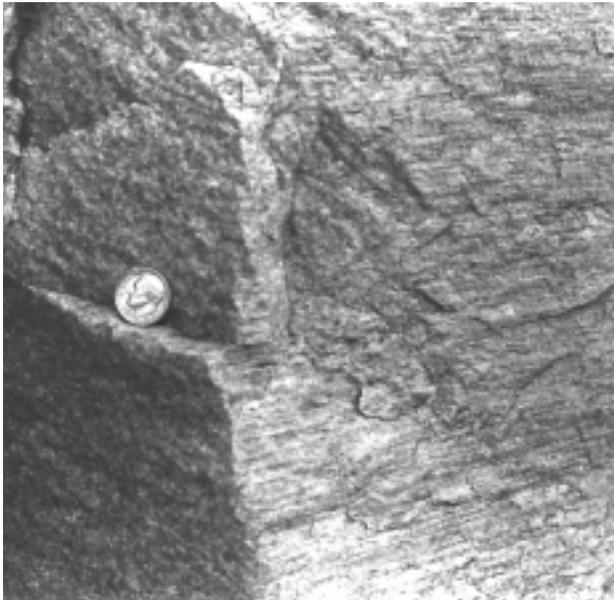


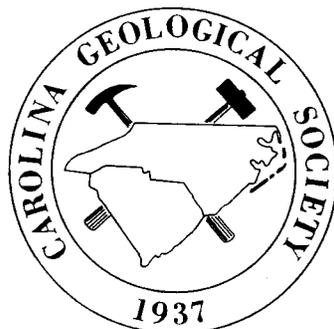
# GEOLOGY AND FIELD TRIP GUIDE, WESTERN FLANK OF THE RALEIGH METAMORPHIC BELT, NORTH CAROLINA

EDITORS:

Edward F. Stoddard  
David E. Blake



CAROLINA GEOLOGICAL SOCIETY  
Field Trip Guidebook 1994



November 5 - 6, 1994  
Raleigh, North Carolina

## **COVER PHOTOGRAPHS**

Fresh (left) and weathered exposures of leucogranitic orthogneiss at Stop 9, west Raleigh. View is toward the ESE in both photos. The linear-dominated tectonic fabric is typical of the Falls leucogneiss and adjacent rocks in the Crabtree and Raleigh terranes. It is a characteristic regional feature that resulted from Alleghanian right-lateral shear along the Nutbush Creek fault zone. See the article by Druhan and others, and the descriptions for Stops 9, 9A, and 10 of the Field Guide, for further discussion of the lineated orthogneiss and the Nutbush Creek fault zone.

**CAROLINA GEOLOGICAL SOCIETY  
FIELD TRIP GUIDEBOOK**

**November 5 - 6, 1994**

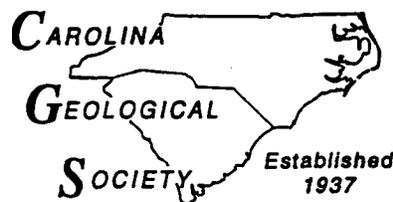
**GEOLOGY AND FIELD TRIP GUIDE,  
WESTERN FLANK OF THE RALEIGH  
METAMORPHIC BELT,  
NORTH CAROLINA**



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## FOREWORD AND ACKNOWLEDGMENTS

Beginning with the mapping of John Parker and his students, and continuing through to the current mapping of the Raleigh 1:100,000 sheet by the North Carolina Geological Survey, much progress has been made toward understanding the geologic evolution of the eastern Piedmont of North Carolina. The papers in this guidebook provide the most recent coverage of the stratigraphy, petrology, and structure of the western flank of the Raleigh metamorphic belt. We hope that this work provides a bridge between recent geologic research in the eastern Piedmont of Virginia and South Carolina.

The papers are arranged in a sequence from general to specific, and in a chronological sequence from Neoproterozoic to Mesozoic, with two papers on hydrogeology at the end.

We are grateful for advice and assistance of all whose efforts contributed to this guidebook and the field trip. First we thank the authors of the 11 papers and 13 stop descriptions. Timely peer reviews were instrumental in improving the content and clarity of the manuscripts. We believe that the volume provides a comprehensive account of current research and perspectives on the geology of this region. We thank all the reviewers, most of whom reviewed more than one manuscript: Bob Butler, 5 papers reviewed; Bill Hoffman, 4; Wright Horton, 3; Tim Davis, 3; Jerry Bartholomew, 2; Bryson Trexler, 2; Kent White, 2; Jim Hibbard, 2; Kevin Stewart, Neal Blair, John Huntsman, and Chuck Welby.

We would like to especially commend Bob Butler, Wright Horton, and Tim Davis for offering valuable advice that was made possible from their experiences with other CGS field conferences, and Bill Hoffman for preparing the index map for the field trip, and all 13 of the stop location maps. Heather Bowden has been a big help with the meeting announcement, registration, and guidebook cover.

As of the time of this writing, we are happy to acknowledge the financial support of the 1994 CGS meeting that have been received from: Bartlett Geological Consultants; GeoSolutions, Inc.; Teer Aggregates; Wake Stone Corporation; Atlanta Testing and Engineering, Inc.; Vulcan Materials; and Law Engineering. We hope there will be more to report at the meeting.

We are grateful to the North Carolina Geological Survey and the U.S. Geological Survey, for financial support of mapping and related analytical work by Blake, Stoddard, Speer, Butler, and Goldberg, through the COGEMAP and STATEMAP programs. Such support is vital if we are to further our understanding of the geological evolution of this or any other region.

Last but not least, we thank Duncan Heron, who bravely took on double duty this year, the result of offering to publish the guidebook through the facilities of *Southeastern Geology*. He has worked efficiently and tirelessly, and we surely needed him to carry it off.

Skip Stoddard and Dave Blake

## DEDICATION

### John M. Parker III

We are pleased to dedicate the 1994 Carolina Geological Society Guidebook to John M. Parker III, whose field work in the eastern Piedmont of North Carolina set a standard for all of us who have followed his footsteps into the woods and along the creeks.

Dr. Parker instilled a love and appreciation of geology in all his students at North Carolina State University. His career there, as professor and mentor, spanned five decades, from 1935 to 1972.

With his students, he mapped the geology of Wake County. This work resulted in Bulletin 86 of the North Carolina Geological Survey in 1979, and along the way, a number of other important contributions to our understanding of the geology and mineral resources of North Carolina. Because of the care and attention he took, his mapping in Wake County provides the framework for current 1:24,000-scale efforts in the eastern Piedmont. A common experience for geologists now working in this area occurs when they “discover” a contact relationship previously mapped by Parker. The stratigraphic approach he adopted for Piedmont mapping is the precursor and basis for our current terrane concepts in the region. It is not surprising that the reference “(Parker, 1979)” occurs more frequently in this volume than any other.

The editors, authors, and trip leaders of the 1994 CGS meeting proudly join together with former students and colleagues, and the community of geologists and non-geologists alike, in saluting John M. Parker III.

