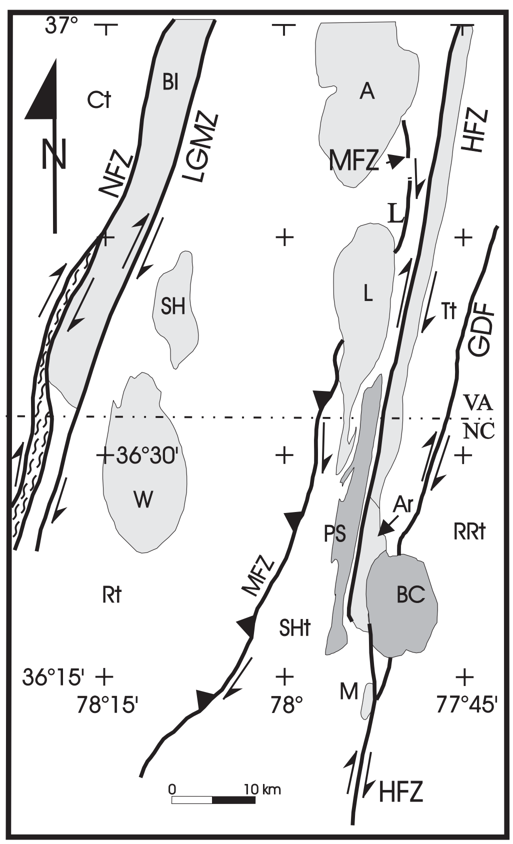
Geology of the Fall Zone Region along the North Carolina – Virginia State Line

Guidebook for the 1999 Meeting of the CAROLINA GEOLOGICAL SOCIETY

Emporia, Virginia

November 6 & 7, 1999



Edited by Paul E. Sacks

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CONTENTS

1 Geologic Overview of the Eastern Appalachian Piedmont along Lake Gaston, North Carolina and Virginia
by Paul E. Sacks

16 Porphyroblast textures in the Spring Hope Terrrane, Lake Gaston
by Edward F. Stoddard

29 Application of aerial gamma-ray spectrometric and magnetic surveys in geologic mapping - A case study in southern Virginia and northern North Carolina
by J. Wright Horton, Jr., and David L. Daniels

37 Bouger gravity study along the Hollister fault zone, eastern North Carolina
by David P. Lawrence

49 A field guide to the geology of the Fall Zone region, North Carolina and Virginia state line: Road log for the Carolina Geological Society Field Trip, November 6 & 7, 1999
by Paul E. Sacks, Edward F. Stoddard, Rick Berquist, and Clay Newton

Carolina Geological Society

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Geologic Overview Of The Eastern Appalachian Piedmont Along Lake Gaston, North Carolina And Virginia

by
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Abstract

In the area of Lake Gaston, along the North Carolina and Virginia state line, the Raleigh, the Spring Hope, the Triplet, and the Roanoke Rapids terranes are alternating, fault-bounded terranes of high grade and low grade metamorphic rocks. Late Paleozoic granite have intrudes these rocks. The bounding fault zones of these terranes are, from west to east, the Nutbush Creek/Lake Gordon mylonite zone, the Macon fault zone, the Hollister fault zone, and the Gaston Dam fault zone. The Macon mylonite zone and the Gaston Dam fault zone both are cut by the Late Paleozoic granite intrusions. The Late Paleozoic granites are synkinematic with the Nutbush Creek/Lake Gordon mylonite zone and the Hollister fault zone. These fault zones all display evidence of predominantly dextral shear.

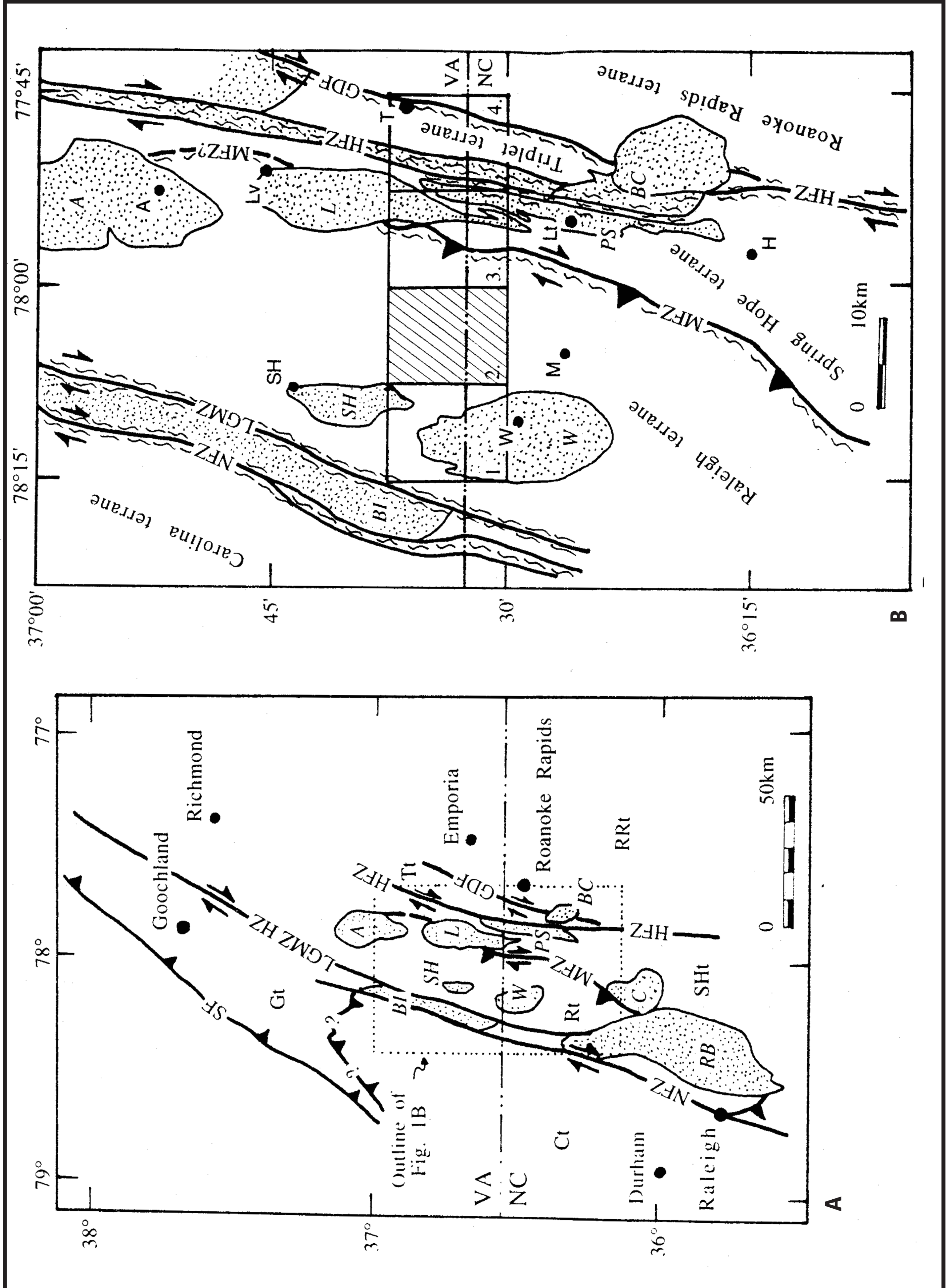
Introduction

The geologic and tectonic framework of the northeastern North Carolina Piedmont was given its modern basis in the work of Farrar (1985a, b), and Stoddard, and others (1991). The work presented here builds on this previous work, and is based on geologic mapping of the Bracey, South Hill SE, Gasburg, and Valentines 7.5-minute quadrangles along Lake Gaston, and on mapping southward along the Hollister fault zone (Fig. 1; Plate 1; Sacks, 1996a, b, c, d; Sacks, unpublished data). Along Lake Gaston, North Carolina and Virginia, the eastern Appalachian Piedmont consists of fault-bounded blocks of greenschist-facies, and amphibolite-facies rocks, and intrusive rocks. Near the eastern end of the lake, the hill tops are covered with strata of the Atlantic Coastal Plain. The purpose of this paper is to provide an overview of the rocks, the tectonostratigraphic terranes and the tectonic structures of the eastern Piedmont of North Carolina and Virginia.

Regional Geologic Setting

The Eastern Piedmont of North Carolina and adjacent Virginia consists of fault bounded blocks of greenschist-facies metavolcanic and metasedimentary rocks and other blocks of amphibolite-facies gneiss and schist (Fig. 1; Plate 1). From west to east, these are the Raleigh terrane, the Spring Hope terrane, the Triplet terrane, and the Roanoke Rapids terrane (Horton and others, 1991; Stoddard and others, 1991; Sacks, 1996d). The Raleigh terrane (Fig. 1) is bounded on the west by the Nutbush Creek fault zone, Lake Gordon mylonite zone and Hylas fault zone; the Macon fault zone is the boundary to the east. To the east, rocks of the Spring Hope terrane are bounded by and late Paleozoic granites are deformed in the Hollister fault zone. The Gaston Dam fault separates the Triplet terrane from the Roanoke Rapids terrane.

FIGURE 1



A
38°
37°
36°
79°
78°
77°
Richmond
Goochland
Emporia
Roanoke Rapids
Durham
Raleigh
Outline of Fig. 1B
VA
NC
SF
Gt
LGMZ HZ
HFZ
GDF
MFZ
NFZ
Tt
RRt
SHt
Rt
Ct
A
L
SH
W
BI
PS
BC
C
RB
50km
0
B
37°00'
45'
30'
36°15'
78°15'
78°00'
77°45'
Carolina terrane
Raleigh terrane
Spring Hope terrane
Roanoke Rapids terrane
Triplet terrane
LGMZ
NFZ
MFZ
MFZ?
HFZ
GDF
SH
Lv
Lt
PS
BC
M
H
T
1.
2.
3.
4.
10km
0

The Raleigh terrane is composed of amphibolite-facies (sillimanite-grade) schists and gneisses that were metamorphosed and intruded by numerous granitic plutons during the late Paleozoic Alleghanian orogeny (Farrar, 1985b; Russell and others, 1985; Stoddard and others, 1991). Locally, there is evidence for a greenschist facies overprint on the higher grade rocks. The Raleigh terrane is considered in some tectonic models to be a basement terrane, perhaps part of the Goochland terrane (Farrar, 1984, 1985b, Horton and others, 1991, Stoddard and others, 1991). In the Goochland terrane (Fig. 1), Farrar (1984, 1985b) interpreted a Grenvillian age for relict granulite-facies metamorphism that was overprinted by Alleghanian amphibolite-facies metamorphism. The Raleigh terrane is here considered to be a distinct terrane because it is separated from the Goochland terrane by a system of faults that include the Lake Gordon mylonite zone, and the Hylas fault zone (Horton and others, 1993a, 1993b; Virginia Division of Mineral Resources, 1993). Rocks similar to the Raleigh terrane gneiss also occur in a fault bounded block east of the Hollister fault zone (Fig. 1), and Farrar (1985a, 1985b) considered these rocks (his Littleton gneiss) to be equivalent to gneiss of the Raleigh terrane. Because the relationship of the fault bounded gneisses east of the Hollister fault to those in the Raleigh terrane is uncertain, they are designated the Triplet terrane (Fig, 1; Sacks, 1996d). The Triplet terrane is named for a narrow, elongate block of gneiss and schist situated between the Hollister and Gaston Dam faults in the Piedmont of northeastern North Carolina and southeastern Virginia (Fig. 1).

The Spring Hope terrane consists of metavolcanic and metasedimentary rocks that are interpreted to have accumulated in an arc setting (Farrar, 1985a, 1985b; Boltin and Stoddard, 1987; Stoddard and others, 1991; Horton and others, 1991). Rocks of the Spring Hope terrane are separated from those of the Raleigh terrane by the Macon fault zone. The eastern boundary of the Spring Hope terrane is the Hollister fault zone. The Roanoke Rapids terrane named by Horton and others (1991), and comprises the metavolcanic and metasedimentary rocks east of the Gaston Dam and Hollister fault zones. Both the Spring Hope and the Roanoke Rapids terranes consist of rocks metamorphosed at greenschist to amphibolite facies.

ROCK UNITS

Raleigh Terrane

The oldest rocks in the Raleigh terrane are schists and gneisses. These are intruded by pegmatites and by at least two types of granite. The schists and gneisses of the Raleigh terrane along the Roanoke River are subdivided into biotite gneiss (bg), amphibole-biotite gneiss (bag), augen-biotite gneiss (abg), sillimanite-muscovite schist (ms), biotite-muscovite schist (ps), and

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FIGURE 1A. *(Opposite Page)* Tectonic map of the Eastern Piedmont of Virginia and North Carolina.
FIGURE 1B. *(Opposite Page)*Tectonic map showing location of the Bracey, South Hill SE, Gasburg, and Valentines quadrangles and some gologic and geographic features mentioned in the text.
Abreviations used used on both maps are as follows:
Fault zones: Gaston Dam fault zone - GDF, Hollister fault zone - HFZ, Hylas fault zone - HZ, Lake Gordon mylonite zone - LGMZ, Macon fault zone - MFZ, Nutbush Creek fault zone - NFZ. Granite plutons: Alberta pluton - A, Buggs Island pluton - BI, Butterwood Creek pluton - BC, Castalia pluton - C, Lawrenceville pluton - L, Panacea Springs pluton - PS, Rolesville batholith - RB, South Hill pluton - SH, Wise pluton - W. Terranes: Carolina terrane - Ct, Goochland terrane - Gt, Raleigh terrane - Rt, Roanoke Rapids terrane - RRt, Spring Hope terrane SHt. Towns: Alberta - A, Hollister - H, Lawrenceville - Lv, Littleton - Lt, Macon - M, South HIll - SH, Triplet - T, Wise - W. Quadrangles: 1. - Bracey quadrangle, 2. - South Hill SE quadrangle, 3. - Gasburg quadrangle, 4. Valentines quadrangle.
(Modified from Horton and others, 1991, 1993b; Virginia Division of Mineral Resources, 1993; and Sacks, unpublished data).

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phyllonite (ph) talc schist (ta) and mylonitic biotite gneiss (mbg). Manganiferous schist and gneiss occurs as thin layers in the amphibole-biotite gneiss. The biotite gneiss (bg) west of the Wise pluton (PIPw) corresponds to the Raleigh gneiss (informal name) of Farrar (1985a, 1985b), and his Macon schist (informal name) corresponds to the gneisses and schists east of the Wise pluton. The relative ages of the schists and gneisses are not known. The structurally lowest unit in the Bracey quadrangle is biotite gneiss along the eastern edge of the quadrangle. To the east in the adjacent South Hill, SE quadrangle, this biotite gneiss contains a pod of talc schist, and in the Gasburg quadrangle, a similar gneiss unit in a similar structural position, contains numerous pods of talc schist. The eastern unit of biotite gneiss is structurally overlain by medium to coarse grained sillimanite-muscovite schist. This aluminous schist contains muscovite, sillimanite, quartz, minor plagioclase, and sparse biotite and garnet. Locally, sillimanite occurs as crystals and aggregates up to 4 cm long, and locally, it may be the most abundant mineral in the rock. Replacement of sillimanite by chloritoid is common.

The biotite gneiss and sillimanite-muscovite schist units also contain contains pods of talc schist. Most of the talc schist in the eastern part of the Raleigh terrane consists of massive to foliated talc schist, soapstone, and talc-actinolite schist. However, in the western part of the South Hill Se quadrangle, the massive talc-serpentine-actinolite gneiss exposed just south of the Roanoke River contains pseudomorphs of olivine-clinopyroxene-orthopyroxene websterite. The sillimanite-muscovite schist is structurally overlain by amphibole-biotite gneiss. This unit is predominantly amphibole-biotite gneiss, but contains thin interlayers of biotite gneiss, muscovite-biotite gneiss, and manganiferous schist and manganiferous gneiss. It also contains map-scale pods of augen biotite gneiss. In-folded with the amphibole-biotite gneiss is biotite-muscovite schist. The relationship of the amphibole-biotite gneiss with the biotite gneiss to the west is not clear, but the biotite gneiss appears to be structurally higher. The western biotite gneiss does contain some amphibole-bearing units and a pod of augen biotite gneiss with microcline porphyroblasts similar to the amphibole-biotite gneiss to the east. It is possible that the contact is gradational.

Along the eastern side of the Raleigh terrane, mylonitic biotite gneiss (mbg) is composed of biotite gneiss, muscovite biotite gneiss, and contains bodies of augen biotite gneiss and thin sheets of muscovite granite. These rocks in the upper part of the Macon fault zone are variably mylonitic. The sheets of granite are typically very mylonitic, but contain late muscovite porphyroblasts that probably replace felspar augen.

Bulk compositions of rocks in the Raleigh terrane suggest that protoliths of the biotite gneiss, and the amphibole-biotite gneiss probably include volcanic rocks and volcanoclastic sedimentary rocks; the augen biotite gneiss units may represent crystal tuff units. The schists probably formed in part from pelitic sedimentary rocks, but abundance of aluminous minerals and the sparseness of quartz in some of the more aluminous schists suggests they may have formed from hydrothermally altered volcanic rocks. Some of the more massive talc-bearing rocks contain textures that appear to be psuedomorphic after olivine pyroxenite cumulates. The talc schist and talc-actinolite schist may have formed from either dolomitic rocks or ultramafic igneous rocks. The scattered distribution of the different rock types, especially the talc-bearing rocks, suggests that these rocks may have accumulated in an accretionary complex. Biotite metagranite that contains the same fabric elements as the schists and gneisses is considered to be an early, premetamorphic intrusion.

Pegmatite intrusions are numerous in the schist and gneiss of the Raleigh terrane and occur as thin pods, dikes, and sills. Many of the pegmatite bodies are foliated and appear to be synmetamorphic and syntectonic with respect to the foliation. Other pegmatites have sharp contacts, are not deformed, and must be younger than at least some of the deformation.

Two types of granite intrude the schist and gneiss of the Raleigh terrane in the Bracey quadrangle. The older granite occurs as elongate, moderately concordant sill-like bodies composed of garnet-bearing muscovite granite (mg); locally, this granite contains biotite. The muscovite granite is predominantly medium grained, but it is typically coarse grained to pegmatitic along the margins. The muscovite granite is foliated in most outcrops. In many cases, the foliation in the margins of the granite is nearly concordant to foliation in the adjacent schist and gneiss. The muscovite granite is interpreted to be synmetamorphic and syntectonic with respect to the second phase of folding. Granite of the Wise (PIPw) and South Hill (PIPsh) plutons is typically medium grained muscovite-biotite granite that occurs as large discordant plutons. These granites are weakly foliated, but they are considered younger than the garnet-bearing muscovite granite because of cross-cutting relationships. The presence of weak foliation in these granites indicates they are late syntectonic intrusions.

Spring Hope Terrane

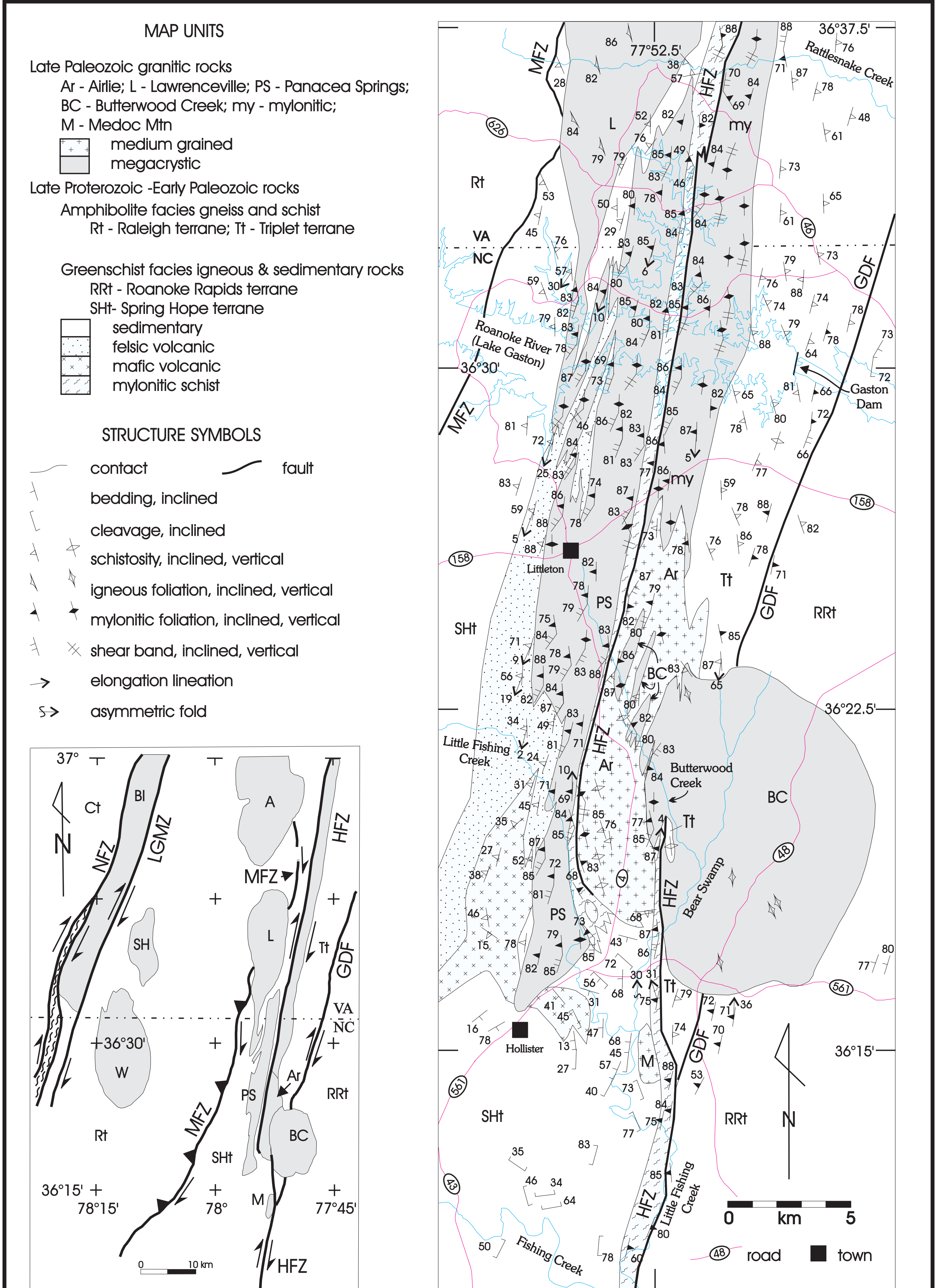
Spring Hope terrane consists of metasedimentary, and felsic and mafic metavolcanic rocks. In the Gasburg and Valentines quadrangles, these rocks consist of greenschist-facies, staurolite grade, and epidote-amphibolite-facies schist, gneiss and phyllite. Near the contact with the Raleigh terrane along the Macon mylonite zone, muscovite porphyroblasts are aligned with an early axial planar cleavage, and staurolite has grown across the foliation. Further south and away from the Macon fault zone, rocks of the Spring Hope terrane are at lower greenschist grade (Boltin, 1985; Farrar, 1985; Russell and others, 1985; Boltin and Stoddard, 1987). Along and within the western part of the Hollister fault zone, the rocks of the Spring Hope terrane have been metamorphosed to epidote-amphibolite-facies, and locally sillimanite occurs near the Late Paleozoic granite bodies. The map pattern of, and structural features within these units indicates complex relationships that are probably a result of complex facies relationships further complicated by deformation. Contacts between these units on the map are shown as faults. These rocks probably accumulated in an arc during the Late Proterozoic or Cambrian (Farrar, 1985a, 1985b).

