the geology of Piedmont rocks along the Fall Line in South Carolina. Then it had just been realized that the deformed granites and amphibolite facies metamorphic rocks in the Kiokee belt were the products of an episode of late Paleozoic ductile deformation and regional metamorphism. This deformed belt was the central theme of the 1978 field trip, although at that time, its regional significance was uncertain. Shortly after the 1978 meeting we began referring to this belt as "Hercynian" because we felt that the region had more in common with the Hercynian in Europe and/or northwestern Africa than it did with the Alleghanian of the Appalachian foreland. More recently, it has become apparent that rocks in the southeastern Piedmont comprise one or more exotic terranes that were proximal to Laurentia by the early or middle Paleozoic. COCORP seismic reflection studies have shown that the suture with rocks of clear African affinity is located beneath the Coastal Plain in southern Georgia, and that the crystalline rocks north of the suture are most likely allochthonous and part of a northwest vergent crystalline thrust sheet that arrived in its present position during the late Paleozoic Alleghanian orogeny. Thus, it now appears that the late Paleozoic deformed belt in the Piedmont and the Alleghanian foreland fold and thrust belt are both manifestations of the same regional decollement. We now refer to the late Paleozoic deformation in the Piedmont as "Alleghanian" because the deformation is thought to be kinematically and chronologically linked to the Alleghanian foreland deformation.

The central theme of this year's field trip is the Alleghanian deformations along the Georgia-South Carolina border in the Carolina slate, Kiokee and Belair belts. We believe that the chronology and kinematics of these Alleghanian deformational events furnish important clues regarding plate interactions that occurred during the late Paleozoic collision between Gondwana and Laurentia. The detailed mapping in the Clark Hill Reservoir area described in this field guide has important implications both for the regional geology and for the mechanics of plate interactions in collisional orogens.

Dedicated to Duncan Heron
in appreciation for his service
to the Carolina Geological Society

CAROLINA GEOLOGICAL SOCIETY
Guidebook for 1987 Annual Meeting
Pages 1-11

REGIONAL OVERVIEW

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INTRODUCTION

Geological and geochronological studies have indicated that important belts of late Paleozoic penetrative deformation and regional metamorphism are present in the Appalachian Piedmont Province (Snoke and others, 1980; Pavlides and others, 1982; Glover and others, 1983; Farrar, 1985; Russell and others, 1985; Dallmeyer and others, 1986; Horton and others, 1987). This late Paleozoic deformation in the Piedmont is contemporaneous with the Alleghanian orogeny recorded in the western Appalachian foreland (Secor and others, 1986b; Elliott and Aronson, 1987), and seismic reflection data has been interpreted to indicate that the Piedmont is structurally linked via a regional decollement to both the Alleghanian foreland to the northwest (Cook and others, 1983) and to the late Paleozoic suture with Gondwana to the southeast (Nelson and others, 1985). Since 1984, we have been engaged in detailed geologic mapping and structural studies in rocks that were intensely deformed during the Alleghanian orogeny in the Clark Hill Reservoir area of South Carolina and Georgia. Our results have important implications regarding the kinematics of both the Alleghanian orogeny and the late Paleozoic collision with Gondwana. The purpose of this field trip and guide is to present our data and interpretations from the Clark Hill Reservoir area.

The effects of the Alleghanian orogeny in the Piedmont are overprinted on rocks that were penetratively deformed and regionally metamorphosed in the early and/or middle Paleozoic. This chapter presents necessary background information on the regional geology. The deformational episodes of the Alleghanian orogeny are detailed in subsequent chapters.

LITHOTECTONIC BELTS

Early workers (Crickmay, 1952; King, 1955; Hatcher, 1972) subdivided the Piedmont into several northeast trend-

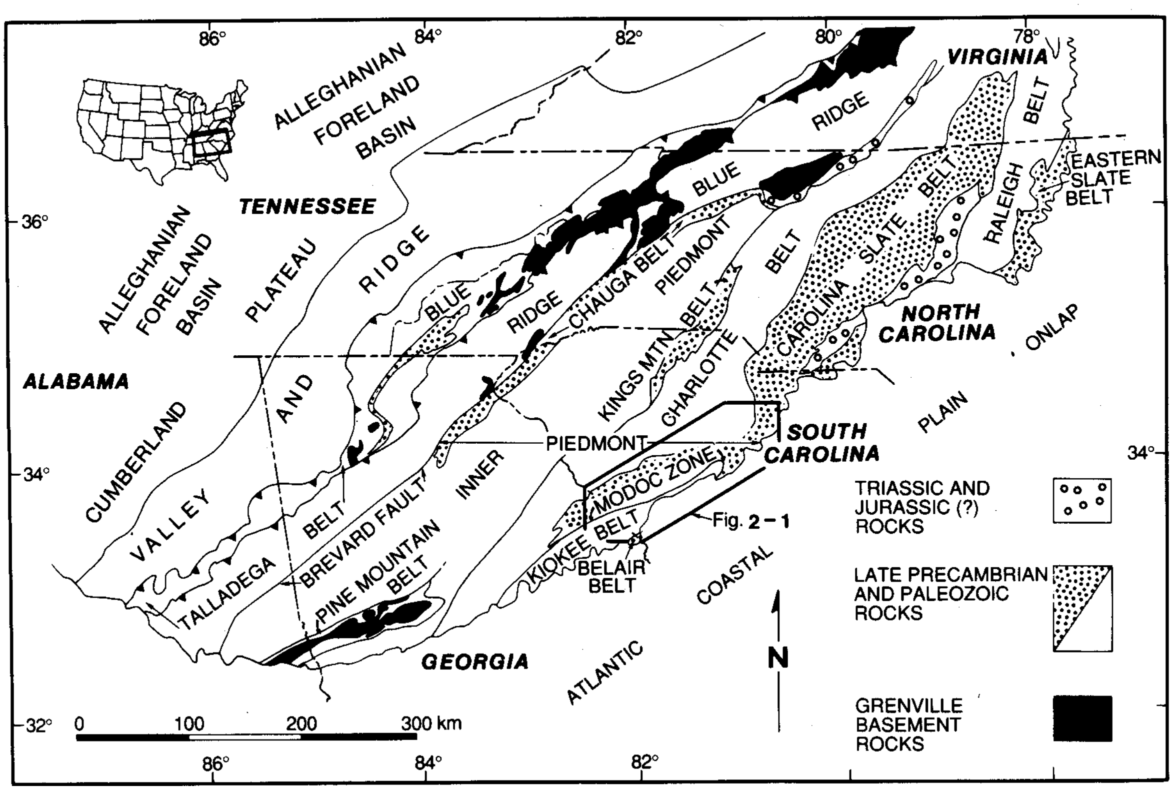


Figure 1-1. Index map of a part of the Southern Appalachian orogen showing some geographic and geologic features referred to in the text. Massifs of crystalline basement rock are shown in black (modified from Secor and others, 1986b; and from Williams, 1978).

ing lithotectonic belts (Fig. 1-1). In South Carolina, belts characterized by low to medium grade regional metamorphism (Belair, Carolina slate, Kings Mountain, Chauga) alternate with medium to high grade belts (Kiokee, Charlotte, Inner Piedmont). The

lithotectonic belts of the Piedmont are interpreted to have formed as a result of folding and faulting of paleoisothermal surfaces (Secor and others, 1986b) and the belts are therefore thought to have little or no fundamental regional stratigraphic significance. The general area of the field trip (Fig. 1-2) encompasses parts of the Charlotte, Carolina slate, Kiokee, and Belair belts as well as the Atlantic Coastal Plain Province. The Clarks Hill and Leah quadrangles (Plate 1) are located along the boundary between the Carolina slate and Kiokee belts.

STRATIGRAPHY

Gneisses and Schists in the Charlotte Belt

(PЄgn1 on Figure 1-2)

In central and western South Carolina the Charlotte belt contains sequences of paragneiss, mica schist, feldspathic quartzite, and amphibolite, with small amounts of calc-silicate rock and altered ultramafic rock. In places, some of the above lithologies contain relict textures indicating derivation from sedimentary and/or volcanic protoliths. The relationship of the gneisses and schists in the Charlotte belt to the less metamorphosed rocks in the Carolina slate belt is controversial and uncertain. Higgins and others (1984; 1987) have suggested that the Charlotte belt is predominately made up of rocks that were incorporated in a late Precambrian-Cambrian accretionary complex located adjacent to a subduction- related volcanic arc. In the Blair-Salem Crossroads area near Monticello Reservoir, Hauck (1984) noted similarities between the rocks in the Charlotte belt and those in the slate belt and suggested that the rocks in the two belts were, at least in part, stratigraphic equivalents. Along the southeastern edge of the Charlotte belt, the metavolcanic and metasedimentary rocks are characteristically cut by sheets and irregular intrusive bodies of variably deformed felsic orthogneiss (these are not shown on Figure 1-2). In many places these orthogneisses are porphyritic and/or contain relict

granophyric texture suggesting that they originated as hypabyssal, sub-volcanic plutons. In South Carolina, it has been suggested that the above plutons represent the intrusive equivalents of eruptive felsic volcanic rocks in the adjacent Carolina slate belt (Weisenfluh and Snoke, 1978; Peck, 1981; Simpson, 1981; Secor and others, 1982; Halik, 1983; Kirk, 1985). Petrologic and geochemical comparisons of intrusive hypabyssal rocks in the Charlotte belt with their supposed extrusive equivalents in the Carolina slate belt have indicated that some of the hypabyssal rocks are richer in potassium than any of the volcanic rocks in the slate belt (Biggs, 1982; Secor and others, 1982; Halik, 1983). These differences may indicate more intensive diagenetic alteration of the originally glassy extrusive rocks. Alternatively, as argued by Biggs (1982), the hypabyssal intrusive rocks may not be the equivalents of the felsic volcanic rocks in the slate belt. A recent U-Pb zircon upper intercept age of 550 ± 4 Ma for the hypabyssal Little Mountain pluton (Dallmeyer and others, 1986) indicates a Lower Cambrian(?) age for the hypabyssal rocks. The sequences of metasedimentary and metavolcanic rocks in the Charlotte belt that are cut by the above Lower Cambrian(?) intrusives must therefore be somewhat older, perhaps late Precambrian.

Migmatitic Gneisses and Schists in the Interior of the Kiokee Belt

(PЄgn2 and PЄ um on Figure 1-2)

The interior of the Kiokee belt is a migmatitic complex made up of biotite amphibole paragneiss (mbag on Plate 1), leucocratic paragneiss (lpg, Plate 1), sillimanite schist (ms, Plate 1), amphibolite locally containing ultramafic schists and serpentinite (ma, Plate 1), and feldspathic metaquartzite (not present on Plate 1). Thin layers and nodules of rock containing calcium rich garnet and plagioclase, diopside, and epidote (calc-silicate assemblage?) are a ubiquitous but minor component of the migmatitic complex. The ba and bag units in the southeastern part of the Modoc zone may be deformed equivalents of ma and mbag in the interior of the Kiokee belt (Sacks and Dennis, this volume, and Plate 1). The rocks in the interior of the Kiokee belt are thought to be bounded by faults on both the southeast and northwest. The southeast boundary is the Augusta fault which juxtaposes the migmatitic rocks against the low-grade metavolcanic rocks of the Belair belt (Maher, 1987; Fig. 1-2). The northwest boundary is interpreted to be a cryptic fault embedded in the Modoc shear zone (Sacks and Dennis, this volume) which juxtaposes deformed equivalents of the migmatic complex against the rocks of the Asbill Pond formation (Fig. 1-2). Farrar (1985) suggested that the rocks in the interior of the Kiokee belt might be middle Proterozoic basement similar to that thought to be present in the interior of the Raleigh belt. However, neither anorthosites nor textural evidence for relict Precambrian granulite facies metamorphism have been found in the Kiokee belt. Structural evidence presented by Sacks and Dennis (this volume) suggests that the migmatic rocks in the interior of the Kiokee belt were located relative to the Carolina slate belt at least tens of kilometers north-northeast of their present position prior to the Alleghanian orogeny. The migmatic rocks may be stratigraphic equivalents of the POAL(C,–)gn1 unit in the Charlotte belt which they resemble lithologically. Alternatively, the migmatic rocks may represent a basement on which the slate-Charlotte belt volcanic arc was constructed, or they may be a separate terrane, exotic with respect to both North America and the volcanic arc rocks.

Persimmon Fork Formation and Related Intrusive Rocks

(Єpf1, Єpf2, and Cgr on Figure 1-2; mv1, mv2 and gr1 on Plate 1)

Rocks here judged to belong to the Persimmon Fork Formation of Secor and Wagener (1968) outcrop extensively in the Carolina slate belt and locally in the adjacent Charlotte belt (Figs. 1-2 and 2-1). The Persimmon Fork is composed predominately of coarse grained intermediate to felsic ash-flow tuff. Along the northwest side of the Carolina slate belt, the Persimmon Fork contains a thick sequence of coarse-grained dacitic lava flows or lava domes (the Lincolnton Metadacite; Crawford, 1968a; Paris, 1976; Fig. 1-2). The Persimmon Fork also contains lesser amounts of vitric tuff, volcaniclastic wacke and mudstone, and layers of quartz sericite schist which are interpreted to be tuffs that have undergone exhalative alteration (Biggs, 1982). A Cambrian(?) age has been obtained for the Lincolnton Metadacite by both the Rb-Sr whole-rock (554 ± 20 Ma) and U-Pb zircon (c. 568 Ma) methods (Carpenter and others, 1982). The thickness of the Persimmon Fork Formation probably exceeds a few kilometers, although precise estimates are precluded by penetrative post- depositional strain and other tectonic complications. Whitney and others (1978) suggested that the volcanic rocks in the Carolina slate belt in this region accumulated in a subduction-related volcanic arc founded on oceanic crust, whereas Rogers (1982) suggested a continental margin setting.

Asbill Pond Formation

(Єa on Figure 1-2)

In the Clark Hill Reservoir area, the Asbill Pond formation is a sequence of quartzite and quartz-sericite schist, sericite phyllite and biotite-amphibole gneiss (qs, sp, and bag on Plate 1), that outcrop in the southeastern part of the Carolina slate belt and in the central and northwestern part of the Modoc shear zone in the Kiokee belt. The above lithologies are present in a semi- continuous band for 70 kilometers to the northeast to the vicinity of Batesburg, SC where a stratigraphic section of Asbill Pond formation exceeding 5 km in thickness is present in the Carolina slate belt. In the Bates-

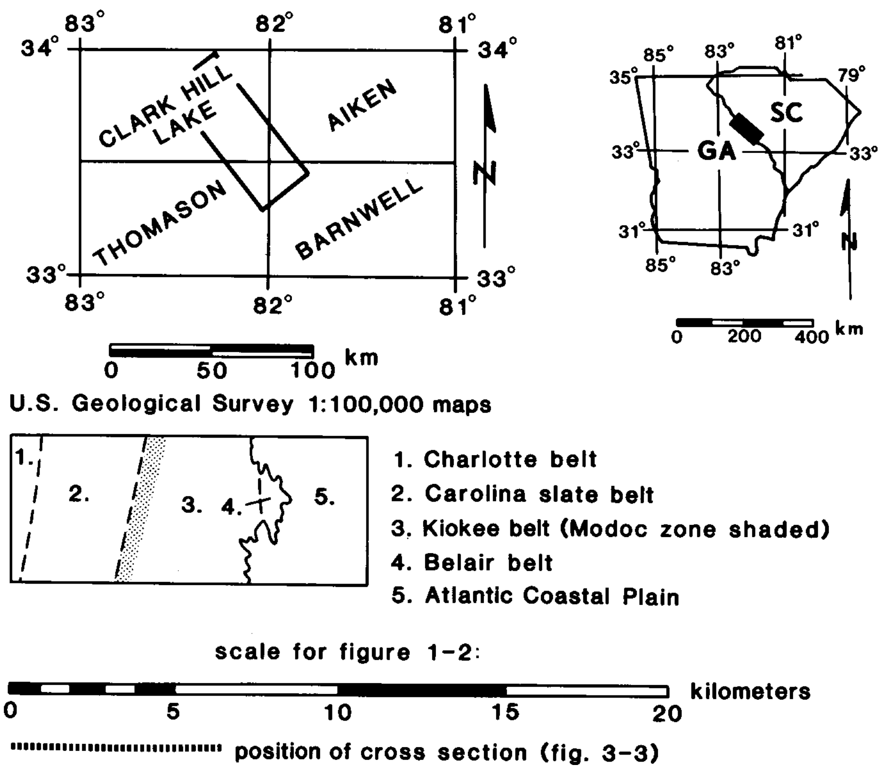
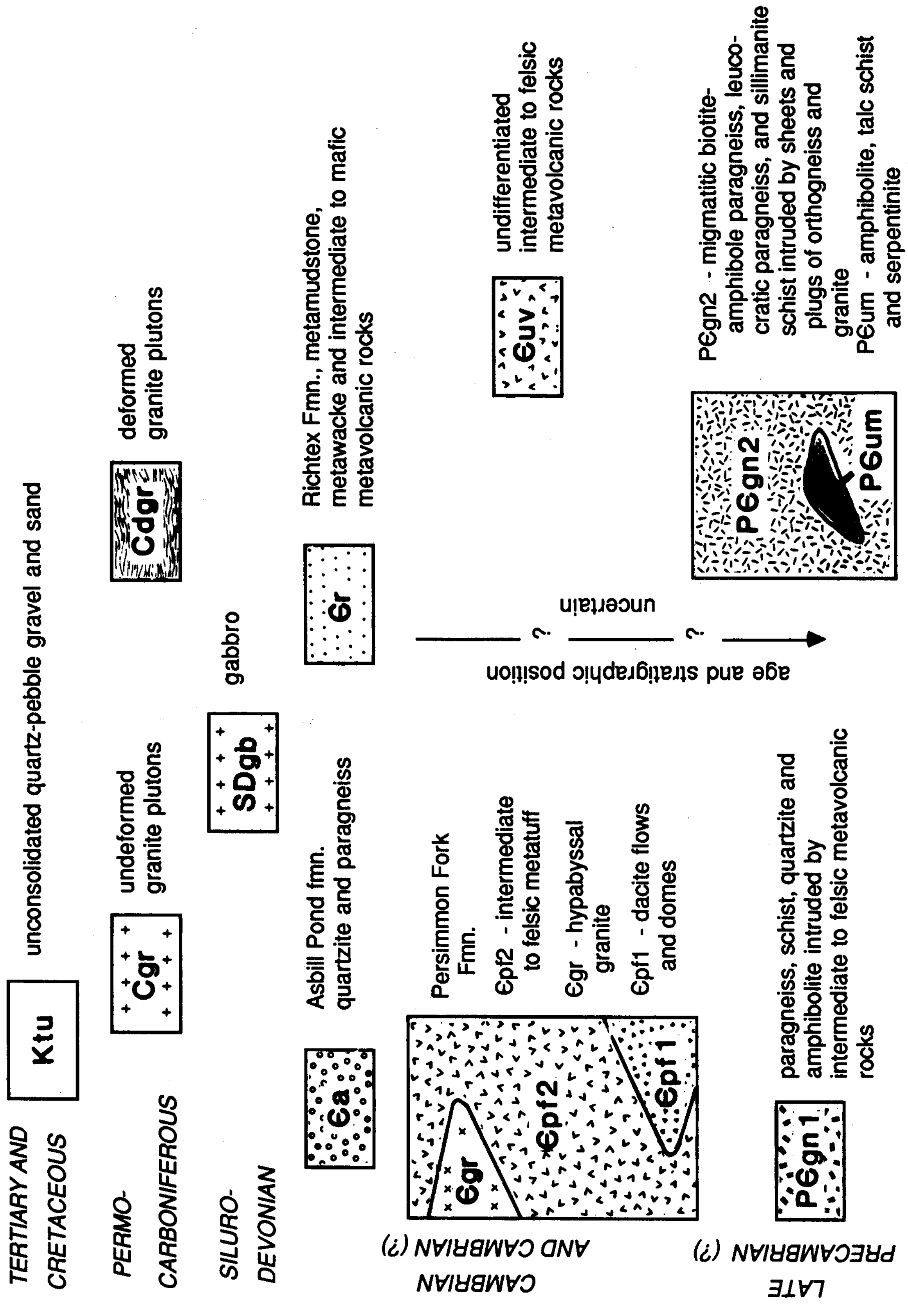
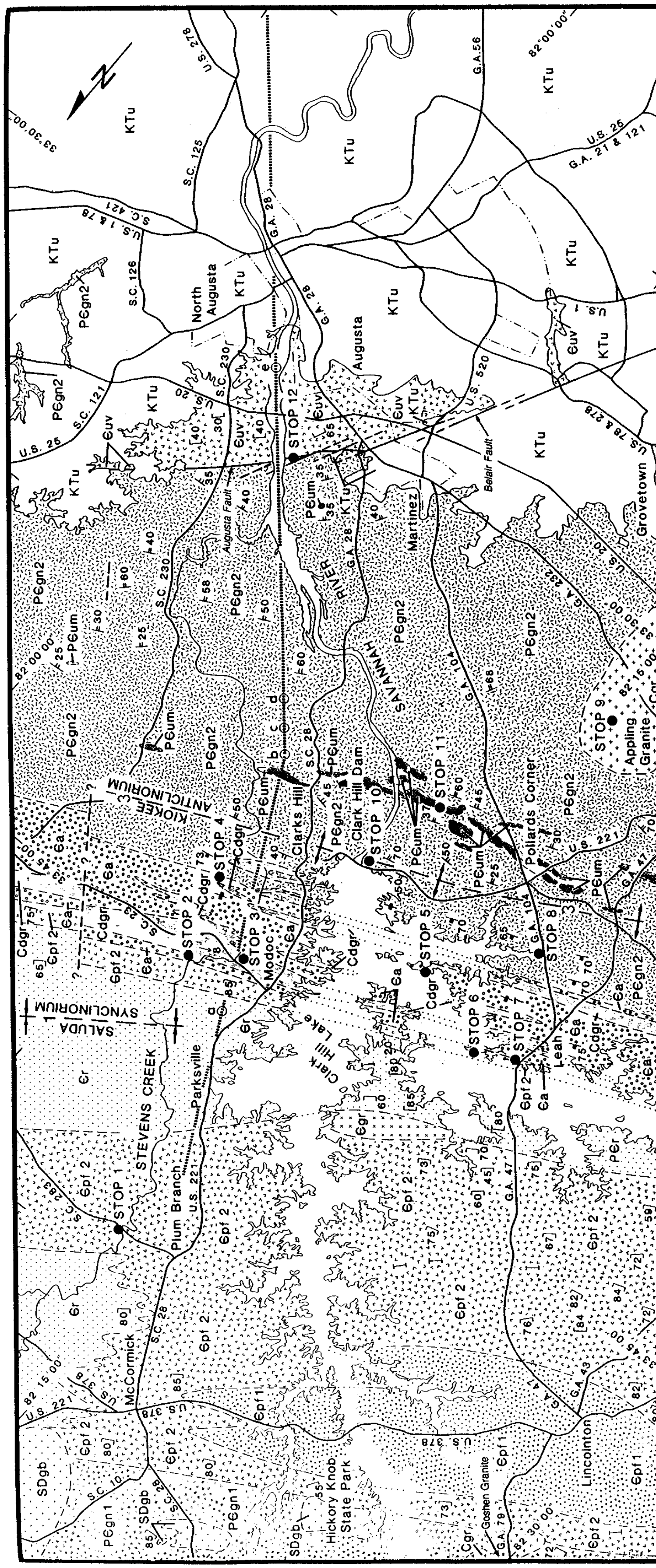


Figure 1-2. Interpretative geologic map (page 5) from the Charlotte belt to the Atlantic Coastal Plain along the Savannah River valley (From field work by Maher, Sacks, and Secor; and modified from Crawford, 1968a, 1968b; Georgia Geological Survey, 1976; O'Connor and Prowell, 1976; Paris, 1976; Biggs, 1982; Delia, 1982; Pirkle, 1982; and Nystrom and others, 1986). NOTE: The scale above is not correct for the geologic map. The original size of the map is 9 7/16 by 22 3/4 inches


TERTIARY AND CRETACEOUS
Ktu
unconsolidated quartz-pebble gravel and sand
PERMO-CARBONIFEROUS
Cgr
undeformed granite plutons
Cdgr
deformed granite plutons
SILURO-DEVONIAN
SDgb
gabbro
CAMBRIAN AND CAMBRIAN (?)
Ɛa
Asbill Pond fmn. quartzite and paragneiss
Ɛr
Richtex Fmn., metamudstone, metawacke and intermediate to mafic metavolcanic rocks
Ɛuv
undifferentiated intermediate to felsic metavolcanic rocks
Ɛgr
Ɛpf2
Ɛpf1
Persimmon Fork Fmn.
Ɛpf2 - intermediate to felsic metatuff
Ɛgr - hypabyssal granite
Ɛpf1 - dacite flows and domes
age and stratigraphic position ? ? uncertain
LATE PRECAMBRIAN (?)
PƐgn1
paragneiss, schist, quartzite and amphibolite intruded by intermediate to felsic metavolcanic rocks
PƐgn2
PƐum
PƐgn2 - migmatitic biotite-amphibole paragneiss, leucocratic paragneiss, and sillimanite schist intruded by sheets and plugs of orthogneiss and granite
PƐum - amphibolite, talc schist and serpentinite


North Augusta
Augusta
Martinez
Grovetown
Belair Fault
Augusta Fault
SAVANNAH RIVER
Clarks Hill
Clark Hill Dam
Clark Hill Lake
Pollards Corner
Appling Granite
KIOKEE ANTICLINORIUM
SALUDA SYNCLINORIUM
STEVENS CREEK
Modoc
Parksville
Plum Branch
McCormick
Hickory Knob State Park
Goshen Granite
Leah
Lincolnton
STOP 1
STOP 2
STOP 3
STOP 4
STOP 5
STOP 6
STOP 7
STOP 8
STOP 9
STOP 10
STOP 11
STOP 12
33°30'00"
82°00'00"
82°15'00"
33°45'00"
82°30'00"

burg area, the Asbill Pond formation is less strongly deformed than it is in the Clark Hill Reservoir area, and it has experienced only low-grade regional metamorphism. In the Batesburg area, the following protolithologies can be recognized in the Asbill Pond Formation:

1) thin bedded (1-10 mm) fine-grained quartz sandstone containing relict sedimentary structures suggestive of deposition in a tidal shelf environment.

2) medium to coarse grained quartzofeldspathic sandstone containing lenticular crossbeds 2-200 cm thick. In some places these crossbeds are draped by thin pelitic partings, suggestive of deposition in an environment where sediment transport was dominated by tidal currents.

3) thin-bedded to massive mudstone and feldspathic wacke.

4) intermediate tuff and tuff breccia, and/or flow breccia.

The above lithologies intergrade with each other and also are interlayered with the underlying Persimmon Fork Formation indicating that the Asbill Pond is conformable above the Persimmon Fork. Along the northwest side of the Clouds Creek granite near Batesburg, the upper part of the Asbill Pond formation contains a mudstone sequence which has yielded an assemblage of Middle Cambrian, Acado-Baltic trilobites (Samson, 1984). This assemblage indicates that the South Carolina slate belt was faunally isolated from North America (Laurentia) during the Middle Cambrian and has been interpreted to indicate that the slate belt comprises an exotic terrane (the Carolina terrane) that was accreted to North America subsequent to the Middle Cambrian (Secor and others, 1983).

Richtex Formation

(Єr on Figure 1-2; mm on Plate 1)

The Richtex Formation is a sequence of thin bedded to massive mudstone and wacke interlayered with intermediate to mafic tuffs and flows, and intruded by sheets and plugs of hypabyssal (?) mafic igneous rocks. The thickness of the Richtex Formation probably exceeds a few kilometers; more precise estimates are not possible because of penetrative strain and extensive folding. The Richtex Formation is a widespread stratigraphic unit in the slate belt of central and western South Carolina (Fig. 2-1). Structural relationships in central South Carolina (Simpson, 1981; Peck, 1982; Halik, 1983; Kirk, 1985; Secor and others, 1986a) indicate that the Richtex overlies the Persimmon Fork; however, it is uncertain if the contact is stratigraphic or tectonic. The following working hypotheses are considered in a subsequent analysis of the relationship between the Richtex Formation and the other stratigraphic units in the Carolina slate belt:

1) the Richtex and Asbill Pond Formations represent different depositional environments; however, they are both approximately the same age and both conformably overlie the Persimmon Fork Formation;

2) the Richtex Formation is younger than both the Asbill Pond and the Persimmon Fork Formations and is separated from them by an angular unconformity;

3) there is a fault separating the Richtex Formation from the Asbill Pond and Persimmon Fork Formations.

The following observations are useful in discriminating between the above hypotheses:

1) On Bussey Point in Clark Hill Reservoir, outcrop bands of Richtex Formation and Asbill Pond formation occur within 500 meters of each other on opposite sides of an outcrop band of Persimmon Fork Formation (Plate 1). Their proximity here would seem to rule out an interpretation [such as 1) above] wherein they are the same age and conformable above the Persimmon Fork but accumulated in different depositional environments.

2) Mafic hypabyssal rocks are scarce or absent in many areas of the Persimmon Fork Formation whereas they are common in the Richtex Formation. The Persimmon Fork Formation should contain more mafic intrusive rocks if the Richtex Formation had been deposited (either conformably or unconformably) on top of it.

3) On a regional scale, the surface separating the Richtex and Persimmon Fork Formations is discordant to lithologic subunits within both Formations.

4) The Richtex Formation contains the same penetrative deformational fabrics (D_1, discussed subsequently) in approximately the same orientations as in the adjacent Persimmon Fork and Asbill Pond Formations.

5) At least locally in central South Carolina (near Stop 14 in Secor and Wagener, 1968), the contact between the Richtex and Persimmon Fork Formations has been observed in outcrop to be a ductile, pre- to early syntectonic fault (relative to D_1 deformational fabrics).

An interpretation in which the Richtex is in depositional contact with the Persimmon Fork (either conformably or unconformably) is difficult to reconcile with the evidence listed above, whereas an interpretation in which the Richtex is in fault contact with the Persimmon Fork and Asbill Pond seems to be compatible with the evidence. We therefore tentatively interpret the Richtex to be part of a regional allochthon that was emplaced prior to or during the D_1 deformation. Hopefully, during the next few years, the above hypothesis will be tested by additional field and geochronological studies.

The age of the Richtex Formation is uncertain. If it is in depositional contact above the Persimmon Fork, it must be younger than c. 550 Ma (Cambrian? or younger). However, if the Richtex is allochthonous, it could be older than the Persimmon Fork. A late Precambrian age would be compatible with the observed very unfossiliferous character of the Richtex.