# **GEOLOGIC MAP OF THE FALLS LAKE-WAKE FOREST AREA, NORTH-CENTRAL NORTH CAROLINA -- A SYNOPSIS**

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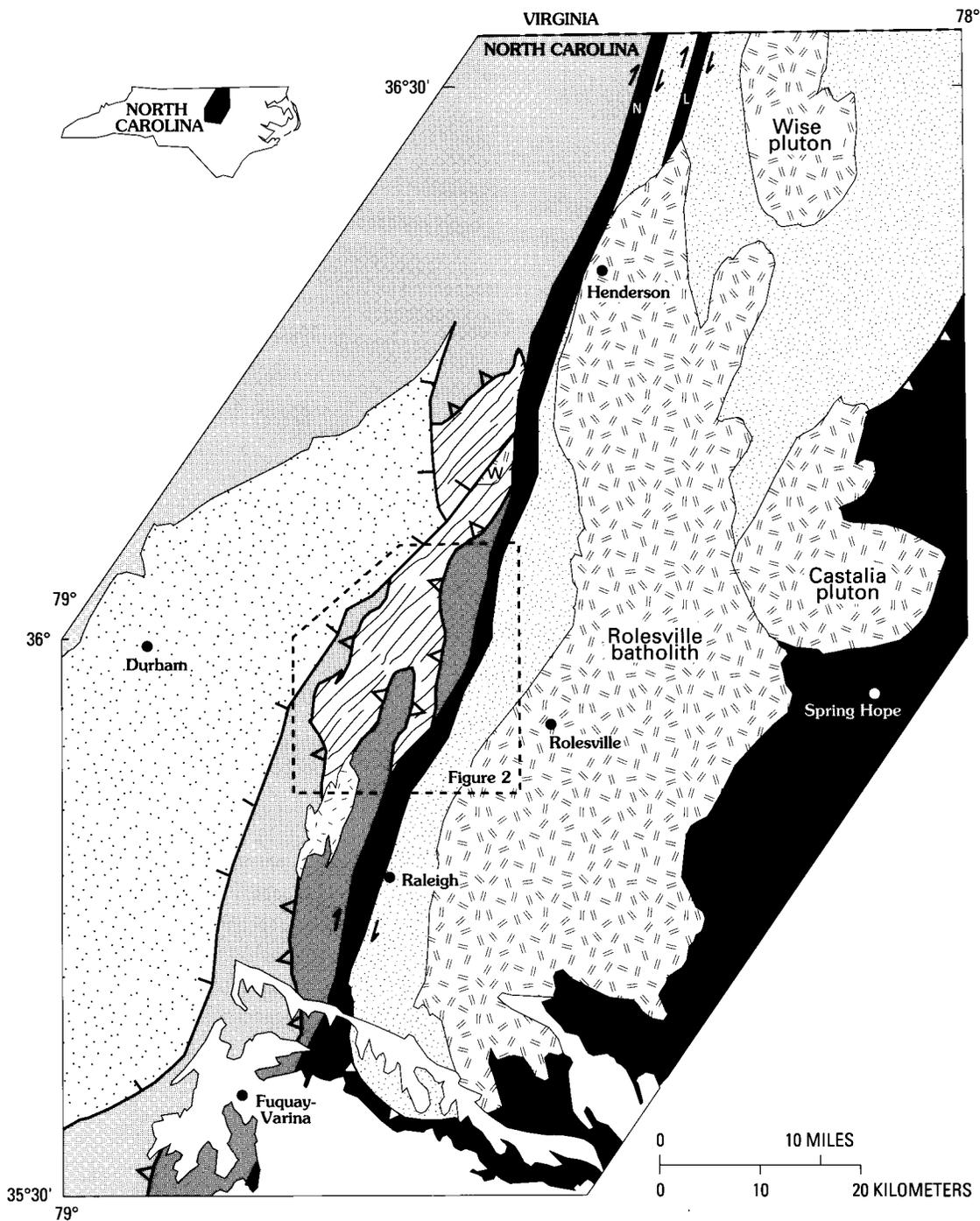
## **ABSTRACT**

The Falls Lake-Wake Forest area, North Carolina, as described herein, encompasses most of the rock units and several of the stops to be visited on the 1994 Carolina Geological Society field trip. 1:24,000-scale geologic mapping of this area provides a detailed transect across the western flank of the Raleigh metamorphic belt from the Rolesville batholith on the east to the Durham sub-basin of the Triassic Deep River basin on the west. The Raleigh gneiss (informal name) of the Raleigh terrane on the east side of the map is a heterogeneous gneiss composed mainly of hornblende-biotite gneiss and biotite gneiss. It contains intercalated gneissic granitoid bodies and is intruded by late Paleozoic granites of the Wyatt pluton and Rolesville batholith. The Raleigh gneiss is bounded on the west by the late Paleozoic Nutbush Creek fault zone, which in this area contains a lineated granitic gneiss, the Falls leucogneiss (informal name). Farther west, a metamorphic suite of the Crabtree terrane, containing felsic gneiss and lesser amounts of garnet-kyanite schist and aluminous graphite schist, is structurally overlain by the Falls Lake melange along the Falls Lake thrust. This thrust and juxtaposed units are folded around the gently north-plunging Raleigh antiform and truncated on the east by the Nutbush Creek fault zone. Farther west, sharp contacts and mylonites suggest a fault, inferred to be a thrust, between the Falls Lake melange and the structurally higher Carolina terrane. The latter contains felsic metavolcanic rocks of the informally named Cary formation, which is

intruded by the now metamorphosed Beaverdam diorite-gabbro complex (informal name). The Jonesboro fault separates these rocks from east-dipping Triassic strata at the western edge of the map.

## **INTRODUCTION**

Most of the rock units and several of the stops to be visited on the 1994 Carolina Geological Society field trip based in Raleigh, North Carolina, are exposed in the Falls Lake-Wake Forest map area as located in Figure 1. A geologic map of this area by Horton and others (1992) provides a transect across the west flank of the Raleigh metamorphic belt from the Rolesville batholith on the east to the Durham sub-basin of the Triassic Deep River basin on the west (Figure 2). The map also includes the type area of the Falls Lake melange. This paper outlines the geologic setting of the Falls Lake-Wake Forest area as background information for the field trip. It is based on, and should be used in conjunction with Horton and others' (1992) 1:24,000-scale geologic map, which includes all of the Bayleaf and Wake Forest 7.5-minute quadrangles and parts of the Creedmoor, Franklinton, Grissom, Rolesville, and Southeast Durham 7.5-minute quadrangles in parts of Wake, Franklin, Granville, and Durham Counties, North Carolina. Other results of this geologic mapping are contained in Wylie (1984), Horton and others (1986), Blake (1986), and Stoddard and others (1986). Previous work in the area is discussed by Parker (1978, 1979). Geologic map units and symbols are listed in Table 1.



EXPLANATION

- |   |   |   |                       |   |                     |
|---|---|---|-----------------------|---|---------------------|
|  | Atlantic Coastal Plain                            |  | Alleghanian granites  |  | Crabtree terrane    |
|  | Triassic Deep River basin                         |  | Crabtree Creek pluton |  | Falls Lake melange  |
|  | Nutbush Creek (N) and Lake Gordon (L) fault zones |  | Carolina terrane      |  | Raleigh terrane     |
|   |   |   |                       |  | Spring Hope terrane |

## FALLS LAKE - WAKE FOREST AREA SYNOPSIS

Table 1. List of units and symbols from Horton and others' (1992) geologic map of the Falls Lake-Wake Forest area. The same letter symbols are used on Figure 2. Single asterisk (\*) indicates unit omitted from Figure 2 for page-size reduction; double asterisk (\*\*) indicates unit shown on Figure 2 but not on Horton and others' (1992) map.