Triplet Terrane

Rocks of the Triplet terrane consist predominantly of medium to coarse grained biotite gneiss, with lesser amounts of biotite-muscovite schist, and granitic gneiss. These gneisses are compositionally layered, and locally, the gneisses contain layers, lenses, and pods of amphibole-biotite gneiss, porphyroblastic biotite gneiss with porphyroblasts of feldspar, and schist. The gneiss is locally migmatitic. The porphyroblastic biotite gneiss is similar to porphyroblastic biotite gneiss in the Raleigh terrane, and there are coarse, euhedral amphibole porphyroblasts in the amphibole-biotite gneiss similar to what was found in the Raleigh terrane suggesting a possible correlation.

Small bodies of muscovite granite have intruded the biotite gneisses of the Triplet terrane.

FIGURE 2


MAP UNITS
Late Paleozoic granitic rocks
Ar - Airlie; L - Lawrenceville; PS - Panacea Springs;
BC - Butterwood Creek; my - mylonitic;
M - Medoc Mtn
medium grained
megacrystic
Late Proterozoic -Early Paleozoic rocks
Amphibolite facies gneiss and schist
Rt - Raleigh terrane; Tt - Triplet terrane
Greenschist facies igneous & sedimentary rocks
RRt - Roanoke Rapids terrane
SHt- Spring Hope terrane
sedimentary
felsic volcanic
mafic volcanic
mylonitic schist
STRUCTURE SYMBOLS
contact
fault
bedding, inclined
cleavage, inclined
schistosity, inclined, vertical
igneous foliation, inclined, vertical
mylonitic foliation, inclined, vertical
shear band, inclined, vertical
elongation lineation
asymmetric fold
37°
N
Ct
Bl
NFZ
LGMZ
A
MFZ
HFZ
SH
L
Tt
GDF
VA
NC
36°30'
W
Ar
PS
RRt
Rt
BC
SHt
36°15'
78°15'
78°
M
77°45'
0
10 km
36°37.5'
77°52.5'
Rattlesnake Creek
my
Rt
Roanoke River
(Lake Gaston)
36°30'
Gaston
Dam
Littleton
Tt
RRt
SHt
36°22.5'
Little Fishing
Creek
Butterwood
Creek
Bear Swamp
36°15'
Hollister
Fishing Creek
Little Fishing
Creek
0
km
5
road
town

Most are medium grained but are locally porphyritic, massive to foliated, muscovite to muscovite-biotite granites. Many of these granite bodies are concordant or nearly concordant to foliation in the surrounding gneisses.

The eastern margin of the Triplet terrane is characterized by deformed rocks of the Gaston Dam fault zone. Fault rocks within the Gaston Dam fault zone, including mylonitic gneiss and phyllite, and fault breccia, are poorly exposed. Most rocks displaying ductile deformation fabrics are granitic in composition. The ductile fabrics include quartz ribbons, asymmetric feldpsar porphyoclasts and shear bands. Layered gneiss, schist and phyllite also display quartz ribbons and shear bands.

Roanoke Rapids Terrane

Rocks of the Roanoke Rapids terrane crop out only along the eastern edge of the Valentines quadrangle. They consist of slaty to phyllitic metasedimentary rocks. Elswehere, the Roanoke Rapids terrane includes the metavolcanic and hypabyssal rocks of the Roanoke Rapid complex and the mafic and ultramafic rocks of the Halifax County complex. The age of the rocks in the Roanoke Rapids terrane has not been determined. No fossils have been found, and the rocks may be Cambrian or Late Proterozoic in age.

Intrusive Rocks

Two types of granite intrude the schist and gneiss of the Raleigh terrane. The older granite occurs as elongate, moderately concordant sill-like bodies composed of garnet-bearing muscovite granite (mg); locally, this granite contains biotite. The muscovite granite is predominantly medium grained, but it is typically coarse grained to pegmatitic along the margins. The muscovite granite is foliated in most outcrops. In many cases, the foliation in the margins of the granite is nearly concordant to foliation in the adjacent schist and gneiss. The muscovite granite is interpreted to be synmetamorphic and syntectonic with respect to the second phase of folding. Granite of the Wise (PIPw) and South Hill (PIPsh) plutons is typically medium grained muscovite-biotite granite that occurs as large discordant plutons. These granites are weakly foliated, but they are considered younger than the garnet-bearing muscovite granite because of cross-cutting relationships. The presence of weak foliation in these granites indicates they are late syntectonic intrusions.

Late Paleozoic granite underlies much of the eastern third of the Gasburg quadrangle and the western portion of the Valentines quadrangle. The Lawrenceville pluton and the Panacea Springs pluton lie west of the Hollister fault zone (Figs. 1 and 2; Plate 1). The Lawrenceville pluton is an elongate granite body that is mappable from Lawrenceville, Virginia to south of the Roanoke River in North Carolina (Fig. 1). The Lawrenceville pluton consists of foliated, coarse-grained biotite granite, that has a southern and western phase that contains megacrysts of microcline. The microcline megacrysts are as much as 5 cm long, and many display evidence of zoning. The granite is foliated through out the pluton. In the southern part of the Gasburg quadrangle, however,

FIGURE 2. *(Opposite Page)* Geologic map of the Hollister fault zone, southern Virginia and North Carolina. Compiled from Sacks, 1999b, c; Sacks unpub. data. Faults and plutons labeled as follows: Faults: NFZ - Nutbush Creek, LGMZ - Lake Gordon , HZ - Hylas, HFZ - Hollister, MFZ - Macon, GDF - Gaston Dam. Terranes: Rt - Raleigh, SHt - Spring Hope, RRt -Roanoke Rapids, Tt - Triplet. Late Paleozoic plutons: RB - Rolesville batholith, C - Castelia, W - Wise, BI - Buggs Island, BC - Butterwood Creek, PS - Panacea Springs, L - Lawrenceville, A - Alberta, P - Petersburg. Mesozoic basin: RiB - Richmond basin.

the fabric is composite consisting of both foliation and shear bands oriented to indicate dextral simple shear. The Lawrenceville Granite was previously considered part of the Alberta or Butterwood Creek plutons (Calver, 1963; Bobyarchick, 1979; Farrar, 1985a, 1985b; Russell and others, 1985; Stoddard and others, 1987, 1991). New mapping by Berquist (see Virginia Division of Mineral Resources, 1993) has shown that the Lawrenceville Granite is separate from the granite at Alberta, and mapping in North Carolina (Figure 2; Sacks unpublished) has shown that the Lawrenceville pluton is separate from the Butterwood Creek and Panacea Springs plutons. The Lawrenceville pluton is called the Western granite (informal name) by Nowroozi and Corbin (1993). The Panacea Springs pluton also consists of coarse grained to megacrystic biotite granite. These plutons are elongate parallel to the fault zone, but discordant to structures in the country rock. South of the Virginia state line, sheet-like fingers of granite trend about 10-15° clockwise from the trend of the main fault and from the main parts of the plutons (Fig. 2). Granite in the western part of the Panacea Springs pluton and the deformed southern part of the Lawrenceville pluton is moderately to strongly foliated, and contains shear bands and asymmetric feldspar porphyroclasts that indicate dextral simple shear. The western part of these granites, however, are still medium to coarse grained and do not fit a sensu-stricto definition of mylonite. Instead, the textures indicate magma was intruded into an active shear zone, and that shearing continued after crystallization (see Blumenfeld and Bouchez, 1988). The intensity of deformation in the Panacea Springs pluton increases to the east, and the eastern margin of the Panacea Springs pluton is strongly mylonitic and is oriented parallel to the fault zone.

Granites along the eastern side of the Hollister fault zone include the early-synkinematic, megacrystic Butterwood Creek pluton and the younger, crosscutting, finer-grained Airlie pluton (Fig. 2). The main body of the Butterwood Creek pluton bulges eastward from the northern tip of the eastern segment of the Hollister fault zone. Its contacts are discordant to foliation in the surrounding rocks, and the pluton cross-cuts the Gaston Dam fault zone. Except in the northwestern margin of this part of the pluton, the granite is primarily massive, megacrystic biotite granite. Only in a few outcrops are the K-feldspar megacrysts aligned to define a weak magmatic foliation. In the northwestern margin, and in small, elongate pods contained within the Airlie pluton, granite of the Butterwood Creek pluton is deformed. The megacrysts are strongly aligned, quartz ribbons are developed, and the foliation is composite with both a mylonitic foliation defined by aligned feldspars, biotite and quartz ribbons, and shearbands that offset the main foliation in a dextral sense (Fig. 3). The Airlie pluton is comprised of medium to fine-grained muscovite and muscovite-biotite granite, that locally contains small garnets. Cross-cutting relationships indicate the Airlie pluton is younger than the Butterwood Creek pluton: Small dikes of granite of the Airlie pluton intrude the Butterwood Creek pluton. The northern part of the Airlie pluton contains enclaves of deformed megacrystic granite that are probably derived from the northwestern part of the Butterwood Creek pluton. The granite in the Airlie phase is strongly mylonitic along the western margin, and is variably foliated or massive in other parts. Deformed portions of the Butterwood Creek and Airlie plutons contain shear bands and asymmetric porphyroclasts indicating dextral shear. North of the Airlie pluton, granitic rocks along the east side of the fault zone are mylonitic and intensely deformed along the western, fault contact with the Spring Hope terrane, but they are only weakly deformed along the eastern contact with gneiss of the Triplet terrane (Plate 1).

These mylonitic granites may represent a sheared out northern extension of the Butterwood Creek pluton or a separate intrusion.

Precise dates on emplacement and crystallization of these granites are not available. Russell et al. (1985) used the Rb/Sr method to obtain an age of 292 ±31 Ma for the Butterwood Creek pluton (recalculated to 292±13 Ma in McSween et al.1991; Speer et al.1994), but this age was obtained with samples from what are now recognized to be both the Butterwood Creek and the Panacea Springs plutons. Based on Al-in-hornblende geobarometry, the undeformed Butterwood Creek pluton and the deformed Panacea Springs pluton were emplaced at pressures of 2.1±0.5 kb and 3.1±0.5 kb respectively, corresponding to depths of 8.1 and 12.0 km (Vyhnal and McSween 1990). Hence, granites of the Butterwood Creek, Panacea Springs and Lawrenceville plutons were intruded into the mid-crust during the late Paleozoic.

Dikes of Early Jurassic porphyritic rhyolite and olivine diabase cut the older crystalline rocks in the transect area. The dikes of porphyritic rhyolite are more numerous in the Gasburg and South Hill SE quadrangles than the olivine diabase. The porphyritic rhyolite forms north-northwest-trending, steeply dipping dikes in a north-northwest-trending swarm in the southwestern part of the quadrangle, and is part of a suite of porphyritic rhyolite and alkali basalt dikes described by Stoddard and others (1986) and Stoddard (1992). The porphyritic rhyolite is a very dark gray to black, contains phenocrysts of sanidine and quartz, and is locally amygdaloidal (Stoddard and others, 1986, Stoddard, 1992). These dikes are as much as 10 meters thick. The olivine diabase is fine- to medium-fine grained and forms north-northwest trending, steeply dipping dikes that are as much as 3-4 meters thick. These dikes have chilled margins and the internal portions display columnar joints.

Rb/Sr analysis yielded an apparent age of 202 ± 5 Ma for a nine-point isochron consisting of several rock types and mineral separates from the swarm, and an apparent age of 196 ±8 Ma for rhyolite only (Stoddard and others, 1986). High precision $^{40}Ar/^{39}Ar$ analysis on two sanidine samples gave plateau ages of 196.6 ±0.7 Ma and 196.3 ± 0.7 Ma (Ganguli and others, 1995). A paleomagnetic study gave a pole position similar to those established for approximately 200 million year old rocks of stable North America (Stoddard and others, 1986).

Younger Cover

The crystalline rocks are locally overlain by Upper Tertiary deposits of the Atlantic Coastal Plain and by Quaternary alluvial terrace deposits. Fluvial terrace deposits consisting of sand and gravel are locally preserved on the crests of hills near the Roanoke River. The gravels consist of rounded pebbles and small cobbles of quartzite and vein quartz. Lag gravel from some of the deposits occurs down slope from the terrace deposits and on the crests of hills where terrace deposits once existed.

STRUCTURAL GEOLOGY

Four major faults, the Lake Gordon mylonite zone, the Macon mylonite zone, the Hollister fault zone, and the Gaston Dam fault zone, are exposed along this transect. The Late Paleozoic Lake Gordon mylonite zone and the Hollister fault zone are parts of the Eastern Piedmont fault zone of Hatcher and others (1977). The Macon mylonite zone and the Gaston Dam fault zone are parts of the D_2-decollement of Farrar (1985). Each of the Raleigh Spring Hope, Triplet and Roanoke Rapids terranes, which are separated fault zones, contain their own unique fabric elements. The fabric elements of the terranes are first described below, followed by description of the fault zones.

Fabric Elements of the Terranes

Rocks in the Raleigh terrane contain several phases of structures. Compositional layering and schistosity is a fundamental stucture in these gneisses and schists. The earliest recognized structures are outcrop- to map-scale isoclinal folds of compositional layering, and the regional schistosity (S_1) is parallel to the axial surfaces of the isoclinal folds. Away from these fold hinges, the fold limbs are parallel, and the fold limbs are folded by outcrop- to map-scale open folds. The isoclinal folds are considered to be F_1 folds and much of the layering and schistosity in the gneiss and schist is a transposed surface. Most, but not all, F_1folds plunge gently northwest or southeast. There are two sets of open folds that fold the S_1 surface. The older of the two sets are open folds (F_2) that trend north to northwest. In the hinge regions of these folds, an axial planar foliation (S_2) is sparsely developed: In biotite gneiss and amphibole-biotite gneiss, this foliation is defined by aligned biotite. The schists have an axial planar crenulation cleavage. The younger open fold set (F_3) plunges gently west-southwest. Interference of F_2 and F_3 in the southwestern and northwestern parts of the Gasburg quadrangle controls the outcrop patterns.

Rocks in the Spring Hope terrane consist of interleaved metasedimentary and metavolcanic rocks that are now schist and gneiss. Compositional layering in the metasedimentary rocks is inferred to be relict primary layering. These rocks are also foliated. This foliation is particularly well developed in the metasedimentary rocks where it is marked by muscovite porphyroblasts. This foliation is interpreted to be an early slaty cleavage (S_1) that was marked by new minerals during higher grade metamorphic conditions. Limited exposure, complex facies relationships, folding, and probable faulting make structural and lithologic relationships uncertain.

Fault Zones

The Lake Gordon mylonite zone (Horton and others, 1993a, 1993b) affects rocks along the western side of the Raleigh terrane (Fig. 1; Plate 1). Most of the rocks in the eastern side of this zone of simple shear are layered biotite gneisses of the Raleigh terrane, and are not mylonites by strict definition. However, the abundance of consistently dextral asymmetric quartz and feldspar porphryoclasts, and dextral shear bands and local development of phyllonites demonstrates that these rocks underwent simple shear, and should be considered part of the Lake Gordon mylonite zone. The Lake Gordon mylonite zone is synkinematic with Late Paleozoic granite of the Buggs Island pluton, and is considered to be a Late Paleozoic fault (Horton and others, 1993a, 1993b).

The Macon fault zone is a complexly folded zone of mylonitic schist and gneiss that lies between the Raleigh terrane and the Spring Hope terrane. It dips moderately west beneath the Raleigh terrane. Rocks in the fault zone contain kinematic indicators that include shear bands, asymmetric folds, and asymmetric porphyroclasts that consistently indicate dextral strike-slip. Most lineations plunge gently parallel or slightly oblique to the trend of the fault. These are interpreted to indicate oblique dextral and reverse motion on the Macon fault zone. Folding of some of the sheared rock within the fault zone seems to be of the same phase as the F_3 folds in the

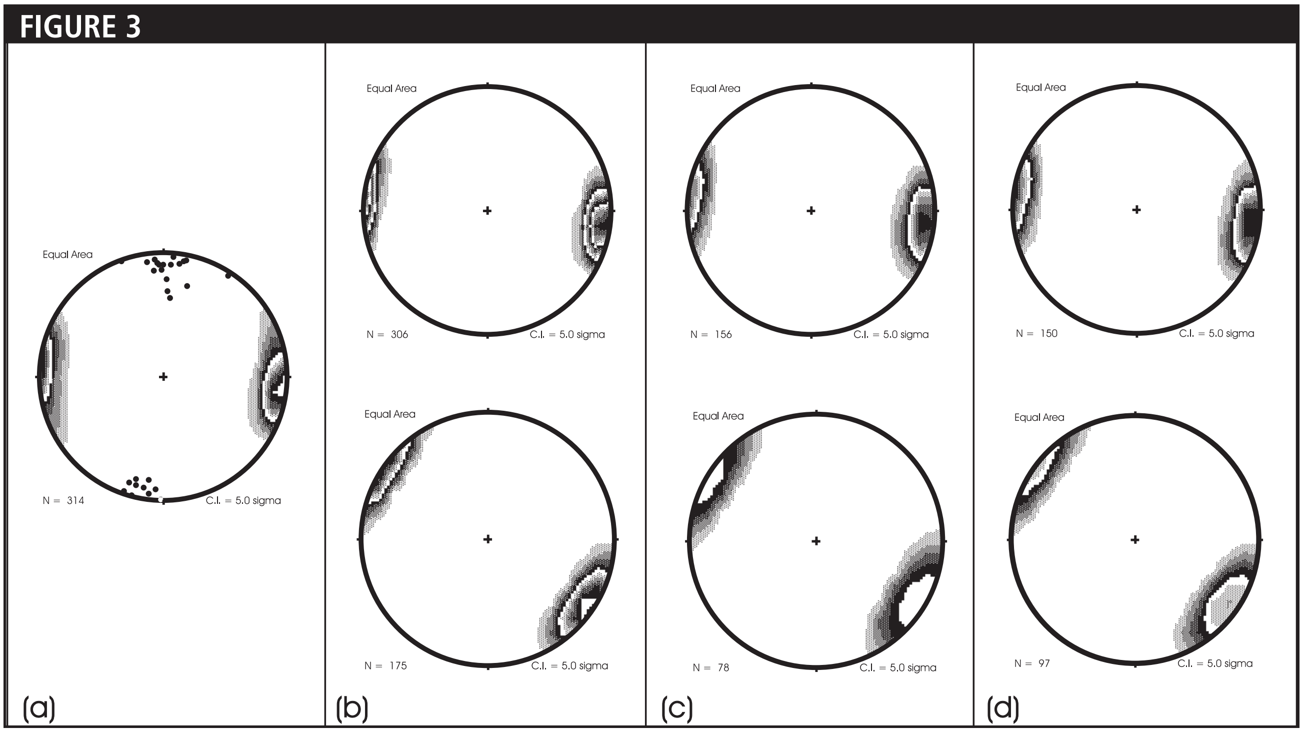


FIGURE 3. Lower hemisphere equal area stereonet projections of foliations, shear band, lineation data: (a) contoured poles of mylonitic foliation from the Hollister fault zone, and dots showing orientation of elongation lineations; (b) contoured poles to mylonitic foliation (top) and shear bands (bottom) for the Panacea Springs pluton; (c) contoured poles to mylonitic foliation (top) and shear bands (bottom) for the eastern part of the Panacea Springs pluton; (d) contoured poles to mylonitic foliation (top) and shear bands (bottom) for the western part of the Panacea Springs pluton, especially the granite sheets.

Raleigh terrane. Mylonitic textures are more extensisvely developed, and occur in a thicker interval of rock at the base of the Raleigh terrane than in the Spring Hope terrane. Ductile textures in the Raleigh terrane that are overprinted by muscovite porphyroblast growth, as well as the apparent static overprint of higher grade minerals on rocks of the Spring Hope terrane near the Macon fault zone suggests that the Raleigh terrane was hot during and for some time after motion on the fault. whereas the Spring Hope terrane was cooler, and heated as a result of motion on the fault. The Macon fault is intruded and cut by the Lawrenceville Granite. Farrar (1985a, 1985b) interpreted an Ordovician age of initial movement on the Macon mylonite zone, with later motion during the Late Paleozoic Alleghanian orogeny. The time of motion on this fault has not been determined, but it must predate intrusion of granite of the Lawrenceville pluton.

The Hollister fault zone is a ductile late Paleozoic dextral strike slip fault zone that cuts the crystalline rocks of the eastern Piedmont in North Carolina and Virginia (Farrar, 1985; Russell and others, 1985; Boltin, 1985; Boltin and Stoddard, 1987; Stoddard and others, 1991; Sacks and others, 1991; Sacks, unpublished data 1991-93). In the Gasburg quadrangle, rocks deformed in the Hollister fault zone crop out in the southeastern edge of the map. The sheared rocks consist of foliated biotite granite of the Lawrenceville and Panacea Springs plutons which were intruded as sheets into felsic metavolcanic rocks of the Spring Hope terrane. The foliated granite is coarse grained and some rocks contain megacrysts of microcline. The foliation is defined by fine to medium grained quartz and feldspar ribbons and aligned biotite. There are two sets of foliations (Fig. 3):

One is a closely spaced, dominant slip foliation (Dennis and Secor, 1987), the other is a spaced, shear band. The relative orientations of these two foliations indicate dextral shear for the fault zone. Other kinematic indicators include asymmetric and rotated feldpar porphyroclasts. These textures consistently indicate simple shear was accomodated in the granite, but granite is typically so coarse grained that it would not be considered mylonitic. The felsic metavolcanic rock into which the granite was intruded contains no evidence of simple shear. The granite was intruded as sheets into the metavolcanic rock. Sacks and Horton (1991) interpreted these sheets of granite to have been intruded into, and deformed along Reidel shears associated with the Hollister fault zone. To the south, in North Carolina (Fig. 2), granite of the Butterwood Creek pluton was intruded at the north end of a segment of the Hollister fault during an earlier phase of faulting. Most of the pluton is undeformed. The western side of the Butterwood Creek pluton was then intruded by synkinematic granite of the Airlie pluton. Granites of both the Butterwood Creek and the Panacea Springs plutons have yielded Late Paleozoic ages (Russell et al., 1985); hence motion on the Hollister fault zone must be Late Paleozoic.

Fault rocks within the Gaston Dam fault zone, including mylonitic gneiss and phyllite, and fault breccia, are poorly exposed. Most rocks displaying ductile deformation fabrics are granitic in composition. The ductile fabrics include quartz ribbons, asymmetric feldpsar porphyoclasts and shear bands. Layered gneiss, schist and phyllite also display quartz ribbons and shear bands. Rocks having fabrics indicative of simple shear are interlayered with rocks containing no evidence of simple shear. South of the Valentines quadrangle, the sheared rocks of the Gaston Dam Fault zone are cut by undeformed granite of the Butterwood Creek pluton. Locally, masses of vein quartz, locally brecciated, and recemented fault breccia are present. Along the Gaston Dam fault zone. Some of the fault breccia is cemented by what appears to be psuedotachylite. As discussed above, the Butterwood Creek pluton is considered to be synkinematic with movement along the Hollister fault zone. Therefore, movement along the Gaston Dam fault zone must have preceded motion along the Hollister fault zone, and was interpreted to possibly be of Ordovician age (the D2 decollement of Farrar, 1985). Cross-cutting relationships only constrain this fault to be older than the late Paleozoic Butterwood Creek pluton (Farrar, 1985; Russell and others, 1985; Sacks, unpublished data), and local, brittle fabrics suggest additional younger movement.