D_1 (DELMAR) DEFORMATION

In South Carolina, the slate belt has been affected by an early to middle Paleozoic deformational event (the Delmar deformation of Secor and others, 1986a) characterized by penetrative strain, tight to isoclinal folding and greenschist facies (Carolina slate belt) to amphibolite facies (Charlotte belt) regional metamorphism. Major D_1 folds (such as the Saluda synclinorium, Plate 1 and Figure 1-2) are primarily responsible for the distribution of stratigraphic units in the Carolina slate belt. D_1 must have occurred more recently than Middle Cambrian because the fossiliferous Middle Cambrian rocks in the Asbill Pond formation contain D_1 fabric elements. D_1 is constrained to be older than c. 340 Ma by $^{40}Ar/^{39}Ar$ whole-rock phyllite ages in central South Carolina (Dallmeyer and others, 1986). Field studies along the slate belt-Charlotte belt border (Secor and others, 1982; Halik, 1983; Kirk, 1985) suggest that the same D_1 fabric elements are present in the Charlotte belt. In the Charlotte belt of central South Carolina, the c. 415 Ma Newberry granite (Fullagar, 1981) contains xenoliths which contain rotated D_1 fabric elements. If the D_1 events in the slate and Charlotte belts are the same, D_1 in the slate belt must have occurred prior to c. 415 Ma.

SILURO-DEVONIAN(?) INTRUSIVE ROCKS

(SDgb on Figure 1-2)

The Charlotte belt of North and South Carolina contains a suite of post-D_1 intrusive rocks (granite, syenite, gabbro) which range in age from c. 385-415 Ma (Fullagar, 1971; Butler and Fullagar, 1978; McSween and others, 1984). The bodies of intrusive gabbro in the Charlotte belt at the northwest end of Figure 1-2 are tentatively interpreted to belong to this Siluro-Devonian suite. The regional tectonic significance of the Siluro-Devonian intrusive rocks is uncertain.

MIDDLE PALEOZOIC DEFORMATION

In North Carolina the Siluro-Devonian intrusive rocks in the Charlotte belt are interpreted to have experienced a relatively mild mid-Paleozoic deformation (Butler and Fullagar, 1978). It is uncertain if the above deformational effects extend eastward into the Carolina slate belt (Glover and others, 1983) or southwestward as far as the Georgia- South Carolina border. In central South Carolina, $^{40}Ar/^{39}Ar$ whole-rock phyllite age spectra from the northwestern Carolina slate belt and $^{40}Ar/^{39}Ar$ hornblende age spectra from the southeastern Charlotte belt indicate rapid cooling from a mid Paleozoic (c. 340-360 Ma) thermal event. It is uncertain if this event was accompanied by deformation or if it affected the Carolina slate and Charlotte belts in the Clark Hill Reservoir area.

LATE PALEOZOIC GRANITIC INTRUSIVE ROCKS

(gr2 and dgr on Plate 1; Cgr and Cdgr on Figure 1-2)

An intrusive magmatic arc, containing dozens of individual granitic plutons of Carboniferous and Permian age, extends through the Piedmont from Maryland to Georgia (Sinha and Zietz, 1982). In most places, the above plutons have not been penetratively deformed, and their contact metamorphic aureoles overprint fabric elements in the surrounding rocks. Conversely, in some places along the Fall Line (Kish and Fullagar, 1978; Secor and Snoke, 1978; Snoke and others, 1980; Pavlides and others, 1982; Farrar, 1985; Russell and others, 1985; Dallmeyer and others, 1986) and locally within the Kings Mountain belt (Horton and others, 1987) the late Paleozoic plutons contain a moderate to strong, locally mylonitic deformation fabric. These deformed late Paleozoic granites are an important manifestation of Alleghanian deformation in the Piedmont. In the Clark Hill Reservoir area, undeformed granitic rocks at the northwest and southeast ends of Figure 1-2 (the Goshen and Appling granites, respectively) are interpreted to be of late Paleozoic age. Within the Modoc zone (Plate 1), there are numerous sheets of strongly deformed granitic rock, up to 1 km in thickness and several kilometers long, that are interpreted to be of late Paleozoic age. This belt of deformed granites in the Modoc zone extends continuously into central South Carolina where the inferred late Paleozoic ages have been confirmed by Rb-Sr whole-rock dating (Snoke and others, 1980) and by U-Pb zircon dating (Dallmeyer and others, 1986). Geochronological studies in central South Carolina indicate that the late Paleozoic plutonic activity and peak of regional amphibolite facies metamorphism coincided approximately in time with the most intense deformation.

LATE PALEOZOIC (ALLEGHANIAN) TECTONOTHERMAL ACTIVITY

Introduction

In central South Carolina field and geochronological studies indicate that the effects of the Alleghanian orogeny can be divided into the following deformation phases: D_2 (Lake Murray deformation, 295-315 Ma), D_3 (Clark Hill deformation, 285-295 Ma), and D_4 (Irmo deformation, 268-290 Ma), (Dallmeyer and others, 1986; Secor and others, 1986a). Our studies indicate that these same deformation phases are present in the Clark Hill Reservoir area, and that fabric elements attributable to these phases are present at many intermediate locations in the northwestern Kiokee belt between Clarks Hill and Columbia. Maher (1987) has obtained a few conventional potassium-argon ages from the Savannah River area which are compatible with the more detailed geochronological studies (Dallmeyer and others, 1986) completed in central South Carolina. Therefore, we are confident that the above correlation of deformation phases is correct.

The effects of the Alleghanian orogeny are exceptionally well exposed in the Clark Hill reservoir area, and field studies here have greatly improved our understanding of the Alleghanian deformation events and their regional significance. The results of our studies are detailed in subsequent chapters (this volume) by Sacks and Dennis (D_2), Maher (D_3), and Dennis and others (D_4). These chapters supplement the following brief summary of Alleghanian deformation in the Savannah River area.

The Modoc Zone

In the Clark Hill Reservoir area, the Modoc zone is an approximately 5 km thick D_2 ductile shear zone that separates the upper amphibolite facies migmatites in the interior of the Kiokee belt from the greenschist facies Carolina slate belt. The quartzite, phyllite, and paragneiss units within the Modoc zone are, for the most part, interpreted to be correlative with the Asbill Pond formation in the low-grade Carolina slate belt of central South Carolina. The elevated metamorphic grade of the Asbill Pond in the Modoc zone (M_2 regional amphibolite facies) is interpreted to be a consequence of tectonic juxtaposition against the hot rocks in the interior of the Kiokee belt during D_2. The Modoc zone is thought to have originally dipped gently to the northwest and to have had major components of normal slip and dextral strike slip. The net slip of the Modoc zone is at least tens of kilometers. The Modoc zone contains virtually all of the strongly deformed Permo-Carboniferous granite in the Savannah River area and may be the only D_2 structure present in the northwestern Kiokee belt. The age of the tectonic fabrics in the interior of the Kiokee belt is uncertain.

The Augusta Fault

The Augusta fault is located along the southeast side of the Kiokee belt where it juxtaposes low-grade metavolcanic rocks of the Belair belt against migmatic rocks in the Kiokee belt. The fault is spectacularly exposed in the Martin-Marietta quarry near Augusta (Stop 12) where it is associated with 100-200 meters of mylonite and dips c. 45^o southeastward. The Augusta fault approximately coincides with a series of prominent aeromagnetic anomalies (Daniels, 1974) that are interpreted to indicate a regionally important “eastern Piedmont fault system” (Hatcher and others, 1977). The Augusta fault has been variously interpreted as a strike slip fault (Bobyarchick, 1981), as a thrust (Maher, 1978, 1979; Snoke and Secor, 1982), and as a low angle normal fault (Maher, 1978). A recent study of shear-sense criteria in the mylonite (Maher, 1987) indicates a major component of normal displacement. Secor and others (1986a) suggested that the Modoc zone may be folded over the crest of the Kiokee anticlinorium and may correlate with the Augusta fault. This interpretation is incompatible with the observed shear sense and is here abandoned. Although the time of movement of the Augusta fault is not well constrained by geochronological data, field studies suggest that it was active near the peak of M_2 amphibolite facies regional metamorphism (c. 295-315 Ma).

The Kiokee Antiform

The D_3 Kiokee antiform is defined by folded foliation surfaces of various ages. These include the S_1 foliation in the Carolina slate and Belair belts, the S_2 foliation in the Modoc zone, and the migmatic layering of uncertain age in the interior of the Kiokee belt. The Kiokee belt and adjacent portions of the Carolina slate and Belair belts contain a population of horizontal to gently plunging, northwest vergent mesoscopic folds that are interpreted to be F_3. Secor and others (1986b) interpreted the Kiokee antiform to be a ramp-antiform associated with northwestward motion along a regional decollement. Maher (this volume) finds that the geometry of the antiform more closely approximates the form to be expected for a fault propagation fold. The vertical to steep northwest dips in the Modoc zone and throughout much of the Carolina slate belt in the Clark Hill Lake area are interpreted to be a result of rotation in the steep limb of the fault propagation fold. Geochronological studies in central South Carolina (Dallmeyer and others, 1986) suggest an episode of uplift, erosion and cooling during c. 285-295 Ma, which is interpreted to be a consequence of northwestward vergent thrusting and F_3 folding.

The Irmo Shear Zone

The D_4 Irmo shear zone was first recognized in central South Carolina (Secor and others, 1986a; Dennis and Secor, 1987) where it crosses from the Kiokee belt to the Carolina slate belt (Fig. 2-1). The primary manifestation of the Irmo shear zone are normal slip and reverse slip crenulations which overprint D_2 and D_3 fabric elements and which indicate a predominately horizontal dextral shear- sense. At the east end of Lake Murray, the D_2 Modoc zone is dextrally folded by the northeast plunging Irmo antiform and Lexington synform. This dextral pattern is interpreted to result from the constructive interference of F_3 and F_4 folds. Structural studies in the above area suggest that the displacement on the D_4 Irmo shear zone is at most c. 30 km. In the Clark Hill Lake area, D_4 strain is in part concentrated in two narrow bands of sericite phyllite, leading to the development of spectacular normal slip crenulations (Stops 4 and 5).

The Belair Fault

In the vicinity of Augusta, the southeastern edge of the Kiokee belt and the Augusta fault are offset by the north-

northeast trending Belair fault (Fig. 1-2; Stop 12). the last stages of movement on the Belair fault were high- angle reverse resulting in cumulative offsets of 30 meters and 12 meters for Late Cretaceous and Eocene strata, respectively, in the Atlantic Coastal Plain (O'Connor and Prowell, 1976; Prowell and O'Connor, 1978). The horizontal separation of the late Paleozoic Augusta fault by the Belair fault is c. 23 km (sinistral, Prowell and O'Connor, 1978). Bramlett and others (1982) have suggested that in the late Paleozoic the Belair fault functioned as a tear, genetically related to movement on the Augusta fault.

SUMMARY OF REGIONAL GEOLOGICAL HISTORY OF THE SAVANNAH RIVER AREA

1. The Persimmon Fork and Asbill Pond Formations were deposited during the early and middle Cambrian in association with a subduction related (?) volcanic arc.

2. The Richtex Formation of unknown age is tentatively interpreted to comprise an allochthon that was emplaced in the early Paleozoic.

3. During the D_1 Delmar deformation (sometime during c. 415 and 525 Ma), the rocks in the Carolina slate and Charlotte belts were penetratively deformed and tightly folded. M_1 was geeenschist facies in the slate belt and amphibolite facies in the Charlotte belt.

4. During c. 385-415 Ma a mafic to felsic suite of plutonic rocks were emplaced in the Charlotte belt.

5. It is uncertain if mid-Paleozoic deformation and/or thermal activity affected the rocks in the Savannah River area.

6. The Savannah River area contains granitic plutons from a regionally extensive late Paleozoic (c. 285-330 Ma) magmatic arc. These plutons are strongly deformed in the northwestern part of the Kiokee belt (Modoc zone) but are weakly deformed to undeformed elsewhere in the Savannah River area.

7. Three deformation events (D_2-D_4) comprise the Alleghanian orogeny in the Savannah River area.

a. The D_2 (Lake Murray) deformation (295-315 Ma) is associated with deformation in the c. 5 km thick Modoc shear zone. The Modoc zone originally dipped gently northwest and had important components of both normal slip and dextral strike slip. The Augusta fault, along the southeast side of the Kiokee belt, has an important component of normal movement and may also be a D_2 structure.

b. The D_3 (Clark Hill) deformation (285-295 Ma) is associated with northwestward motion of the Piedmont crystalline thrust sheet above a regional decollement. The D_3 Kiokee anticlinorium is interpreted to be a fault propagation fold above the decollement.

c. The D_4 (Irmo) deformation (268-290 Ma) is associated with dextral motion in the northeast trending Irmo shear zone. In the Clark Hill area, the Irmo shear zone coincides with the Modoc zone and overprints the associated D_2 structures. The Irmo shear zone is interpreted to indicate dextral motion between Laurentia and Gondwana in the final stages of the Alleghanian orogeny.

8. During the Triassic and/or Jurassic the Piedmont rocks were cut by northeast trending brittle faults and intruded by northwest trending diabase dikes.

9. During the late Mesozoic and early Cenozoic, the Coastal Plain and Piedmont near Augusta were cut by the north- northeast trending Belair fault. The Belair fault is a high angle reverse fault which moved approximately 18 meters and 12 meters in the Upper Cretaceous and Lower Tertiary, respectively (Prowell and O'Connor, 1978). The Belair fault may be a reactivated late Paleozoic tear fault (Bramlett and others, 1982).

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THE MODOC ZONE - D_2 (EARLY ALLEGHANIAN) IN THE EASTERN APPALACHIAN PIEDMONT, SOUTH CAROLINA AND GEORGIA

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VIEW AND INTRODUCTION

Geologic and geochronologic studies summarized by Secor and others (1986a), Dallmeyer and others (1986), and Secor (1987 this issue) demonstrate a long history of deformation in the eastern Appalachian Piedmont. Briefly, the Delmar deformation (D_1) of early or middle Paleozoic age, produced the S_1 slaty cleavage in the Carolina slate belt and the regional scale (F_1) anticlinoria and synclinoria which control the outcrop pattern of slate belt stratigraphic units. At the beginning of the Alleghanian orogeny, the Lake Murray deformation (D_2) produced greenschist facies regional metamorphism in the southeastern part of the Carolina slate belt and amphibolite facies regional metamorphism in the Kiokee belt. This metamorphism was accompanied by granitic plutonism in both belts. At the same time, intense shearing along the boundary between the slate belt and the Kiokee belt juxtaposed migmatites of the Kiokee belt against lower grade rocks of the Carolina slate belt. The D_2 shear zone was folded during Clark Hill (D_3) deformation (Secor and others, 1986a; Maher, 1987 this issue). Map scale F_3 folds include the Kiokee and Irmo antiforms and the Lexington synform (Fig. 2-1). The latest Alleghanian deformation involved ductile shear during the Irmo deformation (D_4). Shear criteria formed during D_4 indicate dextral shear along a nearly vertical, northeast trending shear zone - the Irmo shear zone (Dennis and Secor, 1987a; Dennis and others, 1987 this issue). In central South Carolina, the Irmo shear zone cuts across the nose of the F_3 Irmo antiform; in the Clark Hill Lake area of western South Carolina and Eastern Georgia, the Irmo shear zone is parallel to and overprints the D_2 shear zone.

The boundary between the Carolina slate belt and the Kiokee belt is a tectonic feature that formed during Lake Murray deformation (D_2). This boundary, which is called the Modoc zone, and the D_2 structures that are within it are the subjects of this paper.

THE MODOC ZONE

The northwest boundary of the Kiokee belt with the Carolina slate belt was first recognized as a tectonic feature by Overstreet and Bell (1965) and Daniels (1974). On the basis of studies of the boundary along Clark Hill Lake near Modoc, SC, Howell and Pirkle (1976) named the feature the "Modoc fault zone". Subsequent reports have described and emphasized the polyphase deformation and metamorphic history of the rocks along the Carolina slate belt/Kiokee belt boundary (Secor and Snoke, 1978; Snoke and others, 1980; Snoke and Secor, 1982; Secor and others, 1986a). Other reports have discussed the Modoc fault zone in the context of an "Eastern Piedmont fault system" (Hatcher and others, 1977; Bobyarchick, 1981, 1982).

The Modoc zone in the Clark Hill Lake area is a 4-5 km wide zone of steeply northwest dipping, strongly deformed metamorphic rocks (Plate 1). To the northwest are greenschist facies rocks of the Carolina slate belt and to the southeast are migmatites of the Kiokee belt. The Modoc zone is recognized by the following features which are interpreted to have formed during the Lake Murray deformation (D_2) of Secor and others (1986a):

1) As the Modoc zone is approached from the northwest, the S_1 slaty cleavage is overprinted by upper greenschist and amphibolite facies mineral assemblages which comprise a locally mylonitic foliation (S_{2s}) in the Kiokee belt,

2) Within the Modoc zone, numerous sheets of felsic orthogneiss, from a few centimeters to more than 1 km thick are oriented approximately parallel to S_{2s}. These orthogneisses have a strong foliation (S_{2g}) approximately parallel to S_{2s} and a strong mineral elongation lineation (L_2),

3) The Modoc zone contains an M_2 metamorphic gradient between greenschist facies in the Carolina slate belt and upper amphibolite facies in the Kiokee belt,

4) The northwest edge of the Modoc zone coincides with a deformation front that marks the northwestern limit of intense penetrative D_2 deformation,

5) The southeastern edge of the Modoc zone coincides with the northwestern limit of partially melted migmatite and the sillimanite isograd.

These characteristics suggest that the Modoc zone formed as a synmetamorphic, synplutonic ductile shear zone (or ductile fault in the terminology of Wise and others, 1984).

In the Clark Hill Lake area, the Modoc zone includes deformed rocks of both the Carolina slate and Kiokee belts. Although recrystallized and highly deformed, rocks in the northern part of the Modoc zone bear strong lithologic affinity to rocks of the Carolina slate belt, especially to those of the Asbill Pond formation. The rocks in the southern part of the Modoc zone and in much of the interior of the Kiokee

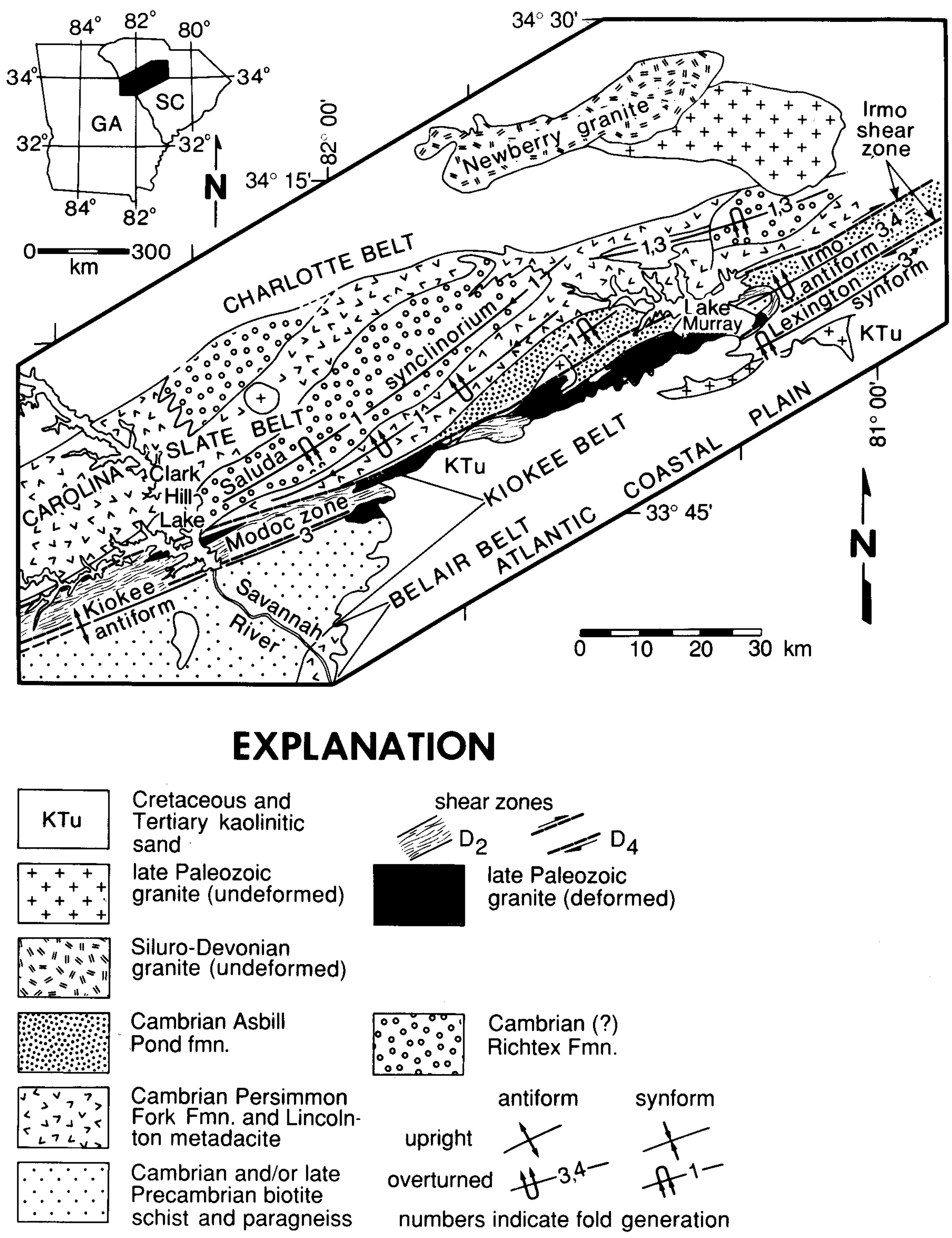


Figure 2-1. Generalized geologic map of west-central South Carolina and eastern Georgia showing some geographic and geologic features referred to in the text (modified from: Secor and others, 1986a; Halik, 1983; Kirk, 1985).

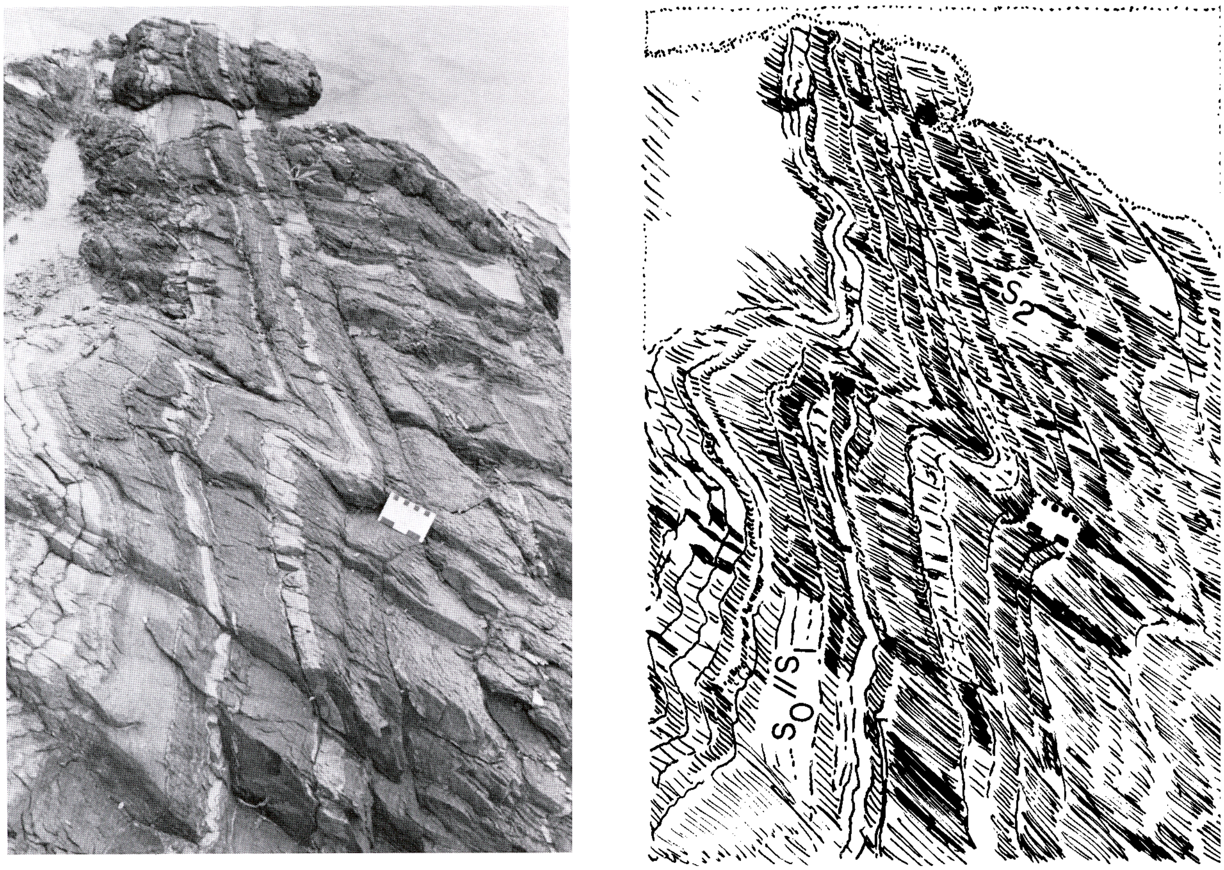


Figure 2-2. Photo and sketch showing a shallowly southwest plunging, northwest vergent F_2 (RSC_2) fold in the Modoc zone at field trip Stop #6; the view is to the southwest. Here, S_0 layering in the volcaniclastic rocks is parallel to the S_1 foliation. The $S_0||S_1$ surface is deformed by F_2 (RSC_2); the foliation axial planar to F_2 is S_2. Photo provided by H. D. Maher.

belt seem to be lithologically distinct from the Carolina slate belt. The approximate location of the ill-defined boundary between these two packages of rocks is along the trend of the sericitic phyllite units (sp) on Plate 1 and along the line separating Ꞓa from PꞒgn2 on Figure 1-2.

D_2 SHEAR SENSE CRITERIA AND KINEMATICS

In this section, structures that formed in the Modoc zone during D_2 are described. The kinematic significance of the microstructures are discussed with reference to Simpson and Schmid (1983). The kinematic significance of crenulations and lineations is discussed with reference to Dennis and Secor (1987a, 1987b).

D_2 Structures

In the Modoc zone, $S_0 \parallel S_1$ surfaces and compositional banding are folded by antiform-synform pairs. These fold pairs are intrafolial, and characteristically have the axis of the synform located northwest of the antiform (Fig. 2-2). In the Clark Hill Lake area, where the Modoc zone is situated on the southwest limb of the Saluda synclinorium (F_1) and the northwest limb of the Kiokee antiform (F_3), the intrafolial folds have the wrong sense of vergence to be parasitic to F_1 or F_3. Because these folds deform $S_0 \parallel S_1$, and because their axial planes are folded by parasitic F_3, the intrafolial folds are interpreted to be F_2.

The F_2 hingelines typically plunge at a shallow angle toward the southwest (Fig. 2-3a), and their axial planes dip northwest at a shallower angle than the layer that is folded (Fig. 2-2). The F_2 folds in rocks of slate belt affinity that lie within the Modoc zone typically have an approximately axial planar foliation (S_{2c}). This S_{2c} foliation is present to a much lesser degree in paragneisses of the central part of the Modoc zone where it is defined as a second alignment of biotites with a more shallow northwest dip than an earlier layer-parallel foliation. This S_{2c} foliation has typically not been observed south of the northern belt of crenulated sericitic phyllite (sp unit on Plate I). The intersection of S_{2c} with compositional banding produces a lineation that is parallel to F_2 hingelines.

Orthogneiss sheets are present throughout the Modoc zone. These are oriented approximately parallel to, but locally cut across compositional banding. A strong foliation

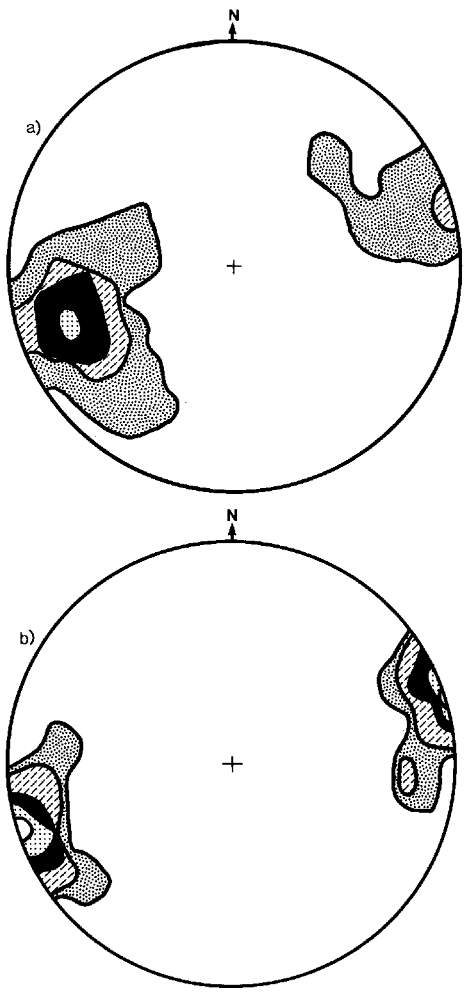


Figure 2-3. Lower hemisphere equal area net plots of: a) 185 F_2 (RSC_2) hingelines (contours of 0%, 5%, 10%, 20% of 1% area, b) 132 L_2 mineral elongation lineations in orthogneiss sheets (contours of 0%, 2%, 15%, 25%, and 50% of 1% area).

(S_{2g}) is defined by aligned micas and quartz ribbons. A very strong lineation (L_2) defined by pulled- apart feldspar augen and the long axis of quartz ribbons trends 072 and is horizontal in the Clark Hill Lake area (Fig. 2-3b). This lineation is also present in some of the orthogneiss sheets in the Modoc zone in central South Carolina between Edgefield and Lexington where it has a gentle plunge to the northeast. Locally, S_{2g} is folded by small intrafolial folds with the geometry of F_2, and thin sheets of orthogneiss are folded by F_2. Orthogneiss sheets and S_{2g} within them are folded by mesoscopic and macroscopic scale F_3 folds that are parasitic to the Kiokee antiform.