**TERTIARY AND QUATERNARY SURFICIAL DEPOSITS**

- \* af, artificial fill
- \* Qal, alluvium
- \* Qt, terrace deposits along Neuse River
- \* Ts, upland sand and gravel

**JURASSIC DIKES**

- \* Jd, olivine diabase

**DURHAM SUB-BASIN OF TRIASSIC DEEP RIVER BASIN**

Chatham Group

- TRcc, conglomerate
- TRcs/c, sandstone and conglomerate
- TRcsc, pebbly sandstone
- TRcs, sandstone
- TRcs/si, sandstone and siltstone

**FAULT ROCKS**

- \* sc, siliceous cataclasite
- \* my, mylonite and mylonite gneiss

**ORDOVICIAN THROUGH PENNSYLVANIAN PLUTONS**

- †Pgw, muscovite-biotite granite of Wyatt pluton
- †Pgr, biotite monzogranite of Rolesville batholith
- †Pzgg, gneissic biotite granitoid
- †SOgf, Falls leucogneiss (informal name)

**CAMBRIAN AND LATE PROTEROZOIC PLUTONS**

Crabtree Creek pluton

- \*\* CZg, leucogranitic orthogneiss

Beaverdam diorite-gabbro complex and related plutons

- CZdi, metadiorite
- CZgb, metagabbro
- \* CZto, metatonalite

**CAROLINA TERRANE**

Cary formation (informal name)

- CZcf, felsic metavolcanic rock and phyllitic metasiltstone
- \* CZcm, ilmenite-magnetite quartzite
- \* CZcc, phyllitic conglomerate

**CRABTREE TERRANE**

- cf, felsic gneiss of Crabtree Creek
- cgk, garnet-kyanite schist of Horse Creek
- cgs, graphite schist
- \* cmq, muscovite-quartz schist
- cam, hornblende gneiss and amphibolite
- cfs, interlayered felsic gneiss and mica schist

**FALLS LAKE MELANGE**

- CZfs, biotite-muscovite schist
- \* CZfua, actinolite rock and actinolite-chlorite schist
- \* CZfut, talc schist
- \* CZfus, serpentinite
- \* CZfu, ultramafic rocks (undivided)
- \* CZfa, amphibolite
- \* CZfqz, quartzite
- \* CZfq, siliceous rock
- \* CZfp, pebbly paragneiss and schist

**RALEIGH TERRANE**

Raleigh gneiss

- rgn, heterogeneous gneiss
- \* rb, biotite gneiss
- rh, hornblende-biotite gneiss
- rl, fine-grained leucocratic gneiss

### PROTEROZOIC AND PALEOZOIC ROCKS

#### Raleigh Terrane

#### Raleigh Gneiss

The Raleigh gneiss (informal name of Farrar, 1985a) lies adjacent to the Rolesville batholith on the east side of the Falls Lake-Wake Forest map area (Figure 2). The gneiss is well banded, variably migmatitic, and in this area is mainly a heterogeneous gneiss (rgn) composed of interlayered hornblende-biotite gneiss (rh) and biotite gneiss, with minor amphibolite and fine-grained leucocratic gneiss (rl). Leucosomes and crisscrossing dikes of granite, pegmatite, and aplite are widespread in the Raleigh gneiss, which Parker (1979) aptly described as "injected gneiss and schist." The 1994 Carolina Geological Society field trip will examine the Raleigh gneiss in downtown Raleigh just south of this map area.

Farrar (1985b) interpreted the Raleigh gneiss as a southern extension of the Grenvillian(?) Goochland terrane, but Stoddard and others (1991) questioned this interpretation

Figure 1 shows the setting of the Falls Lake-Wake Forest area relative to terranes that have been proposed in the eastern North Carolina Piedmont. Tectonostratigraphic terranes are fault-bounded crustal units that have a stratigraphy and geologic history different from that of adjacent terranes. The terranes on Figure 1 (discussed below) are adapted from preliminary maps (Horton and others, 1989, 1991; Stoddard and others, 1991), which tentatively treat fault blocks as separate terranes if their internal stratigraphy and geologic history are poorly understood. Terranes are conceptually different from the geologic belts traditionally used in the southern Appalachian Piedmont (Horton and others, 1989; Horton and Zullo, 1991), and their boundaries can differ. For example, the Raleigh terrane is interpreted by Stoddard and others (1991) to represent continental crust exposed in a structural window and separated by thrust faults from structurally higher magmatic-arc terranes, whereas the Raleigh metamorphic belt is a region of higher-grade late Paleozoic metamorphism superimposed on parts of several different terranes (Horton and Zullo, 1991; Stoddard and others, 1991).

Figure 1. Tectonostratigraphic map of the eastern North Carolina Piedmont showing location of the Falls Lake-Wake Forest map area (Figure 2) with respect to terranes that have been proposed. Terrane nomenclature and usage of Horton and others (1989, 1991) has been modified to include the Raleigh terrane of Stoddard and others (1991). Map symbols: L - Lake Gordon fault zone; N - Nutbush Creek fault zone; W - Wilton pluton. Geologic boundaries adapted from North Carolina Geological Survey (1985), Horton and others (1992, 1993), Druhan (1983), and D.E. Blake (this guidebook).

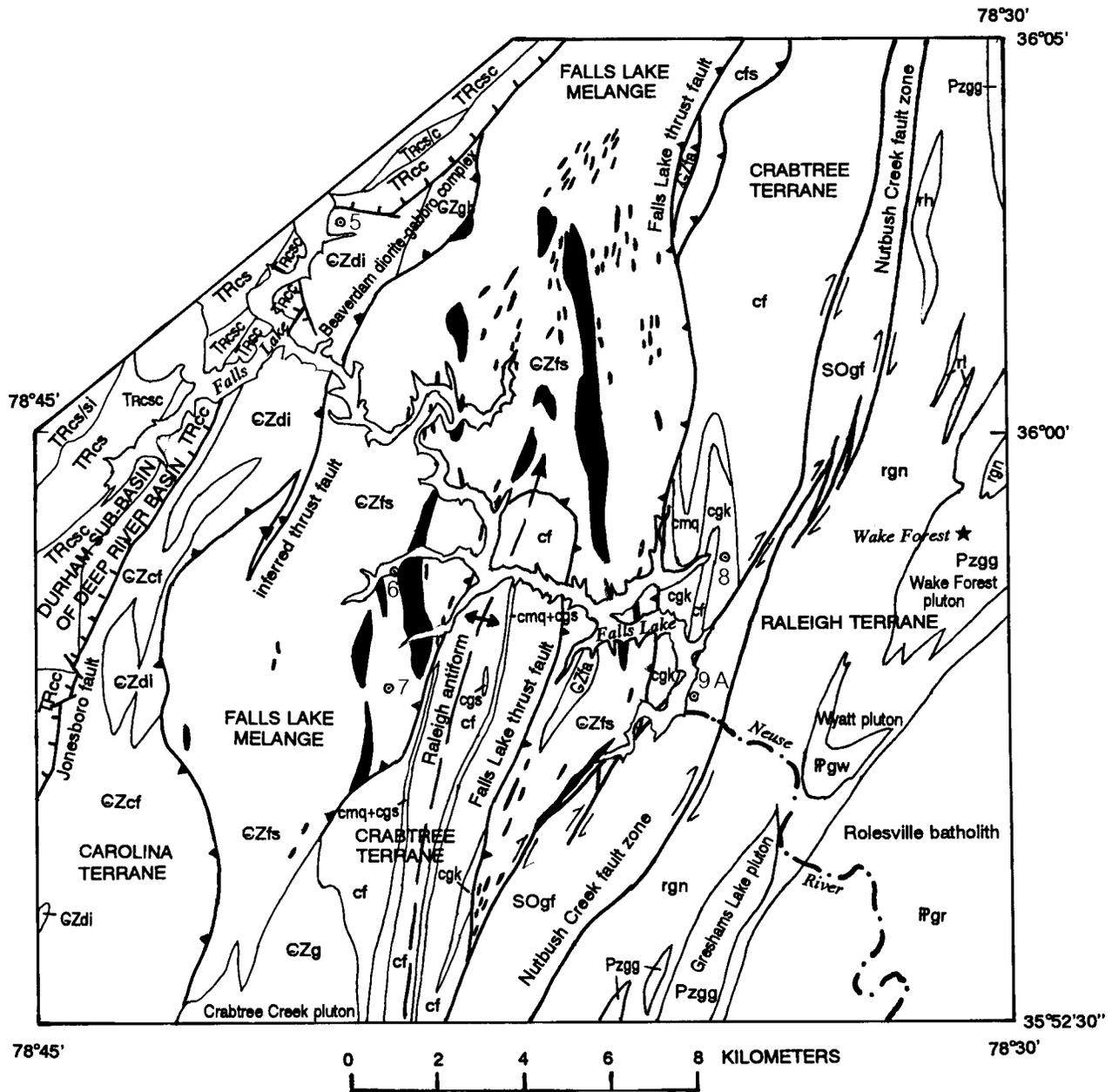


Figure 2. Generalized bedrock geologic map of the Falls Lake-Wake Forest area, simplified with modified boundaries from Horton and others (1992). Map-unit symbols are explained in Table 1, and ultramafic rocks are shown collectively in black. Contacts - thin lines; faults - thick lines with standard decoration for thrust (teeth on upper plate), normal (hachures on downthrown side), or strike-slip (arrows indicating sense of movement). Numbers indicate localities described for the 1994 Carolina Geological Society field trip: 5 - metamorphosed quartz diorite of Beaverdam diorite-gabbro complex (optional stop); 6 - ultramafic rocks in Falls Lake melange; 7 - Falls Lake melange (saproli-tized) in creek bank; 8 - garnet-kyanite schist in road cut near Horse Creek; 9A - Falls leucogneiss at spillway (extra stop).