Joints

Joints are planar fractures in rock that provide important conduits for fluids flow in crystalline rocks. All types of crystalline rocks in the area are jointed. Most of the joints observed have steep dips and strike in a wide range of directions, however, significant numbers of joints strike about east-west and dip steeply north or south (Fig. 2). Another set dips steeply northeast or southwest, and a third dips steeply northwest or southeast. These rocks also contain curved exfoliation fractures. The Mesozoic dike rocks typically contain columnar joints that are perpendicular to the walls of the dike.

Metamorphism & Deformation

The ages of the schist and gneiss in the Raleigh terrane are poorly determined. Farrar (1985b) interpreted a Grenvillian age of highest grade metamorphism for the schist and gneiss of the

Raleigh terrane based on inferred continuity of these rocks with those in the Goochland area of Virginia. If this is true, then these rocks must be older than about 1 Ga. As discussed above, new mapping indicates the Goochland terrane and the Raleigh terrane are separated by a fault. Farrar (1985a, 1985b), Russell and others (1985) and as well as workers have recognized an Alleghanian amphibolite facies metamorphism in the Raleigh terrane. Widespread replacement of sillimanite by chloritoid and white mica indicates a retrograde greenschist facies overprint. At least some possible protoliths of the Raleigh terrane exist in the adjacent Carolina or Spring Hope terranes (Horton and others, 1991), and they are here interpreted to be Cambrian or Upper Proterozoic rocks (Horton and Stern, 1994). The earlier phases of folding and the age of metamorphism of the Raleigh terrane must be younger than the age of the protoliths, and is probably older than the intrusion of the only slightly foliated Wise and South Hill plutons and development of the Lake Gordan mylonite zone (Fig. 1). Deformation and metamorphism during the early part of the Alleghanian orogeny is thus permitted by the existing data. F3 folding in the eastern part of the Raleigh terrane is may be related to or postdate motion on the Macon fault zone. Motion on the Macon fault zone occurred while the rocks were hot and may be a late metamorphic event. If the metamorphism was Alleghanian, the Macon fault zone must be an Alleghanian fault. Folding and cleavage development in the Spring Hope terrane seems to predate the metamorphic overprint caused by emplacement of the Raleigh terrane onto it along the Macon fault zone. Intrusion of the Lawrenceville Granite post-dated motion on the Macon fault zone, and is synchronous with motion on the Hollister fault zone (Sacks and Horton, 1991) during the Alleghanian.

Acknowledgements

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Porphyroblast Textures in the Spring Hope Terrane, Lake Gaston

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Abstract

Rocks of the Spring Hope terrane in the Lake Gaston area contain abundant evidence of a polymetamorphic history. Textural relationships among metamorphic porphyroblasts, their relations to microstructures and fabrics, and mineral compositions may be used to deduce the following sequence of events: (1) crystal growth, pre- and/or syn-kinematic, during prograde middle amphibolite facies metamorphism; (2) static postkinematic porphyroblast growth at higher temperatures and at least locally lower pressures as a result of intrusion of granitoid plutons; and (3) late, localized retrogressive mineral growth related to faulting. Though the second and third events are clearly Alleghanian in age, the timing of the first event is unclear. It may be the result of pre-Alleghanian regional metamorphism, or may itself be a manifestation of Alleghanian orogenesis.

Introduction & Regional Geology.

The eastern Piedmont of North Carolina and Virginia is an amalgamation of fault-bounded terranes, overprinted by Alleghanian plutonism, deformation, and metamorphism (Farrar, 1985a; Horton and others, 1989, 1991; Stoddard and others, 1991). Terrane-bounding faults in many cases are Alleghanian in age; in other cases they are interpreted to be older faults reactivated during the Late Paleozoic. The work of Farrar (1985a, b) constituted a stratigraphic and structural synthesis of the area that continues to be tested and has held up well. Still, studies in the northeasternmost Piedmont of North Carolina that involve detailed geologic mapping have been few in number. Now, however, recent work by the U.S.G.S. along the Roanoke River corridor (e.g. Horton and others, 1993; Sacks, 1996a, b, c, d) and by the N.C.G.S. in the Raleigh 30 x 60 minute quadrangle (e.g. Stoddard, 1993; Carpenter and others, 1995; Stetler, 1997), provide a framework for future projects in the intervening area. See Figure 1.

The purpose of this short paper is to present petrographic descriptions and interpretations of rock samples originally collected during reconnaissance mapping 20 years ago (Stoddard and McDaniel, 1979; McDaniel, 1980). Mapping at that time suggested that a relatively well defined apparently homoclinally dipping sequence of metasedimentary and metavolcanic rocks could be traced from northern Franklin County, North Carolina, northward across Warren County, to the Virginia border. A more detailed study by Boltin (1985) examined part of this sequence in the Hollister quadrangle. Inferred protoliths of the mapped units were felsic and mafic volcanic rocks and fine-grained clastic sedimentary rocks. These units were grouped together within the Spring

Hope formation by Farrar (1985b).

Boltin and Stoddard (1987) documented a regional metamorphic gradient, from greenschist facies in the east to amphibolite facies in the west, overprinting these rocks in the Hollister quadrangle. Several exposures, described in some detail by Stoddard and others (1987), illustrate the regional metamorphic gradient in Spring Hope metapelites. In addition, the rocks show local effects of thermal metamorphism attributed to Alleghanian granitoid plutons, and of retrograde metamorphism, especially in areas affected by late shearing (Boltin and Stoddard, 1987). In the Hollister quadrangle, the west-dipping map units were interpreted (Boltin and Stoddard, 1987) to lie within the western, overturned limb of the Spring Hope synform (Farrar, 1985a).

Relict sedimentary and/or volcanic layering is evident in many exposures and at microscopic scale, defining S_0. In addition to primary compositional layering, two prominent regional metamorphic fabric elements were defined for Spring Hope rocks in the Hollister quadrangle (Boltin and Stoddard, 1987) and in the Gasburg quadrangle (Sacks, 1996c): (1) a dominant regional phyllosilicate schistosity, parallel to S_0 in most exposures; and (2) a cleavage most apparent in

FIGURE 1

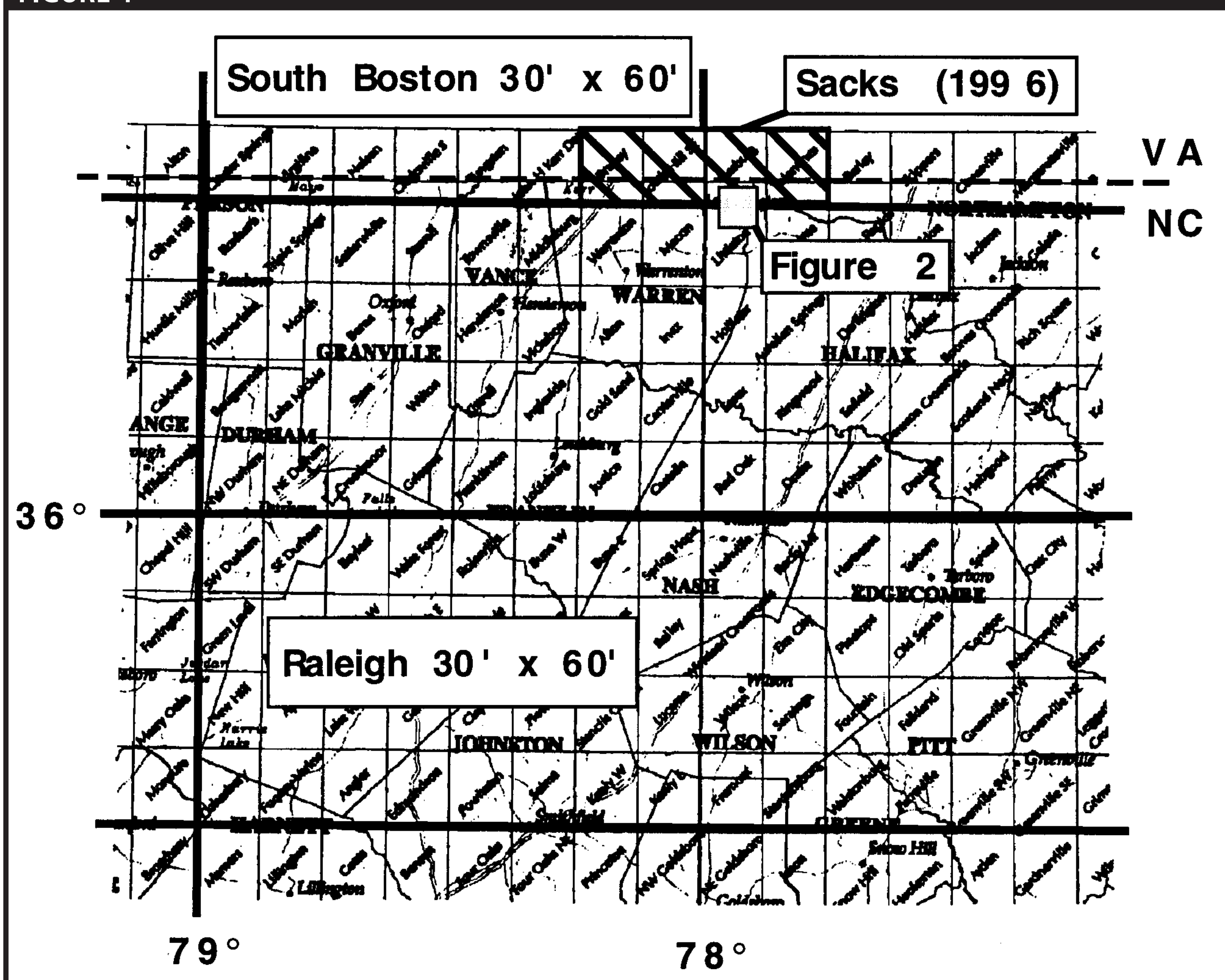

FIGURE 1. Index map of the northeastern Piedmont of North Carolina and surrounding region (N. C. Geological Survey, 1996). Areas of relatively recent 1:24,000-scale geologic mapping are indicated. Location of Figure 2 is also shown.

FIGURE 2

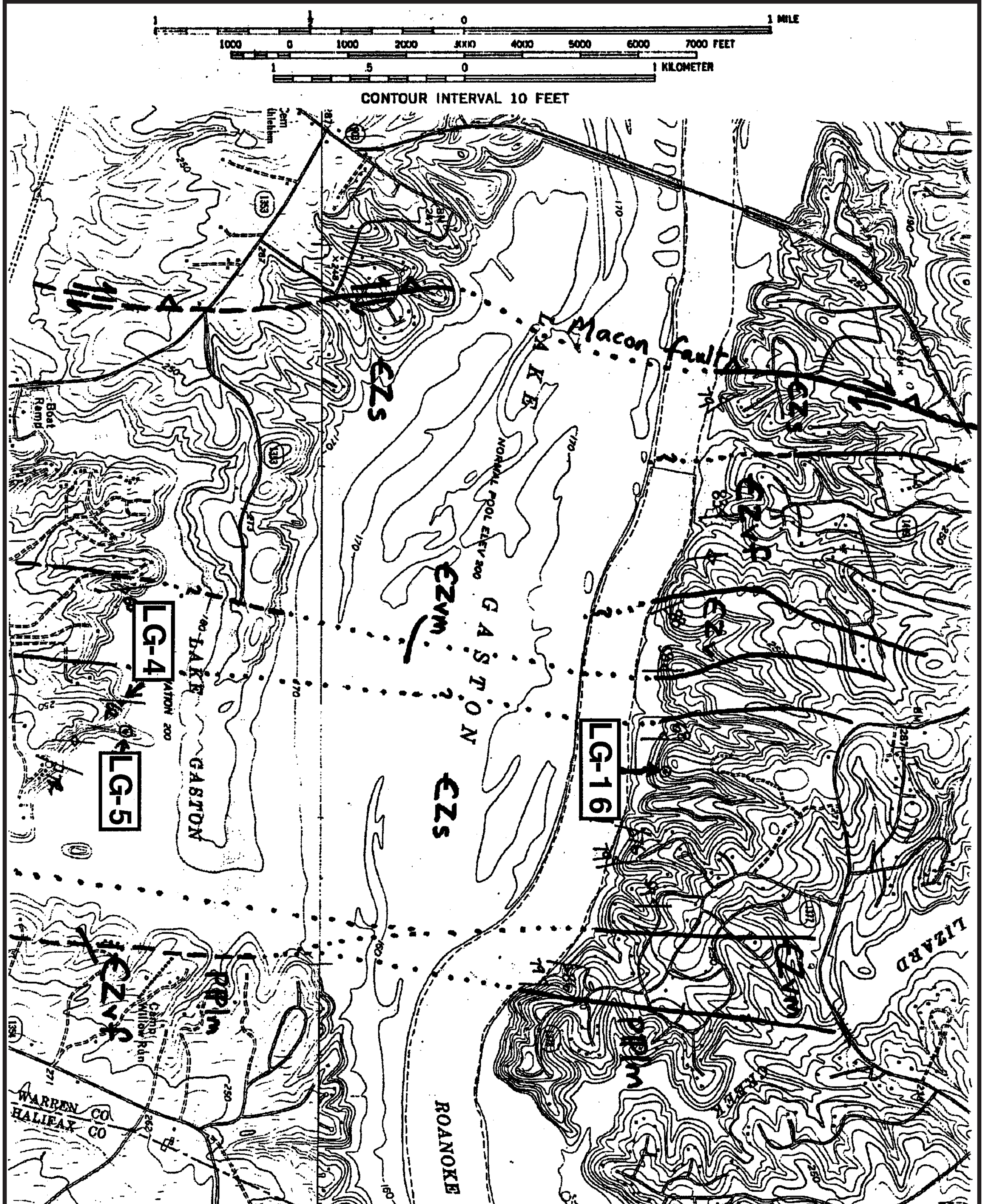

FIGURE 2. Generalized geologic map of a portion of the Lake Gaston area in the southern Gasburg 7.5-minute quadrangle (northern 2/3 of figure; from Sacks (1996c)), with contacts extrapolated onto the northern Littleton 7.5-minute quadrangle (southern 1/3 of figure). Spring Hope terrane rocks lie between the Macon fault, on the west, and granite of the Lawrenceville pluton (PPlm (from Sacks, 1996c)), on the east. CZs: metasedimentary rocks, dominantly pelitic schist; CZvf: felsic metavolcanic rocks; CZvm: mafic metavolcanic rocks; CZv: undifferentiated metavolcanic rocks. Strike and dip of regional (S1) schistosity indicated. Localities referred to in text indicated by LG-4, -5, and -16.

muscovite-rich metapelites. Both studies also recognized a local mylonitic foliation.

Where metamorphic grade reaches middle amphibolite facies, porphyroblasts in this belt commonly contain microscopic evidence of multi-stage growth (Stoddard and others, 1987). Outcrops along the shore of Lake Gaston in the Gasburg and Littleton quadrangles (Fig. 1) are the sources of samples discussed here. However, similar textures are known from elsewhere in the Littleton quadrangle, as well as from the Hollister and Inez quadrangles to the south.

LOCAL GEOLOGY & SAMPLE DESCRIPTIONS

Figure 2 depicts the geology in northern Warren County, North Carolina as mapped by Sacks (1996c). Between the terrane-bounding Macon fault on the west, and the Late Paleozoic Lawrenceville granitoid pluton (PPlm) on the east, map units of the Spring Hope terrane include metasedimentary rocks (CZs), here mainly pelitic schist, mafic metavolcanic rocks (CZvm), felsic metavolcanic rocks (CZvf), and undifferentiated metavolcanic rocks (CZv). On Figure 2, contacts mapped in the Gasburg quadrangle by Sacks (1996c) are projected south into the Littleton quadrangle based on the work of McDaniel (1980) and later reconnaissance. The regional schistosity generally strikes within 20° of north, and dips steeply east or west, and numerous meso- and macro-scale folds of schistosity are present (Sacks, 1996c). Localities of samples discussed below are LG-4 and LG-5, from the Littleton quadrangle on the south shore of Lake Gaston, and LG-16, from the Gasburg quadrangle on the north shore. All three outcrops lie within the dominantly metasedimentary CZs map unit.

LG-4

At locality LG-4, highly micaceous pelitic schist contains the assemblage muscovite + chlorite + garnet, with thin (approx 1 mm) layers of quartz (S_0?). The quartz layers are disrupted and tightly folded. Regional schistosity (S_1) is defined by the fine-grained muscovite matrix, also exhibiting microfolds. Crenulation cleavage (S_2) is developed along the axial planes of the folds. Both chlorite and a generation of late muscovite flakes have grown along S_2. The rock thus illustrates transposition of foliation, as the earlier foliations (S_0 and S_1) are in the process of being obliterated by S_2 (Fig. 3a). Garnets are generally idioblastic; some contain inclusion-rich cores and inclusion-free rims, while in others, inclusion trails continue to the margin of the porphyroblast.

LG-5

This locality is a narrow peninsula which, prior to being paved over in the mid-1980's, featured a number of good exposures of pelitic schist. Also at LG-5, quartzite layers up to 10 cm in thickness are present within the schist. Four different samples are described.

Sample LG-5Q is from a quartzite interlayer. Although it is composed primarily of quartz, it also contains sparse muscovite plus four metamorphic AFM minerals: staurolite, chloritoid, chlorite, and biotite. It is not known whether this represents an equilibrium assemblage, but there are no textures or other features suggesting otherwise.

Sample LG-5A is a muscovite + garnet schist with well-developed crenulations defined by folded muscovite (Fig 3b). Garnet is confined to a three-mm thick layer, thus defining S_0; garnet porphyroblasts are elongate parallel to the crenulation cleavage direction. Some garnets in this sample contain subtle idioblastic (not elongate) cores with inclusion patterns distinct from the outer portions of the same grain (Fig. 3c).

Sample LG-5A3 is a muscovite-biotite schist with porphyroblasts of staurolite and garnet, both of which contain curved inclusion trails of opaque minerals and quartz (Fig. 3d). Inasmuch as these inclusion trails are continuous with the folded schistosity in the rock matrix, they do not require that the growing porphyroblast rotated; it may have merely nucleated upon and overgrown a pre-existing crenulation hinge (e.g. Bell and Rubenach, 1983).

Sample LG-5E contains the assemblage muscovite + biotite + garnet + staurolite + quartz + plagioclase (+ relict and/or retrograde chlorite). In this sample, garnet is commonly partially to completely included within staurolite porphyroblasts. Some garnets contain inclusions of relict(?) chlorite (Fig. 3e). Additionally, garnets display texturally distinct cores and rims (Fig. 3f), generally with an included core foliation that is curved and sits at a high angle to the schistosity in the matrix of the rock. If a foliation is preserved in the outer portion of the garnet, it is discordant to the core's foliation as well (Fig. 4a).

Microprobe analyses from the double garnet pictured in Figure 4a reveals chemically distinct core and rim (Table 1). The core is rich in spessartine component, and poor in pyrope component, compared with the rim. A chemical profile (Fig 4b) implies that the core region is fairly homogeneous. Then, beginning at the textural break, the garnet's composition changes continuously outward across an intermediate region, with Mn decreasing, Fe and Mg increasing, and Ca remaining relatively constant, until the composition levels off.

LG-16

This exposure is located in the Gasburg quadrangle, on the north shore of Lake Gaston. Though it is dominated by pelitic schist, there are also interlayers of quartzite and minor amphibolite. Sample LG-16A2 is from an amphibolite layer, whose protolith is inferred to be a mafic volcanic rock. The assemblage is hornblende + plagioclase + garnet + quartz + opaque minerals (ilmenite?). The foliation is defined by the tiny lath-shaped opaque minerals. Hornblende is unoriented and strongly poikiloblastic; it overgrows and includes the opaque mineral trails, which continue into the matrix uninterrupted. Garnet porphyroblasts exhibit several textural features. Many have elongate, discontinuous, xenoblastic cores that appear to have been stretched out. Most exhibit partial idioblastic overgrowths (Fig. 5a). Many of the garnets in this sample also display texturally distinct cores and rims. One (Fig. 5b) shows curved inclusion trails in its core, whereas the outer portions have fewer inclusions which generally are continuous with the matrix foliation. This same garnet exhibits well-defined crystal overgrowths.