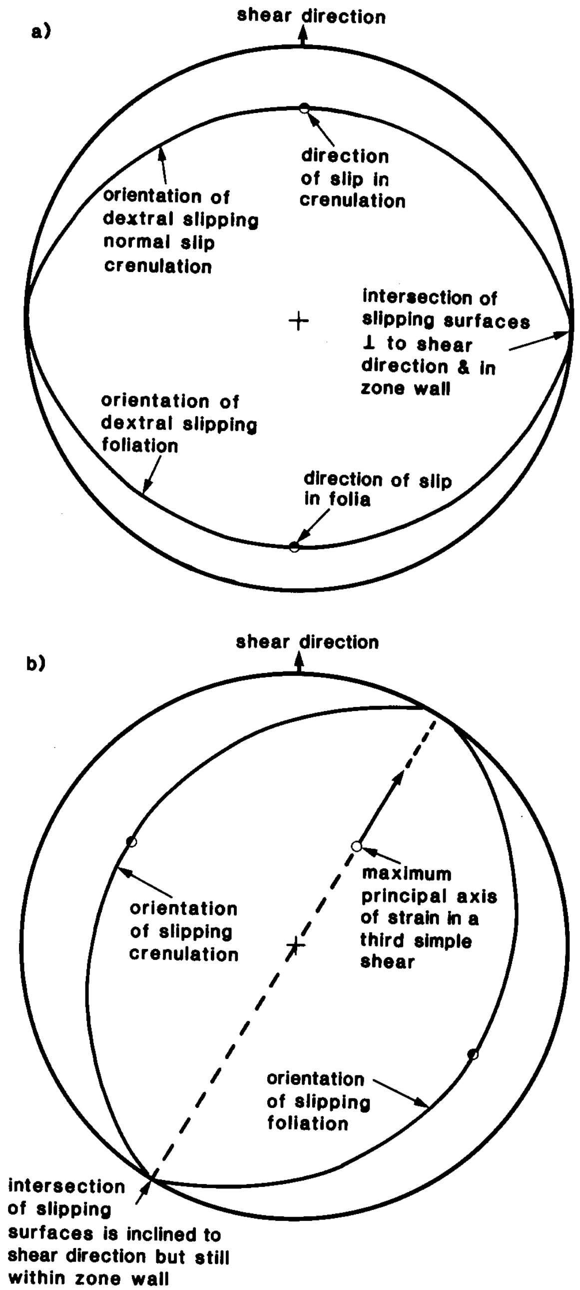
D_2 Sense of Shear

Microstructures present in the orthogneisses include quartz ribbons, augen with asymmetric tails, fractured and faulted feldspar augen, “mica fish” and crenulations (Simpson and Schmid, 1983). Where these features are present in sections cut normal to the elongation lineation and the foliation, they consistently show a northwest side down sense of shear. In sections cut parallel to the lineation and perpendicular to the foliation, asymmetric tails on augen and crenulations consistently indicate a dextral sense of shear.

The uniform northwest sense of vergence of F_2 folds is compatible with the interpretation that they formed as a result of simple shear during movement on the Modoc zone. The observation that F_2 are locations where slip has `ramped' across foliation suggests that slip on foliation is an important part of strain in the shear zone.

The role of slip on foliation and its consequences in zones of simple shear has been addressed by Dennis and Secor (1987a, 1987b). They find that where foliation is oriented at a small oblique angle to the shear zone wall, components of slip on that foliation that are normal to the shear zone wall are compensated by slip on crenulations. Foliation and crenulation slips are simple shears, acting along foliation and crenulation planes, in a plane normal to crenulation axes (Fig. 2-4). These crenulation axes lie within the shear zone wall. If the foliation and crenulation pair slip in a plane oblique to the zone's overall shear direction, a third simple shear is required in order to preserve the required overall simple shear path (Fig. 2-4b). Mathematically, the requirements for this third simple shear are that: 1) its shear plane is parallel to the shear zone wall, and 2) its displacement direction parallels crenulation axes. A consequence of this third simple shear is that its maximum principal axis of strain will initiate at 45^{o} from the direction of the third simple shear in a plane perpendicular to the shear zone wall; with progressive strain, the axis will rotate toward parallelism with the displacement direction of the third simple shear.

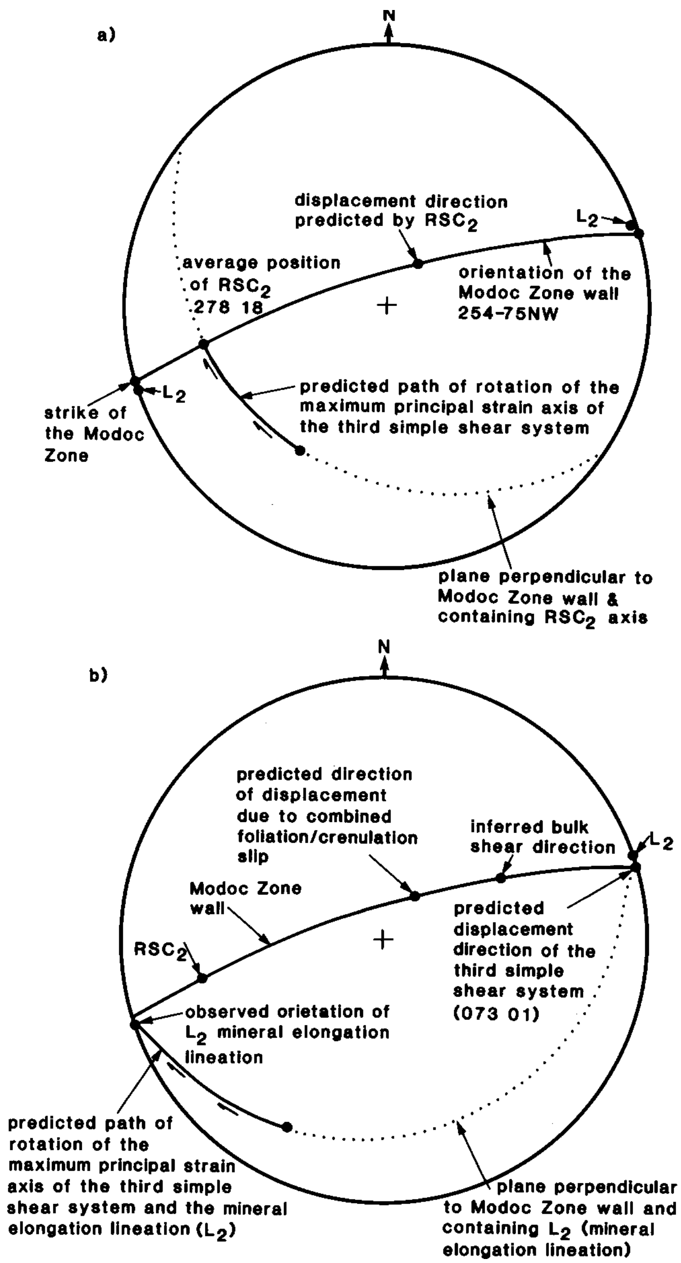
Where foliation in a shear zone is oriented at a small angle clockwise from the shear direction, crenulations will form at an anticlockwise angle to the shear direction. These crenulations are reverse slip crenulations (RSC) and the slip direction is in the direction of RSC vergence (Dennis and Secor, 1987a). In the Modoc zone, the morphology of F_2 folds suggests that they are reverse slip crenulations and hereafter, F_2 will be referred to as RSC_2. Because the crenulation axis lies within the plane of the shear zone wall (Dennis and Secor, 1987b), the orientation of the Modoc zone can be determined as the plane that contains the strike line, as shown by the geologic map, and the orientation of the RSC_2 axes; this plane has a strike and dip of about 254-75NW (Fig. 2-5a). The direction of simple shear resulting from combined foliation and crenulation slip will be along a line in the plane of the shear zone and perpendicular to the crenulation axes. This line plunges moderately steeply north-northeast. The sense of vergence of RSC_2 indicates that the northwest side of the shear zone, the hanging wall, moved down to the north-northeast relative to the footwall.



The mineral elongation lineation (L_2) indicates a third component of simple shear strain in the Modoc zone. The lineation is interpreted to initiate parallel to the maximum principal strain axis of the third simple shear and to rotate with the maximum principal strain axis in a plane perpendicular to the shear zone wall. The path that the L_2 mineral elongation lineation should follow with progressively increasing shear strain is indicated in Figure 2-5a. In the Modoc zone, the pole representing the average L_2 orientation does not fall exactly on the predicted path (Fig. 2-5b), as it should if it had formed in strict adherence to the theory presented above. The disparity between the observed and predicted orientations for L_2 suggests that additional components of simple shear may have acted prior to or following the time that foliation and crenulation slip were occurring in the Modoc zone. Perhaps the penetrative mineral elongation fabric in the Modoc zone began to form prior to the time that foliation slip was initiated. Alternatively, the simple shear deformation in the Modoc zone may have been spatially partitioned into a normal down-dip component in the paragneisses that contained a strong pre-existing S_1 foliation and a strike slip component in the synkinematic intrusive rocks which were hot, easily deformed and initially unfoliated. If such partitioning has occurred, then the condition that the third simple shear system's displacement vector act parallel to crenulation axes may be relaxed and the line 073-01 (Fig. 2-5b) may represent the direction of the third simple shear. The orientation of L_2 is slightly oblique to the shear plane, and this indicates large strains due to the slip on the third simple shear system.

The bulk shear direction for the Modoc zone lies in the shear plane between the vectors representing the displacement for combined foliation/crenulation slip and the displacement for the third simple shear system (Fig. 2- 5b). The relative magnitudes of these vectors will give the orientation of the bulk shear direction. The amount of strain due to slip on foliation and crenulation surfaces is not known, but it is probably small relative to the amount of strain recorded by the third simple shear in the lineated orthogneiss. However, the amount of crenulated paragneiss relative to the amount of lineated orthogneiss in the Modoc zone is large. If we assume 1) that shear strain in the Modoc zone has been parti-

Figure 2-4. In parallel-sided zones deformed in simple shear, crenulations form in order to preserve the zone's width and orientation when slip on foliation is an important deformation mechanism. a) This stereo diagram depicts angular relationships with respect to the zone wall. The wall is the primitive circle, the shear direction is at the top of the diagram. Slip sense on foliation and crenulation is consistent and perpendicular to the crenulation axis. Crenulation slip compensates for the component of foliation slip normal to the zone wall, and restores the bulk deformation path to simple shear. b) When foliation slip has components of movement 1) normal to the zone wall and 2) within the wall but normal to the shear direction, a third simple shear is also required to maintain an overall simple shear path. Crenulation slip compensates for displacement components of foliation slip normal to the zone wall, and both crenulation and foliation slip perpendicular to crenulation axes. The third simple shear compensates for displacement components of the crenulation-foliation pair within the zone wall, and normal to the shear direction. The third simple shear is required to have a shear plane parallel to the zone wall and slip direction parallel to crenulation axes. According to the model, a mineral elongation lineation oblique or parallel to crenulation axes is interpreted to be the maximum principal axis of strain in the third simple shear. (Adapted from Dennis and Secor, 1987b).



tioned into slip on foliation and crenulation surfaces within the paragneisses and displacements due to the third simple shear within the orthogneisses, and 2) that the total contribution of each of these to the bulk shear strain could be approximately equal, then the bulk shear vector will lie in the shear zone wall about halfway between the vector representing displacement for combined foliation/crenulation slip and the vector representing the displacement direction for the simple shear in the orthogneisses. If we further assume (with full cognizance of the limitations of the data and the overprinting of two subsequent deformations) that the average of RSC_2, L_2, and shear plane data are representative of the shear zone, then the bulk slip vector would plunge 34° toward 064 in the present orientation of the shear zone (Fig. 2-5b).

Original Orientation of the Modoc Zone

Mesoscopic and macroscopic evidence show that the Modoc zone is folded (Secor and others, 1986a; Maher, 1987 this issue). Sheets of orthogneiss and D_2 fabric elements within the Modoc zone are folded on an outcrop scale and on the map scale (Plate 1, and Fig. 2-1). In central South Carolina, the Modoc zone is folded around the northeast plunging Irmo antiform and the Lexington synform (Tewhey, 1977; Kimbrell, 1984). Secor and others (1986b) suggest the Kiokee antiform formed over a ramp in a decollement at depth during northwestward transport of the crystalline thrust sheet. Maher (1987 this issue) suggests that the Kiokee antiform is a fault propagation fold. In any case, the Modoc zone has been rotated to its present steep orientation as a result of D_3 folding. The point of interest in this discussion is its original orientation when it formed during D_2.

The amount of D_3 rotation of the Modoc zone is not known. However, several bits of evidence suggest that the Modoc zone had a shallow northwest dip at the time it formed. An important piece of evidence is the juxtaposition of rock types across the Modoc zone. High grade migmatitic mid- to lower-crustal rocks of the interior of the Kiokee belt contrast markedly with the lower grade, and therefore probably shallower crustal rocks of the Carolina slate belt. A

Figure 2-5. a) Lower hemisphere equal angle projection showing the orientation of the Modoc zone wall and the average orientation of RSC_2 hingelines. L_2 is the average orientation of the mineral elongation lineation in orthogneiss sheets. The predicted displacement direction for combined foliation and crenulation slip is 90° from the orientation of RSC_2 along the wall of the Modoc zone. The plane perpendicular to the shear zone wall that goes through the crenulation axis (RSC_2) is shown by the dotted line, and the predicted path of rotation of the maximum principal strain axis associated with the third simple shear is shown by the arrows along the solid portion of that line. b) Lower hemisphere equal angle projection showing the orientation of the Modoc zone wall, the average orientation of RSC_2 hingelines, and the average orientation of the mineral elongation lineation (L_2). The dotted line shows the orientation of the plane perpendicular to the shear zone wall that contains L_2. If strain due to the third simple shear has been partitioned into the synkinematic orthogneisses, then the path of rotation of the maximum principal strain axis of the third simple shear and the associated mineral elongation lineation (L_2) is expected to follow the arrows along the solid portion of the dotted line. The predicted direction of displacement due to the third simple shear is along the line of intersection of the shear zone wall and the perpendicular plane that contains L_2. If the total contributions of the foliation-crenulation slip component and the third simple shear displacement component to the bulk shear strain are equal, then the bulk shear direction will lie within the shear zone wall about halfway between the directions for these two simple shear systems.

thrust fault origin for this juxtaposition seems unlikely in that shallower crustal rocks were emplaced on top of deeper crustal rocks. There is no evidence to support the possibility that the high grade rocks were originally emplaced on top of the lower grade rocks and then subsequently structurally inverted into the present orientation.

In its present orientation, the Modoc zone strikes northeast and dips steeply northwest. To the northwest, at depth, COCORP data shows shallowly northwest dipping reflectors (Cook and others, 1983). These reflectors are at the south end of Georgia line 1, just north of the surface trace of the Modoc zone, and have dips of 18-25^o (unmigrated). These reflectors are probably sheets of orthogneiss within the Modoc zone. This northwest dip here may be a result of D_3 folding. Alternatively, the shallow dips in the Modoc zone at depth to the northwest may represent an original dip, and only the steeper dips at the surface may be due to the proximity to the crest of the Kiokee antiform and the effects of D_3 folding.

If the Kiokee antiform is a ramp antiform, then the amount of rotation of the hanging wall block might be estimated from the geometry of the fold. Maher (1987 this issue) estimates that the ramp below the antiform dips ~30-35^o to the southeast. If the dips in the northwest limb have been steepened by an amount approximately equal to the dip of the subsurface ramp, then the Modoc zone may have had an original dip of ~40-45^o to the northwest.

Regional geological relations also support the possibility of an original northwest dip of the Modoc zone. Structural studies in the Charlotte belt of central South Carolina suggest that these high grade rocks are exposed in the crest of a D_3 ramp antiform (Halik, 1983; Kirk, 1985; Secor and others, 1986b). Geochronological studies by Dallmeyer and others (1986) indicate that the Charlotte belt rocks were at mid-crustal depths during D_2, but was not penetratively deformed at that time. There is no evidence that the Modoc zone reemerges along the southeastern edge of the Charlotte belt or within the Charlotte belt. Therefore the Modoc zone must have cut down to deeper crustal levels to the northwest in its original orientation.

The Modoc zone probably formed as a shallowly northwest dipping shear zone with Kiokee belt rocks in the footwall and Carolina slate belt rocks in the hanging wall. The direction of shear indicated for the Modoc zone is toward the north-northeast and has components of normal and dextral shear. There was sufficient displacement along the shear zone to juxtapose deeper crustal rocks of the Kiokee belt against the shallower crustal rocks of the Carolina slate belt. The north-northeast movement of the hanging wall of the Modoc zone relative to the footwall, with a significant component of normal slip, indicates the Modoc zone formed during an episode of extensional deformation.

Regional Implications

Knowledge of the sense of shear on the Modoc zone provides information about some aspects of the pre-Alleghanian geology of the eastern Piedmont. It also provides information about the tectonic evolution of the metamorphic core of the Alleghanian orogeny.

The sense of shear on the Modoc zone indicates that the rocks of the migmatitic interior of the Kiokee belt were located to the north-northeast of their present position relative to the Carolina slate and Charlotte belts prior to the earliest Alleghanian deformation (D_2). The amount of displacement on the Modoc zone is not known. However, the Kiokee belt may have originally underlain the Carolina slate belt and/or the Charlotte belt. If this is true, then the rocks within the Kiokee belt, like those of the Charlotte belt, may have originated as the roots to the slate belt volcanic arc. Alternatively, the Kiokee belt may have been the basement on which the slate belt arc accumulated, or the Carolina slate belt and the Kiokee belt may not have had any connection to each other prior to the Alleghanian orogeny.

Geologic relations in the Raleigh belt are somewhat similar to those observed in the Kiokee belt. In the Raleigh belt (Fig. 1-1), a late Precambrian to early Cambrian volcanogenic sequence is juxtaposed on top of a high grade basement terrane of possible Grenville age. The contact between the two terranes is the D_2 decollement of Farrar (1985). Farrar suggests that the volcanic cover sequence was thrust over the basement from the southeast. The movement on the fault is constrained to be prior to the emplacement of the Castalia granite (301 Ma, Stoddard, 1987, pers. comm.). The D_2 decollement and the cover sequence has been overprinted by amphibolite facies metamorphism, similar to the metamorphic overprint on slate belt lithologies in the upper part of the Modoc zone. The D_2 decollement in the Raleigh belt has been folded and overprinted by steeply dipping dextral shear zones, like the D_3 and D_4 Alleghanian events along the Kiokee belt. These similarities between the Modoc zone and the D_2 decollement in the Raleigh belt suggests that they may represent similar events or even possibly the same event.

An extensional tectonic regime is indicated by the sense of movement that occurred on the Modoc zone during the Lake Murray deformation (D_2). The direction of extension indicated by the sense of shear on the Modoc zone is nearly orthogonal to the suture between the Carolina terrane and the Suwannee terrane in the subsurface of Florida. Radiometric dating or rocks from the Wiggins Uplift suggests collision along the suture between 307-315 Ma (Dallmeyer, 1987 in press). At the same time, clastic wedge sediments were being shed into the Alleghanian foreland basin (Secor and others, 1986b, Fig. 2). Following the extensional event, northwestward vergent folding and thrusting occurred in both the eastern Piedmont and the Valley and Ridge (Dallmeyer and others, 1986; Secor and others, 1986b; Elliott and Aronson, 1987). Subsequent to folding in the eastern Piedmont, dextral shear occurred on several steeply dipping, northeast trending zones; examples of these include the Irmo shear zone (Dennis and Secor, 1987a), the Brookneal shear zone (Gates and others, 1986), and the Nutbush Creek, Macon and Hollister mylonite zones (Farrar, 1985) (Fig. 4-1).

The geochronological data and overprinting deformation events indicate that extension in the eastern Piedmont occurred early during the collision of Laurentia and Gondwana. Timing and geometric relationships between the Modoc zone and the Suwannee terrane boundary suggest a genetic relationship between the extension and collision. Therefore, models for the Alleghanian orogeny in the southern Appalachians must include an episode of extension accompanied by metamorphism and granitic igneous activity before major amounts of crustal shortening.

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D_3 FOLDING IN THE EASTERN PIEDMONT ASSOCIATED WITH ALLEGHANIAN THRUSTING

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INTRODUCTION

The eastern Piedmont has long been characterized as a series of alternating high-grade and low grade belts (Crickmay, 1952). The high-grade Kiokee and Charlotte belts form asymmetric foliation anticlinoria, whereas the intervening Carolina slate belt is a complex synclinorium (Fig. 1-1). The southeastward dip of Belair belt rocks, flanking the Kiokee belt on the southeast, also show evidence of shallowing to the southeast and could be part of another synclinorium presently mostly hidden under Atlantic Coastal Plain sediments. These large scale crustal folds, which expose rocks from deeper crustal levels in the anticlinoria cores, along with associated smaller scale structures and fabrics, are defined as D_3 structures.

D_2 fabrics in orthogneisses in the northwest limb of the Kiokee belt antiform in the Lake Murray region have been constrained in age between 295 and 315 Ma, whereas D_4 fabrics are constrained between 268 and 290 Ma (Dallmeyer and others, 1986). D_3 is therefore narrowly bracketed by these time spans, although considering the error bars on the dates and probable transition periods between Alleghanian deformation events, it is possible that the time span for D_3 structures is longer than the 5 Ma suggested above. The time of D_3 coincides with the 10-20 Ma period between hornblende and biotite $^{40}Ar/^{39}Ar$ ages in Kiokee belt rocks and Charlotte belt rocks, with plateaus for hornblende at 292-298 Ma and for biotite at 278-288 Ma (Dallmeyer and others, 1986). This indicates that D_3 occurred during a retrograde metamorphic path from D_2 amphibolite facies conditions to greenschist facies conditions or lower.

The age of D_3 in the eastern Piedmont is roughly synchronous with the thin-skinned Alleghanian crustal shortening evident in the Valley and Ridge and in the Blue Ridge. This led Secor and others (1986b) to propose that the large scale D_3 anticlinoria evident in the eastern Piedmont are ramp antiforms associated with Alleghanian thrusting of crystalline thrust sheets in the hinterland of the southern Appalachians.

Another model, loosely used in earlier attempts (Metzgar, 1977; Maher, 1979) to explain the relationship of Kiokee belt rocks to Carolina slate and Belair belt rocks, is a variant of the stockwerk model of Wegmann (1935). In this model a diapirically rising, mobile Kiokee belt infrastructure formed beneath a semi-rigid slate belt suprastructure and resulted in the Kiokee belt foliation arch. A zone of mylonitic rocks, the abscherungszone, developed between the infrastructure and a detached superstructure. However, this model does not explain: 1) the asymmetric character of the Kiokee belt foliation arch with a steep northwest limb, 2) the difference between the age of metamorphism in the Charlotte and in the Kiokee belts, or 3) the tectonic context of Alleghanian strain, metamorphism and igneous activity. For these reasons the model is clearly inadequate. What follows is a detailed description of D_3 structures in the study area, and an evaluation of the ramp-antiform model.

DISTRIBUTION OF D_3 MESOSCOPIC STRUCTURES IN THE STUDY AREA

Mesoscopic D_3 folds and lineations occur sporadically throughout the Kiokee belt and within the flanking Carolina slate and Belair belts, but are concentrated in three subparallel zones (Fig. 3-1). The two northernmost zones are within the Modoc zone (where D_2 strain is concentrated) on the northwest flank of the Kiokee belt foliation arch, and are separated by a zone of sericitic phyllite (sp – Plate 1) where D_4 strain is concentrated. The southernmost zone is along the crest of the Kiokee belt foliation arch and involves migmatitic gneisses and schists. D_3 folds are much more regular in geometry in the northern two zones than in the southern zone on the arch crest (Fig. 3-1). This difference is probably attributable to the more irregular migmatitic layering in the southern D_3 crest zone.

F_3 FOLD STYLE

F_3 folds are usually well rounded in cross section view (Fig. 3-2) and are open to tight (average interlimb angles typically from 80°-45°; Fig. 3-1). Only in some of the very tightest F_3 folds (interlimb angle of about 30°) is significant limb attenuation/hinge thickening evident; i.e., the majority of the folds are approximately parallel in geometry. In several large lake shore outcrops (alternate stop CH-3), where F_3 is conspicuous, conical ends to individual folds were observed. Generally however, fold continuity along the axis is a minimum of tens of meters and the folds can be well approximated as concentric (a geometry also confirmed by the great-circle fits of poles to S_2 where D_3 is well developed, Fig. 3-1). This style suggests that the compositional layering was acting with substantial strength and stiffness and that buckling was a major folding mechanism (Suppe, 1985). The decreased temperatures that would favor buck-

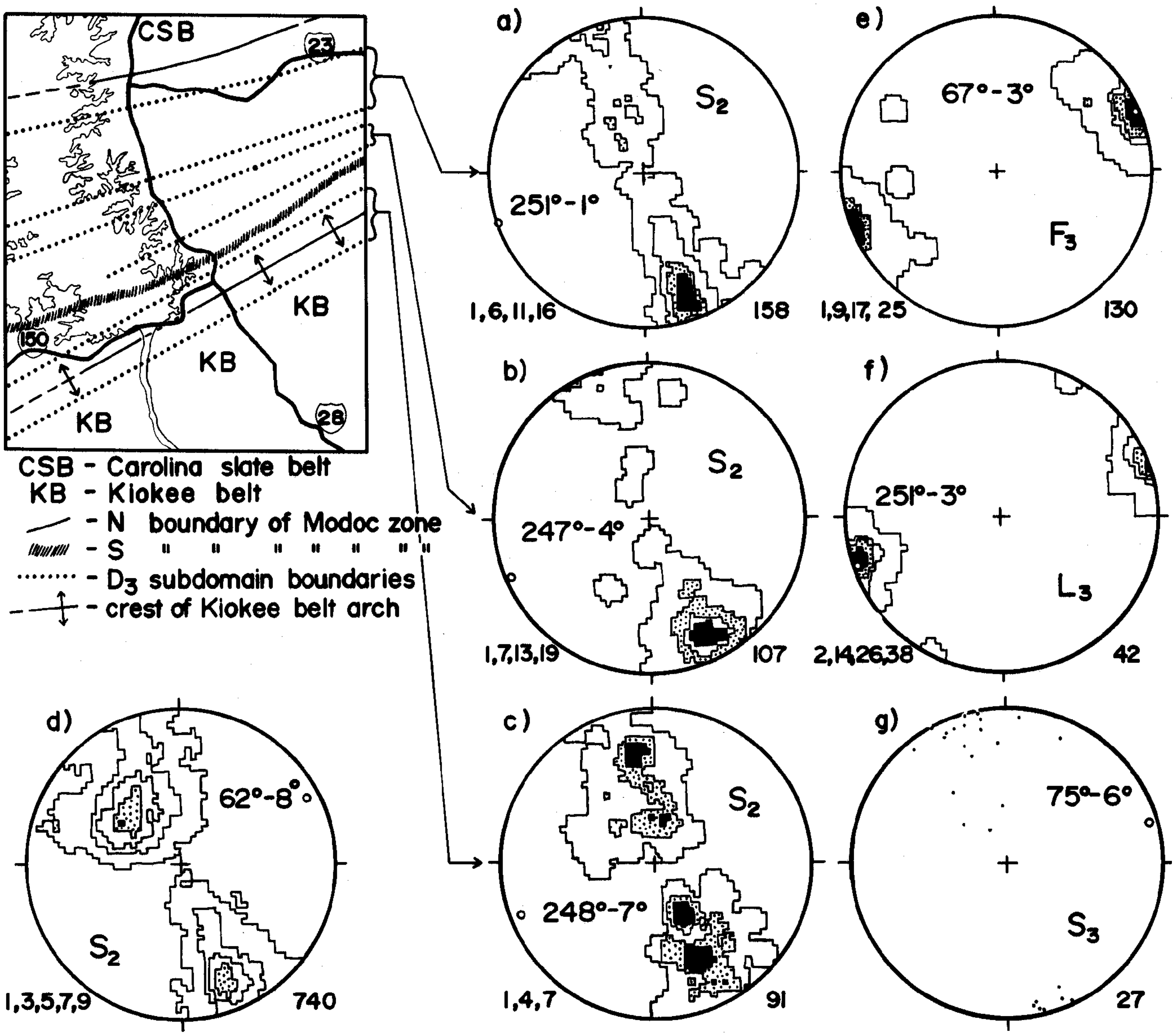

Figure 3-1: Summary diagram of lower hemisphere, equal-area, projection data of D_3 fabric elements. Lower right of each plot is the number of data points; lower left is values of contours. The small circle on each plot represents either the pole to the best-fit great circle girdle (pi plots, a-d) or the mean orientation in plots of linear elements. An index map for three subdomains in the Clark Hill quadrangle where F_3 structures are concentrated is included.
a) Plot of poles to S_2 in northern subdomain within Modoc zone.
b) Plot of poles to S_2 in southern subdomain within Modoc zone.
c) Plot of poles to S_2 in subdomain centered on crest of Kiokee belt foliation arch.
d) Plot of poles to S_2 from all three above subdomains and from Kiokee belt rocks in Martinez quadrangle to the southeast on the southeast limb of the foliation arch.
e) Plot of F_3 axes in Clark Hill and Leah quadrangles.
f) Plot of L_3 in Clark Hill and Leah quadrangles.
g) Uncontoured plot of poles to S_3 in Clark Hill and Leah quadrangles. Note girdle spread due to fanning and refraction.