and assigned the gneiss to a separate Raleigh terrane. Horton and Stern (1994) reported a preliminary  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon age of 544 Ma (interpreted as a minimum age) for the Raleigh gneiss in downtown Raleigh, suggesting that the Raleigh gneiss probably is not part of a Grenvillian terrane. An article in this guidebook by S.A. Goldberg reports comparable  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages ranging from 546 Ma to 461 Ma. The Raleigh gneiss may be similar in age to the Late Proterozoic and Cambrian meta-igneous rocks in the

Carolina and Spring Hope terranes (Horton and Stern, 1994). If so, as noted by Horton and Stern (1994), the Raleigh gneiss may be an amphibolite-facies equivalent of those rocks, and the validity of a separate Raleigh terrane is questionable.

**Granitic Rocks**

The Raleigh gneiss contains bodies of foliated biotite granite and granitic orthogneiss (Pzgg) such as the Wake

## FALLS LAKE - WAKE FOREST AREA SYNOPSIS

Forest and Greshams Lake plutons (Horton and others, 1992). These granitic rocks are interpreted to be Alleghanian based on a preliminary  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon age of 321 Ma for the Greshams Lake pluton (Horton and Stern, 1994).

The Raleigh gneiss is also intruded by massive to foliated granites of Pennsylvanian age, including those of the Rolesville batholith (IPgr) and Wyatt pluton (IPgw). Granite of the Rolesville batholith in this area is equivalent to the Rolesville main facies of Farrar (1985a). This granite (IPgr) is typically a medium- to coarse-grained, massive to weakly foliated biotite monzogranite composed of perthitic microcline, oligoclase (commonly with albite rims), quartz, and minor biotite. Primary and secondary accessory minerals include opaque minerals, allanite, titanite, apatite, zircon, chlorite, epidote, muscovite, calcite, and hematite. Horton and Stern (1994) reported preliminary  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages from the Rolesville batholith of 312 Ma for fine- to medium-grained, light-gray biotite granite, and 298 Ma for medium to coarse grained, very light gray biotite granite. These ages are consistent with field relations indicating that the Rolesville is a composite batholith. Lead, strontium, and neodymium isotopic studies of granite from the Rolesville batholith indicate that Grenvillian (Middle Proterozoic age) crust was not a major source component for the magma (Coler and Samson, 1994). The Rolesville batholith will be examined on the 1994 Carolina Geological Society field trip, and is discussed in a separate article in this guidebook by J.A. Speer.

Granite of the Wyatt pluton (IPgw) is a very light gray, medium-grained, muscovite-biotite monzogranite and pinkish-gray, medium- to coarse-grained, muscovite-biotite monzogranite. The presence of muscovite and accessory garnet are distinctive, although muscovite is less abundant than biotite. Granite of the Wyatt pluton is foliated, and inclusions of Raleigh gneiss are common. The Wyatt pluton has a Rb-Sr whole-rock age of  $307 \pm 3$  Ma (P.D. Fullagar, unpublished data cited in McSween and others, 1991).

### Nutbush Creek Fault Zone and Falls Leucogneiss

The Raleigh gneiss is bounded on the west by the north-northeast-striking, steeply southeast-dipping Nutbush Creek fault zone, a ductile shear zone which constitutes a major strand of the Eastern Piedmont fault system. The time of shearing on the Nutbush Creek fault zone is bracketed between about 312 Ma and 285 Ma by Rb-Sr dates on sheared and unsheared granite plutons (Druhan and others, 1988). Late Paleozoic dextral simple shear on this zone is well documented (Bartley and others, 1984; Druhan and Rollins, 1984; Druhan and others, 1988), but the magnitude of strike-slip displacement remains undetermined. Druhan and others (1988) estimated 160 kilometers of right-lateral slip based on their interpretation of an "offset contact between the Carolina slate belt metavolcanic sequence and

underlying gneisses of the Raleigh-Goochland terrane." However, recent evidence that graphite schist may be transposed into and traceable across the Nutbush Creek fault zone south of Raleigh (Lumpkin and others, 1994) suggests smaller horizontal displacement distributed across a broad zone of ductile shear. A separate article in this guidebook by R.M. Druhan and others provides a comprehensive discussion of the Nutbush Creek fault zone.

The segment of the Nutbush Creek fault zone in the Falls Lake-Wake Forest area contains a highly elongate mass of subhorizontally lineated, granitic orthogneiss (SOgf) informally known as the Falls leucogneiss (Farrar, 1985a) or Falls lineated gneiss (Mims and others, 1990), which contains abundant accessory magnetite. Geologic mapping by Horton and others (1992) supersedes earlier reconnaissance by Farrar (1985b) which located the Nutbush Creek fault zone several kilometers farther west. However, evidence of subhorizontal lineation and dextral simple shear associated with the Nutbush Creek fault zone is intermittently present for several kilometers east and west of the Falls leucogneiss (Mims and others, 1990; Blake and Stoddard, 1993; D.E. Blake, this guidebook).

A preliminary discordant  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon age of 491 Ma for the lineated Falls leucogneiss (Horton and Stern, 1994) indicates that the protolith is significantly older than the Alleghanian deformation. A possible protolith is the felsic gneiss of Crabtree Creek (cf; as discussed below), parts of which are similarly granitic and leucocratic in composition. The eastern contact of the Falls leucogneiss with the Raleigh gneiss is sharp, except for some interfingering, but the western contact appears to be gradational (across a ductile strain gradient) into the felsic gneiss of Crabtree Creek. In the Falls Lake-Wake Forest area, rocks near the contact were generally mapped by Horton and others (1992) as Falls leucogneiss if they appeared more lineated than foliated, and if magnetite was conspicuous. Subhorizontal lineation associated with the Nutbush Creek shear zone is more conspicuous west of the Falls leucogneiss than to the east.

The 1994 Carolina Geological Society field trip will visit exposures of the lineated Falls leucogneiss south of the map area. The unit is also well exposed in the emergency spillway of the Falls Lake dam along the Neuse River (Locality 9A on Figure 2; see field trip description for details), where the lineated fabric and magnetic anisotropy have been described by Mims and others (1990).