FIGURE 3. *(Opposite Page)* Selected photomicrographs of samples from localities LG-4 and LG-5. All in plane-polarized light except 3d, which is in crossed polars. **3a:** Sample LG-4Y, showing transposition of S0 and S1 into S2. **3b:** Sample LG-5A, showing muscovite crenulations and elongate garnet porphyroblasts growing along crenulations. **3c:** Close-up of same thin section as 2b, showing idioblastic, non-elongate garnet cores. **3d:** Sample LG-5A3, showing garnet porphyroblast containing curved trails of included quartz grains. This internal fabric is continuous with the external schistosity. **3e:** Sample LG-5E, garnet porphyroblast almost completely surrounded by staurolite; garnet contains an inclusion of chlorite, possibly relict. **3f:** Sample LG-5E, typical two-stage garnet, with inclusion trails indicating distinct core and rim regions. To view this and the other photomicrographs in color on the internet, go to: <http://www4.ncsu.edu/eos/users/s/stoddard/public/cgsfigs>

FIGURE 3

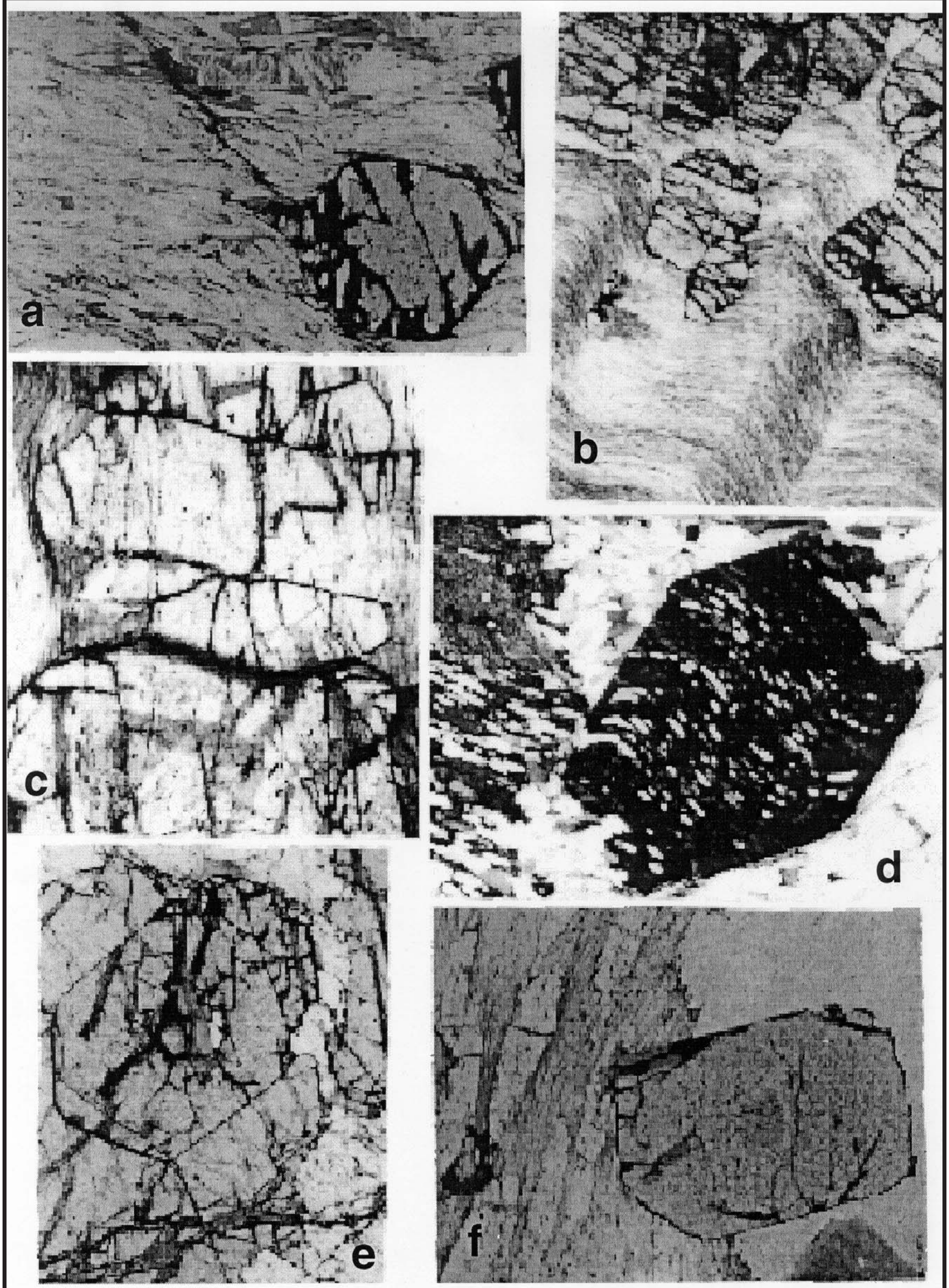

FIGURE 4

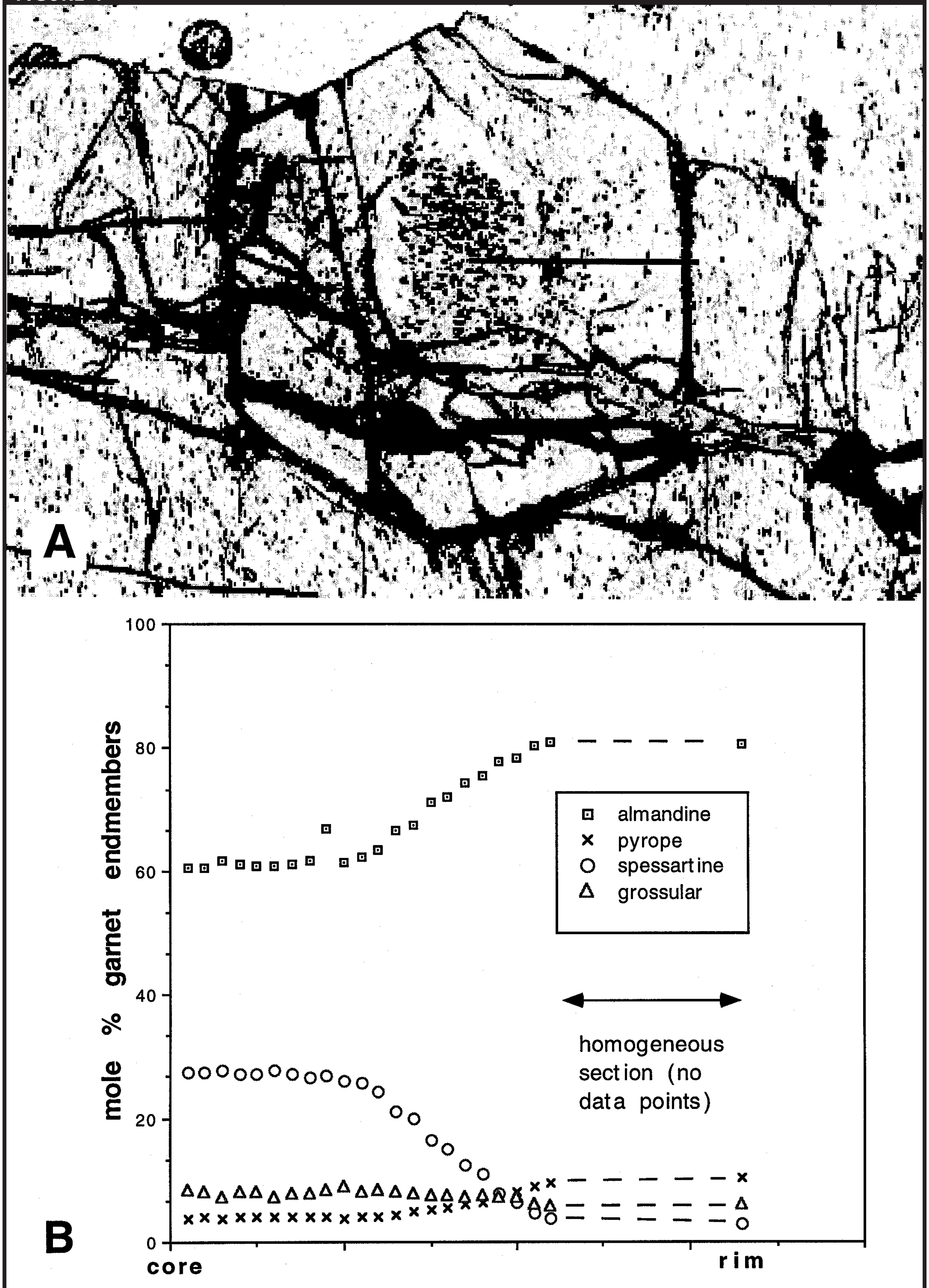
A
B
100
80
60
40
20
0
mole % garnet endmembers
almandine
pyrope
spessartine
grossular
homogeneous section (no data points)
core
rim

FIGURE 5

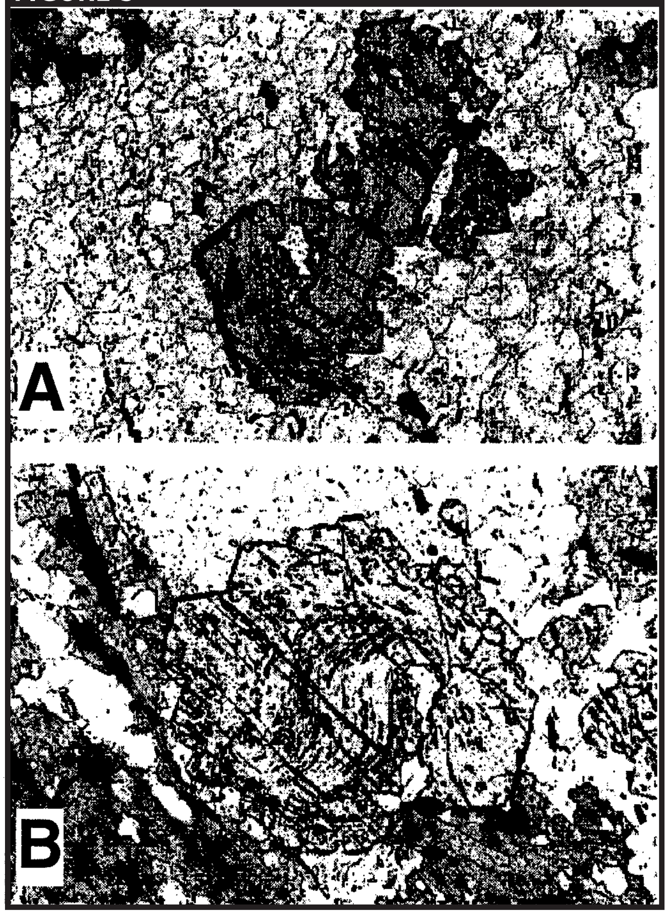

FIGURE 5. Photomicrographs from sample LG-16A2; plane-polarized light. **5a:** Stretched, deformed early garnet core preserves inclusion trail at a high angle to inclusion trail of outer garnet overgrowth. **5b:** Two-stage garnet, whose core contains curved inclusion trails, and showing well-developed crystal overgrowths.

Mineral Chemistry & Thermobarometry

Minerals from two of the samples were analyzed by electron microprobe (Table 1), and the results were used in an attempt to calculate metamorphic conditions, using the program GeoThermoBarometry (Kohn and Spear, 1999). In sample LG-5E, no biotite inclusions were found within the core region of the garnet. Only a very small range in biotite Fe/Mg was observed in LG-5E; two analyses are shown in Table 1. Using the more Fe-rich biotite with the garnet core, garnet-biotite thermometry for sample LG-5E yields garnet rim temperatures as much as 300° higher than garnet core temperatures, depending upon the calibration used. Although the high Mn and Ca contents of the garnet core make it unsuitable for quantitative results, it is clear that the rim of the garnet grew at higher temperature than did the core (probably 650° - 700°C). A lack of aluminum silicate polymorph minerals in the pelitic samples makes pressure estimation difficult in these rocks from the south shore of Lake Gaston.

However, sample LG-16A2, from the north shore of the lake, contains an assemblage that may be used to estimate both P and T (garnet + hornblende + plagioclase + quartz). Table 1 shows analyses of garnet, plagioclase, and hornblende.

FIGURE 4. *(Opposite Page)* Idioblastic "double garnet" from sample LG-5E. **4a:** Photomicrograph under plane-polarized light. Garnet is almost entirely enclosed within staurolite; line shows approximate location of microprobe traverse; **4b:** Compositional traverse across double garnet, showing chemical zoning profiles.

TABLE 1

Sample	LG5E	LG5E	LG5E	LG5E	LG16A2	LG16A2	LG16A2	LG16A2	LG16A2	LG16A2
Mineral	**Gar core**	**Gar rim**	**Biot A**	**Biot B**	**Gar core**	**Gar rim**	**Hbl inc**	**Hbl out**	**Plag inc**	**Plag out**
SiO2	37.35	37.12	36.52	36.98	36.91	36.81	49.73	50.51	45.11	42.955
TiO2	0.06	0.08	1.55	1.37	0.14	0.08	0.14	0.12	—	—
Al2O3	21.49	21.35	20.01	20.14	21.81	21.94	4.97	5.18	36.74	37.09
FeO	26.65	36.39	18.77	20.29	19.17	16.76	17.73	17.49	0.26	0.08
MnO	11.96	1.33	0.02	0.04	4.69	6.56	0.37	0.35	—	—
MgO	0.96	2.62	10.39	10.46	0.66	0.64	11.96	11.89	—	—
CaO	2.74	2.11	0.08	0.14	14.78	15.57	12.02	12.24	18.86	18.92
Na2O	0.00	0.00	0.44	0.36	0.01	0.01	0.26	0.23	0.81	0.4
K2O	0.09	0.06	9.05	8.16	—	—	0.05	0.05	0.01	0.01
Total	101.15	101.04	96.83	97.94	98.17	98.37	97.23	98.06	101.797	99.448
OxNum	**12**	**12**	**11**	**11**	**12**	**12**	**23**	**23**	**8**	**8**
Si	2.995	2.972	2.710	2.713	2.964	2.950	7.399	7.429	2.045	1.995
Ti	0.004	0.005	0.087	0.075	0.008	0.005	0.016	0.013	—	—
Al	2.032	2.016	1.750	1.742	2.064	2.072	0.872	0.898	1.963	2.030
Fe2+	1.788	2.437	1.165	1.245	1.287	1.123	2.206	2.151	0.009	0.003
Mn	0.812	0.090	0.001	0.003	0.319	0.445	0.046	0.044	—	—
Mg	0.115	0.313	1.149	1.144	0.079	0.077	2.652	2.607	—	—
Ca	0.235	0.181	0.007	0.011	1.272	1.337	1.916	1.929	0.916	0.942
Na	0.001	0.000	0.064	0.051	0.001	0.001	0.075	0.065	0.071	0.036
K	0.009	0.006	0.857	0.764	—	—	0.010	0.010	0.000	0.001
Sum	7.984	8.010	7.789	7.748	7.995	8.010	15.192	15.145	5.005	5.007
almand	0.606	0.807			0.435	0.377				
spessar	0.275	0.030			0.108	0.149				
pyrope	0.039	0.104			0.027	0.026				
grossul	0.080	0.060			0.430	0.448				
X Mg			0.497	0.479			0.546	0.548		
anorth									0.928	0.963
albite									0.072	0.037

Plagioclase is exceedingly calcic, and shows only a small difference between analyses of plagioclase that occurs as inclusions in garnet (An92.8), and those grains in the matrix (An96.3). The amphibole analyses from within and outside garnet are nearly identical low-Al actinolitic hornblendes. Garnet shows only small differences from core to rim composition. Using these compositions, P-T conditions for the garnet core may be estimated at about 520° and 3.8 kbar, and for the rim, 550° and 3.4 kbar (Graham and Powell (1984) garnet-hornblende Fe-Mg exchange thermometer and Kohn and Spear (1990) tschermakite-Fe model for hornblende in the barometer). Although these calibrations give a slight pressure decrease from core to rim, other calibrations show a pressure increase; however, all calibrations show temperature increasing from core to rim. Estimated P-T conditions plot near the andalusite = sillimanite reaction. See Figure 6.

INTERPRETATION & CONCLUSION

The occurrence of curved or spiral trails of inclusions in garnet porphyroblasts is common within rocks of the Spring Hope terrane in the northeasternmost Piedmont of North Carolina. The origin of such trails has been the subject of considerable debate (e.g. Johnson, 1993).

FIGURE 6

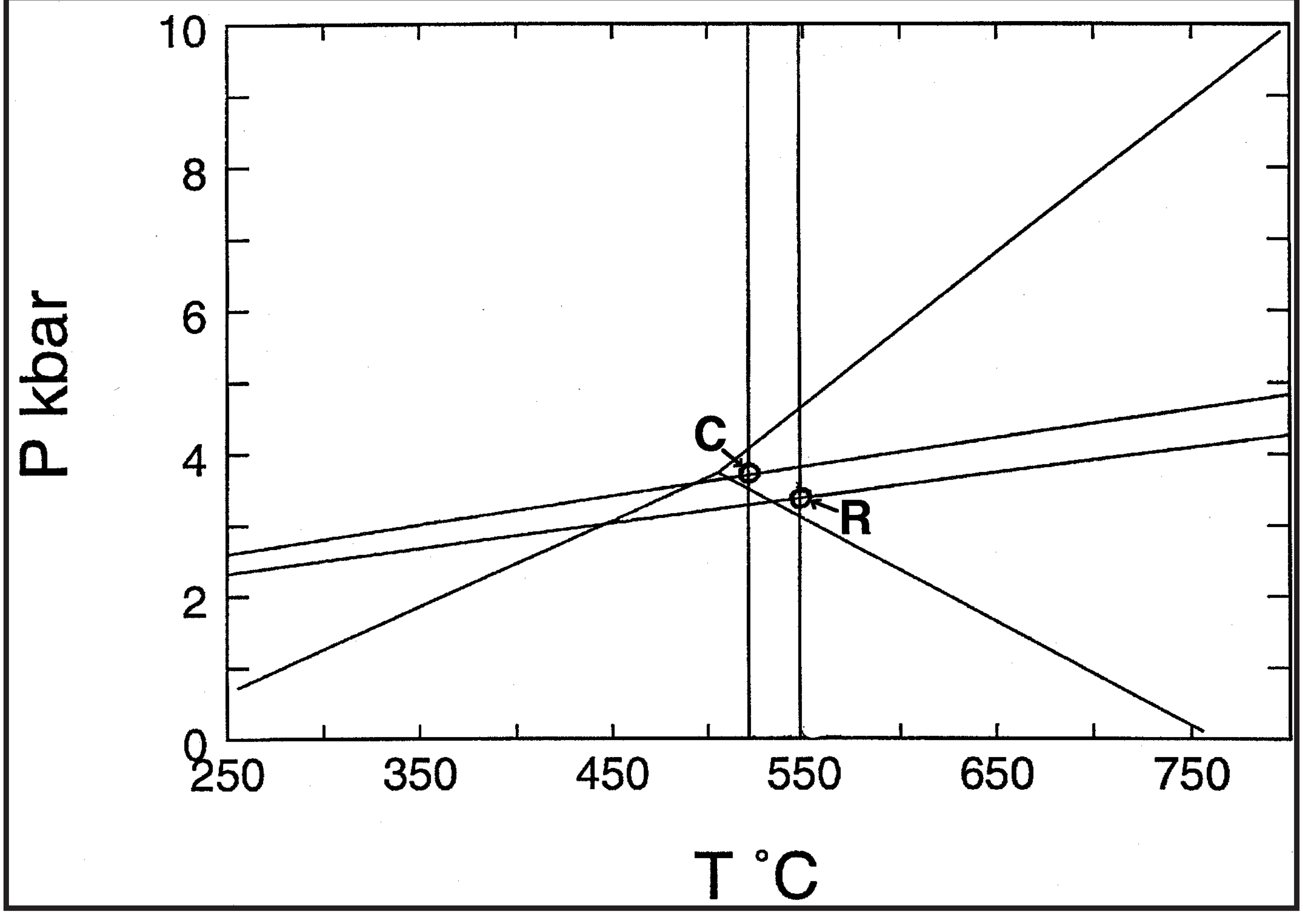

FIGURE 6. Results of thermobarometric calculations for sample LG-16A2, using the analyses in Table 1 and the program GeoThermoBarometry (Kohn and Spear, 1999). The vertical lines are equilibria calculated from hornblende-garnet geothermometer (Graham and Powell, 1984), while the nearly horizontal lines are from the garnet-plagioclase-hornblende-quartz geobarometer of Kohn and Spear (1990). The early-stage conditions (labelled "C") are indicated at the intersection of equilibria involving garnet core and inclusions of hornblende and plagioclase; later-stage ("R") is intersection of equilibria involving garnet rim and matrix plagioclase and hornblende.

Garnets may have rotated as they grew, thus progressively deforming an originally straight line of inclusions. Alternatively, garnets may have nucleated and grown, without rotation, on pre-existing crenulation hinges, thus preserving an "s" or "z" shaped trail. Until further detailed mapping and structural analysis is done in this part of the Piedmont, the garnets described here can add nothing to this debate.

However, garnet textures strongly suggest porphyroblast growth in two or three distinct episodes, or possibly during one prolonged continuous period, during which the deformational (stress/strain), kinematic, and metamorphic (temperature/pressure) conditions changed. Garnets in which cores and rims have discordant inclusion patterns imply either rotation of the garnet or transposition of the external fabric, prior to rim growth. Growth of garnet rims, muscovite flakes, and chlorite along crenulation cleavage must have occurred during or after crenulation formation. Partial idioblastic overgrowths of garnet occurs in samples within about one km of the Lawrenceville pluton, suggesting a late thermal effect. Higher temperatures for garnet rims are also indicated, as described above for samples LG-5E and LG-16A2.

The variety of textural observations here can be understood in terms of the following sequence of events:

(1) Formation of a regional fabric (S_1 of Sacks (1996c)) generally parallel to S_0, and defined by metamorphic minerals, especially white mica and opaque minerals;
(2) Growth of inner portions of most garnets prior to formation of existing crenulation cleavage (S_2), but perhaps synkinematic with respect to earlier events and fabrics;
(3) Growth of outer portions of garnets either synchronous with (synkinematic) or following (postkinematic) the development of S_2;
(4) Postkinematic growth of most staurolite which includes garnet, and growth of garnet overgrowths, owing to thermal metamorphism resulting from intrusion of nearby granitoid plutons; and
(5) Growth of late muscovite and chlorite along crenulation cleavage, perhaps assisted by aqueous fluid derived from pluton crystallization, and mobilized along active shear zones.

Thermobarometry indicates that Event 3 (and 4?) occurred at higher temperatures than Event 2. Events 3, 4, and 5 are clearly Alleghanian in age. Crenulation cleavage (S_2) in the area is believed to be related to Alleghanian map-scale folds, such as the Spring Hope synform (Farrar, 1985a; Boltin and Stoddard, 1987; Sacks, 1996c), but more mapping is needed before correlations may be made with confidence. Dated granitoid plutons (e.g. Butterwood Creek) and shear zones (e.g. Hollister fault) in the area are also Alleghanian (Russell and others, 1985). Available dating of metamorphic minerals in the eastern Piedmont also indicates Alleghanian mineral growth (Kunk and others, 1995).

The protoliths of Spring Hope terrane metamorphic rocks are interpreted to be Neoproterozoic (Horton and Stern, 1994; Goldberg, 1994). Tectonic models for the eastern Piedmont frequently call for an early to middle Paleozoic orogenic event, during which, for example, the Spring Hope terrane may have been juxtaposed against the Raleigh terrane (e.g. Farrar, 1985a; Stoddard and others, 1991). However, no existing geochronologic evidence supports the contention that such events were pre-Alleghanian. More detailed and sophisticated isotopic studies are needed. They should be aimed at dating internal portions of multi-stage porphyroblasts, mineral inclusions within porphyroblasts, or minerals defining distinct s-surfaces. And, such studies should be undertaken in areas that have been mapped in sufficient detail (e.g. 1:24,000 scale).

ACKNOWLEDGMENTS

Ron McDaniel first introduced me to this area and its geology. Microprobe analyses from sample LG-5E were done at U.C.L.A. with assistance from Bob Jones; those from LG-16A2 were done at N. C. State with assistance from Ron Fodor. A review by Allen Dennis, and reviews of an earlier version by Art Snoke and Stewart Farrar, were helpful. I am also grateful to Michael Jordan (no, not THAT one!) for help with the damn computer. I thank all of these individuals and institutions.