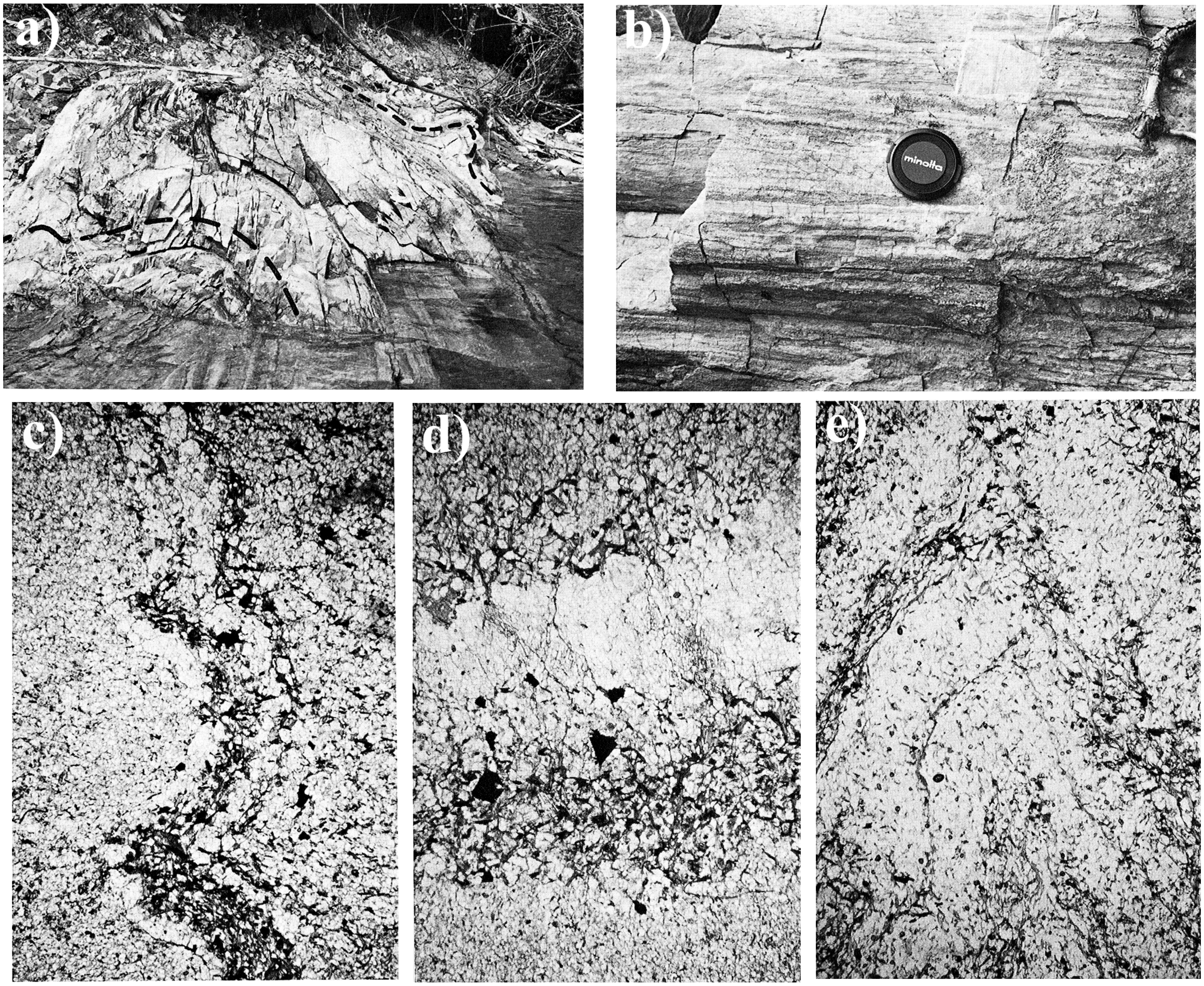

Figure 3-2: a) Photograph looking northeast of lakeshore outcrop (CH-3, alternate stop) where F_3 is well developed. Depicted is one fold in a train of folds at least 30-40 m long. Field of view is 1-2 m. Dashed lines trace some of the folded S_2 surfaces. Note the irregularly developed fracture cleavage that is crudely axial planar. b) Photograph of a folded S_2 surface crinkled by D_3. This is one manifestation of L_3. View is to the north so this is a southeast-dipping F_3 limb. c) Photomicrograph (plain light) of thin section scale D_3 crinkles (view is along L_3 to the northeast, and scale is about 6.6 mm across). Note that a biotite subpopulation is axial planar (S_3) to the D_3 crinkles. The parallel compositional layering and mineral alignment being folded is S_2. d) Photomicrograph of poorly developed biotite-opaque folia (S_3) highly oblique to compositional layering and mineral alignment of S_2 (subhorizontal). Scale is 6.6 mm across and specimen was taken from an F_3 hinge. e) Photomicrograph of fairly tight F_3 fold with axial planar S_3. Scale is 6.6 mm across.

ling are consistent with D_3 being a retrograde, post-main-metamorphic event.

One of the more unusual aspects of F_3 fold style is the widely variable wavelength that exists, from map scale down to wavelengths on the order of centimeters. Much of the variation is attributable to variation in layering thickness. However, within an individual folded layer, several orders of wavelength can be observed. Multi-layered sequences, where individual layer thickness was on the order of 4-10 cm, have fold wavelengths of several meters to tens of centimeters. On a smaller scale, folding of the layer boundary with a wavelength of several cm or less occurs (see discussion on L_3).

Whereas a notable asymmetry in limb length of map-scale F_3 is present, mesoscopic folds may show no notable equivalent asymmetry and do not appear to have formed as flexural-slip drag folds. In that mesoscopic folds are concentrated on the short, southeast dipping limb of map scale F_3, and absent on the steep northwest dipping limbs, the two D_3 subdomains within the Modoc zone can be described as highly corrugated steps on the northwest limb of the Kiokee belt foliation arch (Fig. 3-3, cross section).

F_3 folds can be distinguished from F_2 and F_4 on the basis of orientation, vergence or style. F_4 folds have a steep plunge and an intrafolial RSC style (Dennis and Secor, 1987), and hence are difficult to confuse with the shallowly plunging F_3. F_2 have a similar subhorizontal orientation to F_3, but have a well developed, consistent north-side down vergence and a intrafolial RSC style in contrast to F_3. Whereas F_2 and F_4 are associated with slip on S_2 foliation, F_3 seems to be a buckling phenomena.

CHARACTER OF L_3

Where F_3 folding is concentrated in paragneisses, a fairly strong lineation often occurs parallel to the subhorizontal fold axes (Fig. 3-1f, Fig. 3-2c). An earlier, different lineation, which is 5°-15° clockwise (plunging shallowly to the SW, i.e. an L_2 position) of the strong lineation, is folded by F_3 folds. Where F_3 folds are not present, these two lineations can be confused. Whereas D_4 might be expected to also produce a lineation in this approximate orientation (subhorizontal), no other evidence for notable D_4 strain exists in the same locale. Indeed, the S_2 fabric is in an inappropriate orientation for accommodating D_4 slip where F_3 and the accompanying lineation is particularly strong. Finally, if this strong lineation were L_4 then it should kinematically be a stretching lineation, which it is not. The close spatial association with other D_3 fabrics and inappropriate character for D_4 indicate this strong lineation is a D_3 fabric.

Upon close inspection L_3 is not penetrative, but is found most commonly at the interface of quartzo-feldspathic compositional bands, especially where a thin (1 to several grains thick) surface of intervening sericite exists. L_3 is a crinkling of that surface (Fig. 3-2). In some specimens the crinkling has a cuspate character suggesting the interface was a viscosity boundary, perhaps due to differing quartz/feldspar ratios or grain sizes. Where S_3 is locally developed L is manifest as an intersection lineation.

CHARACTER OF S_3

Locally, a weakly developed foliation approximately axial planar to mesoscopic F_3 folds occurs in the paragneisses. This S_3 foliation is manifest as a parting plane (Fig. 3-2) and a weak preferred orientation of micas. Both outcrop observations and a stereonet plot (Fig. 3-1) indicate that the foliation both fans and refracts, but the majority of S_3 orientations dip steeply southeast in a position that is also approximately axial planar to the large scale Kiokee belt foliation arch. In thin sections from paragneisses, S_3 (when present) consists of thin discordant folia of biotite and minor chlorite. The biotite is notably finer grained than biotite and muscovite aligned in the S_2 plane (Fig. 3-2). This finer grained biotite is the only metamorphic phase demonstrably of D_3 age.

Within some of the granitic intrusives (gr2 – Plate I) in the migmatic interior of the Kiokee belt there is a weak to moderate foliation manifest and an alignment of micas and slight strain of quartz (undulose extinction without recrystallization). The foliation in the gr2 granites is discordant to that in the country rock and therefore these granitoids clearly postdate themigmatitic layering and foliation in the interior of the Kiokee belt. A lack of any dextral sense-of-shear indicators suggests that the foliation in the gr2 granites is not S_4 – D_4 is largely localized elsewhere. The granite fabric is in an appropriate orientation to be axial planar to F_3 and is most likely a S_3 fabric. If so, the suite of gr_2 granitoids could be early to syntectonic with respect to Alleghanian thrusting.

KIOKEE BELT D_3 FOLIATION ARCH

A cross section from the Carolina slate belt to the Belair belt, through the Kiokee belt (Fig. 3-3) shows some of the following salient features of this large scale (tens of kilometers wide) F_3 foliation arch:

1. The foliation arch is markedly asymmetric with a steep northwest limb – a geometry which strongly implies northwestward vergence and transport.
2. The are has a fairly sharp corrugated crest (map width of a kilometer or less), i.e., it is not a classic flat-topped ramp antiform.
3. Whereas most of the southeast limb dips moderately (30°-50°), there are zones, one of which is coincident with a well defined lithologic map unit contact, which are significantly steeper (60°-80°).
4. Within the Kiokee belt the northwest limb has a structural thickness about half that of the southeast limb.

This last observation suggests structural complications beyond that of a simple asymmetric antiform of tabular and originally horizontal units. In that substantial penetrative D_3 strain has not been observed, ductile limb thinning is unlikely. The style of mesocopic F_3 is also inconsistent with such a thinning. Three possible explanations exist for the disparity in limb thickness.

First, subsequent D_4 strain associated with the ductile, dextral, strike-slip movement concentrated in the steep northwest limb could have thinned the limb. Indeed, map units in the Carolina slate belt that can be traced into the Kiokee belt northwest limb where D_4 shear is concentrated do become substantially thinner (Fig. 1-2). Estimates of such thinning due to D_4 strain can be made as a function of the original angle (ϕ) of discordance between D_4 shear zone boundaries and the lithologic units involved (assuming simple shear, i.e. no change in shear zone width). In the Irmo, S.C. area the amount of offset across the D_4 shear zone can be constrained to a maximum of 30 km (Sector and others, 1986a; Secor, pers. comm.). In the study area the D_4 shear

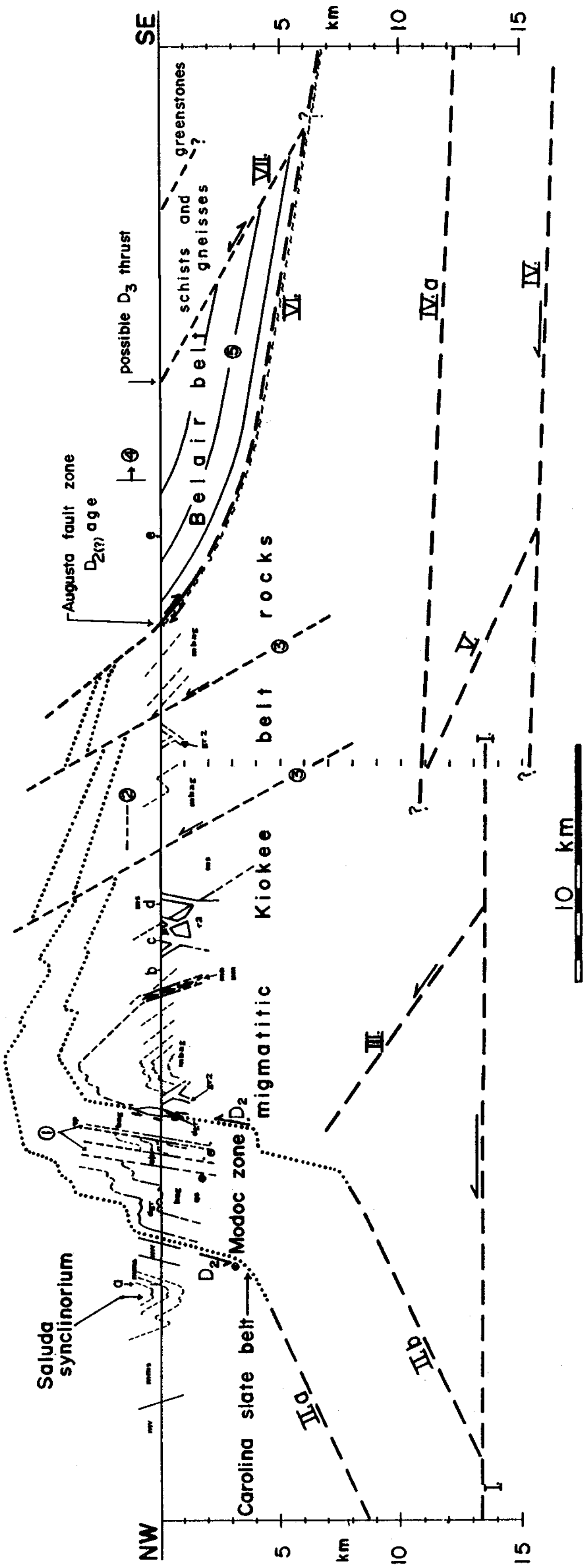

Figure 3-3: Cross section compilation from the Carolina slate belt to the Belair belt through the D_3 Kiokee belt foliation arch. Position of the cross section trace and the locations of the stations a, b, c, d, and e are shown on Figure 1-3. Due to D_4 out-of-the-plane movements and the lack of markers with a well constrained original geometry the cross section is not balanced.

Cross Section Explanation and Key

Seismic reflectors and deep faults

COCORP reflector interpreted to be basal decollement by Cook and others (1983, Fig. 15b) extrapolated from line 1 some 20-25 km off section to the southwest along strike.

IIa, b. The uppermost and lowermost reflectors, respectively, of a series of northwest-dipping reflectors seen under the Carolina slate belt (Cook and others, 1983, Fig. 15b, Line 1). This is interpreted to be the subsurface continuation of the Modoc zone; the strongly deformed orthogneiss sheets are probable good seismic reflectors.

Fault splay off of major decollement postulated in order to explain the cross section geometry of the Kiokee belt as a fault-propagation fold (see text for discussion). A corresponding seismic reflection is not know to exist, but a requisite appropriate velocity contrast might not exist across the fault.

IV a, b. Upper and lower seismic reflectors from COCORP Line 5 (Cook and others, 1983, Fig. 17b) interpreted as possible continuations of the basal decollement. Since Line 5 is offset about 70 kilometers to the SW from the cross section these lines only suggest the general depth range at which the decollement would exist.

A strong SE-dipping reflector (Cook and others, 1983, Fig. 17b) that might represent a possible ramp location.

Inferred position of a seismic reflector of Petersen and others (1984) that approximately coindices with the southeastern boundary of the Belair belt identified geophysically by Daniels (1974).

Cross section construction notes

Zones of relatively incompetent sericitic phyllite in which D_4 dextral shear strain is concentrated.

Level above which cross section reconstruction is very speculative.

Possible sites of D_3 thrust faults of the thicker southeastern limb of the Kiokee belt foliation arch (see text for discussion).

Northernmost extent of Cretaceous Coastal Plain cover.

Four Belair belt informal stratigraphic units of mainly metavolcanic rocks with intercalated volcanic-derived metasedimentary rocks.

zone is approximately 6 km wide. An average finite shear strain of 5 results. For ϕ = 20° the stretch (final over original length) of lithologic unit thickness is 0.37; for ϕ = 5° the stretch is 0.69. Final angles of discordance (ϕ') are 7.4° and 3.5° in these respective cases. However, much of the discordance between Carolina slate belt lithologic units and the Modoc zone (Fig. 1-2) is attributable to D_2 strain. D_4 strain within the study area seems to occur within the Modoc zone, is subparallel to map contacts, and not to transgress it. The angle of discordance, although difficult to estimate, must be fairly low. In conclusion, D_4 could account for a significant proportion of the limb thinning, but an initial discordance between the Modoc zone and D_4 shear zone strain boundaries of close to 18° is necessary to explain all of it. This seems unlikely.

A second explanation lies in the mature of the surfaces being used to gauge Kiokee belt anticlinorium limb thickness. Simply, limb thickness is taken as the distance in cross section measured in a direction perpendicular to the average foliation dip from the fold crest to the Modoc line on the NW side, and from the crest to the August fault zone on the SE side (Fig. 3-3). An implicit, underlying assumption in expecting roughly equal limb thickness would then be that these surfaces (the Modoc zone and Augusta fault zone) were subhorizontal and are the same surface. Both these assumption are possibly in error.

Substantial differences exist between the August fault zone and Modoc zone, even though both do separate high-grade, migmatitic Kiokee belt rocks from low-grade, Precambrian to Cambrian slate belt rocks and are thought to be broadly contemporaneous (both Alleghanian). The August fault zone is much thinner (several hundred meters versus 6 kilometers). The granitic intrusives in the August fault zone are invariably high strained and concordant. Finally, and most importantly, the sense-of- shear textures in the two zones gibe directions and senses incompatible with being the same ductile shear zone simply folded by D_3. The two ductile shear zones are likely different surfaces and this interpretation is depicted in Figure 3-3.

An assumption that the Modoc zone and August fault zone were subhorizontal in a pre-D_3 position might follow from the observation that they are subparallel to metamorphic isograds, and by inference to paleoisotherms, both of which are easily envisioned as originally subhorizontal. However, isotherms are mobile with time, and if related to an intrusion front and involved in ductile faulting, as they are here, there is no reason a significant original dip could not exist. Indeed, analysis of D_2 structures (Sacks and Dennis, this vol.) suggests a Carolina slate belt, hanging wall-down component for the Modoc zone, with an original dip of the zone shallowly to the northwest. A northwest-dipping surface being folded over a deeper flat- lying detachment surface would form an asymmetric foliation arch with a thinner, northwest limb and thicker southeast limb.

A third, intriguing explanation for the disparity of limb thickness is that cryptic D_3 thrusts may exist within the southeast limb, resulting in a greater width. This would be consistent with the convergent nature of D_3. Some candidates exist for the location of such thrusts (Fig. 3-3). A rather sharp and continuous contact (otherwise rare in the migmatitic Kiokee belt core) between a two-mica sillimanite schist and a variety of paragneisses is one possibility. Another candidate is a zone where dips change fairly abruptly from 30-40°SE to 55-65°SE. The existence of these faults is admittedly speculative. Map scale F_3 folds would also produce an apparently thicker southeast anticlinorium limb in a similar way to that ascribed to the thrust faults above. The zones of steep dip may thus be overturned F_3 limbs. However, associated hinge zones have not been observed.

Two sets of equivalent lithologic map units may exist on the foliation arch limbs. The first set are two belts of pods of ultramafic rocks, the northern one of which is much thinner than the southern (Burks Mtn. Belt). The disparity in thickness may be due to D_2 strain (Paul Sacks, pers. comm.). The two belts are almost equidistant from the arch crest. The second correlation is more speculative, but the thick sillimanite schists midway on the southeast limb (just under one of the inferred thrust faults discussed above) could represent a higher grade version of the pelitic portion of the Asbill Pond formation phyllites and sericitic quartzites seen within the Modoc zone on the northwest limb.

D_3 FOLDING AND CRYSTALLINE THRUST SHEETS

Secor and others (1986b) interpret the Kiokee and Charlotte belts each as “a D_3 ramp antiform which developed during northwestward translation of the crystalline thrust sheet” (p. 1350). COCORP data (Cook and others, 1980) suggests the decollement for the eastern Piedmont crystalline thrust sheet lies in the 12 to 15 km depth range, and regional relations suggest a minimum of 175 km of transport on the decollement (Secor and others, 1986b).

The geometry of a ramp antiform is controlled by the height and dip of the ramp and by the amount of offset. Ramp antiforms where all of the hanging wall cut-off has moved off the ramp and onto the flat develop a flat top. With increased transport the flat top grows in width in direct proportion to fault displacement. Whereas the Charlotte belt has an appropriate flat top to be a ramp antiform the Kiokee belt does not. The fairly sharp crest of the Kiokee belt suggests either: 1) a limited amount of movement (equal to or less than ramp length), which is inconsistent with a direct association with the basal major decollement, or 2) suggests an alternate geometry. A fault-propagation fold (Suppe, 1985) can explain the observed asymmetry and sharp crest of the Kiokee belt foliation arch, and it is this interpretation which is depicted in Figure 3-3 (surface III).

^{40}AR/^{39}AR DATA AND D_3

Six ^{40}Ar/^{39}Ar dates on biotite separates from the Kiokee belt in central South Carolina have a spread of 278 to 283 Ma and a mean of 282 Ma (Dallmeyer and others, 1986). These ages are thought to reflect uplift and cooling through the 300 $\pm$ 25° biotite Ar retention temperature (Jager, 1979; Harrison and others, 1985) during D_3 thrusting and folding of Kiokee belt rocks (Dallmeyer and others, 1986). Interestingly, Charlotte belt rocks have a range of ages from 251 to 292 (n=15) and a mean of 271 Ma (Dallmeyer and others, 1986).

If the Kiokee belt and Charlotte belt were both ramp antiforms formed by transport over the same major basal decollement, then it might be expected that the Charlotte belt would have older (since it would have been formed by movement over a higher ramp along the same detachment surface) or equivalent ages to the Kiokee belt. However, if the Kiokee belt is formed as a fault propagation fold over a splay then there is no constrained relative age relationship between uplift in the two belts. Younger Charlotte belt ages may merely reflect foreland migration of thrust movement. This is a speculative conclusion since all the dates from the Kiokee belt are from the northwest limb and a complete sampling traverse does not exist as it does the Charlotte belt. Assuming the disparity of 10-20 Ma between hornblende and biotite ^{40}Ar/^{39}Ar cooling ages (Dallmeyer and others, 1986) represents the age of Alleghanian convergent related thrusting and folding throughout the southern Appalachians, a minimum estimate of shortening rate can be made. With a minimum shortening of 175 km documented (Secor and others, 1986b), a minimum rate of 0.875 cm/yr results – a rate comparable with that observed in modern orogens. This estimate is based on limited data and a lot of assumptions, but it clearly shows the potential ^{40}Ar/^{39}Ar data has for further elucidating and constraining the history of thrusting in the Piedmont.

A COMPARISON OF D_3 IN THE RALEIGH AND KIOKEE BELTS

Farrar (1985) describes a deformational chronology for the easternmost Piedmont in North Carolina that includes a D_3 event that is similar, in part, to D_3 described here for the South Carolina eastern Piedmont. Farrar's D_3 includes two groups of structures: 1) regional scale folds interpreted to have been formed by late Alleghanian compression, and 2) three mylonite zones on the limbs of these major folds.

The following similarities exist between F_3 in the two areas: a) an open to tight, and microscopic to regional-scale fold geometry, b) an associated S_3 that is approximately axial planar to regional scale F_3 folds, and c) an Alleghanian age. However, one substantial difference exists that is especially significant to the discussion here. The largest F_3 fold in North Carolina, the Wake-Warren antiform with high-grade Raleigh belt rocks in the core, has a southeastward overturned limb in its northern portion, and a more upright geometry in its southern portion. If F_3 regional scale folds of North Carolina are related to emplacment of crystalline thrust sheets, as we propose they are in the guidebook area, then a different geometry must exist in the two areas. A southeast directed backthrust would be one possibility for the Wake-Warren antiform.

Farrar (1985) also includes the Nutbush Creek, Macon and Hollister mylonite zones as part of D_3. The Nutbush Creek and Hollister mylonites have sense-of-shear indicators suggesting an important dextral movement component. These zones might be better equated to the D_4 dextral event well documented in South Carolina (Secor and others, 1986a; Dennis and Secor, 1987; Dennis and others, this volume). Although it is likely that a continuum of deformation existed between D_3 and D_4 the fact that they represent different kinematic regimes warrants their differentiation. In South Carolina D_4 fabrics localized along the steep limbs of D_3 folds and therefore D_3 is not completely coeval but must have preceded D_4.

SUMMARY AND DISCUSSION

Secor and others (1986b) suggest that the Kiokee belt and Charlotte belt anticlinorium are ramp antiforms associated with Alleghanian emplacement of crystalline thrust sheets. Geochronologic data (Dallmeyer and others, 1986), geophysical data (Cook and others, 1980; Petersen and others, 1984), and field studies can be used to further test and develop this basic model. With these considerations in mind, the Kiokee belt along the Savannah River is proposed to be a large fault-propagation fold over the major Southern Appalachian decollement.

To the southwest in Georgia, near Washington, the Carolina slate belt terminates (Anon, Georgia Geologic Survey, 1976; Williams, 1978) in what may be NE-plunging F_3 folds and the Charlotte belt and Kiokee belt are adjoining. This is a critical spot for further elucidating the large scale D_3 crustal architecture. On a very speculative note, this area could be the location of a lateral ramp. In any case the D3 architecture changes along strike. Finally, ^{40}Ar/^{39}Ar dates from a sampling traverse across the Kiokee belt and into the Belair belt would provide valuable constraints in developing and testing such models. This work was supported by the University of Nebraska, Omaha, and National Science Foundation grant EAR-8508184.

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NATURE OF THE LATE ALLEGHANIAN STRIKE-SLIP DEFORMATION IN THE EASTERN IRMO SHEAR ZONE

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INTRODUCTION

Along the fall line in North Carolina, South Carolina, and Georgia, steeply dipping, dextral shear zones transect the Alleghanian front of metamorphism and ductile deformation at a small angle. These zones include the Hollister, Macon, and Nutbush Creek mylonites in North Carolina, the Irmo shear zone in South Carolina, and the Towaliga mylonites in Georgia (Fig. 4-1). By both radiometric methods and overprinting relationships, these zones represent the last ductile deformation in Southern Appalachian Piedmont (Table 1). This short contribution outlines the Irmo shear zone and its structures in the context of late Paleozoic strike slip deformation.

Recently Secor and others (1986a) have presented a deformation chronology for the eastern Piedmont of South Carolina. Because we refer to this chronology throughout this report, we summarize it here. D_1 or Delmar deformation is expressed as the slaty cleavage, S_1, and greenschist facies metamorphism, M_1, in the Carolina slate belt. The cleavage is axial planar to map-scale structures: the Delmar synclinorium, Emory anticlinorium, and Saluda synclinorium. D_1 is interpreted to be pre-Alleghanian and may reflect the accretion of the Carolina arc to the ancient North American margin. D_2, or Lake Murray deformation, is the earliest recognized Alleghanian (ca. 325 ma) deformation in the eastern South Carolina Piedmont. D_2 is recognized as amphibolite facies metamorphism (M_2) and deformation (S_2) in the Kiokee belt. The Modoc zone defined by the garnet isograd and the pervasive intrusion of orthogneiss sheets

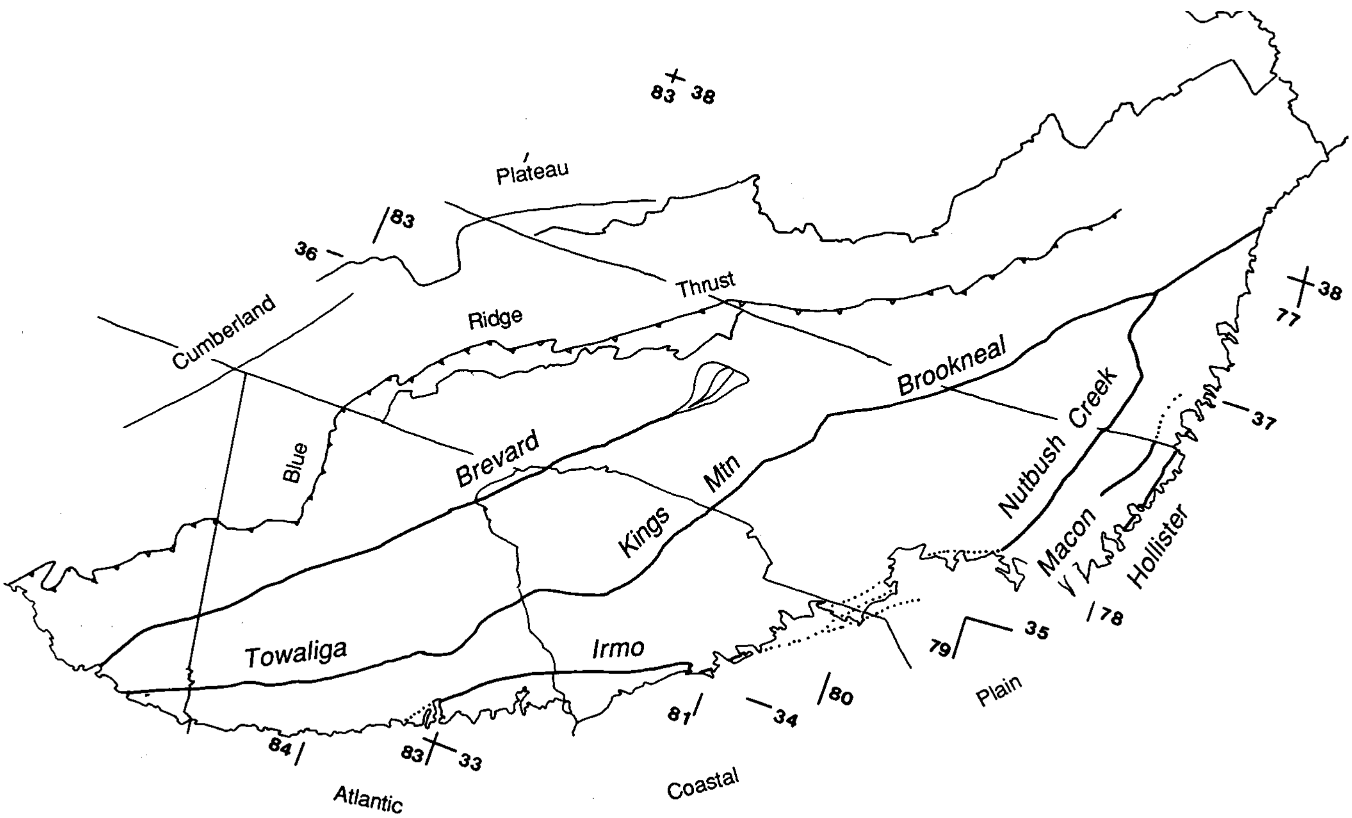

Figure 4-1. Sketch map of southern Appalachians showing the distribution of documented Alleghanian strike slip faulting (italics) relative to the Blue Ridge Fault and the Cumberland Plateau.

Table 1. Compilation of geochronology of Southern Appalachian Alleghanian strike slip zones.

ZONE	CUTS	FABRIC AGE
Brevard	Palmetto granite ca. 325, U/Pb zircon[1] Ben Hill granite ca. 325, U/Pb zircon[1]	?
Brookneal	Melrose granite 512±5, U/Pb zircon[2] fabric in Arvonia fm. 324±3, 40Ar/39Ar hbd[3]	300±5, Rb/Sr biot, w.r.[2]
Hollister	Butterwood Creek granite 292±13, Rb/Sr w.r.[4]	251, Rb/Sr biot, w.r.[4]
Irmo	Batesburg augen gneiss 291±4 , Rb/Sr w.r.[5] Batesburg lineated gneiss 284 ±17, Rb/Sr w.r.[5] Lexington metagranite 292±15, Rb/Sr w.r.[6] Clouds Creek granite 319 ± 27, Rb/Sr w.r.[6] Clouds Creek granite 240 ±75, U/Pb zircon[7] amphibolite fabric, 315-295, 40Ar/39Ar[7]	268±5, 40Ar/39Ar biot[7]
Kings Mountain	High Shoals granite 317, U/Pb zircon[8] amphibolite fabric 318-323, 40Ar/39Ar[8]	?
Macon	amphibolite fabric ca. 300, 40Ar/39Ar [3]	?
Nutbush Creek	Buggs Island granite 313±8, Rb/Sr w.r.[9] Wilton granite 285±10, Rb/Sr w.r.[6] Lillington granite 290, Rb/Sr w.r.[9]	?
Towaliga	High Falls granitic gneiss ca. 325, U/Pb zircon[10] amphibolite fabric, ca. 365[11]	?