### Crabtree Terrane

#### General Geology

West of the Falls leucogneiss, a metamorphic suite described by Horton and others (1989, 1991) as part of the Crabtree terrane is exposed in the core of the Raleigh anti-form and in the Purnell area farther north (Blake, 1986; Horton and others, 1992). This metamorphic suite contains the

felsic gneiss of Crabtree Creek (cf), the garnet-kyanite schist of Horse Creek (cgk), and distinct marker units of graphite schist (cgs). Horton and others (1986) suggested that the highly aluminous and graphite schists may have originated as muds deposited in a restricted basin, and Stoddard and others (1978) proposed felsic igneous or arkosic protoliths for the felsic gneiss. The Crabtree terrane has been interpreted as continental in origin (Stoddard and others, 1978, 1991; Horton and others, 1989, 1991), although the evidence remains equivocal. Rocks here assigned to the Crabtree terrane are structurally overlain by those of the Falls Lake melange along the Falls Lake thrust fault as discussed below, and are truncated on the east by the Nutbush Creek fault zone. A separate article in this guidebook by D.E. Blake discusses rocks of the Crabtree terrane south of the area shown in Figure 2.

### Garnet-Kyanite Schist of Horse Creek

The garnet-kyanite schist of Horse Creek (cgk) is a coarse-grained aluminous schist having abundant, conspicuous porphyroblasts of kyanite and garnet. The rock is composed of quartz, muscovite, biotite, garnet, kyanite, and minor amounts of staurolite and albite. Accessories include apatite, zircon, and opaque minerals. Abundant kyanite blades and garnets in residual soils derived from the schist facilitate mapping areas of poor exposure. Staurolite occurs as small anhedral grains and as inclusions in garnet. Garnets commonly show evidence of two-stage growth, having euhedral to subhedral cores surrounded by euhedral to subhedral rims. These two-stage garnets are consistent with other polymetamorphic textures in the region (Wylie and Stoddard, 1983; Stoddard, Wylie, and Boltin, 1985). Garnet-biotite geothermometry indicates that peak Alleghanian temperatures increase eastward from about 520° to 650° C, and preliminary geobarometry based on other mineral assemblages suggests pressures of about 6.0 to 7.5 kb (Stoddard and Blake, 1992). The garnet-kyanite schist is well exposed near Horse Creek in a road cut on N.C. Highway 98 (Locality 8 on Figure 2), which will be examined on the 1994 Carolina Geological Society field trip. P-T estimates determined by J.A. Speer for a specimen from this outcrop are 660°C and 10 kbar for garnet cores and 645°C and 8 kbar for garnet rims (see field trip description for details).

### Graphite Schist and Muscovite-Quartz Schist

The graphite schist (cgs) is a gray to black, carbonaceous and highly aluminous pelitic schist, which is interlayered with very light gray muscovite-quartz schist (cmq). The graphite schist is composed mainly of quartz, graphite, and muscovite. Porphyroblasts of garnet and staurolite are common, and other constituents include biotite, albite, opaque minerals, and locally kyanite. Work in progress by Lumpkin and others (1994) affirms a sedimentary origin for the graph-

ite schist, and suggests that it may be transposed into and traceable across the Nutbush Creek fault zone south of Raleigh. As described in the separate article in this guidebook by B.L. Lumpkin and others, preliminary analyses of carbon isotopes indicate that the carbon of the graphite schist is organic in origin. An exposure of the graphite schist in west Raleigh, south of the Falls Lake-Wake Forest map area, will be examined on the 1994 Carolina Geological Society field trip.

### Felsic Gneiss of Crabtree Creek and Crabtree Creek Pluton

The felsic gneiss of Crabtree Creek (cf) is very light gray to pinkish-gray, weakly layered and well foliated. It is composed of quartz (50-80%), oligoclase (10-35%), microcline (0-10%), and muscovite (0-15%), with accessory biotite, chlorite, and epidote. The unit includes the "quartz-disk gneiss" of Parker (1979). High quartz content, local quartz disks interpreted by some observers as flattened pebbles, relict plagioclase phenocrysts, and interlayered aluminous and graphite schists (cgk and cgs) have been used as evidence in support of a metasedimentary or metavolcanic origin for the unit (Parker, 1979; Farrar, 1985a, 1985b; Stoddard and others, 1991). Parts of the felsic gneiss of Crabtree Creek (cf) appear to be plutonic in origin as proposed by Kish and Campbell (1986) on the basis of chemical and isotopic data, and by Blake and Stoddard (1993) on the basis of geologic mapping in the Raleigh West quadrangle. Subhorizontal lineation associated with the Nutbush Creek fault zone is prominent on the eastern side of the felsic gneiss unit.

The felsic gneiss of Crabtree Creek (cf) as mapped by Horton and others (1992) encompassed but did not distinguish the northern end of the Crabtree Creek granitic pluton. This leucogranitic to granitic pluton, as described south of the map area by Blake and Stoddard (1993), is now recognized as a separate unit (€Zg) in the area of Figure 2, where it lies in the southern part of the map west of the graphite schists. The Crabtree Creek pluton is best exposed south of the map area at the Teer Aggregates' Crabtree quarry, where it will be examined as a stop on the 1994 Carolina Geological Society field trip. There, the igneous leucogranite composition and lack of well developed layering supports a plutonic interpretation for much of the rock. Some rocks in the Crabtree quarry fit the description of Parker's (1979) "quartz-disk gneiss," in which the origin of ellipsoidal porphyroclasts of polycrystalline quartz is still a puzzle. Preliminary <sup>207</sup>Pb/<sup>206</sup>Pb ages of zircon fractions from granitic gneiss at the Crabtree quarry range from 542 Ma (Horton and Stern, 1994) to 566 Ma (S.A. Goldberg in this guidebook) and are interpreted as minimum ages for crystallization. The zircon ages are significantly older than Kish and Campbell's (1986) Rb-Sr whole-rock age of 382±30 Ma. Horton and Stern (1994) interpret the zircon age as evidence that the granitic

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gneiss is Cambrian or older, similar to dated plutons in nearby parts of the Carolina slate belt (McSween and others, 1991, Table 7-1). Blake and Stoddard (1993) interpret the Crabtree Creek pluton to be intrusive into layered rocks of the Cary formation (discussed below) of the Carolina terrane as well as those here assigned to the Crabtree terrane. An article in this guidebook by D.E. Blake discusses the Crabtree Creek pluton in more detail.

### Falls Lake Melange

#### Overview

The Falls Lake melange (Horton and others, 1985a, 1985b, 1986) lies on the western flank of the Raleigh metamorphic belt, where it structurally overlies the Crabtree terrane, is folded around the gently north-plunging Raleigh antiform, and is truncated on the east by the Nutbush Creek fault zone. The melange consists of a metasedimentary matrix into which ultramafic and mafic fragments of possible oceanic lithosphere have been sliced or imbricated, appears to be bounded by thrust faults, and may have formed in the accretionary wedge of a convergent plate margin (Horton and others, 1985a, 1986; Stoddard, Wylie, and Blake, 1985).

#### Melange Matrix and Blocks

The melange matrix is predominantly biotite-muscovite schist (€Zfs) composed mainly of quartz, sodic plagioclase, biotite, and muscovite. Minor amounts of chlorite, epidote, and garnet are common, but kyanite and staurolite occur only locally. This biotite-muscovite schist, which we interpret as a metamorphosed mudstone, contains lesser amounts of biotite-muscovite-plagioclase-quartz gneiss which we interpret as metagraywacke. The schist matrix contains blocks and pods of amphibolite (€Zfa) and several types of ultramafic rocks ranging from pebble-size to mappable dimensions. A saprolite exposure of the melange in the east-central part of the Bayleaf quadrangle (Locality 7 on Figure 2) will be visited on the 1994 Carolina Geological Society field trip.

Metamorphosed ultramafic rocks, which constitute about 15%-20% of the melange, include serpentinite, chlorite-actinolite schist, soapstone or talc schist, and hornblende (Horton and others, 1986, 1992). All of these ultramafic rock types can be observed at Stop B of Stoddard and others (1986) (Locality 6 on Figure 2) which is being visited on the 1994 Carolina Geological Society field trip. Protoliths inferred from geochemical and mineralogical studies are consistent with an interpretation of the metamorphosed ultramafic rocks as ophiolite fragments (Moye, 1981; Stoddard and others, 1982). Many ultramafic bodies have chloritic or leucocratic metasomatic rims, but none have thermal contact aureoles (Horton and others, 1986). Some ultramafic bodies in the melange contain pods of chromitite. Metamorphic

minerals observed along fractures in the chromitite include chlorite, margarite, fuchsite, kyanite, tourmaline, corundum, and rutile (Stoddard and others, 1989).