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Application of Aerial Gamma-ray Spectrometric and Magnetic Surveys in Geologic Mapping - A Case Study in Southern Virginia and Northern North Carolina

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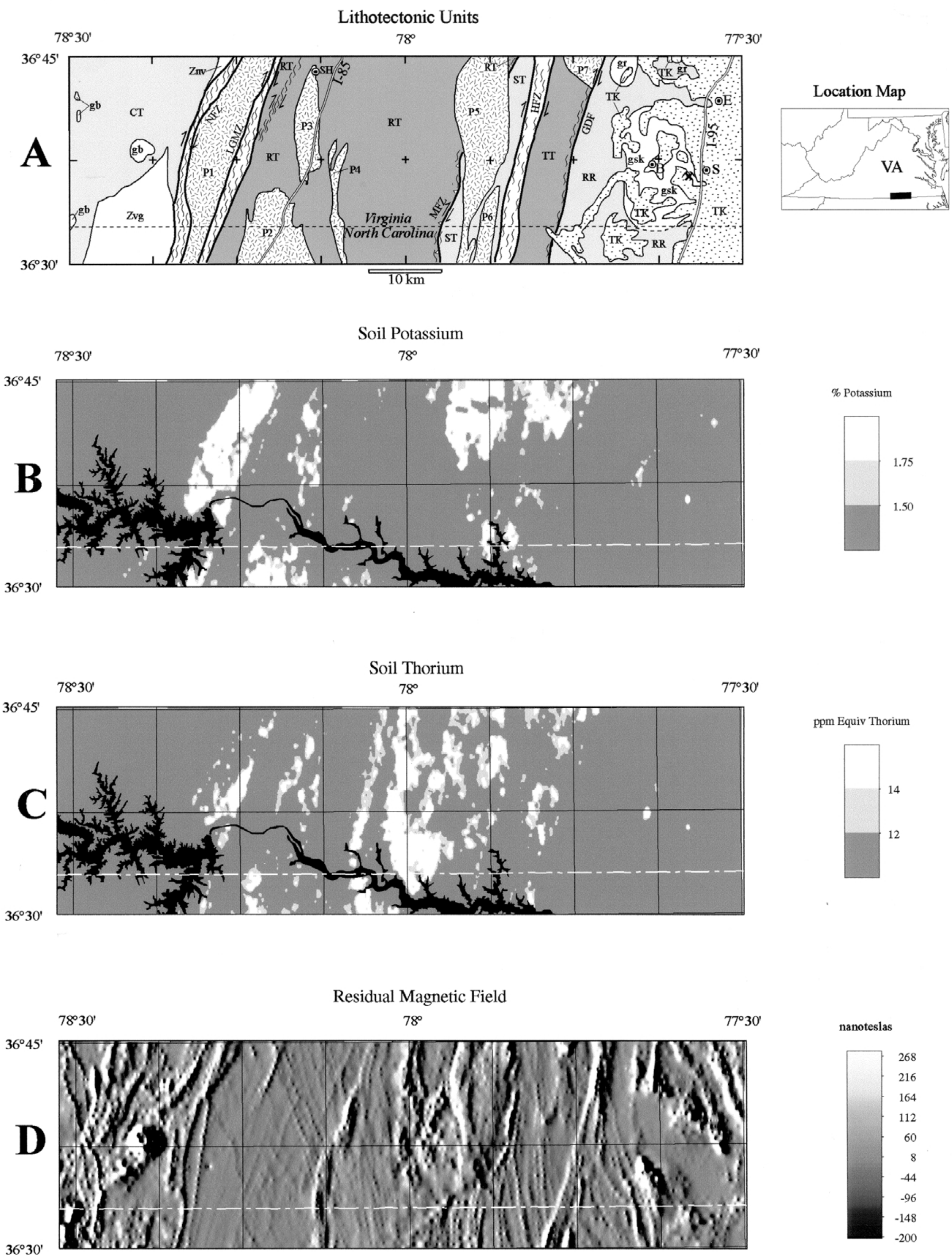
Abstract

Aerial gamma-ray spectrometric and magnetic survey maps are valuable aids for geologic mapping where rocks are poorly exposed in south-central Virginia and northernmost North Carolina. Broad low areas on the potassium and thorium gamma-ray survey maps distinguish the Carolina, Spring Hope, and Roanoke Rapids terranes from more highly radiogenic areas of the Raleigh and Triplet terranes, reflecting differences in the compositions of residual soils. Granitic rocks are delineated most clearly by potassium highs and less clearly by thorium highs. Nearly all the thorium highs other than those related to granites are associated with amphibolite-facies rocks of the Raleigh and Triplet terranes. Contrasting thorium lows within these terranes help to distinguish the individual rock units. In the Carolina and Roanoke Rapids terranes, high-gradient magnetic patterns delineate stratified metavolcanic and metasedimentary units that are not discernible from the gamma-ray surveys. Circular magnetic highs coincide with gabbro plutons, and numerous magnetic lineaments correspond to Jurassic diabase dikes. Magnetically uniform, low-gradient areas coincide with less mafic plutons. A magnetic lineament (high) coincides with the Nutbush Creek fault zone, and other faults are distinguished as boundaries between zones of contrasting geophysical properties. The gamma-ray spectrometric and magnetic survey maps most effectively indicate geologic features in the region if they are employed collectively, and if they are interpreted in concert with simultaneous geologic field investigations.

Introduction

High quality aerial gamma-ray spectrometric and magnetic surveys were conducted in 1994 to support geologic mapping in south-central Virginia and northernmost North Carolina. Maps produced from these geophysical surveys encompass the southern half of the South Boston, Va.-N.C., 30' x 60' quadrangle and the southwestern quarter of the adjacent Emporia, Va.-N.C., 30' x 60' quadrangle (U.S. Geological Survey, 1994a, 1994b). The illustrations in this report (Fig. 1) are limited to the eastern two thirds of this geophysical survey area, which overlaps the Carolina Geological Society's 1999 field trip. Rock units include greenschist-facies metavolcanic and metasedimentary rocks of the Carolina, Spring Hope, and Roanoke Rapids terranes, amphibolite-facies gneisses of the Raleigh and Triplet terranes, intrusive rocks ranging in composition from gabbro to granite, and sedimentary deposits of the Atlantic Coastal Plain (Fig. 1A). Many of the

FIGURE 1


Lithotectonic Units
78°30'
78°
77°30'
36°45'
36°30'
A
10 km
Virginia
North Carolina
Location Map
VA
Soil Potassium
B
% Potassium
1.75
1.50
Soil Thorium
C
ppm Equiv Thorium
14
12
Residual Magnetic Field
D
nanoteslas
268
216
164
112
60
8
-44
-96
-148
-200

geologic boundaries reflect interpretations of field observations in the context of the geophysical maps, which have been used by geologists in the field since 1994.

Aerial gamma-ray spectrometric and magnetic survey maps are useful aids for geologic mapping in this region because bedrock exposures are sparse due to deep weathering, because surface materials (soil and saprolite) are mainly residual (derived from weathering of underlying bedrock) rather than transported except in major drainages, and because the local geology is susceptible to study by these techniques (Daniels and Horton, 1993; Horton and others, 1994).

Although the gamma-ray energy emanates from the top 0.5 meter of ground, the locally-derived residual soil and saprolite contain the three radioelements, potassium, uranium, and thorium, in proportions that are roughly related to those in the underlying bedrock. Potassium and thorium maps of this area (Figs. 1B and 1C) are the most geologically discriminating. The map pattern for uranium (not shown in Fig. 1; see U.S. Geological Survey, 1994b) resembles that for thorium, and these elements typically occur together in minerals such as monazite. Total count gamma-ray survey maps (not shown) combine all three radioelements indiscriminantly, and consequently are less informative about the composition of near-surface materials. Water bodies such as Lake Gaston and Kerr Reservoir coincide with low anomalies on the gamma-ray survey maps, because the water absorbs and blocks gamma radiation.

Magnetic anomalies reflect the distribution of magnetite and other magnetic minerals in the earth's crust. Magnetic sources at the surface or at shallow depths have shorter wavelengths than similar sources at greater depths. In order to accentuate the short-wavelength anomalies generated

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FIGURE 1. *(Opposite Page)* Generalized geologic (lithotectonic) and geophysical maps of the study area in southern Virginia and northern North Carolina:

A. Lithotectonic units. Adapted from Horton and others (1993), Sacks (1996a, 1996b, 1996c, 1996d), Mixon and others, 1989, Peper and others (1996), Peper and Wygant (1997), Virginia Division of Mineral Resources (1993), and North Carolina Geological Survey (1985).

Sedimentary rocks
TK = Atlantic Coastal Plain, undivided
Late Paleozoic granites
P1 = Buggs Island pluton
P2 = Wise pluton
P3 = South Hill pluton
P4 = unnamed pluton
P5 = Lawrenceville pluton
P6 = Panacea Springs pluton
P7 = Edgerton pluton
Other intrusive rocks
gb = gabbro
Znv = North View pluton
Zvg = Vance pluton
gsk = Skippers pluton
gr = unnamed granite and granodiorite

Metasedimentary and metavolcanic rocks
CT = Carolina terrane
RT = Raleigh terrane
ST = Spring Hope terrane
TT = Triplet terrane of Sacks (1996, a,b,c,d)
RR = Roanoke Rapids terrane
Faults and shear zones
NFZ = Nutbush Creek fault zone
LGMZ = Lake Gordon mylonite zone
MFZ = Macon fault zone
HFZ = Hollister fault zone
GDF = Gaston Dam fault zone
Cultural features
B = Brink E = Emporia
S = Skippers
SH = South Hill

B. Gamma-ray survey of soil potassium. Large water bodies are shown in black.

C. Gamma-ray survey of soil thorium. Large water bodies are shown in black.

D. Residual magnetic field illuminated from the west.

by near surface features, Figure 1D shows the partial derivative of the magnetic field and simulates illumination from the west to emphasize north-south gradients. The same anomalies are discernible on the original 1:100,000-scale aeromagnetic map (U.S. Geological Survey, 1994a).

GEOPHYSICAL METHODS & DATA

The aerial survey was flown in 1994 using a fixed-wing aircraft outfitted with a stinger-mounted cesium-vapor magnetometer and a 256-channel, gamma-ray spectrometer having a detector consisting of a 50-liter, downward-looking, thallium-doped sodium iodide crystal and an 8-liter upward-looking crystal for the atmospheric radon correction. The magnetometer sample rate was 0.1 second; the gamma-ray spectrometer sample rate was 1.0 second. Conversion of corrected counts/second to equivalent percent (%) potassium, equivalent parts per million (ppm) uranium, and equivalent ppm thorium ground concentration was based on measurements on the Department of Energy calibration pads at Walker Field, Grand Junction, Colorado, following a procedure described by Grasty (1976).

Flights were east-west at 400 feet (122 meters) above mean terrain with a flight-line separation of 1/2 mile (805 meters). Navigation and post-flight positions were determined from differential GPS instrumentation.

INTERPRETATION OF GAMMA-RAY DATA

Greenschist-facies metavolcanic and metasedimentary rocks of the Carolina, Spring Hope, and Roanoke Rapids terranes and some of the plutons within these terranes are characterized by dark areas on the potassium and thorium maps (Figs. 1B and 1C), indicating low concentrations of both radioelements. This suggests that the metamorphic rocks of these terranes are compositionally similar to one another but distinct from those of the Raleigh terrane. The Nutbush Creek (NFZ), Hollister (HFZ), Macon (MFZ), and Gaston Dam (GDF) fault zones are all coincident with linear boundaries of these low areas on the gamma-ray maps.

Late Paleozoic granite of the Buggs Island pluton (P1) is bounded on the west by the Nutbush Creek fault zone and on the east by the Lake Gordon mylonite zone (LGMZ). This granite is clearly delineated and characterized by its high potassium anomaly, whereas the more heterogeneous thorium distribution suggests unmapped compositional zoning or differences in weathering within the pluton. Similar potassium-high anomalies coincide with Late Paleozoic granites of the Wise (P2), South Hill (P3), Lawrenceville (P5), Panacea Springs (P6), and Edgerton (P7) plutons. The potassium anomaly associated with the Edgerton pluton suggests that this granite pluton may extend south of the limit shown in Figure 1 based on reconnaissance mapping (Virginia Division of Mineral Resources, 1993; Fig. 1B of Sacks, 1996d).

An isolated spot of high potassium and high thorium coincides with a granite quarry 2.7 kilometers west-southwest of Skippers, Va. High potassium levels at the quarry can be attributed to unweathered granite exposed by the removal of overlying Coastal Plain deposits and saprolite. The lower potassium values associated with most areas of the Skippers pluton (gsk) may be explained in part by a thin, surface veneer of colluvium (not shown in Fig. 1A) derived from Coastal Plain deposits. This colluvium typically extends downslope well beyond the original Coastal Plain source units shown on geologic maps (Fig. 1A). The leaching of potassium from residual soils following the breakdown of potassium feldspar may be a contributing factor where residual soils are thick along interfluvial uplands between the Roanoke and Nottoway Rivers. Other isolated spots of high potassium are associated with part of a stream valley (Fountains Creek) overlying the Skippers pluton north of Brink, Va., and with the city of Emporia, Va. (perhaps due to gravel on roads and parking lots).

Spotty high thorium anomalies (Fig. 1C) are coincident with granites of the Buggs Island (P1), Wise (P2), South Hill (P3), Lawrenceville (P5), and Edgerton (P7) plutons as well as smaller granitic bodies, although the thorium map does not delineate these bodies as clearly as the potassium map. The thorium map is useful for detecting compositional differences among granites, as exemplified by the Panacea Springs pluton, which resembles the other granites on the potassium map but lacks a high thorium anomaly. Aside from anomalies associated with the granites, nearly all of the thorium high anomalies are associated with amphibolite-facies metamorphic rock units in parts of the Raleigh terrane and Triplet terrane.

The thorium map (Fig. 1C) is most helpful for delineating metamorphic rock units within the Raleigh terrane. In general, sillimanite-muscovite schists and interlayered mica gneisses on the eastern side of the terrane (approximately east of granite P4) are high, whereas layered gneisses on the western side are generally low (Sacks, 1996b, 1996c). Bands of contrasting thorium highs and lows within these broad subdivisions are useful aids for mapping individual schist and gneiss units.

The Macon (MFZ), Hollister (HFZ), and Gaston Dam (GDF) fault zones are all coincident with linear boundaries on the thorium map. These fault zones separate thorium highs associated with amphibolite-facies schists and gneisses of the Raleigh and Triplet terranes from thorium lows associated with greenschist-facies volcanogenic rocks of adjacent terranes.

In the eastern part of Figure 1C, spot anomalies high in thorium coincide with (1) the granite quarry west-southwest of Skippers, Va., as noted above, and with (2) a heavy-mineral sand deposit at Brink, Va. The latter is similar to the Old Hickory titanium deposit in Sussex and Dinwiddie Counties, Virginia, which is one of several Pliocene(?) heavy-mineral placer deposits along the inner margin of the Atlantic Coastal Plain in Virginia and North Carolina (Berquist and Mallard, 1992; Berquist and Bailey, 1998).

Although the Raleigh terrane in the area of Figure 1 has been interpreted as a southern extension of the Goochland terrane (Farrar, 1985, 1999; Horton and others, 1989), radiometric signatures suggest that the rocks are different (Horton and others, 1994). The Maidens Gneiss of the Goochland terrane north of the study area in central Virginia has a characteristic low potassium, high thorium, high uranium radiometric signature. The Raleigh terrane east of the Lake Gordon mylonite zone in southern Virginia and northern North Carolina (Fig. 1) has notably higher potassium levels (although lower than in the granites), and contrasting bands of relatively higher and lower thorium and uranium levels.

Interpretation of Aeromagnetic Data

Stratified metavolcanic and metasedimentary units within the Carolina and Roanoke Rapids terranes are delineated by parallel, north-northeast-trending, aeromagnetic high and low anomalies (Fig. 1D). Although gabbro plutons in the Carolina terrane lack radiometric signatures, they are characterized by intense (up to 1700 nT) sub-circular aeromagnetic high anomalies. The largest such anomaly in Figure 1D was recently confirmed to be gabbro by field mapping (Peper and Wygant, 1997) although it was unrecognized in earlier reconnaissance (Horton and others, 1993; Virginia Division of Mineral Resources, 1993).

A curvilinear, north-northeast-trending, magnetic-high anomaly delineates the Nutbush Creek fault zone. This fault zone was originally recognized by the associated magnetic lineament (Casadevall, 1977), which is caused by growth of magnetite in the mylonitic fabric (Barifaijo, 1986). The Gaston Dam fault zone (GDF) coincides with a similar, linear magnetic high. Less prominent magnetic lineaments are associated with segments of the Lake Gordon mylonite zone (LGMZ) and Macon fault zone (MFZ).

Large masses of plutonic rock, such as the Vance (Zvg: metamorphosed granodiorite, quartz diorite, and quartz monzonite), Lawrenceville (P5: foliated megacrystic granite to granodiorite), and Skippers (gsk: metamorphosed granite to granodiorite), are recognized as magnetically-uniform, low-gradient areas (Fig. 1D). Contacts of these plutons generally coincide with boundaries between the uniform areas of the plutons and more complex, high-gradient magnetic patterns associated with the surrounding rocks. A magnetic high associated with the Lawrenceville pluton distinguishes it from granite plutons discussed earlier, which all share similar high potassium anomalies.

Boundaries of a magnetically uniform area associated with the Skippers pluton (Fig. 1D) differ from the contacts shown on Figure 1A, which are from the Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993). More detailed geologic mapping of this pluton, which is poorly exposed and partly concealed by Coastal Plain sediments, is needed to determine if it is more accurately located by the magnetic pattern.

Short-wavelength, linear magnetic anomalies are coincident with Jurassic diabase dikes (not shown in Fig. 1A) throughout the area (Fig. 1D). Most of these dikes and associated lineaments strike north-northwest but some strike north-northeast and northeast. The aeromagnetic anomalies are important for locating diabase dikes in the field and for correctly connecting sparse outcrops and residual boulders. One north-northeast-striking diabase dike is nearly coincident with and subparallel to the Nutbush Creek fault zone, which has a similar magnetic signature.

Discussion & Conclusion

High-quality aerial gamma-ray spectrometric and magnetic survey maps have contributed significantly to bedrock and surficial geologic mapping in parts of the South Boston and Emporia 30' x 60' quadrangles. Residual soils derived from compositionally distinct rock units, combined with poor rock exposures due to deep weathering and heavy vegetation, provide an optimum situation for applying gamma-ray spectrometer data to bedrock mapping. The potassium map most clearly delineates masses of granitic rock such as the Buggs Island pluton. The thorium map most clearly delineates amphibolite-facies gneiss and schist units in the Raleigh and Triplet terranes and compositional variations within the plutons. Magnetic data in this region are most effective where gamma-ray data are least definitive, for instance in delineating stratified greenschist-facies metavolcanic and metasedimentary rocks, and some plutonic units in the Carolina and Roanoke Rapids terranes. Because the gamma-ray and magnetic maps depict unrelated parameters associated with rock mineralogy and chemistry, their complimentary nature helps to focus geologic field studies to efficiently visualize and delineate the full distribution of rock types in an area.

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Bouguer Gravity Study Along The Hollister Fault Zone, Eastern North Carolina

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Abstract

This detailed Bouguer gravity study covers 3700 square kilometers in a north-south strip along the Hollister fault zone in eastern North Carolina. Because much of the area is covered by Tertiary and Cretaceous sediments, the gravity study was initiated to help map trace units in the regions where Precambrian metasedimentary and metavolcanic rocks were obscured. Gravity highs are produced by mafic metavolcanics in both the Spring Hope terrane and the Roanoke Rapids terrane. Gravity lows reflect the presence of rhyolitic volcanic rocks and granitic plutons, such as the Rocky Mount batholith and the Sims granite. The observed gravity fits gravity models that have steeply inclined metavolcanics and metasediments, with an underlying decollement at 5 to 10 km depth. Surface geologic mapping has not resulted in the discovery of any outcropping units that may be correlated across the Hollister fault zone to allow calculation of offset. However, the correlation of an elongate gravity low caused by the Princeton rhyolitic volcanics on the west side of the Hollister fault zone with a similar gravity low on the east side indicates a possible right-slip separation of approximately 32 km.

Introduction

Many regions of the eastern North Carolina Piedmont have sufficient outcrop for geologic mapping of metamorphic and igneous rocks; however, the outcrop is sparse, deeply weathered, or covered in areas near the feather edge of the Cretaceous and Tertiary Coastal Plain strata. The north-south trending Hollister fault zone (Farrar, 1985a, b) crops out in the area (Fig. 1) and is buried by Coastal Plain sediments along much of its extent. Thus, gravity and magnetic data are essential for tracing units and faults in the region and are helpful in drawing cross sections. Although numerous authors have noted that magnetic anomalies may be used to trace faults in eastern North Carolina (e. g. Hatcher and others, 1977; Farrar, 1985a; Lawrence and Hoffman, 1993) limited use of gravity maps has been made in the region, since detailed ones have been unavailable. A gravity map for the area in Virginia north of this study has been published by Johnson (1977), and several detailed gravity profiles and models have been published by Nowroozi and Corbin (1993). Recent detailed gravity maps in eastern NC include the Spruill and others (1987) map of the gravity expression of the Rocky Mount pluton, part of the Rolesville batholith,

FIGURE 1

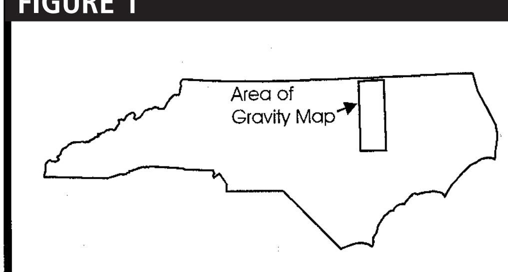


FIGURE 1. Outline map of the state of North Carolina and location of gravity study area.

(Stephens, 1988), part of the Hollister fault zone (Fletcher, 1992, and 1993), and a gravity map of the Raleigh 1:100,000 30 x 60 minute sheet (Lawrence, 1996). New gravity data were combined with data from the above studies in order to improve our knowledge of rock distributions and structure in this region. After covering the methods used in constructing the gravity map, I will review the published geologic maps in the area, and then discuss the usefulness of combining potential field and geologic data in an area of complex structure and little outcrop.

THE GRAVITY DATA

All gravity values in the Hollister fault zone area are referenced to established base stations in the field area (Defense Mapping Agency base station values in Greenville and Rocky Mount). The study included 1420 gravity values which were collected at about 2 km spacing along roads in an area of 3700 square kilometers (approximately 23.5 7.5 minute quadrangles). Where available, bench marks were occupied; otherwise, elevation control was derived from spot elevations and contour lines. The sum of errors for the survey is as follows: Tidal variation and machine drift were compensated for by returning to a base station every 2-3 hours, but linearity was assumed, so +/- 0.03 milligals error could be present. Reading the gravity meter was reproducible in the range of +/-0.03 milligals. Inaccuracies in elevations, which were accurate to approximately +/-5 feet or better (1.5 meters), were the source of less than +/- 0.3 milligals error. The 1980 latitude correction was applied, as well as the free air correction. The Bouguer correction density applied was 2.67 gm/cc, which is a reasonable approximation for much of the area. Because this Bouguer density is too high in regions with thicker Coastal Plain cover near the east margins of the area, and in areas with very deep weathering, and since Bouguer corrections are subtracted from gravity values, anomaly values in areas of Coastal Plain cover are slightly too low, by up to 0.4 milligals. The sum of the errors is within the range of +/-0.7 milligals. Care should be taken if this survey is compared to other previous regional gravity surveys, since earlier ones may not have used updated base station values or the 1980 latitude formula.

GEOLOGIC MAPPING

Geologic maps within the study area include Farrar (1985a and b), Moncla (1990), Carpenter and Carpenter, (1996, and an unpublished map of the Raleigh 30 x 60 minute sheet) Boltin and Stoddard (1987), and Kite and Stoddard (1984). The geologic map in this report (Fig. 5) is a summary of these works in the area west of the Coastal Plain. The basement geology indicated beneath the Coastal Plain sediment cover is interpretive and is based on drill hole data (Lawrence and Hoffman, 1993) and interpretation of the magnetic map of North Carolina (Zietz et al., 1984) and the gravity map (Fig. 4).