1 Higgins and Atkins, 1981
2 Gates and others, 1986
3 Glover and others, 1983
4 Russell and others, 1985
5 Snoke and others, 1980
6 Fullagar and Butler, 1979
7 Dallmeyer and others, 1986
8 Horton and others, 1987
9 Kish and Fullagar, 1978
10R.L. Atkins, personal communication
11Russell, 1976

marks the northwestern limit of D_2. As S_1 is not recognized in the Kiokee belt, neither is S_2 recognized in the Carolina slate belt. Clarks Hill deformation or D_3 upright folding about axes shallowly plunging to the east is responsible for the alternating low and high grade belts in the Carolinas: the Belair, Carolina slate, and Kings Mountain belts are exposed as synclinoria, while the Kiokee, Raleigh, Charlotte and Inner Piedmont belts are antiformal cores of deeper-seated metamorphism. ^{40}Ar/^{39}Ar hornblende and biotite mineral ages (Dallmeyer and others, 1986) support the hypothesis that uplift of high grade belts in the metamorphic core of the orogen accompanied crustal shortening and folding and thrusting in the Valley and Ridge. Secor and others (1986b) have suggested that belt boundaries may be interpreted as approximating the strikes of mid-crustal ramps of the Alleghanian decollement, and that the high grade belts are exposed as ramp antiforms. While mesoscopic F_3 and L_{1x3} are common in the Carolina slate belt, rarely is a mesoscopic cleavage apparent. The Kiokee and Irmo antiforms and the Lexington synform are map-scale expressions of the D_3 in the eastern Piedmont of South Carolina. Finally D_4, or Irmo deformation, dextral shearing overprints some of the subvertical belt boundaries. Strike slip displacements are typically small, on the order of 10 km, and shear strains averaged across the width of the zones are also small, on the order of 1 to 2.

In this report the Irmo shear zone is defined to be an approximately 10 km wide zone of heterogeneous ductile deformation which refolds the core of the D_3 Irmo antiform in a dextral sense, and those splays off the main zone, for example in the Clouds Creek complex (Fig. 4-2). The Irmo shear zone has been mapped from Blythewood and Ridgeway north of Columbia (Dennis, 1985), to Leah, Georgia and west into northern Warren County, Georgia (Crawford, 1968). Along its entire exposed length, the Irmo shear zone appears to be localized near and overprinting the Modoc zone (see Sacks and Dennis, this volume). Hatcher and others (1977) defined the eastern Piedmont fault system on the

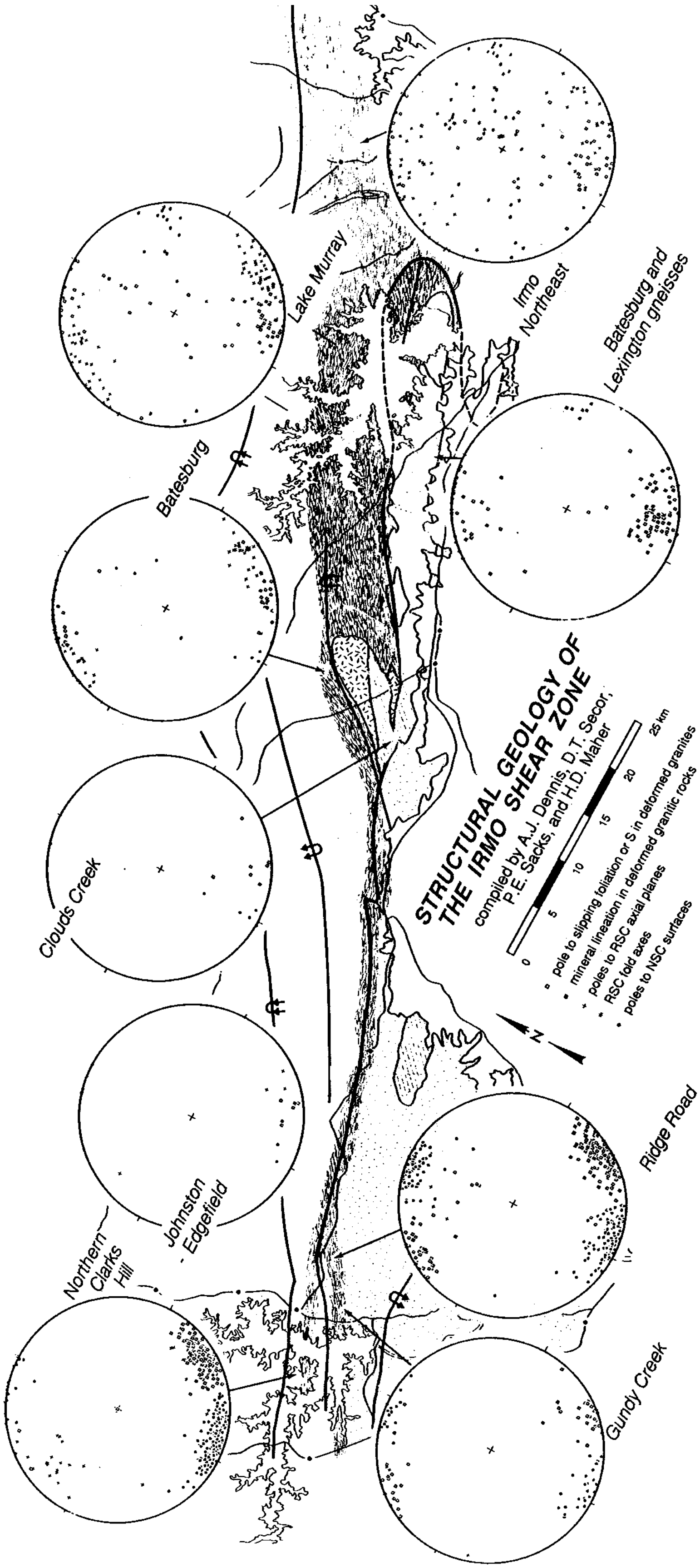

Figure 4-2. Structural geology of the Irmo shear zone. Shear pattern, rocks containing Irmo crenulations; Stipple pattern, Kiokee belt; Oriented line pattern, deformed Carboniferous granitic rocks; Isotropic line pattern, undeformed Carboniferous granitic rocks. Axial traces of major D1 folds shown. D4 structures in previously foliated rocks

basis of a continuous, linear, geophysical signature coincident with known exposures of mylonitic rocks along the fall line. They suggested that the Nutbush Creek mylonite represented a northward continuation of the Modoc zone. Mapping by Druhan and Rollins (1984), Bartley and others (1984), Farrar (1985), and Horton and others (1986) has substantiated this correlation. Based on the coincidence of the Irmo shear zone with the Modoc zone, the Irmo shear zone is inferred to continue southwest to at least Sparta, and north towards North Carolina and the Nutbush Creek mylonite.

The other late Alleghanian strike slip zones also reactivate pre-existing crustal weaknesses defined by thermal contrasts, faulting or both. In North Carolina, the Nutbush Creek mylonite (Casadevall, 1977) on the western side of the Raleigh belt reactivates the contact of the Falls Lake terrane, interpreted to be a tectonic melange by Horton and others (1986), with the Raleigh block, in a dextral strike slip sense. The Nutbush Creek mylonite outcrops within 5 km west of Farrar's (1985) D_2 decollement between allochthonous Carolina terrane lithologies and the Proterozoic Raleigh block within the Raleigh belt. The Nutbush Creek mylonite diverges from the folded D_2 decollement south of Raleigh, and continues southwest towards Hartnett County (Casadevall, 1977). The Hollister and Macon mylonite zones outcrop on either side of the folded D_2 decollement on the eastern side of the Raleigh belt.

The Macon and Hollister mylonites are interpreted by Farrar (1985) to be related to F_3 (his notation) Alleghanian folding about a shallowly plunging axis. Farrar's cross sections suggest that 1) mylonitization is related to attenuation along the limbs of major F_3 structures - the Spring Hope synform to the east and the Wake-Warren antiform to the west; and 2) folding in the mylonites is parasitic on the F_3 folds. However, kinematic indicators show that mylonitization was contemporary with dextral strike slip movement. Boltin and Stoddard (1987) recognized asymmetric tails on porphyroclasts in felsic orthogneisses deformed by the Macon mylonite (their fig. 3), that suggest dextral movement. The Hollister mylonite is another D_3 structure, on the eastern flank of the Raleigh belt, in fact, separating the Raleigh belt from the eastern slate belt. Mylonitic textures in the Butterwood Creek pluton include dextral S-C fabrics and asymmetric, recrystallized tails on feldspar augen indicating dextral shear. Farrar (1985) and Boltin and Stoddard (1987) have noted the subhorizontal biotite mineral lineation which parallels the trend of the Hollister zone. Unfortunately the Hollister zone becomes less mappable in the metavolcanic and metasedimentary terranes to the south.

The Nutbush Creek, Macon, Hollister and Irmo shear zones are associated spatially, if not genetically, with leucocratic orthogneisses: the Falls leucogneiss, the Bens Creek leucogneiss, the unnamed leucogneiss of Boltin and Stoddard (1987), and the Modoc zone orthogneisses, respectively. Indeed, Secor and others (1986a), Farrar (1985) and Boltin and Stoddard (1987) all consider these orthogneisses to be D_2 structures. In North Carolina, the orthogneisses are genetically related to decollement and thrusting of the volcanogenic Carolina terrane over the Raleigh block basement complex. In South Carolina, they are considered related to the down-to-the-north shear zone origin of the Modoc zone. Incidentally, while Farrar (1985) and Sacks and Secor (1986) disagree on the mechanism of the earliest Alleghanian deformation, both models recognize the same shear sense across early pre-thermal peak shear zones. This suggests to us the strong case for reactivation of early, fundamental features in the Piedmont as strike slip zones, particularly as they are folded into subvertical orientations by D_3 ramp folding as suggested by Secor and others (1986a,b) and Horton and others (1987).

The Towaliga mylonites may be correlative with the Kings Mountain shear zones recognized by Horton (1982), by way of the Middleton-Lowndesville zone (Griffin, 1970) and the Hartwell extension to the Towaliga fault, proposed on the State Geologic Map of Georgia, 1976. Interpreting seismic reflection data in the context of the geologic mapping presented by Schamel and others (1980), Nelson and others (1985) confirmed that the Towaliga fault represented a post-thrusting, normal fault dipping steeply towards the foreland. On the basis of the seismic data, Nelson and others (1985) interpreted a 7 km normal offset of the decollement on the Towaliga, with the Pine Mountain belt in the footwall and Piedmont in the hangingwall. In detailed shear sense studies of the Towaliga mylonites, Hooper and Hatcher (1988) present data that indicates subhorizontal, dextral movement on the fault. This suggests that if the Towaliga mylonites formed as a post-thermal peak, post-thrusting normal fault, then subsequently, they were reactivated as a strike slip fault in later Alleghanian time. Gates and others (1986) have correlated the Brookneal mylonite zone, on the western flank of the Carolina terrane, in the vicinity of the Central Piedmont Suture with the Kings Mountain shear zones of Horton (1982).

1) The Irmo, Nutbush Creek, Macon, and Hollister zones, 2) the Towaliga, Kings Mountain, and Brookneal zones, and 3) the Brevard zone (Bobyarchick, 1984, and Vauchez, 1987) define three roughly parallel linear zones of Alleghanian strike slip deformation. All of these zones seem to be related to earlier tectonic boundaries that, with the exception of the Towaliga, have been rotated into a subvertical orientation by Alleghanian ramp folding and reactivated as strike slip faults. The approximately 100 km across strike spacing of these zones may offer clues to the spacing of these major ramps. Within the limits of error of the available dating methods, the zones are contemporary with each other and with continuing deformation in the foreland (see especially Secor and others, 1986b).

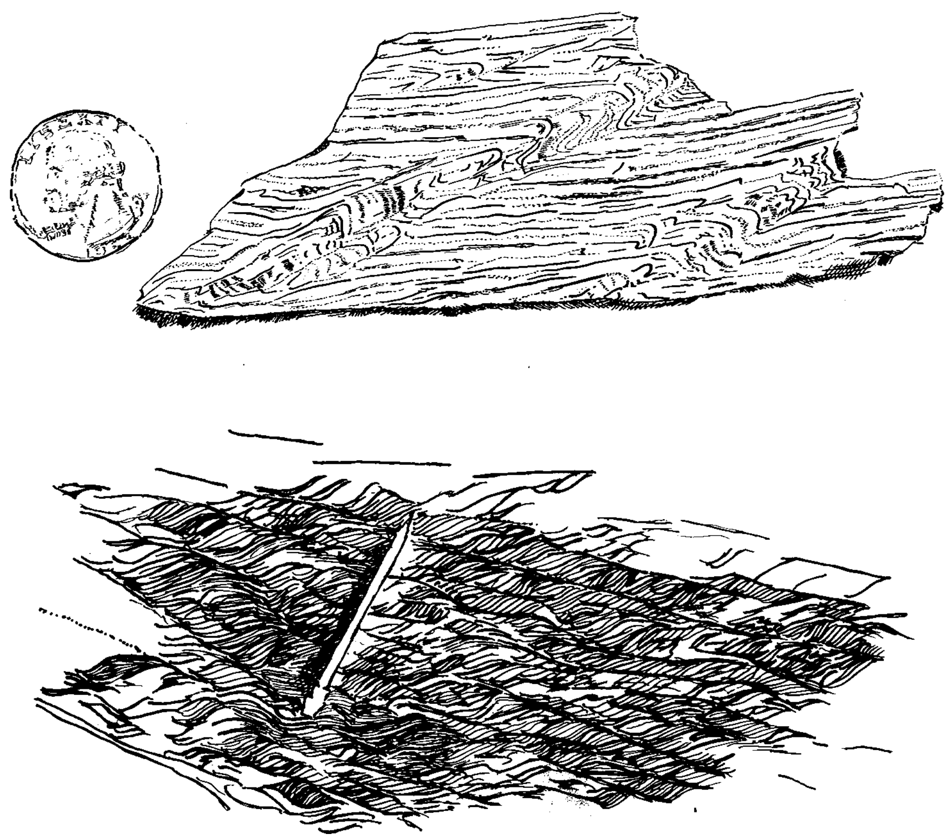

Figure 4-3. Field sketches of reverse and normal slip crenulations, from the south side of Lake Murray and the Ridge Road button schist zone, respectively.

THE IRMO SHEAR ZONE

The Irmo shear zone affected foliated and unfoliated rocks under upper greenschist facies conditions in the period 291-268 Ma. The Irmo shear zone cuts para- and orthogneisses of the Kiokee belt, the previously unfoliated Batesburg augen and lineated gneisses, the Clouds Creek complex and the Lexington metagranite, and the foliated, greenschist facies metasediments and metavolcanics of the Carolina slate belt. Interpretation of map pattern suggests approximately 10 km of subhorizontal displacement over a 10 km wide zone of heterogeneous deformation. Because the Irmo shear zone cuts a variety of rock types which were both well foliated and unfoliated, many different mesoscopic shear sense indicators are recognized within it. We have defined the boundaries of the Irmo shear zone using the outcrop distribution of these mesoscopic structures and the interpreted refolding of units by the shear zone.

In the Kiokee and Carolina slate belts, composite planar fabrics yield consistent, dextral shear sense. Reverse and normal slip crenulations deform S_1 and S_2 foliations. In the Carolina slate belt F_3 fold axes and L_{1x3} lineations are recognized folded by F_4 reverse slip crenulations. Reverse and normal slip crenulations are structures common to many sheared anisotropic rocks (Fig. 4-3). Reverse slip crenulations are rootless, intrafolial folds of foliation with the same vergence as the shear zone. The rootless aspect of these folds is typically controlled by microfaults subparallel to their axial planes that root in foliation surfaces. They are inferred to form as a consequence of slip on foliation when that foliation is inclined at a clockwise acute angle to the shear zone wall (Fig. 4-4a). Normal slip crenulations offset the foliation in a normal sense, consistent with the shear sense of the zone. Normal slip crenulations are inferred to form when a slipping foliation is oriented at a clockwise obtuse angle to the shear zone wall (Fig. 4-4b). Displacement sense is consistent on slipping foliation and crenulation surfaces and the shear zone as a whole. Elsewhere we have presented the case for considering RSC and NSC as mechanisms to conserve the shear zone's width and orientation when slip on a foliation inclined to zone boundaries is an important mode of deformation in the zone (Dennis and Secor,1987a).

Several lines of evidence support this interpretation: 1) RSC and NSC are best developed in strongly anisotropic rocks, whether that anisotropy is a compositional layering (Asbill Pond formation laminated siltstone) or a foliation (Persimmon Fork Formation metavolcanics or foliated Clouds Creek complex). 2) RSC and NSC are best devel-

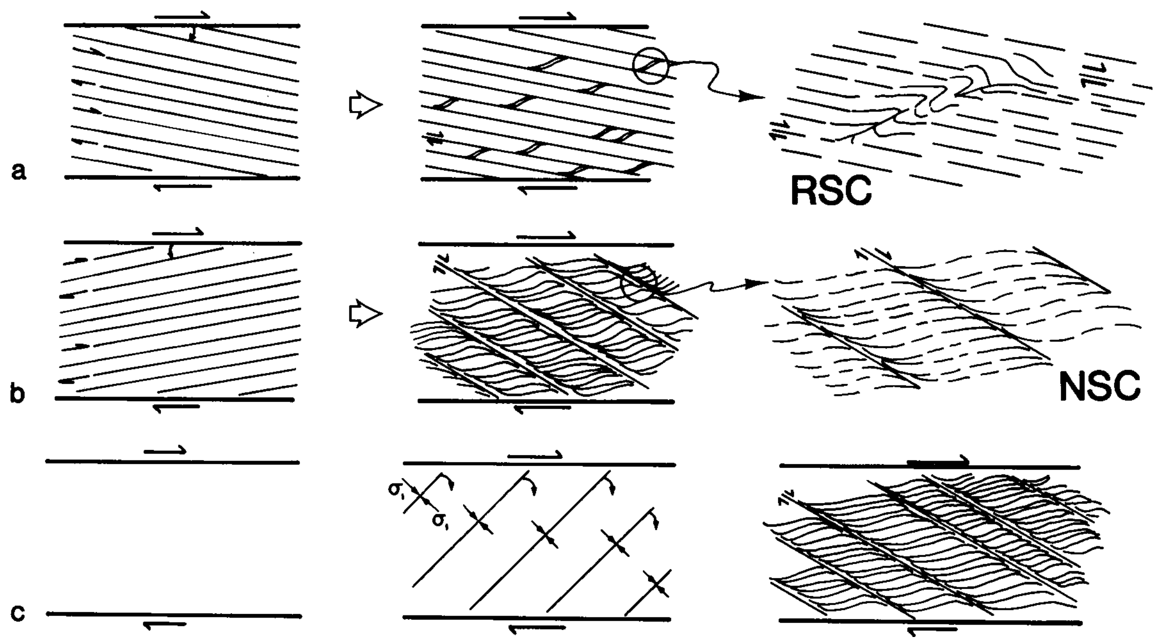

Figure 4. From Dennis and Secor, 1987a. Reverse and normal slip crenulations form so that the orientation and width of the shear zone is not changed when slip on foliation is an important mode of deformation in the zone. a) Reverse slip crenulations form the slipping foliation is oriented at an acute clockwise angle to the shear zone boundary. b) Normal slip crenulations form when that slipping foliation is oriented at an obtuse clockwise angle to the shear zone boundary. c) When an isotropic rock develops a foliation, and that foliation begins to slip, normal slip crenulations form, because according to all models of foliation formation, that foliation will form at an obtuse clockwise angle to the shear zone wall.

oped when the foliation is oriented within 5° of the shear zone wall. 3) RSC and NSC planes commonly root in slipping foliation. 4) RSC and NSC are best developed in rocks deformed under conditions that enhance the mechanical anisotropy, i.e., greenschist facies in quartz-mica schists. 5) Mineral lineations interpreted to be stretching or transport lineations are normal to crenulation axes. 6) Slip on RSC and NSC surfaces may be recognized as marker horizons are offset along crenulation surfaces (Fig. 4-5). 7) Angular relationships between crenulations, foliations and the shear zone wall are consistent.

The outcrop distribution of these crenulations may be explained by the reorientation of S_1 and S_2 surfaces during D_3 time, and the reactivation of those foliations as slip surfaces in D_4 time. Because the Irmo shear zone transects the F_3 Irmo antiform, RSC_4's are formed north-northeast of the of the core of the map-scale D_3 fold as the S_1 and S_2 foliations are folded into the "overturned" limbs of the D_3 structures (Irmo Northeast Domain). As the S_1-S_2 foliations are folded about the D_3 axes over the map view "crest" of the Irmo antiform, they are reoriented: S_1 and S_2 make an acute angle, measured clockwise, from the inferred boundary of the Irmo shear zone (Fig. 4-4a). In the foliated rocks on the "trailing" limbs of these D_3 folds, NSC developed because the orientation of the slipping foliation is obtuse when measured clockwise from the inferred orientation of the Irmo shear zone wall (Fig. 4-4b). In the previously unfoliated granitic rocks deformed during D_4, Irmo shear zone time, NSC's developed because the foliation that developed, and is inferred to have slipped formed at a clockwise obtuse angle (≈15° to 45°) to the shear direction (Fig. 4-4c).

D_4 structures in previously unfoliated rocks

In the Kiokee belt, the Batesburg augen and lineated gneisses and the Lexington metagranite are interpreted to be post-D_2, synkinematic intrusions. The fabric in this post-D_2 suite of granitic rocks is defined by a parallel alignment of K-feldspar augen and biotite flakes, and locally a mineral lineation of recrystallized quartz and feldspar material. The foliation is subvertical and has a strike of approximately 062. The lineation is subhorizontal within that plane. Within that lineation, an oblique grain shape fabric indicates dextral shear (Lister and Snoke, 1985). Well developed core-mantle structures on feldspar augen yield material for asymmetric tails on porphyroclasts; these asymmetric tails indicate dextral shear (Simpson and Schmid, 1984). The slightly retort shape of these recrystallized tails suggests that recrystallization proceeded under retrograde conditions at approximately an order of magnitude slower rate than the deformation (Passchier and Simpson, 1986) Additionally, augen fractured and offset along mineral cleavage planes indicate dextral shear sense. Quartz is not a matrix mineral in these

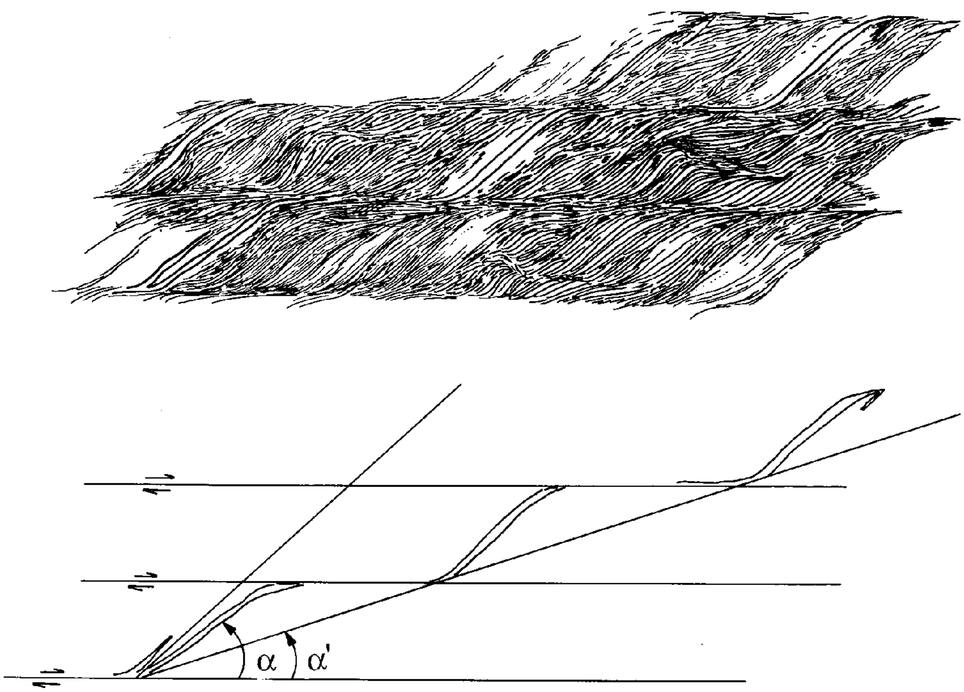

Figure 4-5. Using a foliation parallel quartz vein offset by slip on crenulation to estimate shear strain of lines parallel and perpendicular to crenulation, in a plane normal to crenulation axes. In this sample from the Ridge Road zone, assuming that the quartz vein is parallel to foliation surfaces (a) and that it is the same quartz vein that we see deflected across at least two NSC surfaces (a'), then we can estimate the shear strain due to slip on crenulation, using the relation-ship g = cot a - cot a': cot(19°) - cot(42°) = 1.8. So the shear strain of lines parallel and perpendicular to crenulation in the plane normal to crenulation axes due to crenulation slip is about 1.8.

granitic gneisses, so the orientation of a quartz crystallographic fabric may not be used as a shear sense indicator, though it has been tested.

North of the Modoc zone, a prominent splay of the Irmo shear zone cuts an up-to-3 km thick swath oriented at about N50E through granitic rocks of the Clouds Creek complex. Within this splay, foliation is variably developed, and locally normal slip crenulations deform this foliation. Again, foliation is defined by the parallel alignment of augen and biotite flakes and is typically penetrative only to the mesoscopic scale. Fracture patterns and asymmetric tails on feldspar augen suggest dextral movement. Normal slip crenulations are defined by discontinuous surfaces of biotite spaced at irregularly wider increments than foliation, into which that foliation is deflected. While the biotite flakes defining crenulation surfaces do appear shredded, they are typically not retrograded to chlorite.

The apparent back-rotation of foliation in button schists

In the sheared pelitic rocks of the Irmo shear zone, foliation is consistently penetrative to the microscopic scale while crenulations are penetrative only to the mesoscopic scale. In our interpretation, this helps to explain the apparent back-rotation of foliation between crenulation surfaces in button schists (Dennis and Secor, 1987b). Foliation slip may rotate crenulation planes, but crenulation slip, because it occurs on planes penetrative to the mesoscopic scale, can only translate foliation packets relative to one another. Therefore, in the case of NSC, as foliation slip progresses, the angle between NSC and foliation is expected to increase, while in the case of RSC, the angle the axial plane of the crenulation makes with the foliation is expected to decrease, resulting in highly appressed RSC folding, and an exaggerated intrafolial aspect (Fig. 4-6). Recognizing this effect in sheared pelitic schists suggests that in a plane normal to crenulation axes, the shear strain of lines parallel and perpendicular to foliation prior to deformation, as a result of slip on foliation surfaces, may be estimated by recognizing the rotation of crenulation surfaces by foliation slip.

Figure 7 presents angular relationships between NSC and foliation at sites where NSC was measured, and RSC and foliation in the Irmo shear zone. Often the shear strain across a crenulation surface may be estimated by recognizing the amount some marker, e.g., intrafolial quartz segregations, has been displaced across the crenulation (Fig. 4-5). If the angular relationship between the crenulations and the foliations they deform can be calibrated to shear strain across foliation, then we will have described the contributions of slip on foliation and crenulation to the overall shear strain of

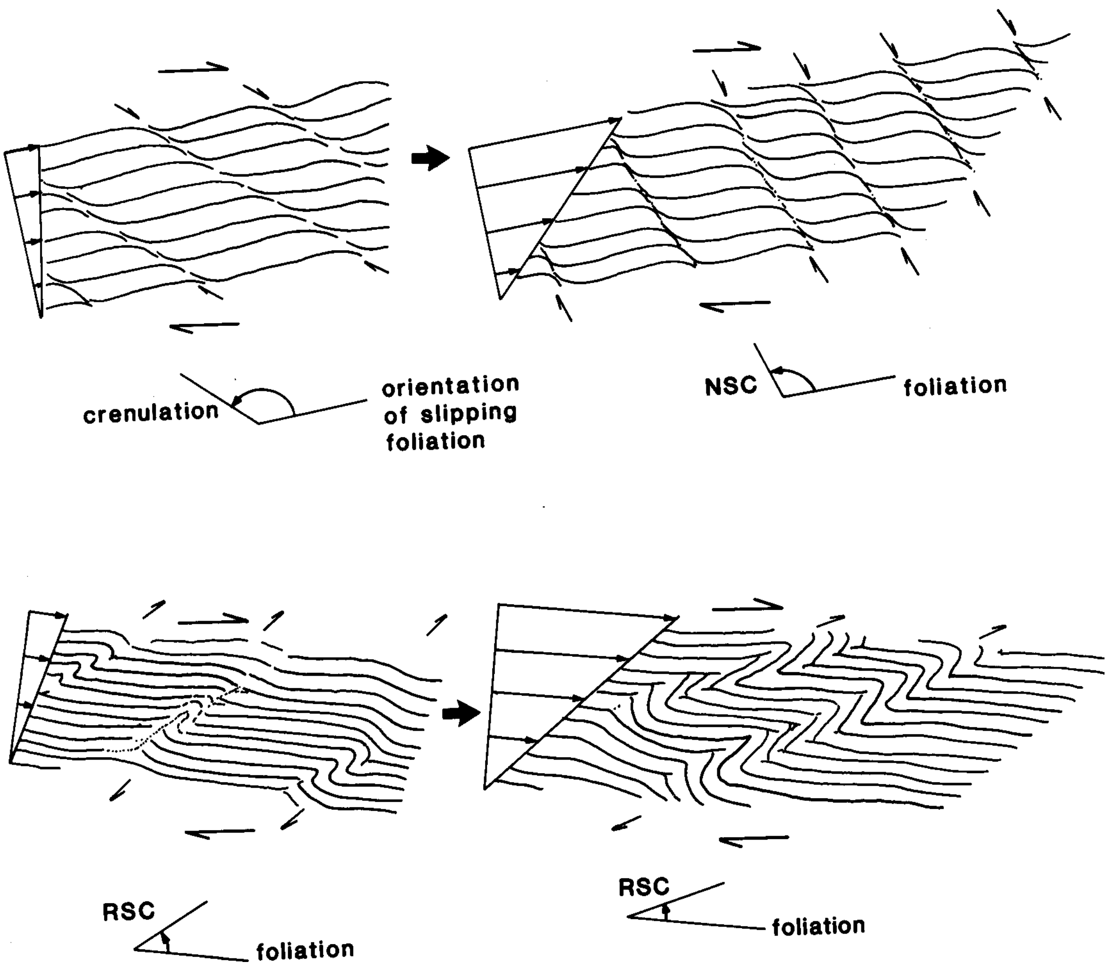

Figure 6. Because foliation, and therefore foliation slip, is penetrative to a finer scale than crenulation, finite slip on foliation surfaces, modelled by us as a simple shear, rotates crenulation surfaces relative to foliation, and early angular relationships are not preserved. Foliation slip shear strain may be estimated by the rotation of axial surfaces of crenulations. a) NSC surfaces' angles with foliation increase as a consequence of finite slip on foliation. b) RSC axial surfaces approach parallelism with foliation, as slip on that foliation continues.

the zone.