Horton and others (1986) interpreted the lenticular shapes, concordant schistosity, and pinch-and-swell structure of most ultramafic and mafic blocks in the melange as boudinage resulting from the ductility contrast between blocks and matrix during regional deformation. However, the earliest schistosity recognized in the matrix, and parallel stringers of granite and pegmatite, cut across some of the smaller blocks without deflection (Figure 2 of Horton and others, 1986), indicating that some of the fragment-in-matrix texture predates this schistosity. Locally, the schist matrix contains ellipsoidal lumps, interpreted to be rounded pebbles up to a few centimeters across, of granite and pegmatite. Evidence that some small fragments of ultramafic and mafic rock originated as sedimentary clasts is equivocal, although the possibility has been suggested on the basis of their round to angular shapes and embayed margins (Figure 3 of Horton and others, 1986). Horton and others (1986) and Blake (1986) suggested that the Falls Lake melange, like many other melanges, may have formed by a combination of sedimentary and tectonic processes. Whether or not this is the case, the fabrics observable now are predominantly tectonic in origin.

#### Age of the Melange

Current age constraints on the Falls Lake melange are consistent with the tentative Late Proterozoic and (or) Cambrian(?) age designation of Horton and others (1992). Dikes of leucogranitic orthogneiss (€Zg), which are associated with the Crabtree Creek pluton, appear to intrude the melange in the southern part of the map area (Figure 2). If leucogranitic orthogneiss of the Crabtree Creek pluton has a minimum age of about 542-566 Ma (Horton and Stern, 1994; S.A. Goldberg in this guidebook) and if it intrudes the melange, then the melange matrix and blocks must be Middle Cambrian or older. S.A. Goldberg (separate article in this guidebook) describes preliminary U-Pb dating of zircons from a garnet-bearing muscovite-biotite-quartz-feldspar orthogneiss collected within the Falls Lake melange. The orthogneiss is more feldspathic than the typical melange matrix, and zircon morphology indicates a meta-igneous origin. Preliminary U-Pb dates cluster near a lower concordia intercept of 590 Ma, which is interpreted as a crystallization age; the Pb-Pb ages and upper intercept suggest inheritance from an older, pre-Grenville source (S.A. Goldberg, this guidebook). The orthogneiss may represent a block of volcanic or plutonic rock within the melange, in which case 590 Ma is a maximum age for the melange, or it may represent a younger intrusion, in which case 590 Ma is a minimum age for the melange.

## Falls Lake Thrust and Other Melange Boundaries

The Falls Lake melange structurally overlies the Crabtree terrane along the Falls Lake thrust, a pre-metamorphic fault which is folded around the north-plunging Raleigh antiform and truncated on the east by the late Paleozoic Nutbush Creek fault zone (Figure 2). A separate article in this guidebook by E.F. Stoddard and others describes the Falls Lake thrust fault and recrystallized mylonitic gneisses along its trace. Another sharp contact separates the Falls Lake melange from the structurally higher Carolina terrane (discussed below). Horton and others (1992) noted the presence of mylonite along this upper contact and interpreted it as a thrust fault on their geologic map (Figure 2). They also mapped the southern termination of the Falls Lake melange in the Falls Lake-Wake Forest area and concluded that the melange does not extend farther south along the western limb of the Raleigh antiform as inferred on earlier reconnaissance maps (*i.e.*, Horton and others, 1986; Stoddard and others, 1989). On the eastern limb of the Raleigh antiform, the map by Horton and others (1992) shows that the melange extends about 3.5 kilometers south-southwest of the limit suggested by Wylie's (1984) mapping.

The Falls Lake thrust fault is transected by younger, late Paleozoic (Alleghanian) metamorphic isograds and by the late Paleozoic Nutbush Creek fault zone (Parker, 1979; Russell and others, 1985; Stoddard and others, 1991; Horton and others, 1986, 1992). Although an early or middle Paleozoic age has been suggested (Stoddard and others, 1991), the age of the Falls Lake thrust is poorly constrained. If the Crabtree Creek pluton (minimum age 542-566 Ma) cuts the Falls Lake thrust, this would suggest thrusting related to a Late Proterozoic or Cambrian (Penobscot or Cadomian) orogeny as described by Drake (1994) in the Virginia Piedmont and discussed in the separate article by Stoddard and others in this guidebook.

## Carolina Terrane

### General Geology

The Carolina terrane (Secor and others, 1983), as used here, includes predominantly greenschist-facies Late Proterozoic and Cambrian volcanogenic and plutonic rocks traditionally assigned to the Carolina slate belt as well as higher-grade equivalents of the same rocks in adjacent belts (Butler and Secor, 1991; Horton and Zullo, 1991). Lithostratigraphic, geochemical, and isotopic data indicate that these rocks originated in a subduction-related, oceanic or continental-margin magmatic arc having a component of rifting, perhaps related to back-arc extension (Butler and Secor, 1991 and references therein; Feiss and others, 1993). The Carolina terrane may represent part of a single exotic terrane, or it may represent an amalgam of two or more Late Proterozoic to early Paleozoic magmatic-arc terranes (Secor

and others, 1983; Horton and others, 1991; Feiss and others, 1993). Middle Cambrian fossils from South Carolina support the interpretation that those rocks are exotic to Laurentia and are compatible with a peri-Gondwana terrane (Samson and others, 1990).

Part of the Carolina terrane is exposed east of the Triassic Deep River basin (Figure 1). The eastern flank of the terrane in the area of Figure 2 includes the informal Cary formation (€Zcf) of Farrar (1985a), intrusive metagabbro (€Zgb) and metadiorite (€Zdi) of the Beaverdam diorite-gabbro complex (informal name of Parker, 1979), and smaller, possibly related bodies of metadiorite (€Zdi), metagabbro, and metatonalite. A sharp contact separating the Falls Lake melange from Late Proterozoic to Cambrian(?) rocks of the Carolina terrane on the western side of the map (Figure 2) is inferred to be a west-dipping thrust fault as discussed above.

### Cary Formation

The Cary formation (informal name of Farrar, 1985a) in the Falls Lake-Wake Forest area is approximately equivalent to the informal Cary sequence of Parker (1979), but extends east of the arbitrary metamorphic boundary shown on the geologic map of Wake County (Parker, 1979, Plate 1). In this area, the Cary formation consists of phyllitic to almost massive, felsic metavolcanic rocks (€Zcf) and interlayered metasedimentary units. On the 1994 Carolina Geological Society field trip, metavolcanic rocks of the Cary formation will be examined in a quarry at Holly Springs, southwest of the map area. The age of the Cary formation is interpreted to be Late Proterozoic based on a preliminary U-Pb zircon age of  $574 \pm 12$  Ma (see article by S.A. Goldberg in this guidebook) as well as similarity and proximity to volcanogenic rocks near Durham, North Carolina, which contain Late Proterozoic metazoan fossils and have a U-Pb zircon age of  $620 \pm 20$  Ma (Glover and Sinha, 1973; Cloud and others, 1976; Harris and Glover, 1988).

The Cary formation is bounded on the west by the Jonesboro fault, which is the eastern border fault of the early Mesozoic Deep River basin (discussed below). The contact between the Cary formation and the Falls Lake melange is inferred by Horton and others (1992) to be a west-dipping thrust fault as discussed above. The nature of the eastern contact of the Cary formation south of the melange is uncertain and is at least partly obscured by intrusive contacts where the Cary formation is intruded by the Crabtree Creek pluton (Blake and Stoddard, 1993).