The study area (Fig. 1 and 2) lies primarily in the eastern volcanic slate belt and partly in the Raleigh belt (Farrar, 1985a). Horton and others (1989) referred to the area northwest of the Macon fault zone (Fig. 2) as Goochland tectonostratigraphic terrane, though the commoner assignment in more recent articles is to place this area in the Raleigh terrane (Stoddard and others, 1991, Sacks, 1996a, b), the area between the Macon fault zone(Fig. 2) and the Hollister fault zone as Spring Hope terrane, and east of the Hollister fault zone as Roanoke Rapids terrane. The northern Raleigh terrane (Farrar, 1984, Stoddard and others, 1991) consists of amphibolite facies gneiss and

FIGURE 2

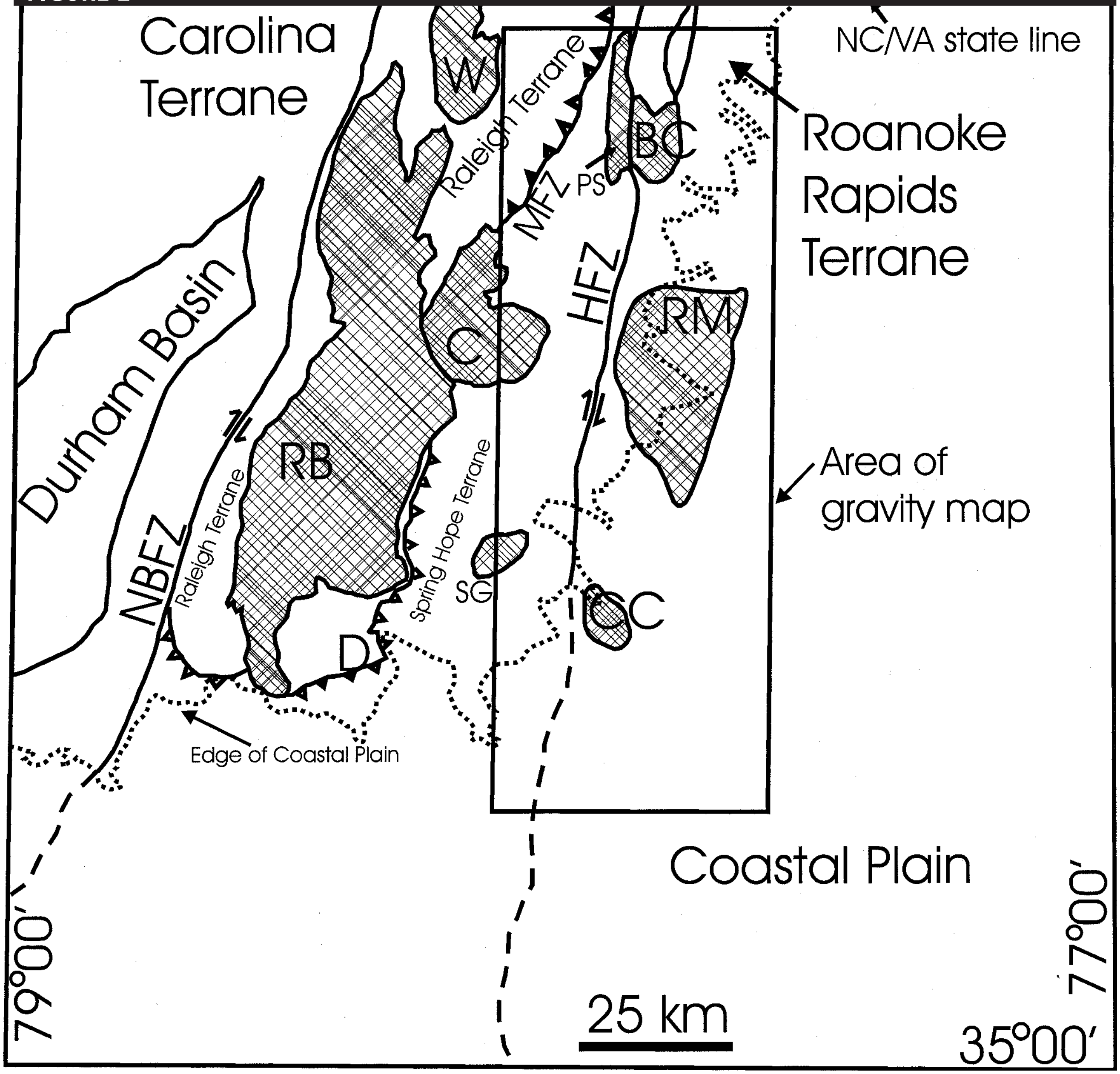


FIGURE 2. Map showing regional tectonic setting of the study area. Abbreviations as follows:
Faults: D, decollement between Raleigh terrane gneiss and Spring Hope terrane; HFZ, Hollister fault zone; NBCFZ: Macon fault zone; NFZ, Nutbush Creek fault zone. Granite plutons: BC, Butterwood Creek pluton; C, Castalia pluton; CC, Contentnea Creek pluton; PS, Panacea Springs pluton; RM, Rocky Mount pluton; S, Sims pluton; W, Wise pluton.

schist and lies outside the area of detailed gravity coverage. The Spring Hope terrane consists of Late Precambrian to Cambrian (?) greenstone, laminated argillite, metarhyolite, metasiltstone, and phyllite, intruded by Carboniferous granite plutons, the largest of which are the Castalia and Sims plutons. The rocks in the area have been deformed and metamorphosed in both the Taconic and Alleghanian orogenies (Farrar, 1985a). The two episodes of folding can be seen in the southwestern part of the geologic map, where earlier folds are refolded by the N-NW-trending Spring Hope synform. The latest important right-slip motion on the Hollister fault zone was Alleghanian (Farrar,

FIGURE 3

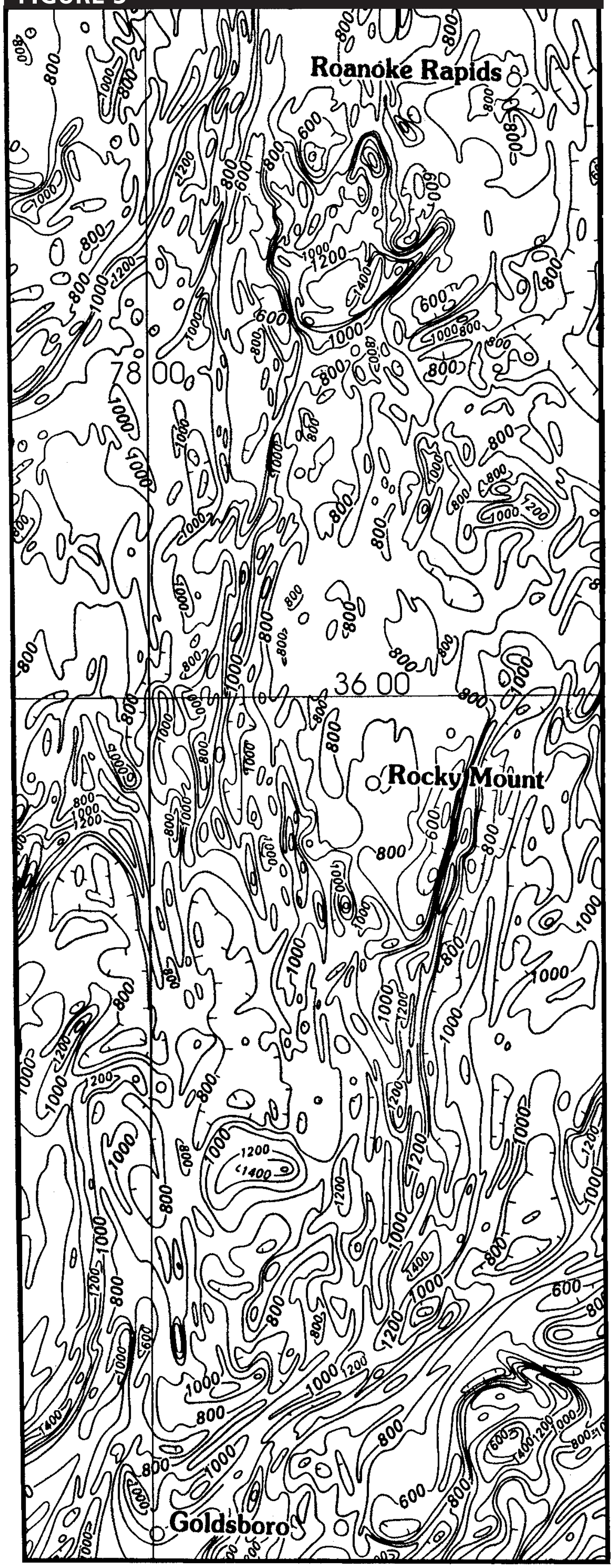


FIGURE 3. *(At Left)* Aeromagnetic map of the study area (from Zietz and others, 1984). Contours are in nanoTeslas.

FIGURE 4. *(Opposite Page)* Bouguer gravity map of the area of the Hollister fault zone in northeastern North Carolina. Contour interval is 2 milligals.

FIGURE 5. *(Opposite Page)* Interpretive geologic map of the Hollister fault zone area. Dark dashed lines represent traces of faults and fault zones. Thin dashed lines are geologic contacts. Dotted line is edge of Coastal Plain cover, which thickens to east and southeast of line. All geologic contacts beneath the Coastal Plain cover are inferred and based on drill holes and potential field maps. Map and gravity model units are as follows:
arg: laminated argillite
Cbcg: Carboniferous Butterwood Creek pluton
Ccg: Carboniferous Castalia granite
ccg: Contentnea Creek two mica granite
Cmg: Carboniferous Rocky Mount granite pluton
Csg: Carboniferous Sims granite
fgn and ms: felsic gneiss and mica schist
fv: felsic metavolcanics
g: granite
gst: greenstone
hbg: hornblende-biotite gneiss
iv: intermediate metavolcanics
mt: meta-tuff
mto: metatonalite
mtr and mk: metatrondjemite and metakeratophyre
mv: mafic metavolcanics
ph: phyllite
ph, ms, v: mixed section of phyllite, mica schist, and metavolcanics
ph+v: mixed phyllite and volcanic section
pv: Princeton rhyolite
rgn: Raleigh gneiss
slt: massive metasiltstone
ss: sericite schist
v: metavolcanics
um + gb: ultramafic and gabbro complex
wmv: Webbs Mill volcanics

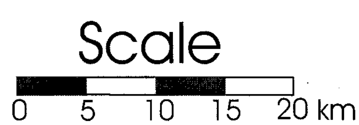


FIGURE 4

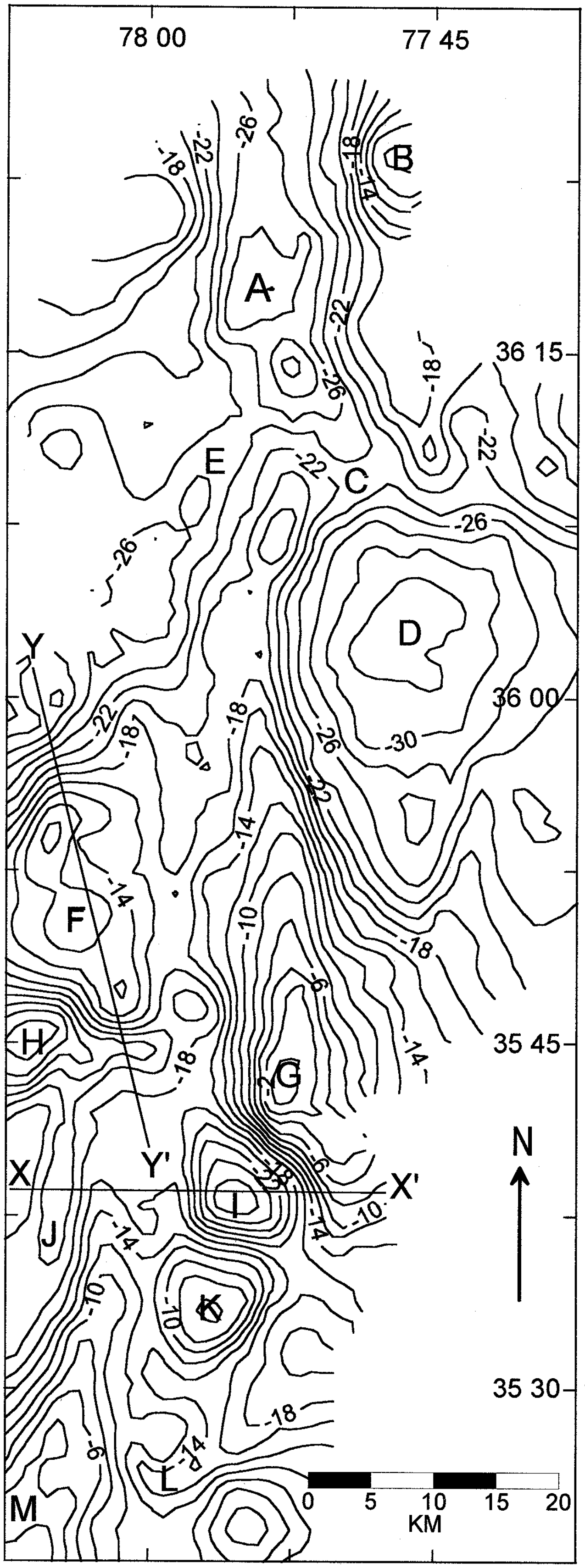
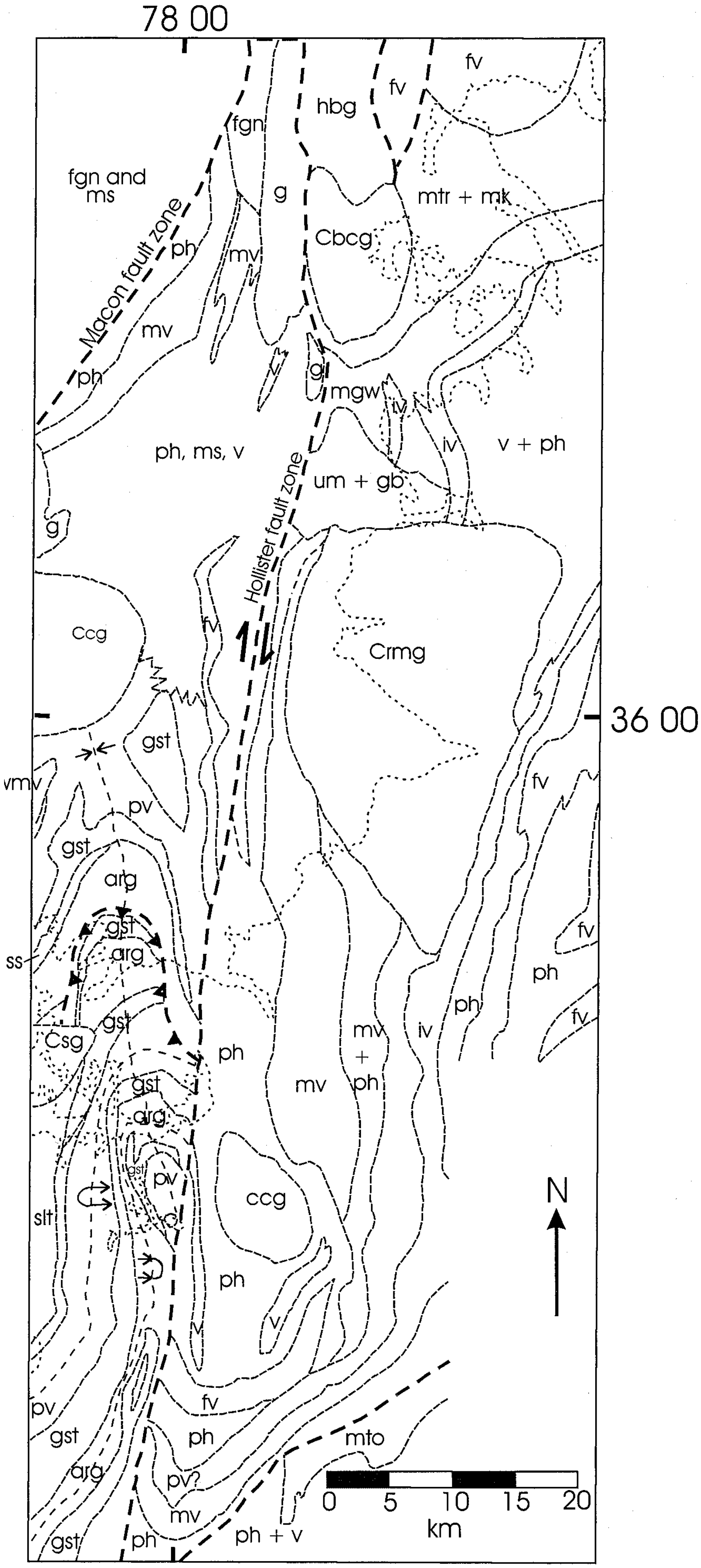


FIGURE 5



1985a). Maps of the Roanoke Rapids terrane east of the HFZ include the regional geologic map by Farrar (1985a, b) and maps of small areas (Kite and Stoddard, 1984; Boltin and Stoddard, 1987; Moncla, 1990; Horton and Stoddard, 1986; Sacks, 1996b). Mesozoic and Cenozoic Coastal Plain sediments cover most of the terrane. The limited evidence that exists indicates that the terrane contains a section very similar to that in the Spring Hope terrane and some units could be correlative. The rocks include metasedimentary phyllite, metagraywacke, felsic to mafic metavolcanic rocks, and a complex of metamorphosed ultramafic rocks, gabbro, and amphibolite (Halifax County Complex of Kite and Stoddard, 1984), metatonalite, and Carboniferous granitic plutons, including the Butterwood Creek (Farrar, 1985a and b, Russell, and others, 1985) and the Rocky Mount batholith (Spruill, and others, 1987).

THE GRAVITY MAP

For purposes of anomaly description and discussion, specific anomalies have been lettered on the Bouguer anomaly map (Fig. 4). Anomaly A is a clear north-trending elongate gravity low, caused by the presence of a sheared granite within the Hollister fault zone. Anomaly B, a relative gravity high on the east side of the Hollister fault zone, lies in the area of metatrondjemite and the volcanic-rich section of the Roanoke Rapids complex (Farrar, 1985b). The volcanics and metatrondjemite at the surface are likely not be dense enough to cause such a large increase in gravity; possibly there is a more mafic mass under them. Anomaly C, a saddle between two low gravity ridges, interestingly enough lies in the region of the Halifax County complex, a mixture of serpentinized ultramafics, dunite, amphibolite, and metaplagiogranite interpreted by Kite and Stoddard (1984) to be an ophiolite fragment. In a cross section, Farrar (1985a) showed this complex as a thin sheet, which given the lack of gravity expression of an ultramafic complex, must be the case. Anomaly D, the largest and best defined gravity low in the area, is caused by the Rocky Mount tonalite-to-granite batholith, Crmg, (Moncla, 1990; Spruill and others, 1987). Since most of the wall rocks of the batholith do not crop out, and outcrop in the batholith is very limited, the density contrast for the pluton is poorly controlled. If the granite is assumed to have a density contrast of 0.10 to 0.15 gm/cc less than the surrounding mafic wall rocks (see Table 1), the batholith is best modeled as an eroded laccolithic shape extending to a maximum depth of 12 km. or less. Anomaly E, a northeast-trending 4-milligal gravity trough about 20 km. long, is caused by the presence of lower density Spring Hope phyllite and metasiltstones (Farrar, 1985a). The rise in gravity to the northwest of the trough is caused by mafic metavolcanics; then at the northwest limit of the gravity data is found a major fault, the Macon fault zone, and a higher grade block of Macon gneiss and schist lies on the west.

TABLE 1

Rock Unit	average density (gm/cc)	range in density (gm/cc)
Raleigh gneiss, mafic phase	2.93	2.81-3.04
Raleigh gneiss, granitic	2.62	2.55-2.77
felsic metavolcanics	2.56	2.35-2.76
mafic metavolcanics	2.80	2.74-2.85
phyllite and argillite	2.81	2.63-2.89
Rocky Mount pluton (granite)	2.64	2.60-2.68

TABLE 1. Densities of selected rocks in the study area (all data from Stephens, 1988, except for new data for Rocky Mount pluton).

Anomaly F, an irregular gravity high, is due to presence of highly inclined greenstones in a synform on the west side of the Hollister fault zone. The southern end of the high coincides with where the greenstone is truncated by the fault. The greenstones have been repeated by folding and a thrust; as a consequence, the gravity high here is caused by more than one greenstone layer. The greenstone may be thicker here than in other areas due to either the presence of a volcanic center, or tectonic thickening (Lawrence, and others, 1997).

Anomaly G, an elongate north-south trending gravity high, is due to dense metavolcanics within Farrar's (1985b) Easonburg formation on the east side of the Hollister zone. Several parallel anomalies on the magnetic map allow the interpretation that the high is due to the presence of several mafic volcanic layers in the section, possibly repeated by folding.

Anomaly H, an abrupt gravity low, is due to the Sims granite pluton (Csg) intruded into the metavolcanics and metasedimentary rocks of the eastern slate belt. Anomaly I is due to the Contentnea Creek granite (Cccg) pluton (Farrar, 1985b) on the east side of the Hollister zone. The pluton contact approximately follows the −18 milligal contour. The straight north trend of the contours on the west side of the anomaly suggests that the pluton may be truncated or deformed by the Hollister fault zone. No outcrops of the west contact of the pluton have been located by Farrar (1985b) or the author.

Anomaly J, an extensive gravity trough on the west side of the Hollister, is due to the low-density rhyolitic Princeton metavolcanics, pv on Fig. 3, (Carpenter and Carpenter, 1996). Anomaly K lies in a region of no outcrop, just on the east side of the Hollister fault zone, where a mixed section of phyllite and volcanic rocks have been shown on the interpretation. Patterns on the magnetic map suggest that this gravity high could be due to a folded mafic metavolcanic unit, although the round shape would seem to better fit a small mafic pluton. The round outline may be misleading and could be due to interruption of the mafic volcanic unit by the Contentnea Creek granite. If so, this high would once have been connected to the ridge of anomaly G. Anomaly M , a long northeast-trending gravity ridge, is attributed to a greenstone unit, which is repeated in a fold. Anomaly L, a northeast-trending gravity trough, is probably due to the presence of felsic metavolcanics and is here tentatively correlated with the Princeton volcanics.

No specific anomaly with the exception of A marks the Hollister fault zone. However, its trace on the gravity map (compare Fig. 2 and 3) follows a sequence of gravity troughs and saddles. Also, elongate highs and lows, such as L or J, are truncated by the fault zone.