The results presented here are preliminary. Field evidence and the model suggest the RSC's initiate at an angle of Ý 50-60° to the foliation they deform, and as that foliation continues to slip, are rotated to within 20-30° of that foliation. Following Ramsay (1967, equation 3-71, also his fig. 3-24, p.88), the slip on foliation required to effect this rotation is calculated to be in the range g =1.3 to 2.0 (Fig. 4-6). Similarly, NSC is interpreted to initiate at an angle of 150-140° to the slipping foliation. This observation is in agreement with data presented by Boyer (1984) and Casas (1986). With progressive simple shear along that foliation, the NSC is rotated to an angle of 120-110° with that foliation. Again, modelling the slip on foliation as a homogeneous simple shear along folia surfaces, the finite shear strain along folia required to effect this rotation of NSC is in the range 0.5 to 1.4. That the angle NSC makes with its foliation can be rotated by such a small foliation slip shear strain may explain the apparently more normal, less skewed distribution of the NSC angle histogram. Furthermore, the apparent back rotation of foliation slip surfaces in button schists may be enhanced by the development of a penetrative fabric, as a consequence of a simple shear acting parallel to the boundaries of the zone, which will rotate NSC surfaces clockwise more rapidly than the foliation they crenulate. In any case, it seems reasonable to consider the shear strain of lines parallel and perpendicular to foliation, in a plane normal to crenulation axes, to be approximately equal to 1. This seems in good agreement with finite shear strains of 1 to 2, recognized by displaced marker horizons, for lines parallel and perpendicular to crenulation, in the plane normal to crenulation axes. This suggests that the contribution of foliation and crenulation slip shear strains to the overall shear strain of the Irmo shear zone is probably less than g = 3. This is consistent with shear

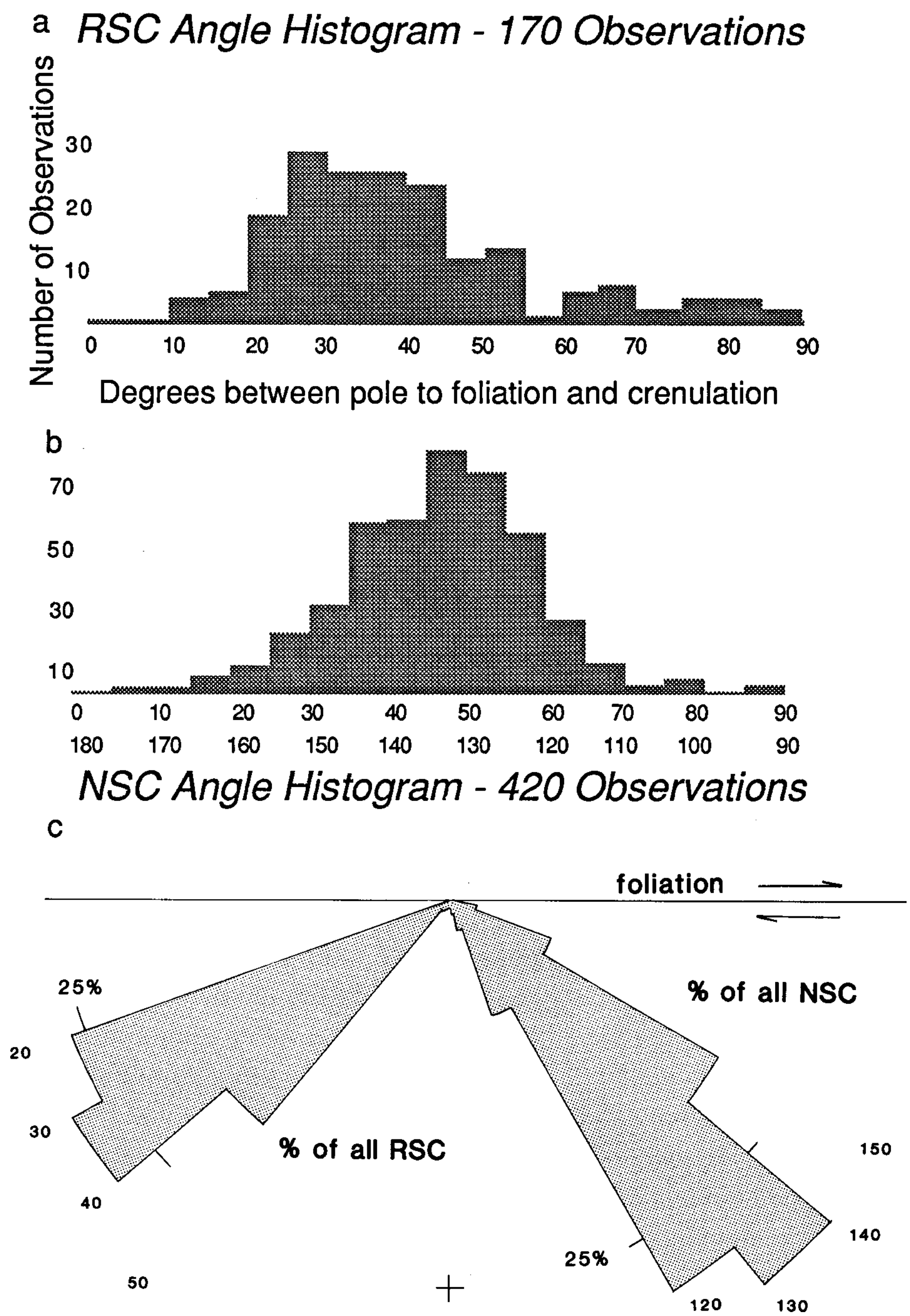

Figure 7. Angle-frequency histogram for the angle between foliation and crenulation for RSC (a), and NSC (b). c) The same data plotted as a rose diagram with 10° petals normalized to a common foliation. Angle measure shown on the perimeter of the diagram follows the convention drawn in Fig. 4-6. These graphs were prepared by calculating poles to foliation and crenulation at a given location, taking the dot product of these poles, then calculating the Arccosine of the dot product, equal to the angle between the two poles.

strain across the width of the zone of about 1, interpreted from the map pattern, or a dextral strike slip displacement of about 10 km.

In the vicinity of Clark Hill Lake, two subvertical zones of button schist with traces of about N68E have been recognized. These are informally referred to as the Ridge Road and Gundy Creek zones. An intense button schist fabric, defined by the intersecting NSC_4 and the foliation, distinguishes these zones which are developed primarily in quartz mica schists. Locally they contain RSC_4 and conjugate NSC. Development of D_4 crenulations is not restricted to these zones, but the crenulated fabric is not typically developed so intensely outside of them. A third domain of less intensely developed button schists is referred to as the Northern Clarks Hill Domain. Two stops on this trip visit sites within the Ridge Road and Gundy Creek zones (5 and 4). These sites demonstrate that with more intense NSC fabric development, the range of angles foliation makes with crenulation increases, i.e. slipping crenulations continue to initiate as "more mature" ones, those with greater and greater angles, continue to evolve.

While this interpretation, that an increasing angle between NSC and foliation surfaces in pelitic schists represents an increasing foliation slip shear strain, is perhaps unconventional (see Simpson, 1984, or Gates and others, 1986), it is no less valid than a model that suggests that a smaller angle between foliation and crenulation planes represents a higher shear strain. In contrast a more conventional model predicts that with increasing shear strains, the angle between foliation (S) and crenulation (C) decreases (Berthe and others 1981, p.33-34). S is interpreted to initiate at 45° to the zone boundary, and C is interpreted to initiate and remain subparallel to the zone boundary. With progressive homogeneous deformation, S is interpreted to track the XY plane of the finite strain ellipsoid, rotating towards C, until the two surfaces are indistinguishable. Based on our mapping we have several objections to this model: 1) crenulation surfaces occur at finite angles to the mapped zone boundaries. 2) In the zones where normal slip crenulations are best developed, for example the Ridge Road and Gundy Creek zones in the Clark Hill area, at any given outcrop a broad range of foliation crenulation angles are recorded from 20-30° up to 60-70°. 3) At sites where crenulations are developed, foliations lie within 10° of the interpreted zone boundaries. It is hoped that the evidence in support of our hypothesis will lead workers to consider it in their evaluation of shear strain in crenulated pelitic schists. It is possible that both models are valid under different conditions. We have here presented evidence that suggests that in sheared anisotropic rocks, with increasing foliation slip the angle between foliation and normal slip crenulations should increase.

CONCLUSIONS

Along the fall line in the Southern Appalachians, a record of late Alleghanian dextral strike slip reactivation of early Alleghanian and older features is preserved. Reactivation was effected as the older features were rotated into steep orientations by ramp folding contemporary with folding and thrusting in the Valley and Ridge. The late Pennsylvanian and Permian ages of this strike slip deformation suggest that it is a late stage, intraplate readjustment to collisional stresses, and not generally a response to transpression or "tectonic escape." Furthermore, while large scale strike slip movement is well known in the Piedmont, the rotation of early flat-lying features, e.g., isograds, decollements, into subvertical orientations documents the role of dip slip movements in the metamorphic core of the orogen.

In the eastern South Carolina Piedmont specifically, the Irmo shear zone overprints the Modoc zone. Nominally over 150 km along strike and up to 10 km in width, the Irmo shear zone experienced about 10 km of dextral strike slip movement in the late Paleozoic. Overprinting relationships and geochronologic studies confirm that this shearing was the last ductile deformation in the Piedmont. Along its length the Irmo shear zone overprints previously unfoliated granitic rocks, well cleaved, greenschist facies metavolcanics and metasediments, and amphibolite facies ortho- and paragneisses. Many mesoscopic shear sense indicators are present in these rocks, and they consistently show dextral shear. These mesoscopic structures include asymmetric, recrystallized tails on feldspar augen, fracture and sinistral offset along feldspar cleavage planes, and the development of zone-orientation-and-width-preserving reverse and normal slip crenulations. Crenulation planes are steeply dipping, and axes are steeply plunging. Subhorizontal mineral lineations developed in orthogneisses suggest strike slip transport, and subgrains typically show an dextral, oblique grain shape fabric.

In this report, we have presented evidence that foliation slip shear strains may be estimated by looking at the angle crenulation, penetrative to only the mesoscopic scale, makes with microscopically penetrative foliation in sheared strongly anisotropic rocks. Microscopically penetrative foliation slip will rotate normal slip crenulation planes so that the angle between foliation and crenulation increases with progressive foliation slip. This results in apparently back-rotated foliation surfaces between crenulation planes. Similarly the angle between reverse slip crenulations and foliation deceases with progressive deformation, resulting in an increasingly intrafolial aspect to these folds. A consequence of this effect may be a misunderstanding of a region's deformation chronology, and an assignment of the most recent folds to an "early isoclinal phase." If the shear strain along crenulation surfaces may be estimated using offset marker horizons, then contribution of foliation and crenulation slips to the overall shear strain of the zone may be calculated.

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CAROLINA GEOLOGICAL SOCIETY
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ROAD LOG FOR SATURDAY AND SUNDAY

NOVEMBER 14-15, 1987

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NOTE: All field trip stops are on the following U.S.G.S. 7 1/2 minute quadrangles: Appling, Clarks Hill, Evans, Leah, Martinez, and Parkville.

Distance between points	Cumulative distance (miles)	
0.0	0.0	The road log begins at the lodge at Hickory Knob State Park on Clark Hill Lake near McCormick, SC.
		Proceed southeast along park road toward park entrance.
3.8	3.8	Entrance to Hickory Knob State Park. Turn right and proceed southeast on SC-7 toward US-378.
1.6	5.4	Junction SC-7 and US-378. Turn left on US-378 and proceed east toward McCormick.
1.1	6.5	Bridge over Little River branch of Clark Hill Lake.
0.9	7.4	Entrance to Baker Creek State Park.
3.7	11.1	Outcrop of felsic metatuff of the Carolina slate belt on the left.
0.1	11.2	Downtown McCormick. Intersection of US-378 with US-221/SC-28. Turn right and proceed south on US-221 toward Plum Branch. McCormick was a local center for gold mining during the 19th century.
4.8	16.0	Plum Branch. Turn left on SC-283, cross over railroad tracks and proceed east through town towards Stevens Creek.
2.0	18.0	**STOP 1:** Bridge over Stevens Creek. At this locality we are in a band of felsic metatuff [Persimmon Fork Formation(?); Figs. 1-2, 2-1]. The best exposure is just below the dam, in the creek bed, north of the highway bridge (Fig. 5- 1a). The rock here is a felsic crystal-lapilli tuff (probably an ashflow). It has been strongly overprinted by static contact metamorphism that postdates the development of the tectonic fabrics in the tuff. This contact metamorphism may be related to the parent magma body which fed the small mafic dikes that can be seen in the adjacent highway roadcuts. The primary features of the tuff and the secondary tectonic features are best seen on slightly weathered surfaces in the outcrop in the creek (Fig. 5-1b). The rock contains a strong foliation that is defined by the plane of flattening of lapilli. This foliation is interpreted to be at least in part primary (S_0) and due to collapse of pumice lapilli during ashflow emplacement. This primary foliation may have been enhanced and/or transposed by subsequent tectonic strain. Careful scrutiny of the creek outcrop reveals that there are numerous mesoscopic folds varying from open to subisoclinal. These are interpreted to have developed at various times during a protracted D_1 deformation. The tight folds have S_1 (c. N40°E 85°NW) as their axial surface. S_1 may be folded by some of the later more open folds, and locally a weak second cleavage is developed. The plunge and vergence of F_1 folds are variable.

Except for the contact metamorphism, this rock is typical of the Persimmon Fork Formation (c. 550-565 Ma) which outcrops widely in the slate belt of central and western South Carolina. This particular belt of Persimmon Fork is flanked on the northwest and southeast by belts containing intermediate to mafic metavolcanic rocks, metamudstone, and metawacke in varying proportions (Figs. 1-2, 2-1). These flanking belts are interpreted to be Richtex Formation in synformal structures. The stratigraphic relationship

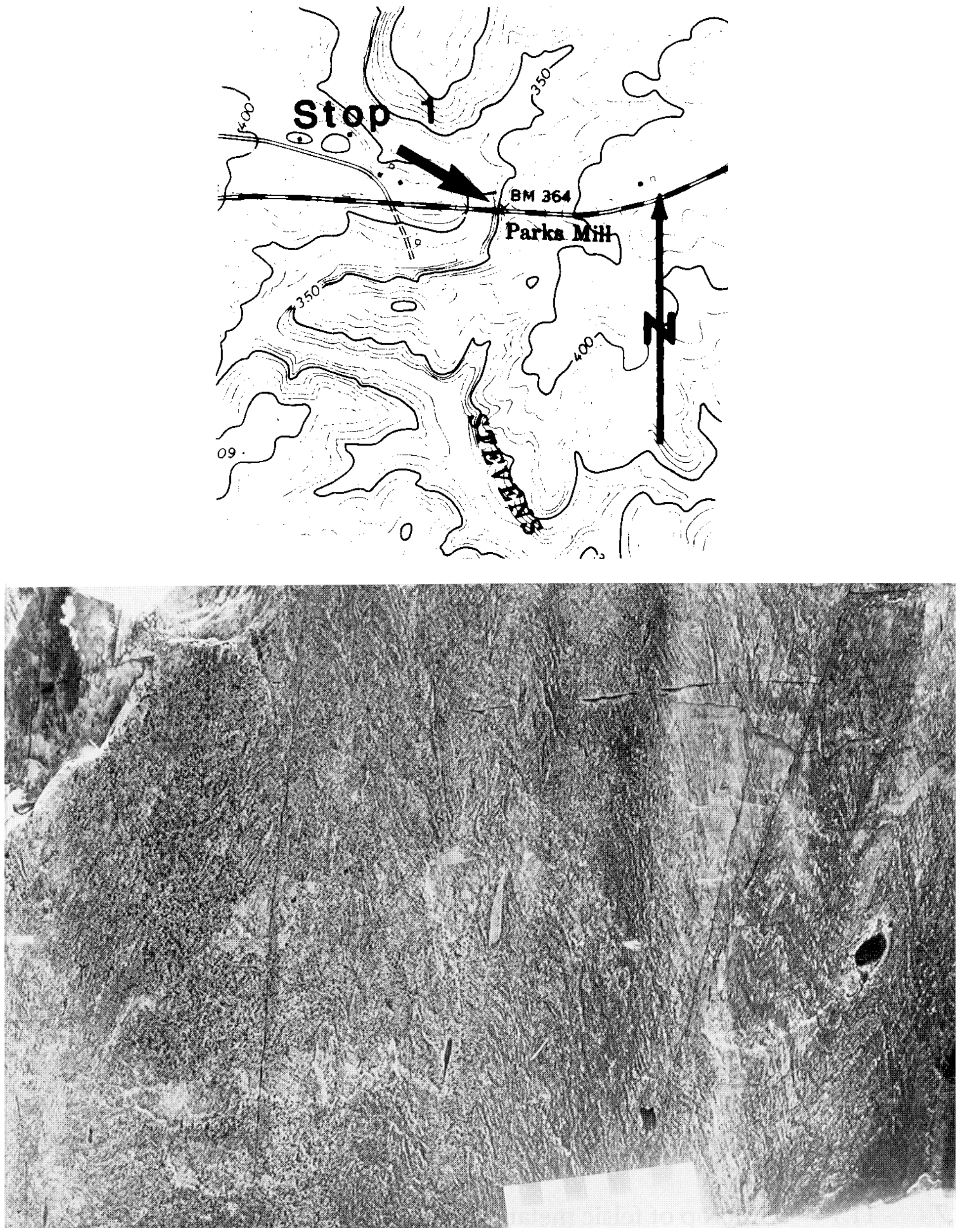


Figure 5-1. a) Map from Parksville quadrangle (scale 1: 24,000) showing location of outcrop at Stop 1. b) Weathered vertical outcrop face at Stop 1 showing lapilli and folds.

between the Richtex and Persimmon Fork is uncertain. Secor (this volume) favors an interpretation wherein the Richtex is allochthonous and the contact between the Richtex and Persimmon Fork is an early syntectonic (D_1) fault.

Turn around and proceed west along SC-283 to Plum Branch.

2.1 20.1 Plum Branch. Turn left on US-221 and proceed south.

5.3 25.4 Parkville traffic light.

2.0 27.4 Modoc Speedway.

0.3 27.7 Hamilton Branch State Park.

1.7 29.4 Hutto's Sporting Goods. Turn left on SC-23 and proceed toward Edgefield.

1.3 30.7 Bridge over Stevens Creek.

2.2 32.9 Turn left on national forest road 631. Proceed to turn-around area at the end of the road, and park.

Follow footpath for several hundred feet down

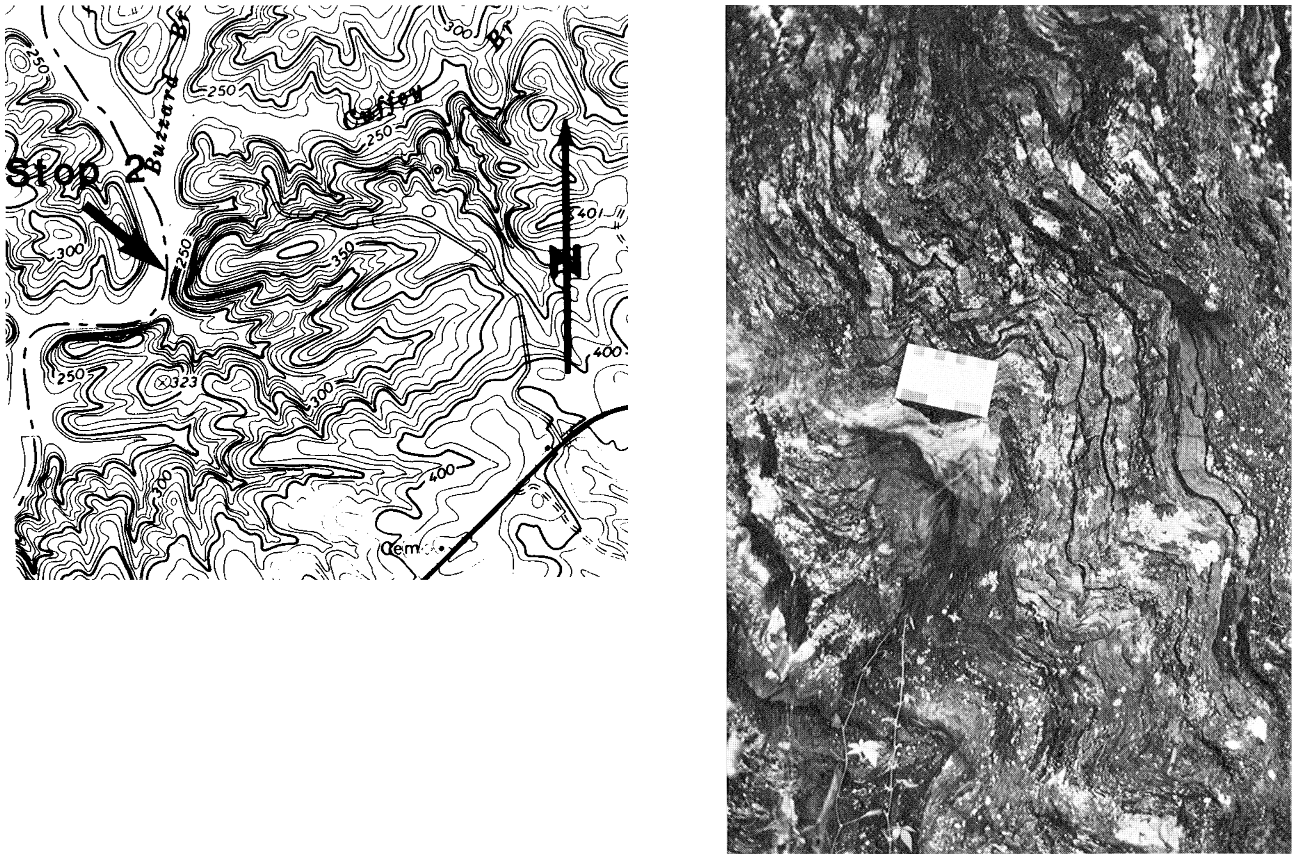


Figure 5-2. a) Map from the northern portion of the Clarks Hill quadrangle (scale 1: 24,000) showing the location of the outcrops at Stop 2. Outcrops include cliffs and ledges above the flood plain on the east side of Stevens Creek in addition to outcrops in the creek bottom. b) Photo of cliff face at Stop 2 showing typical F_2 (RSC_2) folds; north is to the left in the photo. Note that F_2 axial surfaces dip northwest more shallowly than compositional layering in the quartzites.

to the floodplain of Stevens Creek (bear to the left where the trail bifurcates). Proceed for about 600 feet south along the floodplain through poison ivy and stinging nettles to cliff outcrops on the east side of the floodplain.

STOP 2: Outcrops of quartzites and quartz-sericite schists of the Asbill Pond formation occur as cliffs and ledges on the slope along the Stevens Creek floodplain (Fig. 5-2a). Additional outcrops are present in the creek banks and as a pavement in the creek bottom. These outcrops display features typical of the northern part of the Modoc zone.

The numerous mesoscopic folds here are characterized as antiform/synform pairs in which the axis of the antiform is located southeast of the axis of the synform (Fig. 5-2b). The fold hinges plunge gently southwest and the axial planes dip northwest less steeply than the S_0 layering in the quartzites and schists. These folded rocks are located in the southeast limb of the Saluda synclinorium (F_1) and the northwest limb of the Kiokee antiform ($F3_)$, yet the observed geometry of these mesoscopic folds is not compatible with them being parasitic to either the regional F_1 or F_3 folds. With careful observation, particularly in the northern of the cliff faces, it can be seen that the typical northwest vergent antiform/synform pairs deform small, earlier formed folds; these folded folds do have a sense of vergence compatible to be parasitic F1 on the southeast limb of the Saluda synclinorium. Elsewhere in the Modoc zone, rocks containing the northwest vergent folds are folded by mesoscopic to macroscopic folds that are parasitic on the Kiokee antiform (F_3). Because of these overprinting relationships, the northwest vergent folds are interpreted to be F2, and more specifically they are interpreted to be reverse slip crenulations or RSC_2 (Fig. 4-4). As $RSC_{2,}$ these folds indicate a north-side-down sense of shear for the Modoc zone.

Although F_2 folds are the most prominent features present in this outcrop, other structures are also present. Flat or gently sloping outcrop surfaces display D_4 normal slip crenulations (NSC_4). It should be noted that both the NSC_4 and the foliation (DSF_4) that is crenulated are oblique to the overall strike of the compositional layering that contains the crenulations. The foliation is always oriented at a small angle counterclockwise from the strike of the layering, and the crenulation is at a small angle clockwise from the strike of the layer; this relationship indicates dextral strike slip. It is also worth noting that small markers (e.g. small quartz veins) parallel to the foliation are offset in a dextral manner by the crenulations. Although D_4 crenulations like these are more pervasively developed elsewhere (see Stops 4 and 5), the development of these textures here is typical of the style by which the Irmo shear zone overprints the Modoc zone.

Follow national forest road 631 back out to SC-23.

2.0 34.9 Turn right on SC-23 and proceed toward Modoc.

2.2 37.1 Bridge over Stevens Creek. Park just beyond the west end of the bridge and walk west along SC-23 to powerline crossing. Walk south along the powerline. At the first pole beyond the small brook, turn left and follow gully downhill to outcrop along brook (Fig. 5-3a).

STOP 3: The good-sized, unweathered, stream pavement and bank outcrop at this locality is not uncommon in this area. Stream dissection on either side of Steven's Creek and along Gundy Creek in Clark Hill quad has downcut through the saprolitic cover to fresh bedrock. Mapping along roads, which typically follow topographic ridges where saprolitic cover is at its thickest, gives a false impression of outcrop quality in this part of the Piedmont. Hence it is imperative when mapping in the Piedmont to walk all the streams possible.

The highly strained leuco-orthogneiss exposed at this locality is representative of many aspects of the intrusive activity and deformation that defines, in part, the Modoc zone. The orthogneiss here consists of quartz, plagioclase, and K-feldspar with 1% or less green-brown biotite, muscovite and opaque oxides. Common alteration minerals are epidote, chlorite and a very fine-grained sericite. This outcrop locality occurs within the northmost and largest (map width of ≈ 1 km and minimum strike length of 14 km) orthogneiss sheet within the Modoc zone (Plate 1). Elsewhere in this same sheet a garnet-rich, muscovite orthogneiss and a biotite rich (1-2%) orthogneiss occurs. Either the sheet consists of several intrusions of slightly different compositions or local contamination by country rocks has produced the compositional variations. Based on field observations, the garnet muscovite orthogneiss is found adjacent to the pelitic quartz-sericite (qs) unit (Plate 1) and the biotite orthogneiss is usually found adjacent to biotite-amphibole gneisses. This correlation is suggestive of, perhaps, some contamination.

The fabrics evident at this outcrop are a strong, subhorizontal, elongation lineation, a weakly to moderately developed, steeply-dipping foliation, and local small folds of the foliation. The elongation lineation is manifest as recrystallized tails of quartz and feldspar with a central small augen of feldspar (Fig. 5- 3b). While commonly an asymmetry to the augen tails is difficult to discern, it is consistently dextral where apparent (e.g. east end of outcrop at this locality). A strong subhorizontal, dextral elongation lineation would be consistent with D_4 kinematics, but the evidence points to a D_2 age. Map scale F_3 clearly fold some of the orthogneiss sheets (Plate 1) and hence the lineation was clearly D_2 or earlier. The extensive recrystallization of quartz and feldspar is compatible with M_2 peak metamorphic conditions, but is incompatible with the low or sub-greenschist facies conditions of D_4. The orthogneiss sheets were probably relatively competent bodies by the time of D_4. D_2 strain was partitioned into two components, and this elongation lineation (L_2) in the orthogneiss is one - the other component is thought to reside in the paragneisses (Sacks and Dennis, this vol.). Small folds of the orthogneiss foliation at the E end of the outcrop have a style that indicates they are RSC_2 - these probably developed late in the D_2 strain history.

Upstream and around the bend, outcrops of biotite-amphibole paragneiss occur. These are mapped as a country rock screen within the orthogneiss sheet (Plate 1). Screens of all sizes are common.

Turn around and proceed east along SC-23.

1.1 38.2 Turn right on S-19-384.

0.6 38.8 At "T" intersection turn right on S-19-139. Out-

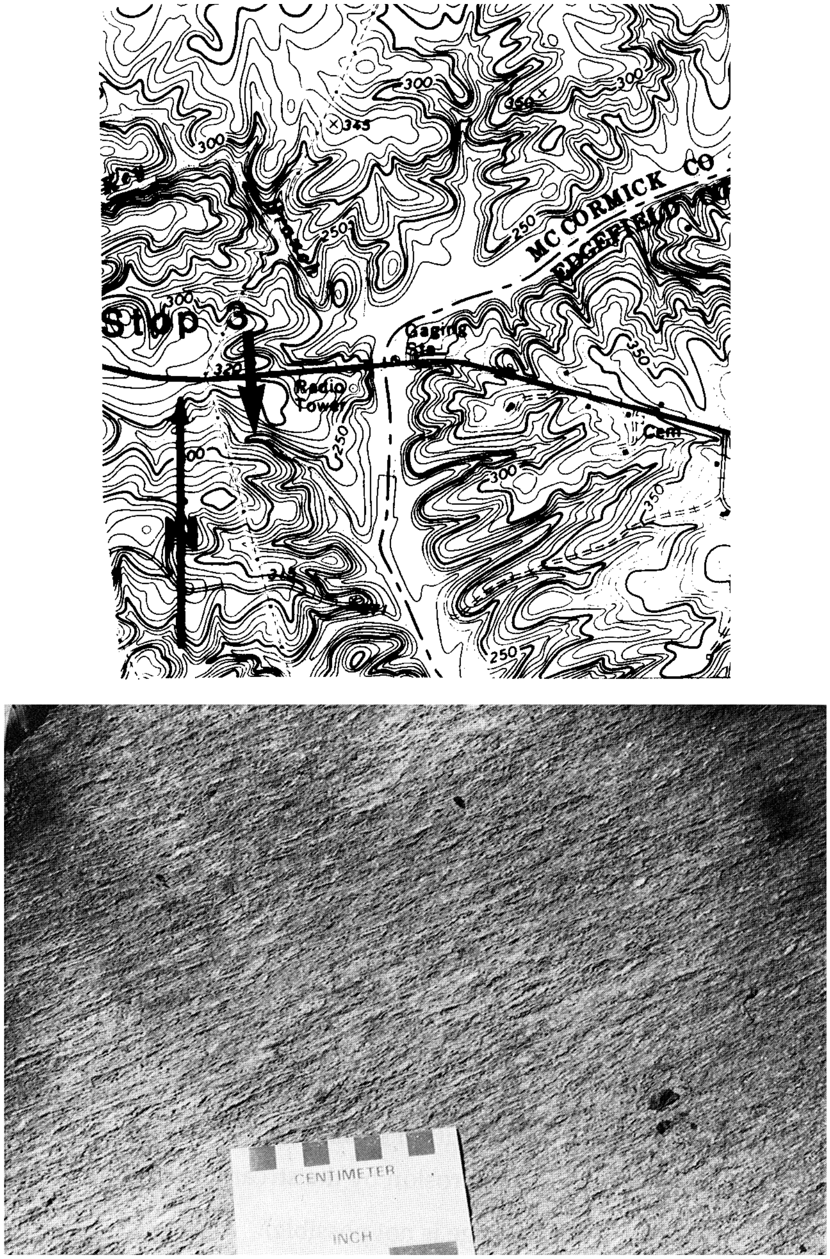


Figure 5-3. a) Map from the north-central part of the Clarks Hill quadrangle (scale 1: 24,000) showing the location of the outcrop at Stop 3. b) Subhorizontal pavement of orthogneiss with prominent L_2. Note dextral sense-of-shear on some of the small augen.

crop of Carboniferous orthogneiss on right.