### Beaverdam Diorite-Gabbro Complex

The Beaverdam diorite-gabbro complex (informal name of Parker, 1979) consists of metamorphosed plutonic rocks that range in composition from hornblende gabbro (€Zgb) to biotite quartz diorite (€Zdi) and tonalite. Hornblendite (metamorphosed pyroxenite?) occurs as cumulate(?) layers

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in metagabbro near the northern end of the complex. Gabbroic dikes are locally conspicuous in diorite. The metamorphic foliation generally dips northwest. The age of the Beaverdam complex, although undetermined, is inferred to be Late Proterozoic or Cambrian based on similarity to dated plutons in nearby parts of the Carolina terrane as summarized by McSween and others (1991, Table 7-1) and references therein. A road cut in metamorphosed quartz diorite of the Beaverdam diorite-gabbro complex (Locality 5 on Figure 2) is an optional stop for the 1994 Carolina Geological Society field trip.

### EARLY MESOZOIC ROCKS

#### Durham Sub-basin of the Triassic Deep River Basin

##### Alluvial Fan Deposits

The Falls Lake-Wake Forest map area extends westward into sedimentary rocks of the Chatham Group in the Durham sub-basin of the Triassic Deep River basin. A separate article in this guidebook by C.W. Hoffman summarizes the stratigraphic framework in this part of the basin.

Alluvial fan deposits of conglomerate (Trcc), sandstone containing interbedded conglomerate (Trcs/c), pebbly sandstone (Trcsc), and sandstone (Trcs) along the eastern margin of the basin are collectively equivalent to Hoffman and Gallagher's (1989) Lithofacies Association III. An exposure of alluvial fan conglomerate south of the Falls Lake-Wake Forest map area will be examined on the 1994 Carolina Geological Society field trip.

##### Fluvial Deposits

In the central area of the rift basin (at the western edge of Figure 2), a unit of sandstone and interbedded siltstone (Trcs/si) in the Chatham Group is part of Hoffman and Gallagher's Lithofacies Association II and is interpreted as fluvial in origin. This sandstone and interbedded siltstone unit consists mainly of fining-upward sequences, 2-5 meters thick, of grayish-pink to pale red, medium- to coarse-grained arkose grading upward into fine-grained arkose and reddish-brown, bioturbated siltstone. Pink K-feldspar is abundant, and the presence of detrital muscovite distinguishes these sandstones from those of the alluvial fans. Hoffman and Gallagher (1989) interpret this fluvial unit as meandering stream deposits.

#### Jonesboro Fault

The Jonesboro fault forms the eastern boundary of the Triassic Deep River basin (Figure 1). In the Falls Lake-Wake Forest area, this steeply northwest-dipping normal fault separates moderately northwest-dipping foliated metamorphic rocks of the Beaverdam diorite-gabbro complex and Cary formation from gently southeast-dipping units of Upper Tri-

assic conglomerate, sandstone, and siltstone of the Chatham Group in the Durham sub-basin of the Deep River basin on the western side of the map (Figure 2). No evidence for pre-Mesozoic movement on the Jonesboro fault has been found in this area (Horton and others, 1992). Horton and others' (1992) geologic map includes the Jonesboro fault segment (just west of Figure 2) described by M.J. Bartholomew and others in a separate article in this guidebook. An exposure of the Jonesboro fault south of the area shown in Figure 2 will be visited on the 1994 Carolina Geological Society field trip.

### Diabase Dikes

Early Mesozoic diabase dikes (not shown on Figure 2) cut across the Jonesboro fault and Triassic sedimentary strata of the Durham sub-basin, as well as older rocks throughout this region of the Piedmont (Horton and others, 1992). Most of the dikes on the 1:24,000-scale geologic map by Horton and others (1992) have steep dip angles and strike north to northwest. The diabase in this area is typically dark gray to black, fine- to medium-grained olivine diabase, and it is probably Early Jurassic in age (Sutter, 1985, 1988). A comprehensive synthesis of diabase dikes in North Carolina and South Carolina is provided by Ragland (1991).

### TERTIARY AND QUATERNARY SURFICIAL DEPOSITS

Surficial deposits in the Falls Lake-Wake Forest area were omitted from Figure 2 to accommodate the page-size format, but are shown on the 1:24,000 scale geologic map by Horton and others (1992). Patches of upland sand and gravel on drainage divides near Leesville and Purnell (see Horton and others, 1992 for location) may represent the westernmost outliers of Atlantic Coastal Plain strata in this region of the Piedmont. Other surficial units in the area include alluvial terrace deposits along the Neuse River and alluvium on floodplains.

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# U-PB GEOCHRONOLOGY OF VOLCANOGENIC TERRANES OF THE EASTERN NORTH CAROLINA PIEDMONT: PRELIMINARY RESULTS

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## ABSTRACT

Neoproterozoic U-Pb zircon ages are reported for crystalline rocks of the Carolina terrane, Crabtree terrane, Eastern slate belt volcanogenic terrane, Raleigh terrane, and the Falls Lake mélange. The data suggest that the eastern Piedmont of North Carolina may be largely one volcanic terrane which experienced two episodes of magmatism at circa 560-590 and 620-640 Ma. Zircons analyzed from the Falls Lake mélange indicate the presence of an inherited component of pre-Grenville age.

## INTRODUCTION

This short note represents a progress report on U-Pb geochronological studies of zircon and sphene from crystalline rocks located in the eastern Piedmont of North Carolina (Figure 1). Samples were collected from the Raleigh terrane, Carolina terrane, Crabtree terrane, volcanogenic terrane of the Eastern slate belt, and the Falls Lake mélange. Terrane designations follow the usage of Horton and others (1989, 1991) and Stoddard and others (1991). The work is part of a collaborative effort involving D.E. Blake, J.R. Butler, P.A. Carpenter III, R.H. Carpenter, P.D. Fullagar, J.W. Horton Jr., and E.F. Stoddard. Funding was provided by the North Carolina Geological Survey. High-precision U-Pb analyses were performed using the new mass spectrometry and clean lab facilities at the University of North Carolina at Chapel Hill.

The intent of this report is to provide new geochronological data which constrain tectonic models for the inferred accreted terranes of the eastern Piedmont. The data are considered preliminary because additional analyses are needed to precisely resolve crystallization and/or deformation ages of several rocks. They are presented here in order to facilitate discussions of geological relations during the 1994 Carolina Geological Society field trip.

## CAROLINA AND CRABTREE TERRANES

### Cary formation

Foliated, medium-grained, felsic metavolcanic rock was sampled from the Triangle quarry of the Wake Stone Corporation (adjacent to the I-40 and Reedy Creek section of Umstead State Park), Cary 1:24,000 quadrangle. The Cary

formation is an informal designation used by Farrar (1985a, 1985b) for phyllites and metamorphosed felsic tuffs and flows, and is regarded as part of the Carolina terrane. The felsic metavolcanic rock is shown on the Geologic Map of North Carolina (North Carolina Geological Survey, 1985) as felsic mica gneiss (€Zfg). Three discordant fractions of euhedral, colorless to light pink zircon yield  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of 573, 574, and 579 Ma and an upper intercept age of  $575 \pm 12$  Ma, interpreted as the time of crystallization.

### Leucogranitic gneiss of Crabtree quarry

Foliated, medium-grained leucogranitic gneiss (quartz + K-feldspar + plagioclase + muscovite) was sampled from the Crabtree quarry, Teer Aggregates, Duraleigh Road, Raleigh (Raleigh West 1:24,000 quadrangle). This leucogranitic orthogneiss is described and discussed as part of the Crabtree Creek pluton by D.E. Blake in this guidebook. On the Geologic Map of North Carolina (North Carolina Geological Survey, 1985), the rock is designated as metavolcanic-epi-clastic rock (€Zve).