GRAVITY MODELS

Gravity models were constructed after adding 18 milligals to profiles XX' (Fig. 6) and YY' (Fig. 7). The 18 milligals compensates for presence of low density deeper crust. Regional gravity studies (Lawrence and others, 1997) and a refraction study (James and others, 1968) have shown that as the crust thins to the east in North Carolina; gravity also shows a regional decrease to the east, which reflects a decrease in average crustal density in the same direction as crustal thinning. The modeling program was two-dimensional (Burger, 1992; Talwani and others, 1959); all bodies in the model extend to infinity normal to the section. In cases where the gravity profile crosses units of great strike extent, this style of model is an excellent approximation. For plutons or layered units that radically change strike, the approximation is not as good. The densities used in the

FIGURE 6

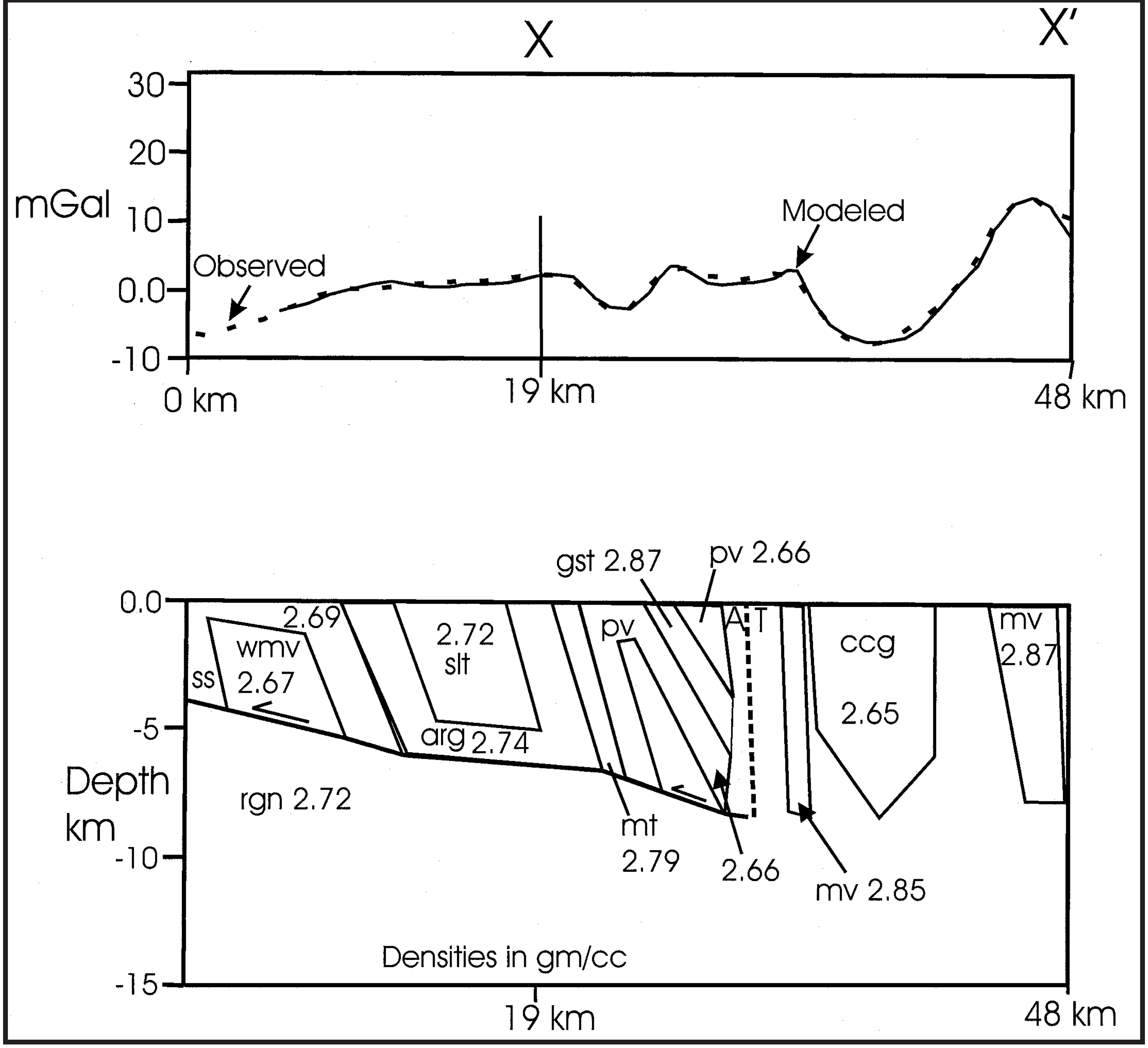


FIGURE 6. Gravity model XX'. For line of gravity profile, see figure 2. Explanation of unit labels is in description of figure 5.

models are consistent with measured densities of fresh rock samples in the region (Table 1).

Model X-X' (Fig. 6) extends east-west across the Hollister mylonite zone, in the southern part of the study area. The west side of the gravity map (Fig. 4) in this study falls at the 19 km line on the gravity profile. The continuation of the observed gravity to the west is from Lawrence (1996), and the geology is from Robert Carpenter's unpublished geologic map of the Stancil's Chapel quadrangle, and a compilation geologic map from Lawrence and others, (1997). Most of the mapped layered units extend with no change in strike approximately perpendicular to the modeled profile, so the two-dimensional model is a good approximation. In the case of the Contentnea Creek granite, the pluton will be modeled at slightly less than its true depth, but it probably does not extend deeper than 10 km., since the anomaly is not large enough for a deeper body. The gravity is consistent with tightly folded rocks, east-dipping axial planes, and a decollement at depth, which

FIGURE 7

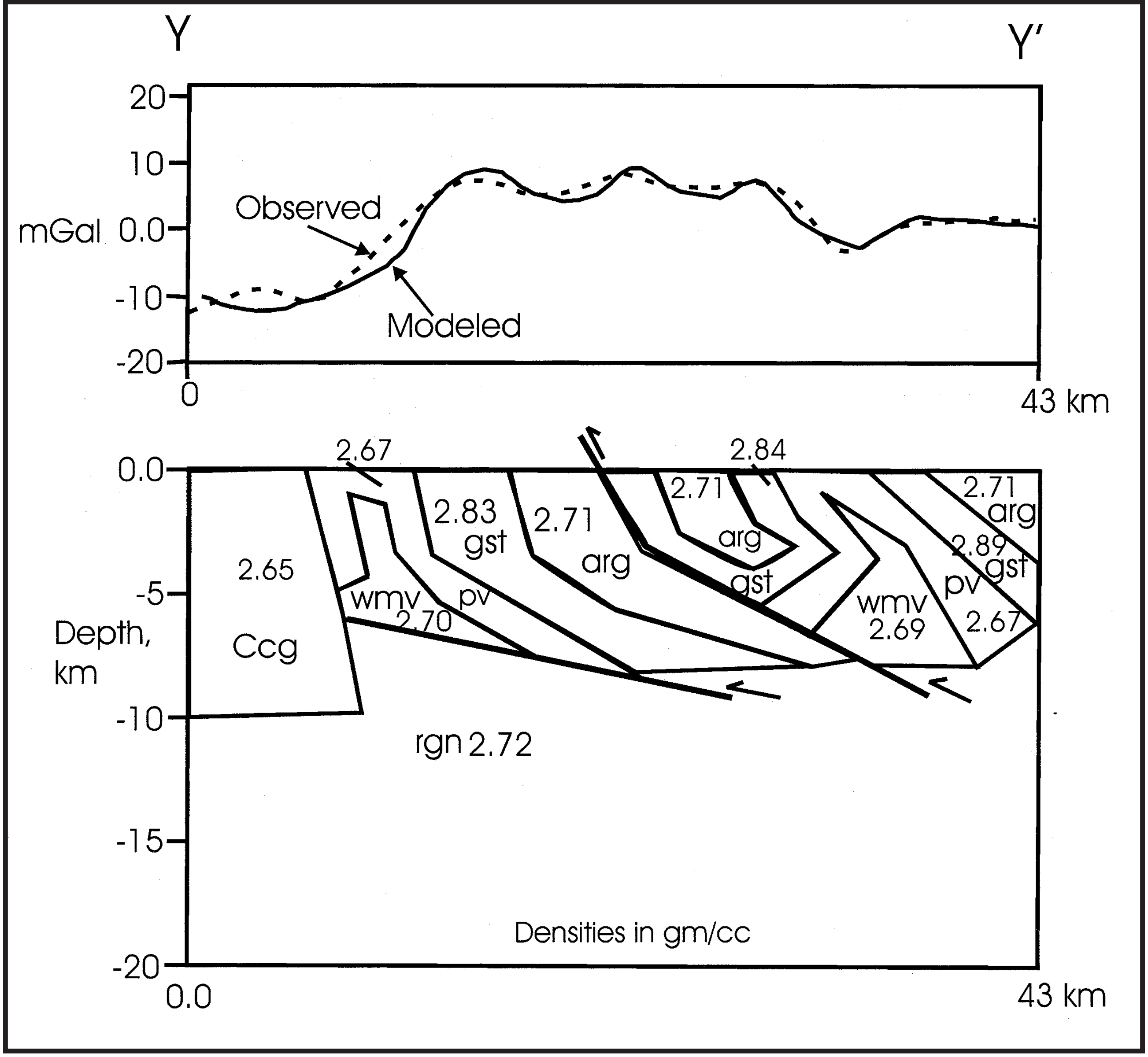


FIGURE 7. Gravity model YY′. For line of gravity profile, see figure 2. Explanation of unit labels is in description of figure 5.

outcrops as a surface thrust approximately 9 kilometers to the west of this area (see Fig. 2) in the Flowers quadrangle (Carpenter and others, 1996). The gravity could be adequately modeled with different dips and fold geometries, so long as the dips were high. Since the foot wall of the thrust in the Flowers quadrangle is the Raleigh gneiss, this unit is shown below the decollement in the models, but really could be any other unit of the indicated density. The model indicates that the fault zone is high angle, and has a density similar to the average for the region. Also, there is little density difference between rocks on the two sides of the zone, suggesting that the rocks themselves may be quite similar. These models may be compared to those of Nowroozi and Corbin (1993), who found that the Hollister fault zone in southern Virginia could best be modeled as steeply dipping at the surface, but dipping gently to the east at depth, and merging with a horizontal decollement at a depth of 15 km. The relationship of the strike-slip Hollister fault zone and the low-angle faults was left ambiguous in this study, but is consistent with Nowroozi and Corbin.

Model Y-Y' (Fig. 7) extends 43 km along the axis of the Spring Hope synform from a northwest end within the gravity low of the Castalia granite to the Hollister fault zone on the southeast end (Fig. 4). Although a perfect fit between the observed gravity and the model was not achieved, several useful observations can be made. The gravity is permissive of fold axial planes dipping to the southeast, greenstone layers as thick as mapped in this area of poor outcrop, and a decollement at less than 10 km. depth. The argillite unit overall must be given a density of 2.71 to 2.74 gm/cc in the models, which implies that the unit is an iron-rich meta-mudstone, or that there are some mafic volcanics contained within the unit.

Offset on the Hollister Fault Zone

The only place in the region that allows a possible correlation across the Hollister fault zone is where the greenstone and Princeton volcanics are truncated on the west side of the zone. Since the Hollister fault zone is primarily a right-slip fault (Farrar, 1985a), these units should reappear to the south, on the east side of the fault. The anomaly that best fits the trough caused by the Princeton volcanics is anomaly L (Fig. 4), which lies in a possible antiform on the east side of the fault. Interpreted mafic volcanics lie on the north and south side of the felsic volcanics, as they do on the other side of the fault. This correlation suggests approximately 32.5 km of right slip separation.

Conclusions

The pattern of anomalies and the average gravity values are similar across the Hollister fault zone, consistent with the similarity in known geology (rock types and structure) and magnetic character on the two sides of the zone. It appears possible that the Princeton volcanics are offset approximately 32 kilometers in right-slip sense across the zone, implying that the Hollister fault zone is not a terrane boundary, but merely a right-slip fault zone cutting the Spring Hope terrane. Most granitic plutons in the area extend to depths between 5 and 10 kilometers. Gravity models are consistent with known folds and rock types and indicate the possibility of a thrust at less than 10 km depth beneath the Spring Hope terrane. In this region with poor to no outcrop of basement rocks, the interpretation of geologic, magnetic, and gravity maps results in more knowledge of rock types and three dimensional geometry than would otherwise be possible.

Acknowledgments

Chuck Fletcher and Richard Spruill helped with the gravity data collection. My understanding of eastern North Carolina geology has greatly benefited from discussions and trips in the field with Bob and Al Carpenter. Thanks are due to Paul Sacks and Bill Smith for very careful and helpful reviews of the manuscript.

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A Field Guide to the Geology of the Fall Zone Region, North Carolina and Virginia State Line: Road Log For CGS Field Trip, 1999

by

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Introduction

In this road log, we have attempted to provide enough information that interested persons, with the aid of the Bracey, South Hill SE, Gasburg, Powellton, Littleton, and Valentines U. S. Geological Survey 7 - 1/2 minute quadrangle maps, will be able to find all the stops described here for the Saturday portion of the field trip. Figures 1, 2, 3, and 4 show excerpts from the geologic maps of the Bracey, South Hill SE, Gasburg and Valentines quadrangles that show the locations of Stops 2, 3, 5, 6, 7, 8 and 9. The geology is described on geologic maps of the Bracey, South Hill SE, Gasburg, and Valentines U. S. Geological Survey 7 - 1/2 minute quadrangles (Sacks, 1996 a, b, c, d, and in the guide book article by Sacks (1999). *If you do use this guide to visit stops at a later time, please be aware that all of the stops are on or adjacent to private land. Please obtain permission from landowners before you venture off the road.* The leaders for the Sunday portion of the field trip will provide information separately.

Saturday Road Log & Stop Descriptions

Saturday, November 6

0.0 Depart Holiday Inn parking lot, Emporia, VA; turn left
0.1 Turn right on Atlantic
0.2 Turn right again, staying on Atlantic
0.6 Turn right on Route 301 South
1.0 Cross Meherrin River
1.3 Turn right on Brunswick Ave. at stoplight
2.1 Cross over Interstate-95, road changes to VA 611, or Dry Bread Road
8.0 Note granite outcrops on right
9.6 Enter Brunswick County
11.5 Ante, VA
14.1 Poplar Mount Crossroads

15.0 Claybo's Disco on right
16.1 Meherrin-Powellton Elementary School, bear left, staying on Route 611
19.5 Turn left on VA Route 667 (Vineland Rd.)
19.6 STOP 1: (Sacks) (Powellton Quadgrangle) Roadside outcrop on east side of road.

STOP 1: Metasedimentary Rocks of the Spring Hope terrane.

Deformed mudstones of the Spring Hope terrane in this roadcut lie just west of Hollister fault zone. These rocks are deeply weathered, but relict features indicate that these are metamudstones. In fresher outcrop, these rocks are brown to green slaty, interlayered shale, siltstone and sandstone. Locally, they occur as hornfels near granite of the Lawrenceville pluton, and phyllitic to schistose near Hollister fault zone and granite of the Panacea Springs pluton. The importance of these rocks here is that they form the western block of the Hollister fault zone in North Carolina and Virginia. To the east of this outcrop, mylonites of the Hollister fault zone consist of highly sheared schists and gneisses, and mylonitic granites like those that will be seen at Stop 3.

Continue south on Vineland Road
23.4 Turn left on Route 46 (Christiana Highway)
24.1 Town of Valentines on the left; stay to the right, on Route 46
27.7 North Carolina state line
28.6 Turn right on River Road (NC 1214)
30.1 Turn left on Webb's Gate Road (NC 1216)
31.2 Bear left, staying on Webb's Gate Road
31.4 Bear left and leave paved road
31.9 STOP 2: (Sacks) (Valentines Quadrangle) Buses will drop off passengers, then continue to parking/turnaround area.

STOP 2: Triplet terrane at northern end of Lake Gaston Dam.

This outcrop is in the deeply gullied area to the east of the dirt road that leads to the dam. This area was cleared years ago, and then abandoned. Gullies are well developed that allow examination of the very deeply weathered gneisses

FIGURE 1

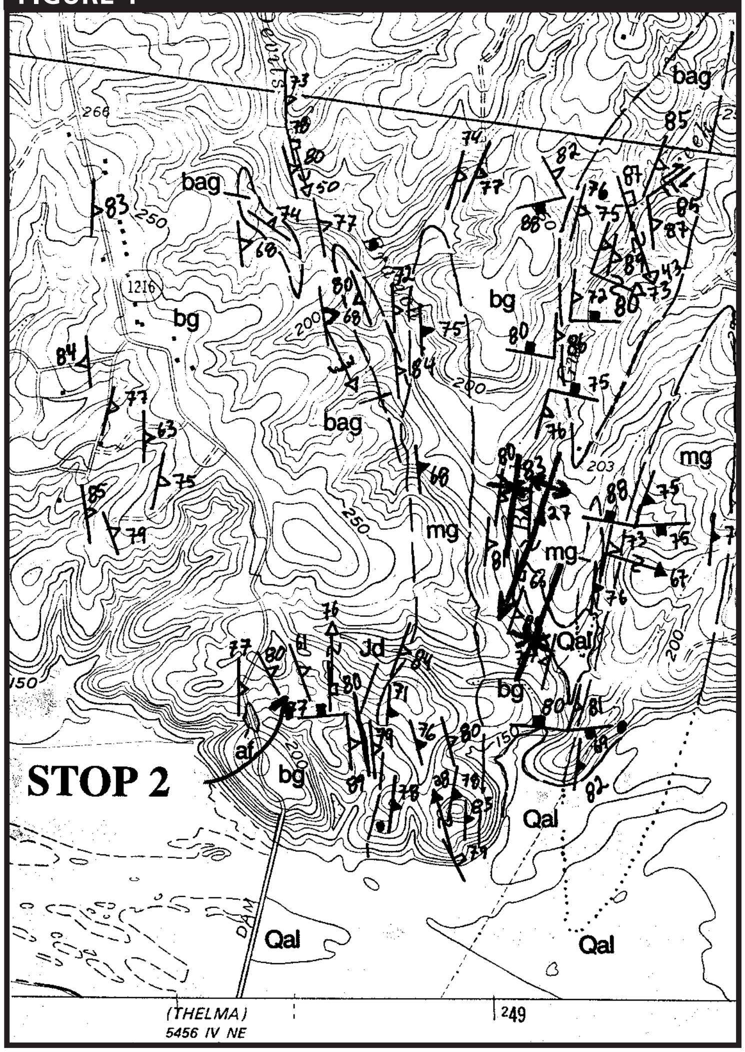


FIGURE 1. Map excerpt from the Valentines Quadrangle showing the location of Stop 2.

of the Triplet terrrane. The ground here is soft, and the slopes of the gullies are probably unstable. Use extreme caution when climbing in an out of the gullies.

The biotite gneisses and schists here are very deeply weathered, but are well exposed in gullies eroded in to the saprolite. The biotite gneiss here is locally interlayered with biotite-muscovite gneiss and muscovite schist. There are also small bodies of muscovite granite. The compositional layering defines the foliation, and the foliation here and throughout the Triplet terrane near the Roanoke River, predominantly dips steeply to the east. Locally, there are small, isoclinal folds of layering. Cutting the metamorphic rocks are several Jurassic diabase intrusions. Note that the intrusions are not all continuous across the outcrop, and that there are small fingers of diabase projected into the wall rock. Although the diabase is also as deeply weathered as the gneiss, there is evidence preserved of columnar joints oriented perpendicular to the subvertical walls of the diabase intrusions. Locally, small slickensided faults cut the foliation in the gneisses. These small fault surfaces may be neotectonic features similar to those described elsewhere in the Piedmont (Bartholomew and others, 1998). Also worth considering here at this stop are the weathering and erosional features that are displayed.

Retrace route to River Road

33.7 Turn left on River Road (1214)
34.4 Henrico, NC; turn right on Post Office Road (1217)
35.0 Turn left on Pine Top Dr.; (sign for Southside Shores)
36.3 Virginia state line
36.5 Cross over Lake Gaston-Virginia Beach pipeline; intake station to left
36.7 Turn left on Bradley Point Dr. (2nd left after pipeline; sign for Windward Point subdivision); proceed to intersection with Clearwater Drive
36.9 STOP 3: (Sacks) (Valentines Quadrangle) Buses drop off passengers, then turn around and wait for passengers, who will examine exposures along the roadside, and at the end of Clearwater Drive on the property of Mr. David Anderson

STOP 3: Granitoid mylonite in Hollister fault zone.

These are typical exposures of mylonites of the Hollister fault zone. The granitoid mylonites here are in the unit of Mylonitic Granite that is intrusive into the eastern side of the Hollister fault zone. Here, it is a medium gray, medium-grained biotite and muscovite-biotite granite with feldspar porphyroclasts. At some localities in this unit, the felspar porphyroclasts are up to 2 cm long. Near the west end of the outcrops here are some deeply weathered exposures of felsic mylonitic gneiss and phyllonite. These are part of the highly deformed units of the Spring Hope terrane that form the western wall of the Hollister fault zone.

Noteworthy at these outcrops are the asymmetric porphyoclasts in the Mylonitc Granite, and the shear bands in both the Mylonitc Granite and in the phyllonites, that are consistent with dextral shear. Lineations are subhorizontal, indicating dominantly dextral strike-slip movement along the Hollister fault zone.

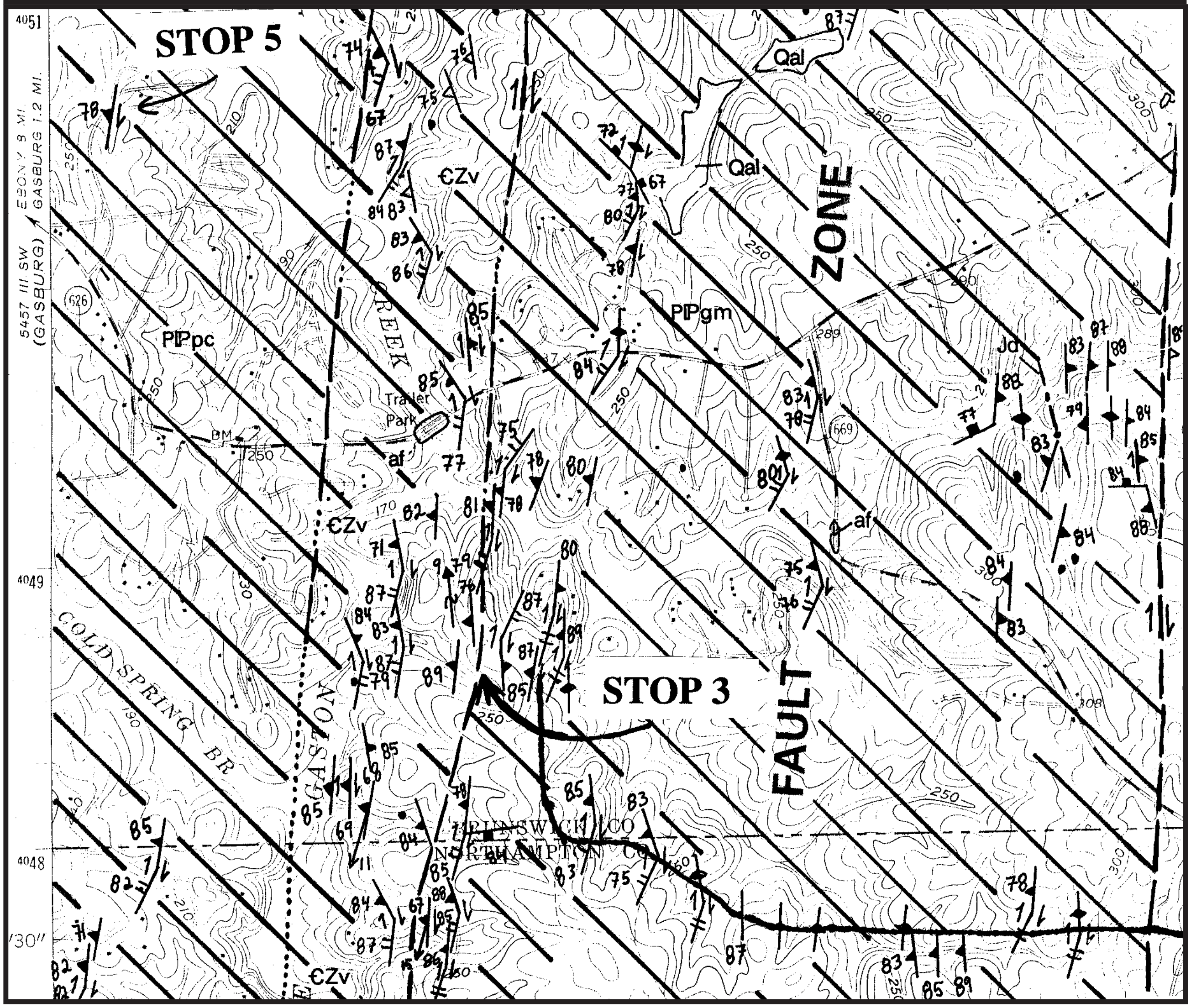


FIGURE 2. Map excerpt from the Valentines Quadrangle showing the location of Stops 3 and 5.