1.6 40.4 Bridge over Gundy Greek.

STOP 4: This location (Fig. 5-4a) contains good exposures of three rock types: a sericite phyllite of the `button schist' zone; a thin band of orthogneiss; and the biotite-amphibole gneiss. Outcrop is nearly continuous for more than 100 meters downstream from the bridge (Fig. 5-4d). Similar stretches of outcrop occur further upstream and downstream.

Normal slip crenulations (NSC_4) are well-developed in the `button schist'. Crenulations are spaced two to four centimeters apart, and are oriented clockwise to the dominant slip foliation (alignment of micas). This unit also contains several tectonic inclusions: isolated small bodies composed primarily of alkali feldspar, quartz, and small tourmaline crystals. The inclusions are frequently elongate in the dominant slip foliation plane, and the size ranges from 5

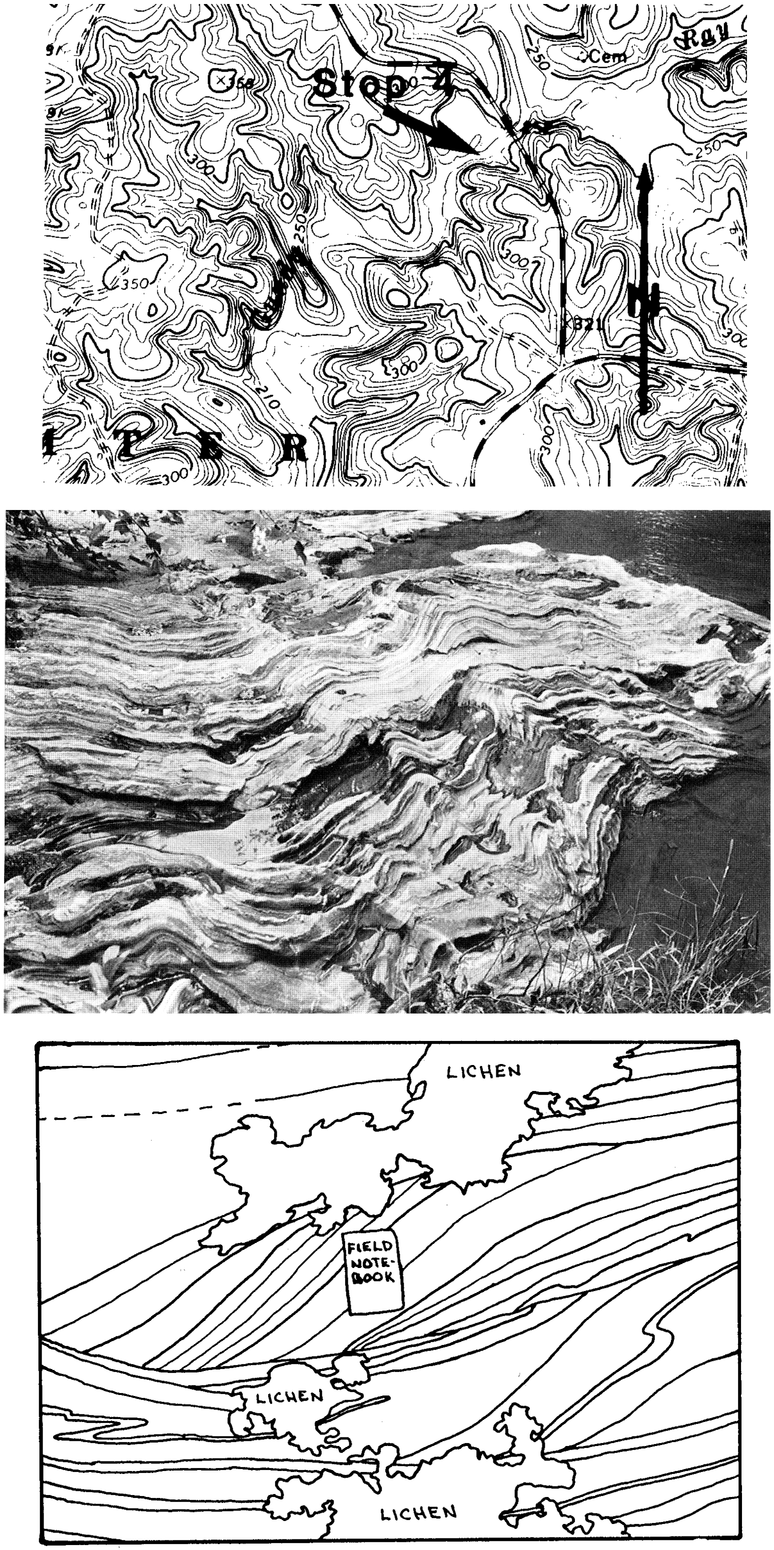
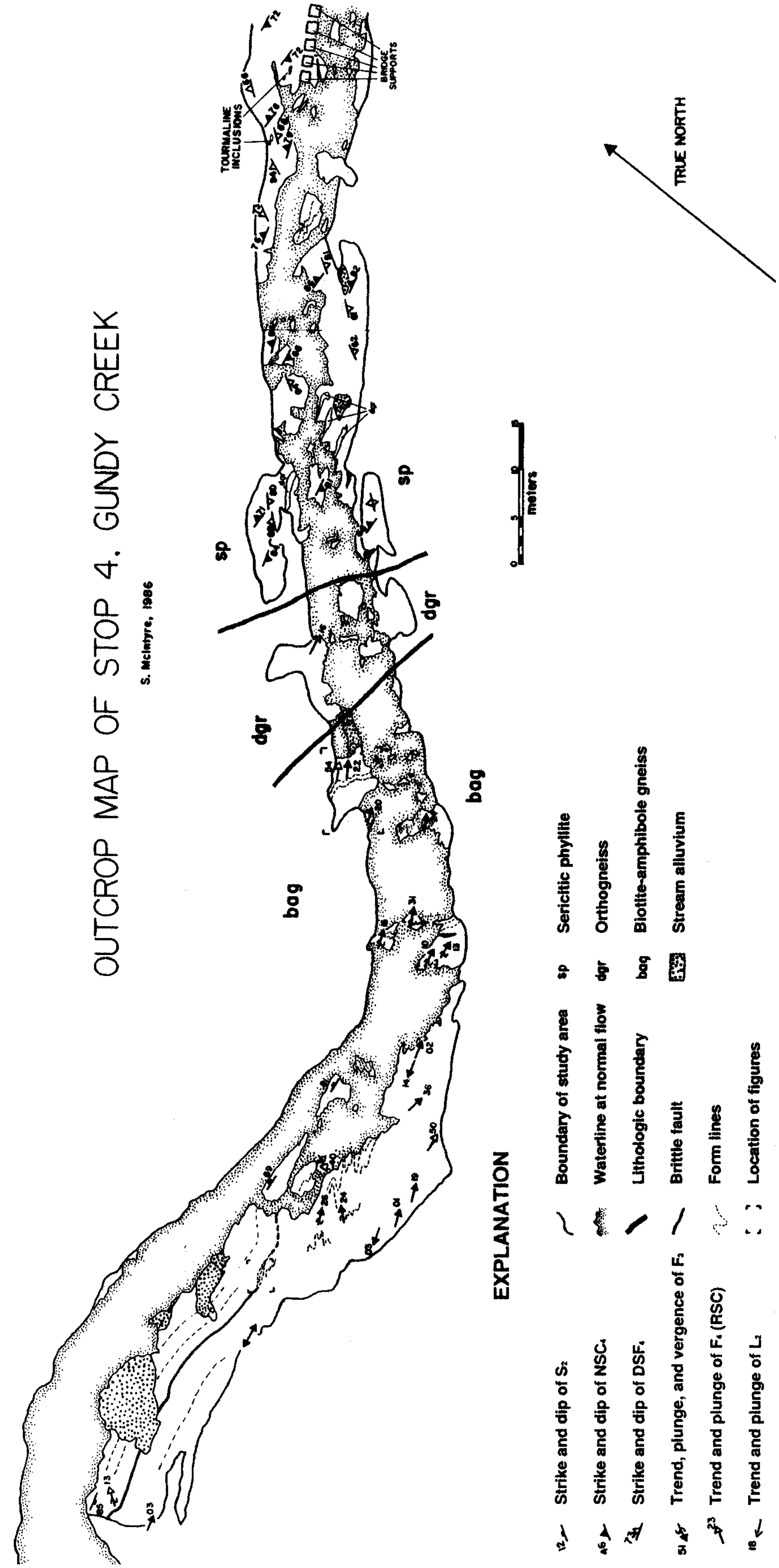


Figure 5-4. a) Map from the eastern part of the Clarks Hill quadrangle (scale 1: 24,000) showing the location of outcrops in Gundy Creek at Stop 4. b) Photo showing series of folds in biotite amphibole gneiss at Stop 4. The dextral overall fold sense coupled with a moderate plunge indicate these could be folds that formed in a D_3 to D_4 transition period. Location marked in central part of the outcrop map. c) NSC-style foliation lozenge found along brittle fault in biotite amphibole gneiss. Location is marked in the south-western end of the outcrop map. d, next page) Outcrop map of Stop 5.



OUTCROP MAP OF STOP 4, GUNDY CREEK
S. McIntyre, 1986
TOURMALINE INCLUSIONS
BRIDGE SUPPORTS
TRUE NORTH
sp
dgr
bag
meters
EXPLANATION
Strike and dip of S_2
Strike and dip of NSC_4
Strike and dip of DSF_4
Trend, plunge, and vergence of F_2
Trend and plunge of F_4 (RSC)
Trend and plunge of L_2
Boundary of study area
Waterline at normal flow
Lithologic boundary
Brittle fault
Form lines
Location of figures
sp Sericitic phyllite
dgr Orthogneiss
bag Biotite-amphibole gneiss
Stream alluvium

to more than 40 centimeters. Thin, alkali feldspar-rich layers exhibiting small dextrally-verging folds occur in the southern portion of the button schist. These folds appear to plunge steeply to the northeast, and are probably F_4 in nature. (Erosion by the stream has produced a smooth, 2-dimensional surface; measurement of actual plunge is not possible)

The thinnest unit here is the orthogneiss. Composed primarily of alkali feldspar, micas, and small tourmaline crystals, this rock is foliated, crenulated and lineated. The lineation trends N78E, plunges 16^o, and is apparent as an elongation of minerals. In association with the crenulations, numerous small faults, with dextral shear of the gneissic fabric, are present. Thin bodies of orthogneiss that extend into the button schist near the contact vary in thickness from about 10 to more than 50 centimeters, and are up to three meters long.

The biotite-amphibole gneiss comprises more than half of the outcrop at this location. The effects of S_2 deformation are manifested as compositional layering and mineral alignment in these rocks. Very thin, more felsic bands alternate with thin mafic-rich layers, making even small folds easily visible (Fig. 5-4b). There appears to be a transition between F_3 and F_4 folds, evident by a continuous range of fold axes oriented from horizontal to steeply plunging. In several places, shallowly-plunging F_3 fold surfaces have been refolded by steeper F_4 folds. F_4 deformation here does not seem to be severe; F_4 folds have produced wrinkles on the F_3 folds, but have not obscured them.

A brittle fault surface is present in the lower portion of the outcrop. Small folds of compositional layers to the south of the fault are truncated, while layers to the north are concordant. Small quartz bodies are found along the fault surface, as well as fine-grained chlorite. Minor antithetic faults to this brittle fault are present at some places. Small, quartz-filled fractures, generally perpendicular to compositional layering, are also found in this area. A large dextral NSC structure is located along the fault (Fig. 5-4c).

The effects of the various deformational episodes are well-preserved in the rocks at this location. Textures in the 'button schist' are dominated by D_4 structures, while the more competent orthogneiss and biotite-amphibole gneiss show a superposition of D_2, D_3, and D_4 structures.

Continue south along S-19-139.

0.5 40.9 Turn right on S-19-143 and proceed toward Clarks Hill.

3.0 43.9 Town of Clarks Hill. Cross railroad tracks and turn right on SC-28.

0.3 44.2 Turn left toward Clark Hill Dam on US-221.

1.0 45.2 Visitors center, Clark Hill Dam (powerhouse tours available).

0.2 45.4 East end of Clark Hill Dam. As we travel across the dam, you can see Burks Mountain and other hills underlain by ultramafic rocks on the skyline to the left.

1.1 46.5 West end of Clark Hill Dam.

3.6 50.1 Turnoff to Petersburg Campground.

2.1 52.2 Pollards Corner. Turn right and proceed north on GA-104 toward Leah.

2.3 54.5 Keg Creek Bridge. Migmatitic biotite amphibole gneiss on right.

1.8 56.3 Turn right on Ridge Road. Proceed east toward Ridge Road Campground.

4.4 60.7 Entrance to Ridge Road Campground.

0.1 60.8 Turn left into boat ramp parking area. Numerous outcrops are within walking distance.

STOP 5: Lakeshore exposures of sericitic phyllite (sp), quartz-sericite schist (qs) and amphibolitic biotite amphibole paragneiss (bag) occur along the north side of the peninsula (Fig. 5-5a). These rock units are some of the structurally lowest of rocks of Carolina slate belt affinity in the Modoc zone. Structures present in these outcrops illustrate the effects of D_2, D_3,and especially D_4. F_2 folds with nearly horizontal hinge lines are present in the quartz-sericite schist and the biotite amphibole paragneiss. Shallow northwest dips in the quartz-sericite schist are due to D_3 folding. These rock units here are also within the Irmo shear zone and have a D_4 crenulation fabric that overprints to varying degrees the other structures. The D_4 fabric is most strongly developed in the sericitic phyllite (Fig. 5-5b) and is least developed in the biotite amphibole paragneiss. The D_4 crenulation fabric consists of a northeast striking, and steeply dipping foliation (DSF_4) that is crenulated by an approximately east-west striking, and steeply dipping normal slip crenulation surface (NSC_4) (Dennis and Secor, 1987). Both of these D_4 fabric elements (DSF_4 & NSC_4) are

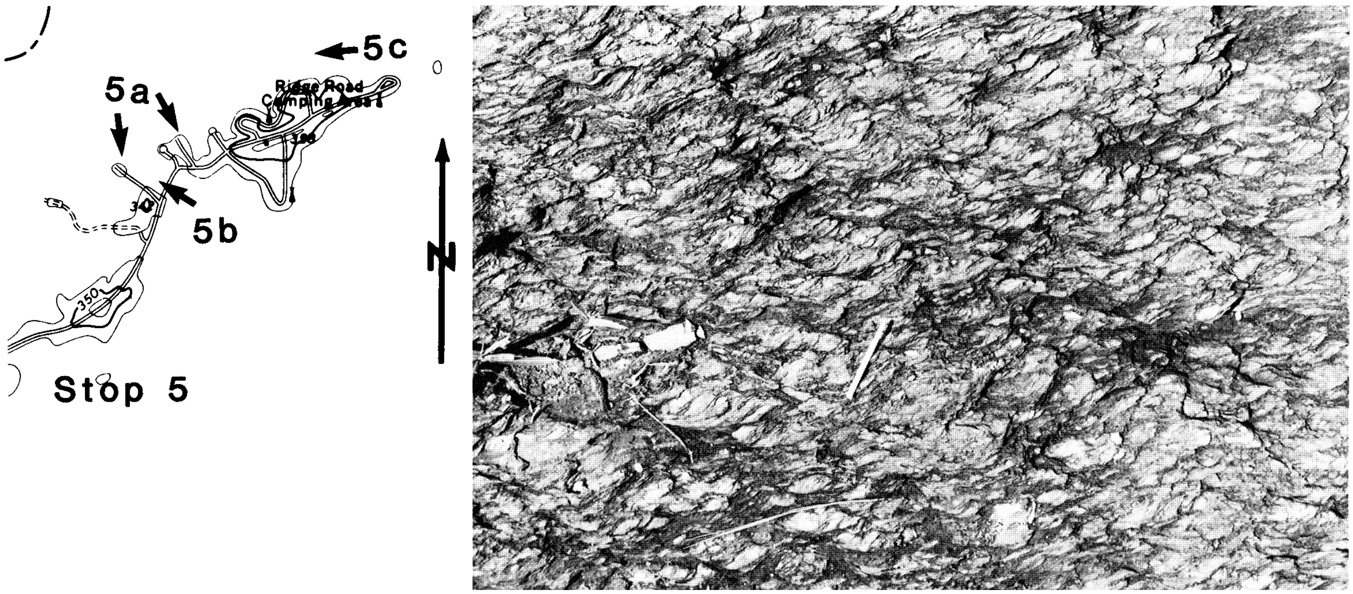


Figure 5-5. a) Map showing the location of the outcrops at Stop 5 in the eastern part of the Leah, GA quadrangle (scale 1: 24,000). 5A shows the location of outcrops of the crenulated sericitic phyllite (sp). 5B shows the location of outcrops of the amphibolitic biotite amphibole paragneiss, and 5C shows the location of outcrops of the quartz- sericite schist. Outcrops 5B and 5C may be concealed if lake levels are at 329' or higher (full pool). b) Photo showing crenulated sericitic phyllite, informally known as "button schist" at Stop 5. Toothpick which is 2 inches long, points north. Note that the penetrative foliation (DSF_4) strikes northeast, and the crenulation surface (NSC_4) strikes approximately east-west.

noticeably oblique to the zone boundaries (Plate 1). Dextral strike slip is the sense of shear indicated by the NSC_4.

The sericitic phyllite is well exposed at location 5A. This unit of pervasively crenulated phyllite, like the crenulated phyllite unit at Stop 4 (Gundy Creek) is traceable across the map area of Plate 1. This rock weathers to form "buttons," and this rock is informally known as a "button schist." Noteworthy features here include the discontinuous nature of the NSC_4 surfaces, and the angular relationship between the penetrative foliation and the spaced NSC_4 and the evidence of back rotation (Dennis and others, this issue). Locally, tightly folded quartzite veins or layers are present within the crenulated phyllite. Typically, only fold hinges are present, but in some cases, fold vergence can be determined. Some of the folds have approximately horizontal hinges and northwest vergence; these are probably RSC_2. Other folds have steeply plunging hinges and are dextral in plan view; these are probably RSC_4.

The biotite amphibole paragneiss at 5B is amphibole rich. The rock at this part of the outcrop weathers to elongate, splintery or pencil shaped fragments. The fold hinges are typically parallel to the long axis of the pencils. The long axes of amphibole needles are in many cases, but not all cases, parallel to fold hinges. The folds are characteristically tight isoclinal folds with highly attenuated or detached limbs.

At 5C, outcrops of quartz-sericite schist exhibit the overprint of the D_4 crenulation fabric on older structures. Here the interlayered quartzose schist and sericitic quartzite have shallow to moderate northwest dips. This is interpreted to be due to the position of these rocks on the shallow dipping part of an F_3 fold. Note that although DSF_4 and NSC_4 are present, they are much less developed here where foliation has a shallow dip than in the sericitic phyllite to the south. The D_4 crenulation fabric is best developed in steeply dipping limbs of F_3 folds.

A few small RSC_2 are present in these rocks. These are difficult to find because of the overprint of D_4 crenulations. These are most easily found by examining steeply northeast or southwest sloping outcrop faces.

Turn around and proceed west along Ridge Road toward GA-104.

4.5 65.3 Turn right on GA-104 and proceed to the north.

0.5 65.8 Downtown Leah. Junction GA-104 and GA-47.

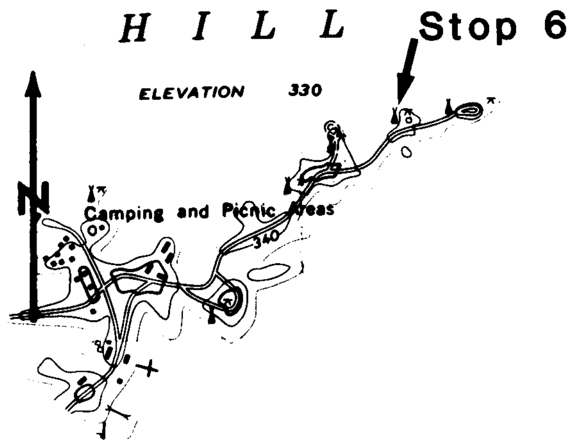


Figure 5-6. Map showing the location of the outcrops at Stop 6 in the central part of the Leah, GA quadrangle (scale 1: 24,000). Parking is available at Camping Area #6 and the outcrops are along the lakeshore around this point.

Continue north (straight ahead) on GA-47.

0.7 66.5 Turn right into entrance to Fort Gordon Recreation Area (also known as Clark Hill Recreation Area). Proceed east along park road toward picnic area.

1.3 67.8 Operations center, check in with park superintendent.

0.2 68.0 Bear right on Pike Avenue.

0.8 68.8 Park in camping area number six. Outcrops on north side of peninsula.

STOP 6: These lakeshore outcrops (Fig. 5-6) display rocks and structures characteristic of the northern part of the Modoc zone in this area. These rocks are located structurally on the northwestern limb of the Kiokee antiform (F_3) and the southeastern limb of the Saluda synclinorium (F_1). The trace of the fold axis of the Saluda synclinorium is located about 1 km to the north in the middle of the Little River arm of Clark Hill Lake.

The rocks here consist of bedded volcaniclastic sediments of the Persimmon Fork formation (mv2 on Plate 1, and OAL(C,–)pf2 on Fig. 1-2). These rocks include felsic crystal tuff, lapilli tuff and mafic tuff with interlayers of brown pelitic schist. Quartz-sericite rich pelitic schists, silver-grey in color are also present, particularly in the southern parts of the outcrop. Several small lenses of boudins of pink felsic orthogneiss are also present here. These are some of the northernmost orthogneisses in the Modoc zone. Larger, map scale orthogneiss sheets are abundant approximately 1 km to the south (Plate 1).

Compositional layering here is S_0, and the layer-parallel foliation (S_1) is defined by flattened lapilli and aligned micas. A second foliation (S_2) is overprinted on $S_0||S_1$. The S_2 foliation is approximately axial planar to the numerous shallowly southwest plunging folds (F_2). S_2 dips moderately northwest and defines a prominent parting surface in the outcrops. Like the F_2 folds seen in other stops, the folds here deform $S_0||S_1$ into northwest vergent antiform/ synform pairs (Fig. 2-2). In each fold pair, the antiform axis is located southeast of the synform axis, the fold axes plunge gently southwest and the axial planes dip moderately northwest. The folds are intrafolial. Like at Stop 2, these folds here are interpreted to be RSC_2 and they indicate a north side down sense of shear.

In addition to D_2 deformation as part of the Modoc zone, these rocks were also deformed during D_4 as part of the Irmo shear zone. Many of the pelitic rocks here show an overprint of DSF_4 and NCS_4. In some places, competent layers of tuff between incompetent pelitic layers are offset dextrally along east-west striking NSC_4-like faults; the faults merge parallel to foliation in the crenulated schists. Where schists contained earlier D_2 structures, the overprint of D_4 crenulations has produced complicated and contorted structures. This is the case in the schists in the southern part of the outcrop.

Turn around and proceed back to GA-47.

2.2 71.0 Turn right on GA-47 and proceed north.

0.9 71.9 South end of causeway and bridge over Little River. Turn right into parking area at lakeshore.

STOP 7: Extensive outcrops are present both

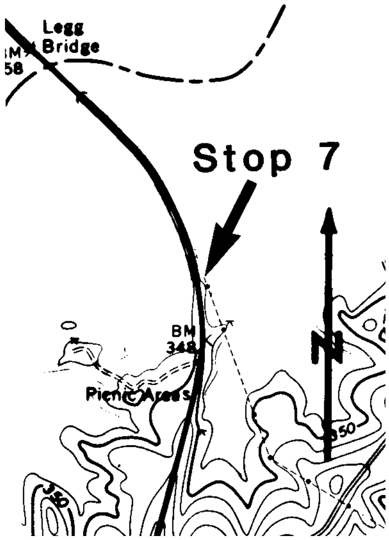


Figure 5-7. Map showing the location of the outcrops at Stop 7 in the central part of the Leah, GA quadrangle (scale 1: 24,000). Outcrops are on the lakeshore to the east of the road at the south end of the Little River bridge and causeway. If lake levels are high and these outcrops are flooded, additional outcrops are available along the dirt road into the 'Picnic Areas' west of GA-47.

east and west of the road at the south end of the Little River bridge and causeway (Fig. 5-7). The outcrops east of the road display the most geology over a smaller area and are the preferred exposures for this stop. However, if lake levels are high, and the outcrops east of the road are flooded, the same geologic features can be found in the numerous outcrops along the dirt roads and along the shoreline west of GA-47 (Fig. 5-7).

The rocks in the flat pavement-like outcrop east of the road consist of felsic volcaniclastic rocks, minor crystal tuffs and pelites, and a few interlayers of intermediate to mafic tuff. Rocks in this outcrop are only mildly deformed. Compositional layering (S_0) and an early foliation (S_1) are parallel, strike northeast and dip steeply northwest toward the core of the Saluda synclinorium. A second foliation dips moderately northwest. Scattered through the outcrop are small RSC_2 folds. These are less abundant here than at Stops 2 or 6. Here, they are best developed in interlayered metasiltstones and pelites in the northern part of the outcrop. Some of the pelitic layers also show the development of DSF_4 and NSC_4 as a D_4 (Irmo deformation) overprint.

Another set of features here that are noteworthy are layer-parallel zones of breccia. These vary in character from chaotically and brittlely deformed metavolcanic and metasedimentary rocks to intensely granulated and silicified breccia. The cementing material is dark grey to black and resistant. These breccia zones are typically confined between layers that are unaffected by the brecciation, yet the breccia zones are discontinuous along strike. These breccia zones occur at several localities along strike of the Modoc zone from here. A similar appearing breccia is present at one other locality west of Leah where it and the enclosing gneisses are recrystallized. This suggests that the breccia formed prior to, or during D_2. If the breccia formed during D_2 then it might represent a zone of brittle deformation in the structurally highest part of the Modoc zone.

Turn around and proceed south on GA-47.

1.7 73.6 Leah, bear left on GA-104.

2.4 76.0 South end of bridge over Keg Creek branch of Clark Hill Reservoir.

STOP 8: The rocks exposed in the lakeshore outcrops east of the road at the south end of the Keg Creek bridge (Fig. 5-8) are in the lower part of the Modoc zone (Plate 1). These rocks are somewhat migmatitic, and south of this locality, pelitic rocks in the Kiokee belt contain sillimanite. These rocks were probably part of the footwall and were deformed as part of the Modoc zone during D_2. F_2 reverse slip crenulations (RSC_2) are present here and indicate a hanging wall down-to-the-north shear sense that is consistent with the shear sense indicated by RSC_2 elsewhere in the Modoc zone.

Ductile faults are also present in this outcrop. They are present in many outcrops along strike from this locality. Most of these faults are oriented counterclockwise from compositional banding and offset banding in a sinistral manner. Where the faults have an approximately east-west strike, clockwise from the strike of compositional banding, the banding is offset in a dextral manner. In some cases, banding on one side of the fault is truncated against the fault, but banding on the other side of the fault is parallel to compositional banding and foliation. Because the faults merge parallel to foliation, slip on foliation is probably an important part of their origin. These faults may have formed as foliation boudinage (Platt and Vissers, 1980), or as asymmetric pull-aparts (Hanmer, 1986).

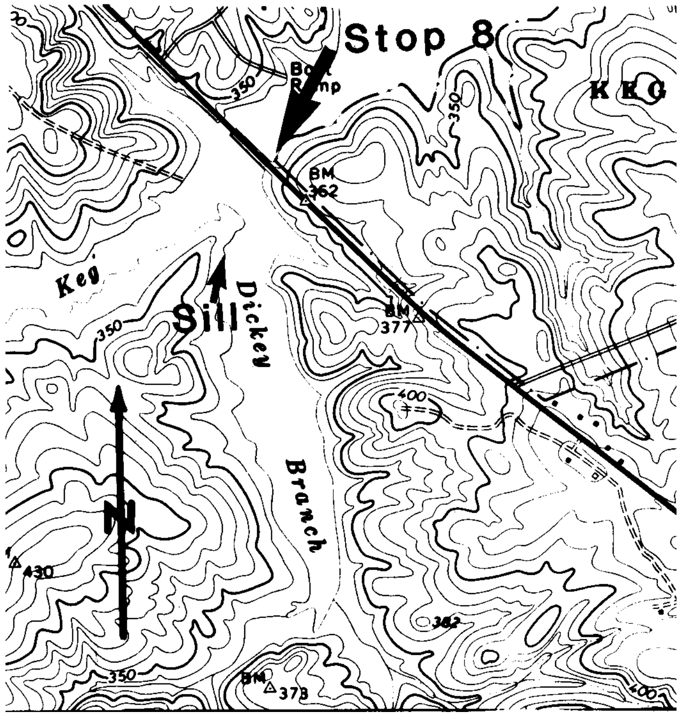


Figure 5-8. Map showing the location of outcrops along the lake shore at Stop 8 in the south-central part of the Leah, GA quadrangle (scale 1: 24,000). Additional outcrops are located to the east of the road at the north end of the bridge and along an unnamed creek 1/2 mile east of the outcrops at Stop 8. 'Sill' notes the location of one of the northernmost outcrops of sillimanite bearing schist in this part of the Kiokee belt and Modoc zone.

Another possible origin is as lateral ramps of RSC_2. RSC form where slip on foliation is an important mechanism of strain (Dennis and Secor, 1987). Where the slip surface "ramps upward" from one foliation to another foliation, RSC folds form along the front of the ramp. The ductile faults may form as lateral ramps of the RSC, and be equivalent to the larger scale lateral ramps that are observed in fold and thrust belts.

Continue south on GA-104.

2.2 78.2 Pollards Corner, turn right on US-221/GA-304.

0.7 78.9 Roadcut in ultramafic rocks of Burks Mountain belt.

2.5 81.4 Bridge over Greenbrier Creek. After crossing bridge immediately turn left onto Kiokee Road. Outcrop of banded migmatitic biotite gneiss along Kiokee Road immediately after turn.

0.7 82.1 Outcrops of banded biotite gneiss and minor amphibolite.