Retrace route to Henrico

37.1 Right from Bradley point Dr onto Pine Top Dr.
37.5 North Carolina state line
38.8 Right on Post Office Road
39.4 Henrico, NC; Turn right on River Road (1214)
41.5 Cross over Pea Hill Creek
44.0 Enter Warren County
45.1 Cross over Lizard Creek
46.7 Continue straight; road changes to Route 903
48.4 Eaton's Ferry Bridge over Lake Gaston
49.7 Turn left, staying on 903 South
51.0 Cross over Big Stone House Creek
52.6 Turn left, staying on Route 903 South
54.5 Turn left on Fleming Dairy Road (1365)

55.4 Turn left on Harris-Jenkins Road
55.7 Owen Lane; STOP 3: (Stoddard, Sacks) (Littleton Quadrangle) Buses drop off passengers, turn around and head back Harris-Jenkins Road to wait.

STOP 4: Felsic metavolcanic rocks of the Spring Hope terrane, and granitoid rocks.

These roadside and ditch exposures display felsic metavolcanic rocks (Cambrian(?) and/(or) Proterozoic(?) of the Spring Hope terrane. These are light grayish-tan, fine grained, layered felsic gneiss composed of plagioclase, quartz, and microline with accessory biotite, muscovite, garnet, epidote and opaques. The fine laminations that dip moderately to steeply toward the west here are thought to represent compositional layering in the felsic volcanic rocks. These rocks are also foliated. This foliation is interpreted to be an early slaty cleavage (S1) that was marked by new minerals during higher grade metamorphic conditions. The lineation is an intersection of layering and the slaty foliation, and plunges at a low angle to the south. Locally, some of the outcrops here also display small dikes of megacrystic granite of the Lawrenceville pluton.

55.9 Continue to end of road
56.0 Turn right on Fleming Dairy Road
56.9 Turn right on Route 903
58.8 Turn right, staying on Route 903
60.4 Cross over Big Stone House Creek
61.7 Turn right, staying on Route 903
62.8 Eaton's Ferry Bridge over Lake Gaston
64.7 Go straight on NC 1362-River Road; (Route 903 takes a sharp left)
66.3 Cross over Lizard Creek
67.1 Turn left on NC 1342 (toward Gasburg)
68.0 Virginia state line; road changes to VA 666 (oh-oh!)
69.7 Turn right on VA 626
69.8 Downtown Gasburg, VA
71.0 Turn left on Delbridge Road
71.4 STOP 5: (Sacks) (Valentines Quadrangle) Note: This is Nature Conservancy land. It contains protected flora. Please treat it gently. Buses continue to boat launch area and park. LUNCH

STOP 5: Granitoid pavement rocks.

Pavement outcrop of granite of the Panacea Springs pluton east of Gasburg. Granite of the Panacea Springs pluton (Permian and Pennsylvanian) is a medium-gray, coarse grained, and porphyritic, foliated biotite granite, composed of plagioclase, microcline, quartz, biotite, opaques and minor muscovite. Locally, it contains microcline phencrysts as much as 3 cm long. Most of the mylonitic textures in the pluton along its eastern margin. Here in this pavement, the granite is foliated, and locally contains mylonitic textures that include dextral shear bands. However, this part of the pluton is west of the main zone of deformation associated with the Hollister fault zone, and the deformation here is weak.

71.8 Turn right on VA 626
73.0 Gasburg; continue straight on VA 626
75.2 Turn right on VA 664/Weaver Road (unpaved)
76.0 STOP 6: (Sacks) Buses drop off passengers and wait. Outcrops are in the creek 200-300 feet upstream and to the west of the road. (Gasburg Quadrangle)

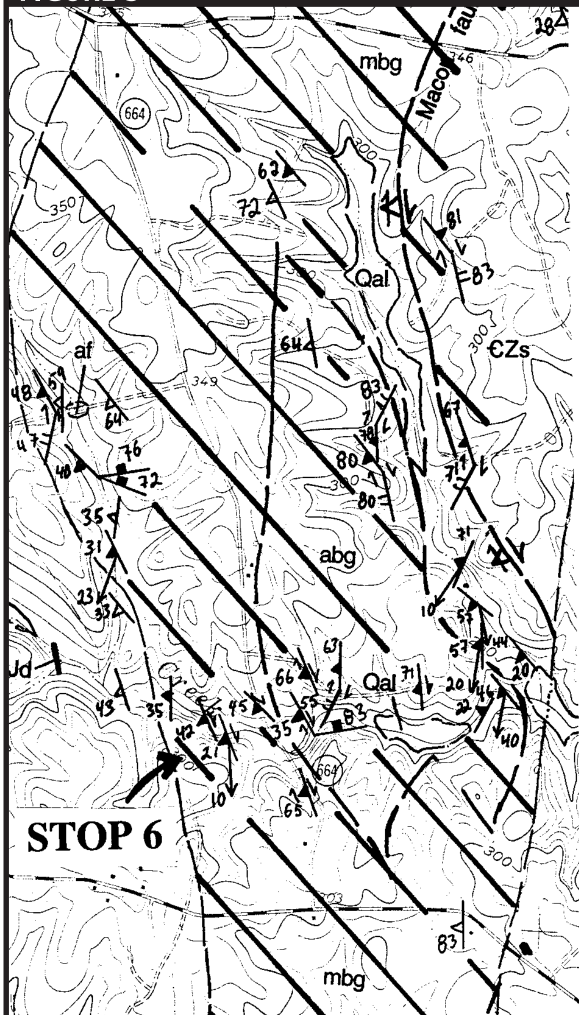
STOP 6: Macon mylonite in Pea Hill Creek, northwest of Gasburg.

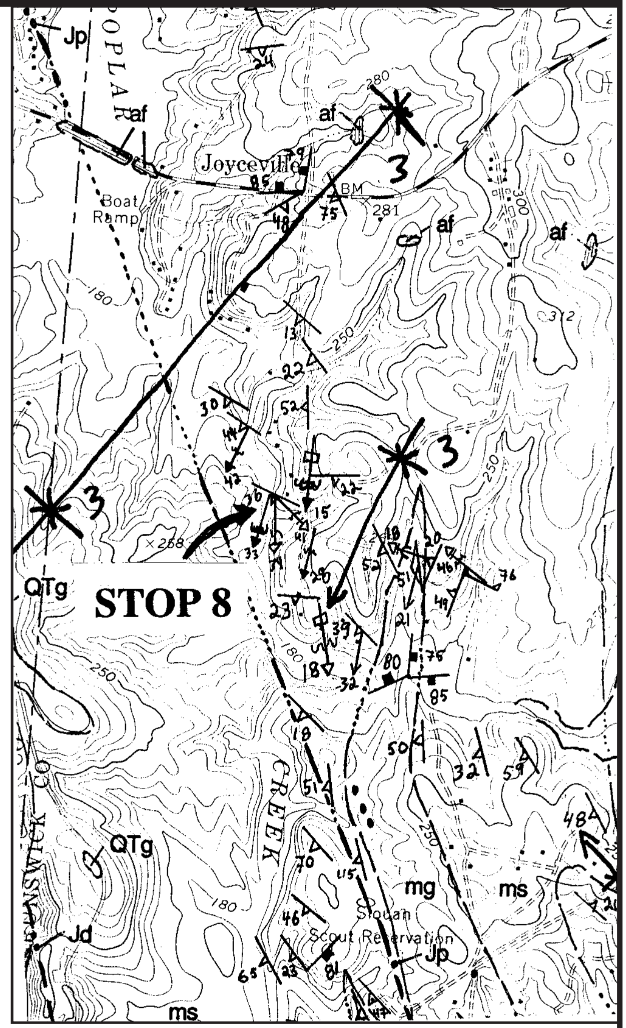
These stream bed and stream bank outcrops display mylonitic biotite gneiss of the Raleigh terrane where they have been deformed in the Maconmylonite zone. Here these gniesses consist of interlayered, variably mylonitic medium gray to greenish-gray biotite gneiss and grayish-tan muscovite-biotite gneiss composed of quartz, plagioclase, biotite, muscovite and garnet with thin layers of silvery-gray schist composed of quartz, muscovite, biotite, plagioclase, sillimanite and minor garnet; microcline-biotite gneiss composed of quartz, biotite, microcline, plagioclase, muscovite and minor garnet; dark grayish-green amphibole gneiss comprised of plagioclase, hornblende, quartz, biotite with minor clinopyroxene and epidote; and light tan granitic mylonite composed of quartz, plagioclase, microcline and muscovite.

The Macon fault zone is a complexly folded zone of mylonitic schist and gneiss that lies between the Raleigh terrane and the Spring Hope terrane. Here, the Macon mylonite zone dips moderately west beneath the Raleigh terrane. Rocks in the fault zone contain kinematic indicators that include shear bands, asymmetric folds, and asymmetric porphyroclasts that consistently indicate dextral strike-slip. Most lineations plunge gently parallel or slightly oblique to the trend of the fault. These are interpreted to indicate oblique dextral and reverse motion on the Macon fault zone. Folding of some of the sheared rock within the fault zone seems to be of the same phase as the F3 folds in the Raleigh terrane. Mylonitic textures are more extensively developed, and occur in a thicker interval of rock at the base of the Raleigh terrane than in the Spring Hope terrane. Ductile textures in the Raleigh terrane that are overprinted by muscovite porphyroblast growth, as well as the apparent static overprint of higher grade minerals on rocks of the Spring Hope terrane near the Macon fault zone suggests that the Raleigh terrane was hot during and for some time after motion on the fault. whereas the Spring Hope terrane was cooler, and heated as a result of motion on the fault. The Macon fault is intruded and cut by the Lawrenceville Granite north of these outcrops.

Continue straight on 664
77.4 Turn left on VA 663
78.4 Turn left on VA 644/Robinson Ferry Road
80.1 Stay straight on Robinson Ferry Road; it becomes VA 626 (toward Ebony)
82.2 Ebony, VA; stay straight
82.6 Bear left on Route 903/Ebony Road
84.9 North Carolina state line
85.5 Turn right on Warren County Acres Road/NC 1361 (Route 903 takes a sharp left at this point)
85.8 Turn left on gravel road for Hillcrest Point
86.0 STOP 7: (Stoddard, Sacks) Buses park on left, uphill side; will turn around. (Gasburg Quadrangle)

FIGURE 3





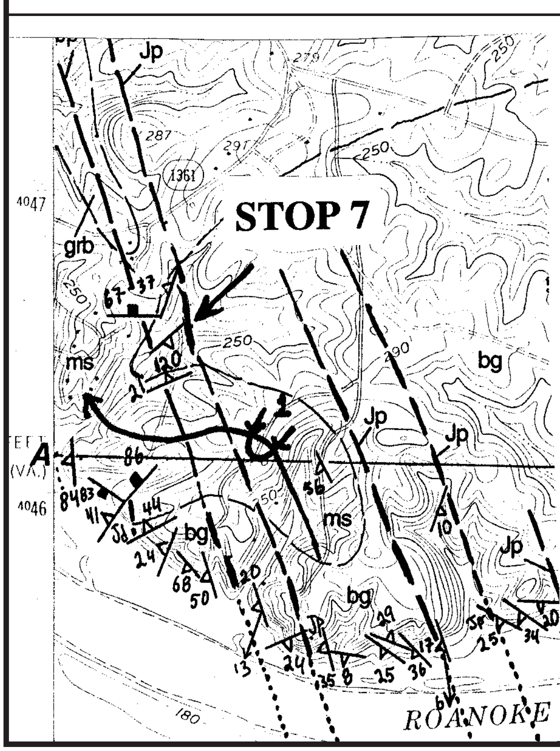


FIGURE 3. Map excerpts showing the locations of Stops 6 and 7 in the Gasburg Quadrangle and Stop 8 in the South Hill SE Quadrangle.

STOP 7: Jurassic porphyry dike cutting Raleigh terrane gneiss, west of Songbird Creek.

CAUTION! THIS ROCK IS VERY HARD AND BRITTLE. EXERCISE EXTREME CARE IF SWINGING A HAMMER! WE WILL TRY TO PREPARE PLENTY OF GOOD HAND SAMPLES FOR THE TRIP AHEAD OF TIME.

At this site, we will examine an exposure (mostly boulders) of one of a swarm of poorly known (and underappreciated?) post-metamorphic dikes that intrude the northeastern Piedmont of North Carolina and adjacent Virginia. The field relations, petrography, paleomagnetics, and Rb/Sr geochronology of this suite were described by Stoddard and others (1986); the petrology and rock and mineral chemistry were presented in a subsequent paper (Stoddard, 1992). $^{40}Ar/^{39}Ar$ results were presented by Ganguli and others (1995; also Ganguli, 1999); a report on additional work by them is in preparation.

The swarm includes several different types of dikes, but the majority are rhyolite porphyry, as at this stop. The rhyolite is strongly porphyritic, and commonly amygdaloidal, with a dark groundmass and abundant phenocrysts of quartz and sanidine. Other phenocrysts include apatite, Fe-Ti oxide minerals, and ferropigeonite. Typically, amygdules contain a dark green clay mineral, but locally the amygdules consist of calcite.

Rock and mineral textures, together with mineral chemistry, indicate crystallization of the phenocrysts at high temperature, a shallow level of emplacement, and relatively low temperature of crystallization for the groundmass (Stoddard and others, 1986; Stoddard, 1992; Ganguli and others, 1995).

Rb/Sr analysis yielded an apparent age of 20 ±5 Ma for a nine-point isochron consisting of several rock types and mineral separates from the swarm, and an apparent age of 196±8 Ma for rhyolite only (Stoddard and others, 1986). High precision $^{40}Ar/^{39}Ar$ analysis on two sanidine samples gave plateau ages of 196.6 ± 0.7 Ma and 196.3±0.7 Ma (Ganguli and others, 1995). A paleomagnetic study gave a pole position similar to those established for approximately 200 million year old rocks of stable North America (Stoddard and others, 1986).

The dikes typically trend N10°W - N30°W, as do the more familiar diabase dikes of the region, and they dip steeply. Because these dikes are parallel to, and of the same general age as diabase dikes of the Piedmont, they and the magmas they came from must also be associated with continental rifting and the opening of the Atlantic Ocean during the early Mesozoic.

Stoddard (1992) reported whole-rock analyses of major elements and some trace elements for six samples of rhyolite porphyry and for five of more mafic dike rocks belonging to the suite; in addition, REE analyses for three mafic samples were presented. These rocks constitute an alakli-rich, chemically coherent suite with geochemical characteristics quite distinct from diabase and related rocks (e.g. high Fe/Mg, K/Na, and Rb/Sr; enrichment in incompatible elements; steep negative REE patterns and high K_2O in the mafic samples analyzed). Whether these magmas were derived from a tholeiitic parent magma or from a separate source is still open to question.

Retrace route

86.2 Right on Warren County Acres Road

86.5 Turn left on Route 903 North

87.1 Virginia state line
89.3 Turn left, staying on Route 903
91.8 Turn left on Poplar Creek Road
92.5 STOP 8: (Sacks) (South Hill SE Quadrangle) Buses drop off passengers, walk west to outcrop ledges on the lake shore with landowner's permission, and respecting landowner's property.

STOP 8: Sillimanite schist of the Raleigh terrane.

These outcrop ledges of Raleigh terrane sillimanite-muscovite schist display silvery gray to greenish gray, medium to coarse grained schist containing muscovite, sillimanite, quartz, and chloritoid, with accessory garnet, biotite, and locally, tourmaline. This unit locally contains grayish-tan layers and lenses of felsic gneiss composed of quartz, plagioclase and(or) microcline, muscovite and biotite. In the schist, sillimanite occurs both in fibrous masses and as coarse, prismatic grains as much as 4 cm long. Much of the sillimanite is replaced by white mica and chloritoid, some of the biotite is replaced by chlorite.

The dominant foliation displayed in these outcrops is a moderately southwest dipping S1 schistosity and compositional layering. There are small-scale, isoclinal folds of compositional layering with axial planes parallel to the schistosity. These folds generally plunge gently toward the south. The schistosity is folded by more upright folds that plunge southward. The long axes of the sillimanite needles are parallel to the axes of these second generation folds. The second generation folds are in turn folded by small crinkles and more open folds.

Return to Route 903
93.2 Turn left on Route 903 West
93.6 Cross over Poplar Creek; enter Mecklenburg County
94.6 Bear left, staying on Route 903
95.5 Cross over Holly Grove Creek
100.7 Bracey, VA; abandoned railroad cut contains good exposure of Raleigh terrane saprolite. (Bracey Quadrangle)

OPTIONAL STOP – Railroad cut through Raleigh terrane ampibole-biotite gneiss and granite of the South Hill pluton, Bracey, VA.

The railroad cut is into very deeply weathered gneiss and granite. Much of the outcrop in the banks of the cut is now overgrown, however much can be seen by scrambling through the pines and up the banks, especially under the bridge. Exposed directly under the bridge is muscovite-biotite granite of the South Hill pluton (Permian and Pennsylvanian). This is a medium gray, medium grained, massive to foliated biotite granite composed of plagioclase, microcline, quartz, biotite and muscovite, with accessory garnet. While much of the exposure is deeply weathered, there is some fresh outcrop under the west bridge piling. The granite intrudes discordantly the highly metamorphosed amphibole-biotite gneiss of the Raleigh terrane. This is dark grayish-green, layered, medium to coarse grained amphibole-biotite gneiss composed of plagioclase, biotite, hornblende, quartz, with minor chlorite and epidote. This gneiss contains interlayers of brown biotite and tan muscovite-biotite gneiss composed of plagioclase, quartz, biotite, and variable

FIGURE 4

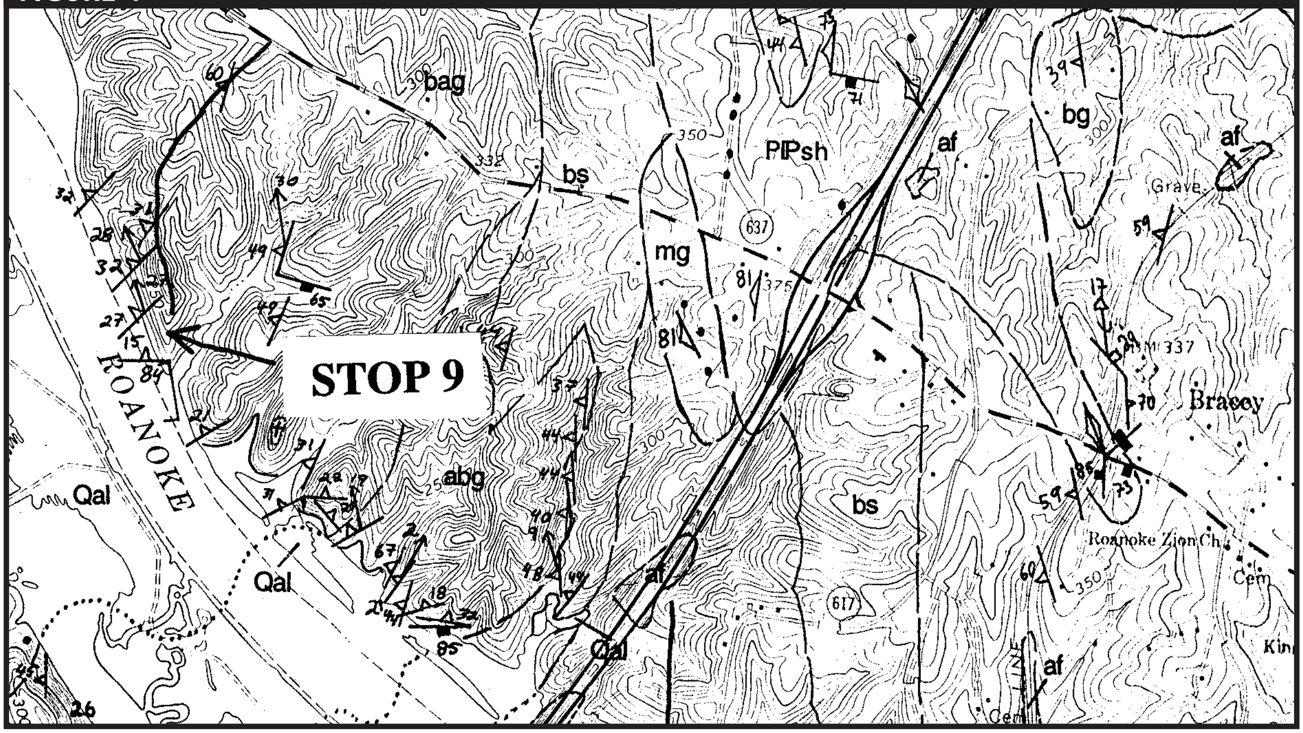


FIGURE 4. Map excerpt from the Bracey Quadrangle showing the locations of the optional Bracey railroad cut stop and Stop 9.

amounts of muscovite. There are minor dark brown or greenish-brown biotite schist. Locally, about 1 mile to the southwest, thin layers of sooty black weathering manganiferous garnet schist composed of biotite, quartz, and garnet, and manganiferous gneiss composed predominantly of garnet, with quartz, hornblende and opaques crops out discontinuously.

The foliation in these gneisses dips either northeast or southwest at moderate angles. There also small, outcrop-scale isoclinal folds of compositional layering in a few places in the railroad cut. Where observed, these folds plunged gently toward the northwest.

101.2 Cross over Interstate-85; continue straight on 903
102.4 Turn left on Hicks Drive; proceed to end. STOP 9: (Sacks) (Bracey Quadrangle)

STOP 9: Ledges of Raleigh terrane amphibole-biotite gneiss above Roanoke River, west of Bracey, VA.

Exposed in the yard and, northward, in the woods above the river bank here are outcrops of the highly-metamorphosed amphibole-biotite gneiss of the Raleigh terrane. This is dark grayish-green, layered, medium to coarse grained amphibole-biotite gneiss composed of plagioclase, biotite, hornblende, quartz, with minor chlorite and epidote. This gneiss contains interlayers of brown biotite and tan muscovite-biotite gneiss composed of plagioclase, quartz, biotite, and variable amounts of muscovite. There are minor dark brown or greenish-brown biotite schist. Foliation in these gneisses dips to the north or northwest. Evident here are small-scale isoclinal folds with limbs transposed parallel to foliation. There is also a second, crenulation folation superposed here. It strikes north-northwest and dips steeply. The northwest plunging lineation is formed by the intersection of the two foliations.

102.8 Return to Route 903 and turn right

104.0 Return to Holiday Inn-Emporia, via I-85 North (8 miles) and US Route 58 East (34 miles)

146.0 Holiday Inn and END OF SATURDAY TRIP.

SUNDAY ROAD LOG & STOP DESCRIPTIONS (BERQUIST, NEWTON)

The fieldtrip on Sunday will be to the Old Hickory Mine operated by Iluka Resources, Inc., and the stops will be led by Rick Berquist and Clay Newton. They will provide materials for this part of the fieldtrip. Note that you will need a hard hat, safety glasses, and steel-toed boots to visit the mine. You will also have to sign waiver forms.

OPTIONAL STOP IN THE ROANOKE RAPIDS TERRANE: THE ROANOKE RAPIDS SPILLWAY

Greenschist facies volcanic and hypabyssal intrusive rocks of the Roanoke Rapids terrane are very well exposed along the edges of the tailrace below the Roanoke Rapids Dam in Roanoke Rapids, NC. The stop location and outcrops are described in detail by Horton and Stoddard (1986) in the Southeastern Section volume of the Geological Society of America Centennial Field Guide.

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