0.3 82.4 Biotite gneiss and amphibolite intruded by granitic sheets in roadcut on left.

0.3 82.7 Bridge over Kiokee Creek.

0.2 82.9 Marshall Historical Site sign.

1.4 84.3 Turn right on Louisville Road.

1.7 86.0 Turn left on dirt road leading to Heggies Rock.

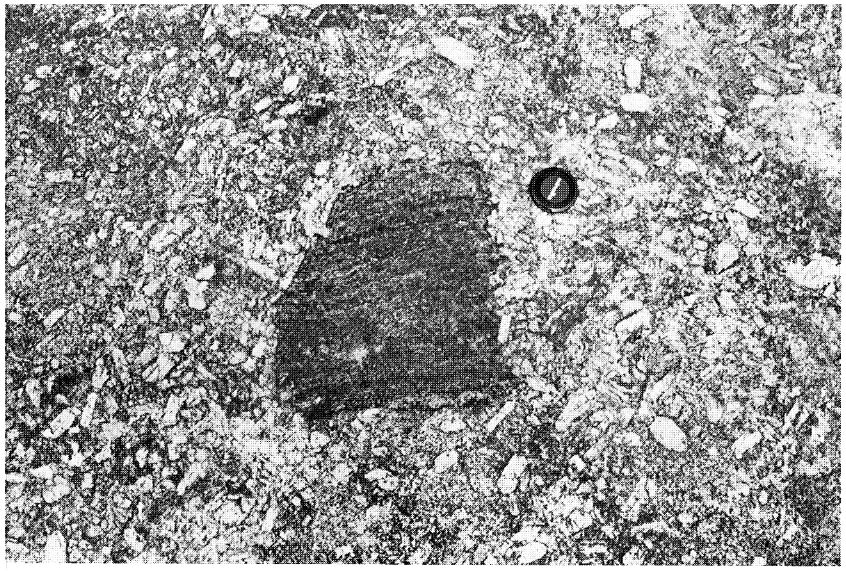
0.2 86.2 Drive to residence and park.

STOP 9: About one-third of a mile walk along path to Heggies Rock (Fig. 5-9a). Heggies Rock is an exceptional place, both biologically and geologically, that is being returned to its pristine condition by careful Nature Conservancy management (Figs. 5-9b, 5-9c, 5-9d). PLEASE LEAVE HAMMERS ON THE BUS. WHILE ON THE OUTCROP, TREAD CAREFULLY AND AVOID DAMAGING THE PLANTS GROWING IN THE WEATHERING PITS OR OTHER SOIL COVERED AREAS.

Heggies Rock is regarded as the most important of the Piedmont flat-rocks from a biological point of view, both because of the diversity of rare plants that it contains and because it is less disturbed than most other flat rocks (Godfrey, 1980).

Geologically, Heggies Rock is an exceptional exposure of the Appling Granite (Hurst and oth-

Figure 5-9. a) Map showing the location of outcrops at Stop 9. b-d) Photos showing different parts of the flat rock exposures at Heggies Rock (Stop 9). e, next page) Photo showing xenolith of gneiss within the Appling granite at Stop 9. Note the K-feldspar megacrysts.



ers, 1966). The essential minerals are quartz (c. 20%) and feldspar (c. 75%) with accessory biotite and amphibole(?) and a trace of epidote. Prominent euhedral K-feldspar megacrysts make up c. 35% of the rocks (Fig. 5- 9e). These are locally aligned in a variably oriented flow foliation. A few small gneissic and schistose xenoliths in various stages of assimilation can be found (Fig. 5-9e). The Appling granite is interpreted to be late Paleozoic in age because of its undeformed condition and lithological similarity to other late Paleozoic granitoids. An accurate igneous crystallization age has not yet been determined for the Appling. It has an exceptionally young biotite-whole-rock cooling age of c. 237 Ma (S.A. Kish, personal communication, 1987). It is uncertain whether the granitoids in the interior of the Kiokee belt are weakly deformed to undeformed because they are exceptionally young or because the Kiokee belt interior has not experienced the intense late Paleozoic deformation that is manifested in the adjacent Modoc zone.

Turn around and return to paved road.

0.1 86.3 Turn right on Lewistown Road and proceed northeast.

1.7 88.0 Turn right on Delph Road and proceed east.

2.8 90.8 Turn left on GA-104 and proceed north toward Pollards Corner.

0.8 91.6 Bridge over Kiokee Creek.

0.7 92.3 Migmatitic biotite gneiss and ultramafic rock in roadcut on left.

1.1 93.4 Silicified ultramafic rocks of the Burks Mountain belt.

0.5 93.9 Pollard's sawmill.

0.5 94.4 Pollards Corner. Turn right on US-221. Proceed east toward Clark Hill Dam.

END OF ROAD LOG FOR SATURDAY.

BUSES RETURN TO HICKORY KNOB STATE PARK.

SUNDAY ROAD LOG CONTINUES HERE.

5.0 99.4 Turn right into road leading to the "Below Dam Georgia Launching Ramp."

0.5 99.9 Turn left into parking area. Walk down steep slope to rock outcrops in spillway to Clark Hill Dam.

STOP 10: The spillway to Clark Hill Dam (Fig. 5- 10a) contains an exceptionally good series of outcrops for viewing the lithologic and tectonic features characteristic of the interior of the Kiokee belt. The most common rock type is migmatitic biotite paragneiss containing layers or lenses of migmatitic biotite-sillimanite schist (Fig. 5-10b). The above units are intruded by strongly deformed orthogneiss (Figs. 5-10b, 5-10c) containing mafic xenoliths. Finally, all of the above units are cut by sheets of weakly deformed to undeformed fine- grained gray granite (Fig. 5-10b). The orthogneiss contains an intense foliation that has been strongly refolded, suggesting at least two different deformational episodes. The local presence of eye-

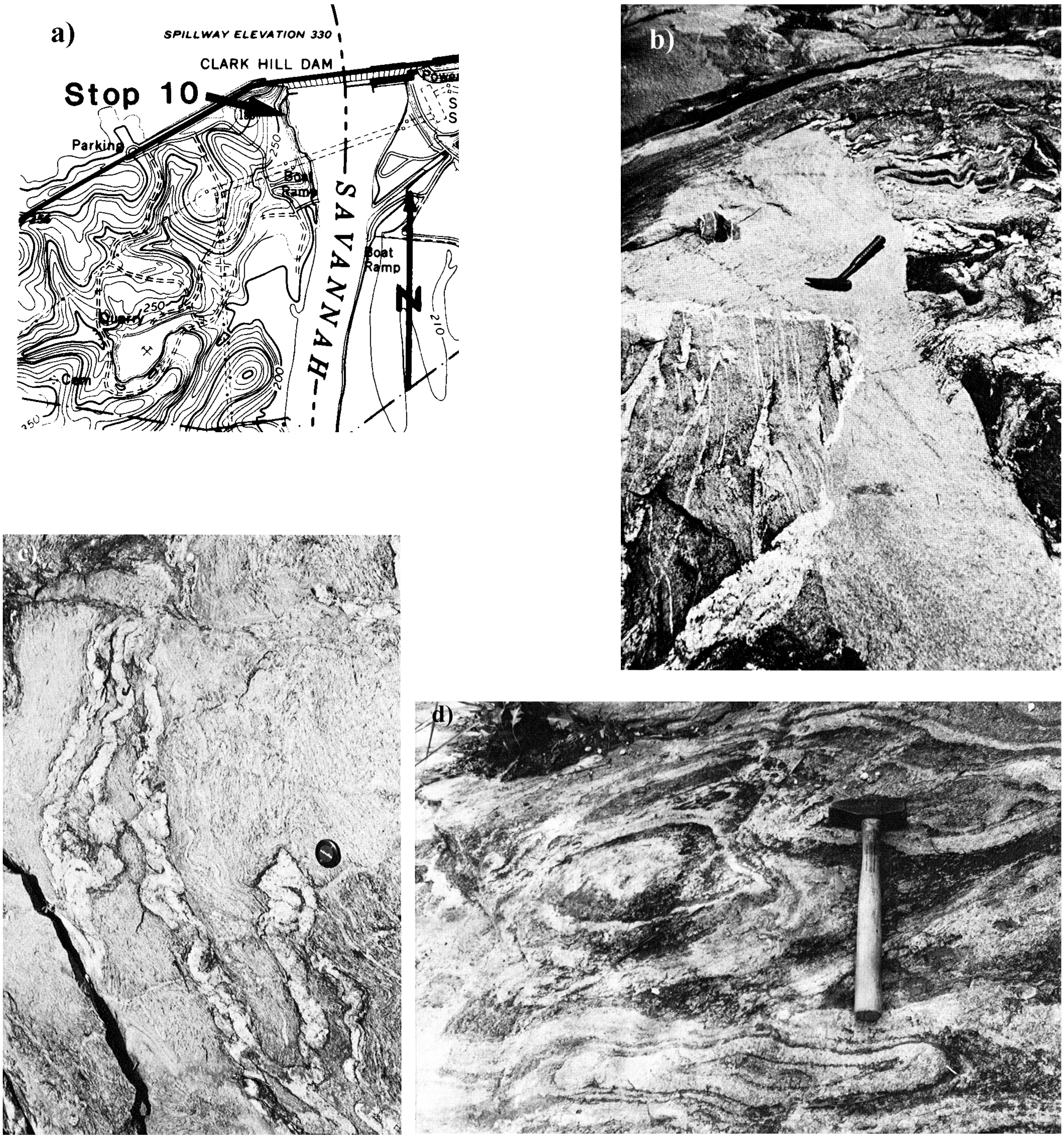


Figure 5-10. a) Map showing the location of outcrops at Stop 10 (scale 1: 24,000). b-d) Photos of some features in the outcrops near the dam at Stop 10 (see text for explanation).

folds in the paragneiss (Fig. 5- 10d) also suggests a complex deformational history. The age(s) of the earlier deformational episode(s) in the spillway are unknown and cannot be correlated with certainty with D_1 and/or D_2 in the Carolina slate belt or Modoc zone. However, in the spillway, there is a series of open to tight, northwest vergent flexural folds that are interpreted to be F3 folds based on orientation, vergence, and style. On average, the migmatitic layering is flat- lying, and the spillway is interpreted to be near the crest of the F3 Kiokee anticlinorium (Maher, this volume; Plate 1)

The age and stratigraphic affinities of the migmatitic sequence in the interior of the Kiokee belt are uncertain (Sacks and Dennis, this volume). Structural data from the Modoc zone suggest that the migmatitic sequence originated at least tens of kilometers to the north-northeast relative to nearby parts of the Carolina Slate Belt. The migmatitic sequence may be Grenville basement (as suggested by Farrar, 1985) but it does not resemble known Grenville basement lithologically, nor is it associated with a "North American" cover sequence. The migmatitic sequence may be a basement terrane on which the volcanic arc(s) of the slate and Charlotte belts was constructed, or it may correlate with felsic gneiss sequences in the Charlotte belt which it resembles lithologically. Finally, it is possible that the migmatitic sequence is completely exotic with respect to other rocks in the Piedmont, and is in fault contact with the Asbill Pond formation along a line that is located in the southeastern part of the Modoc zone (Fig. 1-2).

Turn around and return to US-221.

0.6 100.5 Turn left onto US-221 and proceed west toward Pollards Corner.

5.0 105.5 Pollards Corner. Turn left on GA-104 and proceed south toward Evans.

0.7 106.2 Left turn immediately beyond lumber yard on Old Middleton Ferry Road leading to Second Mt. Carmel Church.

1.6 107.8 Cross Old Petersburg Road. Continue straight ahead on gravel road.

0.9 108.7 Electric substation on left. Biotite gneiss outcrop on left also.

0.5 109.2 Turn around and park.

STOP 11: Burks Mountain ultramafics. Proceed on foot about 500 m east along badly rutted and washed dirt road to base of slope (Fig. 5-11). Turn left and climb uphill to the north along a path to a quarry in serpentinite. Outcrops extend east and west from the quarry along the south side, crest and north side of Burks Mountain. Hurst and others (1966) report that serpentinite was mined here in 1946-1947 for production of magnesia. They also report the presence of chromite and nickel anomalies associated with the ultramafic rocks. A talc- serpentine body approximately 2 km west of here is being investigated by the Georgia Geologic Survey (Phil Perley, pers. comm.). Several prospect pits are scattered throughout the area of the ultramafic bodies.

This serpentinite body is one of several in the Burks Mountain belt of ultramafics (Sacks and others, 1987). The rock here consists of massive serpentinite. A mesh texture, which can be observed in hand sample, and which is especially prominent in thin section, suggests that the serpentine formed from the alteration of peridotite consisting of olivine and pyroxene. In some places, chromites in the serpentinite seem to define a foliation. In some places, alteration along closely spaced, approximately planar surfaces defines a parting in the outcrop. Metamorphism of the serpentinite has resulted in the development of a talc overprint. This overprint varies from the crystallization of isolated flakes of talc within the serpentinite to complete replacement to form soapstone or talc-amphibole schists. Some parts of this and other serpentinite bodies have been silicified. The result of silicification is a replacement of the serpentine with quartz, but with the preservation of the mesh texture.

The serpentinite body here and the associated ultramafic and mafic bodies along strike are enclosed within migmatitic biotite amphibole gneiss (mbag on Plate 1 and POAL(C,ˉ)gn2 on Fig. 1-2). The northern and structurally lower contact of the serpentinite body at Burks Mountain is marked by float of banded recrystallized quartzite with magnetite and minor amphibole. Float of the quartzite is traceable along the north side of Burks Mountain eastward to the Savannah River. To the south, the serpentinite is mostly altered to talc-amphibole chlorite schists and soapstone. The ultramafic and mafic rocks are enclosed in migmatitic gneisses that dip toward the southeast (Fig. 1-2 and Plate 1).

The serpentine body here at Stop 11 is one of several bodies of ultramafic and mafic rock in

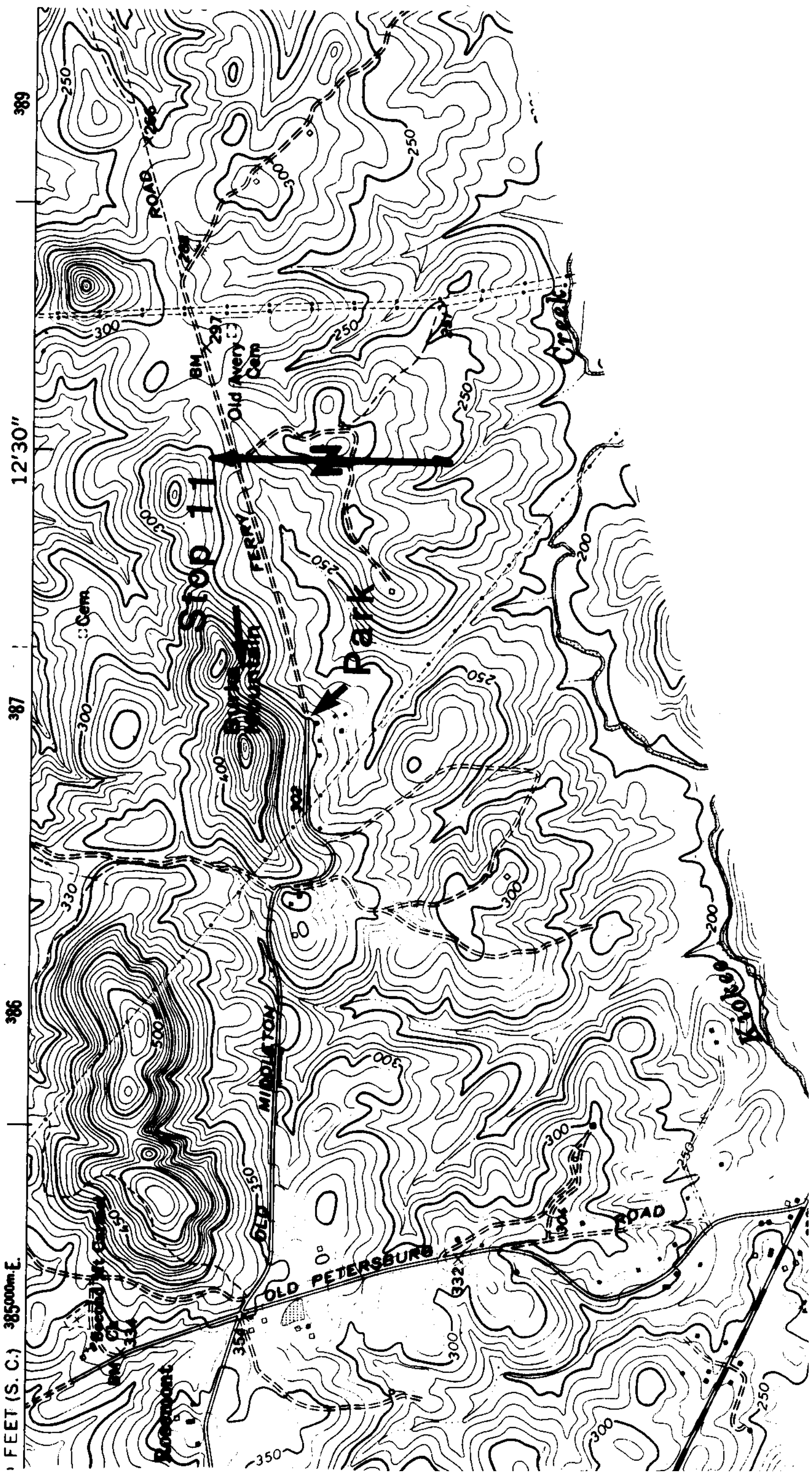


Figure 5-11. a) Map showing the location of outcrops at Stop 11 in the northern part of the Evans, GA-SC quadrangle (scale 1: 24,000). Park at the location shown. Walk east along the badly rutted and eroded road approximately 500 m to the base of the slope, then follow path to the left (north) uphill to the serpentinite quarry and numerous outcrops on Burks Mountain.

this part of the Kiokee belt (Fig. 1-2). These bodies occur in a 20-30 km long concordant belt in the southeast limb of the Kiokee antiform. This belt has been called the Burks Mountain belt of ultramafics (Sacks and others, 1987). Smaller bodies of similar ultramafic rocks are present in the northwestern limb of the Kiokee antiform (Plate 1); these are probably a continuation of the Burks Mountain belt over the crest of the antiform. The geologic relationships of the ultramafic rocks and the enclosing gneisses suggests that they have similar metamorphic and deformation histories. Their origin and history prior to the Alleghanian is as yet poorly known.

Also of geologic interest at this stop is the effect of the serpentine on the plant life. Burks Mountain is the southernmost serpentine barren in the Piedmont (Godfrey, 1980). Magnesium rich soil, especially with chromium and nickel, that develops on the serpentinite retards or eliminates most types of plants. The result is the savannah characterized by dwarf blackjack oak, short and long leaf pines, and grassy open areas.

Return to Old Petersburg Road.

1.3 110.5 Turn left on Old Petersburg Road and proceed south.

0.2 110.7 Outcrop of serpentinite partly altered to talc on east side of road.

0.2 110.9 Migmatitic biotite amphibole gneiss, dipping gently southeast, cut by granitic dike on west side of road.

0.3 111.2 Migmatitic biotite gneiss with boudins of biotite-amphibole gneiss.

0.5 111.7 Intersection of Old Petersburg Road and GA-104. Turn left on GA-104 and proceed southeast toward Evans.

0.1 111.8 Bridge over Kiokee Creek.

7.6 119.4 Evans, GA. Junction of Belair Road Extension. Continue south on GA-104.

5.7 125.1 At second traffic light before I-20 overpass (at Gulf Station), turn left on Stevens Creek Road.

0.3 125.4 Intersection of Stevens Creek Road and Claussen Road. Continue straight ahead on Claussen Road.

0.7 126.1 After crossing railroad tracks, turn left onto Murray Road.

0.3 126.4 Turn right on entrance road toward Martin Marietta quarry.

1.1 127.5 Parking lot at quarry office. Obtain permission before entering.

STOP 12: This large crush rock quarry provides an excellent exposure of the ductile Augusta fault (Figs. 5-12a, 5-12b), which separates Belair belt rocks to the SE from Kiokee belt rocks to the NW. Rocks in the structurally lower NW quarry benches are Kiokee belt gneisses and schists without a mylonitic fabric, but with a more irregular gneissic layering. Rock types in the structurally highest, SE quarry benches are a muscovite schist and a several meter thick, orthogneiss sheet. As suggested by Prowell (1980) the muscovite schist is likely a higher-grade, highly strained and recrystallized version of the lowest stratigraphic unit within the Belair belt. In between are mainly fine- grained, quartzo-feldspathic, blastomylonites. The composition of the mylonites varies notably, and in turn the textures vary. Ductile shear was clearly inhomogenous.

Within the mylonites are numerous granitic veins that vary from discordant and unstrained to semi-concordant, highly folded and internally strained (Fig. 5-12c). Granitic veins, thus, were injected syn- and post-ductile shear and record a portion of the strain history. Analysis of the orientation and geometry of granitic veins suggest they intruded during movement with a hanging wall-down component (Maher, 1987, in press). Occasional intrafolial folds within the mylonite are also consistent with such a kinematic setting (Fig. 5-12d).

While the mylonites are well foliated, only a moderate to weakly developed lineation exists. This lineation is parallel to fold axes, plunging 20-30^{o} to the south. In thin sections cut parallel to the lineation numerous sense-of- shear indicators (Figs. 5-12e, 5-12f) consistently indicate hanging wall-down motion (Maher, in press). Occasionally, s and c surfaces are visible in outcrops of some of the coarser grained mylonites.

Small brittle faults parallel to the mylonitic foliation show a hanging wall-down apparent offset of discordant granitic veins. Striae on chloritic seams on the mylonite foliation are parallel to the mylonitic lineation. Both these observations suggest that Augusta fault movement continued from a ductile into a brittle regime. The timing of movements is uncertain and needs to be ascertained. A ductile to brittle transition is consistent with a D_3 age, but the magmatic activity

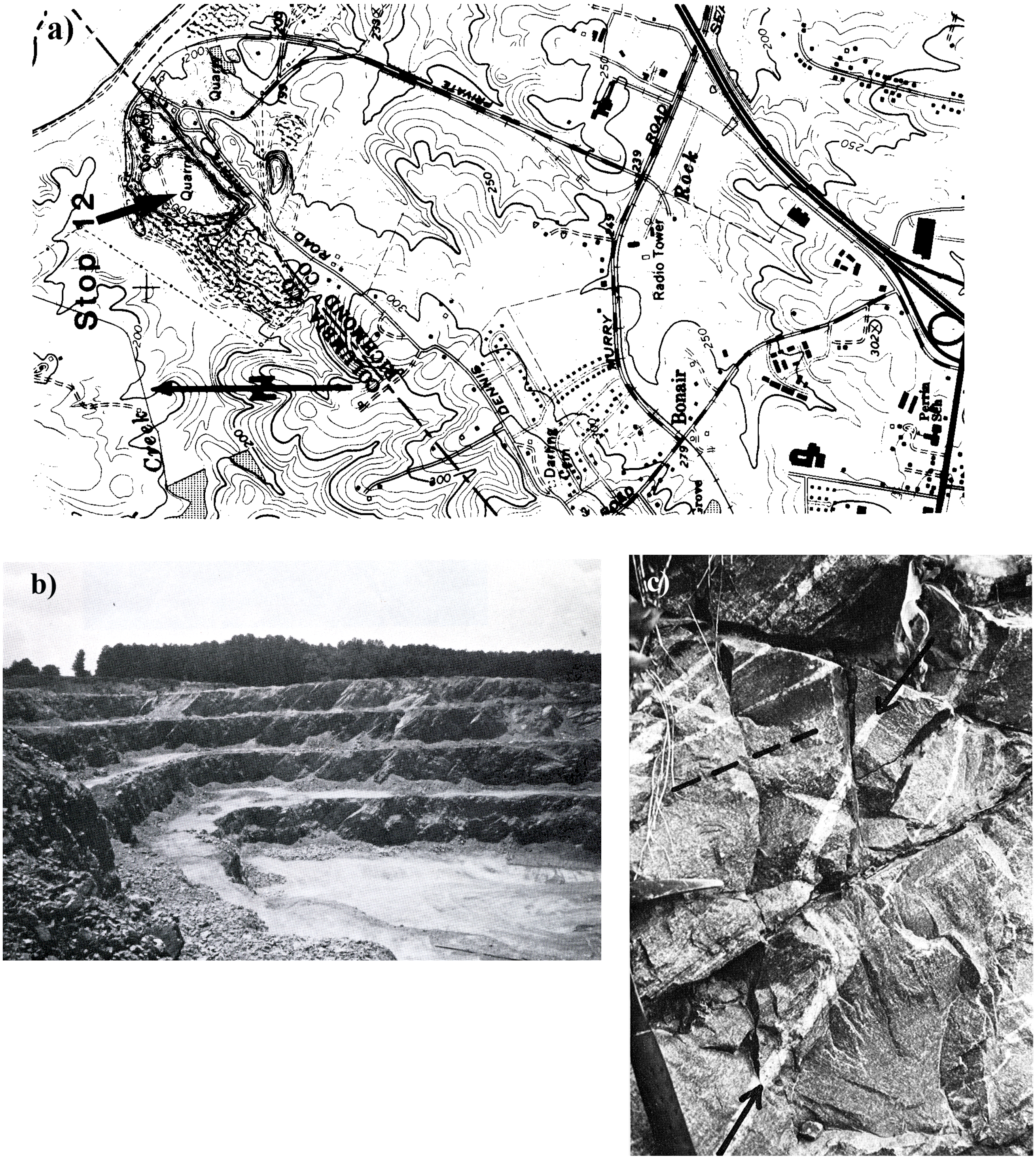
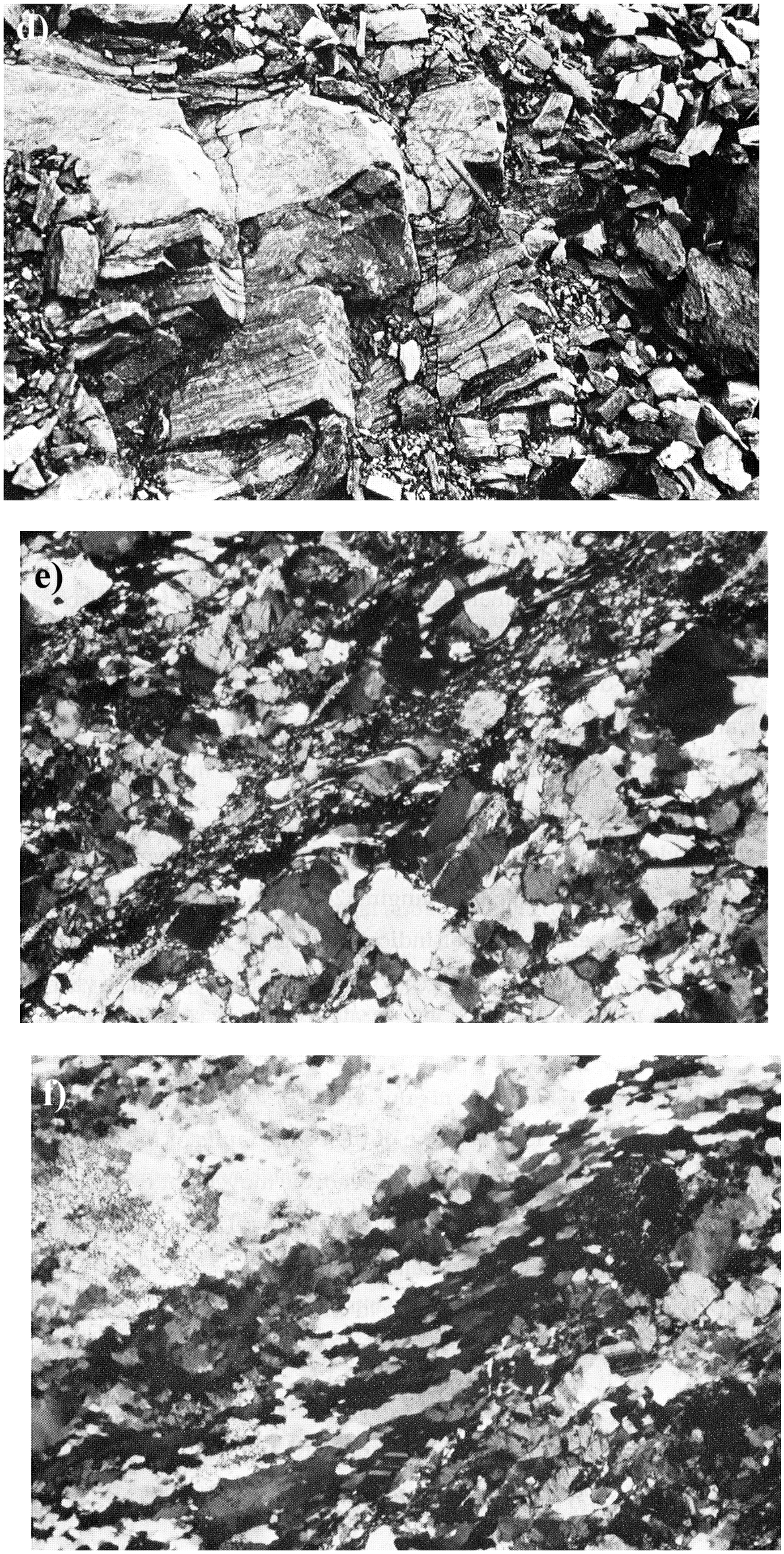


Figure 5-12. a) Map showing the location of Stop 12 in the Martinez quadrangle (scale 1: 24,000). b) View of SW end of Martin Marietta crush rock quarry. Note the moderate dip of the foliation to the left (SE). This is the mylonitic foliation of the Augusta fault zone. c) View to SW of intrafolial fold in mylonitic gneisses. Note the vergence. d, next page) View to SW of discordant folded granitic vein (arrows) with down-dip vergence. Dashed line represents trace of mylonitic foliation. e, next page) C surfaces in quartzo-feldspathic mylonite. View to SW in thin section parallel to the lineation; crossed Nichols. f, next page) Edge of quartz vein with well developed quartz subgrain fabric discordant to the quartz vein margin (arrows).


d)
e)
f)

suggests it is perhaps late D_2 (assuming the magmatic activity is the same age it is on the NW limb of the Kiokee belt).

The SW end of the quarry is cut by one of the brittle faults of the Belair fault zone (Prowell, 1980). This steep fault with well documented Cenozoic movement (Prowell, 1978; Prowell and O'Connor, 1978) offsets the Augusta fault zone in a sinistral fashion. Bramlett and others (1982) discuss the relationship of Augusta and Belair fault zones in more detail. We would like to thank Martin Marietta for permission to bring the field trip here. Permission can and must be obtained at the quarry office before entering the quarry.

END OF SUNDAY ROAD LOG.

BUSES RETURN TO HICKORY KNOB STATE PARK.

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