Zircons selected for analysis are euhedral, colorless to light pink, clear with simple prisms, have mean length:width ratios of 2.7, and lack optically apparent cores or overgrowths. Three discordant zircon fractions yield  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of 554, 564, and 566 Ma. The three fractions have a small range in  $^{206}\text{Pb}/^{238}\text{U}$  and  $^{207}\text{Pb}/^{235}\text{U}$ , and cannot be used to precisely define discordia intercepts. The  $^{207}\text{Pb}/^{206}\text{Pb}$  ages are interpreted to represent minimum crystallization ages. Horton and Stern (1994) reported a slightly younger  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 542 Ma for one zircon fraction of Crabtree Creek orthogneiss.

Zircons from leucogranitic gneiss of the Crabtree Creek pluton have  $^{207}\text{Pb}/^{206}\text{Pb}$  ages similar to zircons from the Cary formation, but exhibit greater discordance. Both data sets from this study are collinear on a 575 Ma U/Pb discordia, and it is suggested that both the Cary formation and leucogranitic gneiss of the Crabtree Creek pluton are coeval Neoproterozoic igneous components of the Carolina slate belt. The use of Neoproterozoic and other nomenclature for subdivisions of the Precambrian time scale is based on IUGS recommendations (Plumb, 1990).

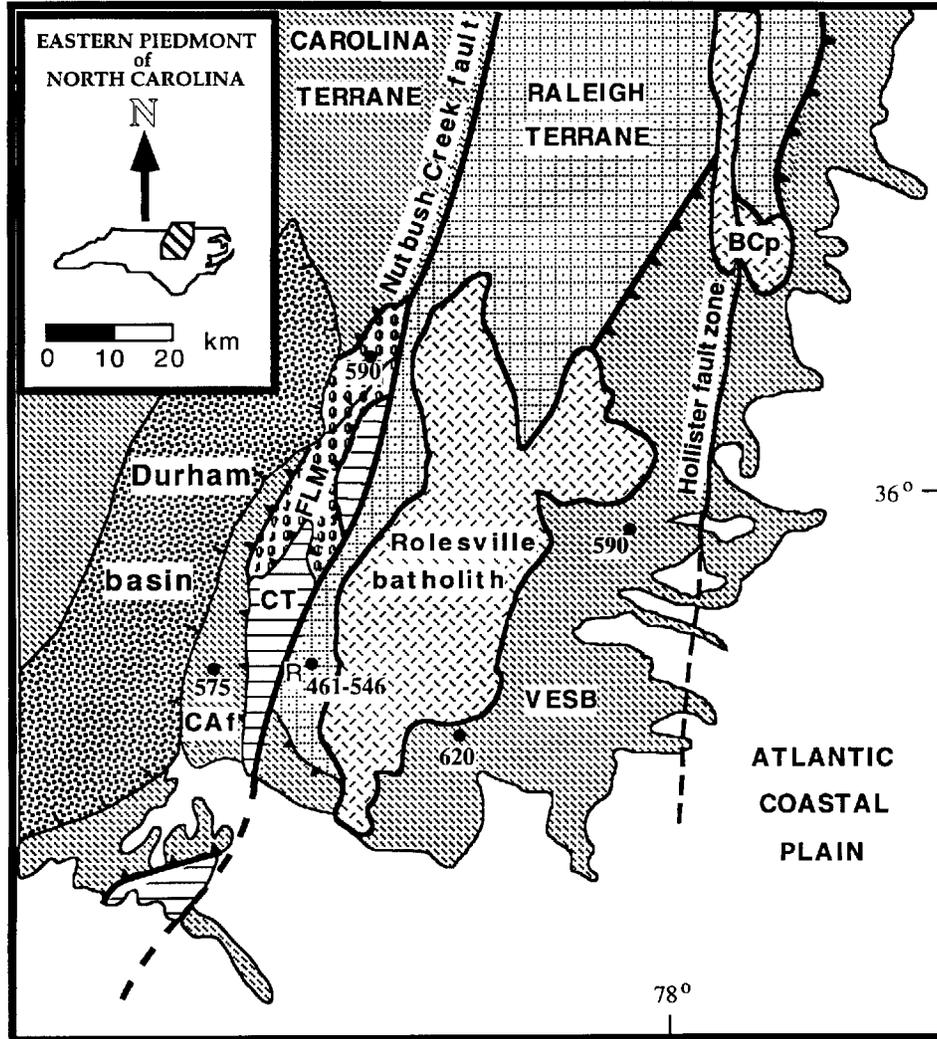


Figure 1. Generalized geologic map of the eastern Piedmont of North Carolina, after Stoddard and others (1991), and references therein, with preliminary U-Pb dates from this study. BCp - Butterwood Creek pluton; CAf - Cary Formation; CT - Crabtree terrane; FLM - Falls Lake mélange; VESB - volcanogenic terrane of the Eastern slate belt (Spring Hope terrane); R - City of Raleigh.

## EASTERN SLATE BELT VOLCANOGENIC TERRANE

### Biotite gneiss at Mill Creek

Four fractions of euhedral, colorless to light pink zircon from biotite-quartz-feldspar gneiss collected along Mill Creek, 0.4 km north of SR 1704 in the Flowers 1:24,000 quadrangle, yield an upper intercept age of  $620 \pm 9$  Ma. One fraction is concordant with a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $619 \pm 1.3$  Ma. The gneiss, which lies within 1 km of the Alleghanian Rolesville batholith, is shown on the Geologic Map of North Carolina (North Carolina Geological Survey, 1985) as biotite gneiss and schist (EZbg) of the Raleigh metamorphic belt. Farrar (1985a, 1985b) mapped the gneiss as part of his volcanogenic, informally named Stanhope formation. The

gneiss has been included in the "volcanogenic terrane of the Eastern slate belt" by Stoddard and others (1991) and as part of the Spring Hope terrane by Horton and others (1989, 1991), which includes volcanogenic rocks traditionally assigned to the Eastern slate belt.

Biotite gneiss at Mill Creek is here interpreted to be a medium-grade metamorphic equivalent of Eastern slate belt felsic volcanic rock which crystallized at 620 Ma. Thermal effects from the batholith did not reset U-Pb zircon systematics, as the lead-loss trajectory intercepts the present-day on concordia.

### Felsic crystal tuff near Spring Hope

Felsic crystal tuff was collected in outcrop in a stream 3 km southwest of Spring Hope in the Bunn East 1:24,000

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quadrangle. The metamorphosed crystal tuff occurs within a unit shown on the Geologic Map of North Carolina (North Carolina Geological Survey, 1985) as undivided felsic metavolcanic rock (€Zfv) of the Eastern slate belt and is part of the informally named Spring Hope formation as used by Farrar (1985a). This metavolcanic rock, like the higher-grade gneiss discussed above, is within the “volcanogenic terrane of the Eastern slate belt” of Stoddard and others (1991) and the Spring Hope terrane of Horton and others (1989, 1991).

Zircons are euhedral with simple prisms and terminations, and are clouded. Two discordant fractions of the least clouded, least magnetic zircon have  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of 589 and 590 Ma. Assuming modern Pb loss, these data yield an upper intercept crystallization age of  $590 \pm 3$  Ma.

### DISCUSSION OF AGES FROM THE CAROLINA, CRABTREE, AND EASTERN SLATE BELT VOLCANOGENIC TERRANES

The new U-Pb data indicate the presence of Neoproterozoic volcanic units in terranes on both the east and west sides of the Raleigh metamorphic belt. These ages are similar to those within the main Carolina slate belt west of the Triassic basins (*e.g.*, Wright and Seiders, 1980). The Eastern slate belt and the Carolina slate belt in North Carolina are now recognized to exhibit similar crystallization ages of volcanic rocks, supporting inferences that the two belts were once continuous (Stoddard and others, 1991). The Raleigh gneiss also appears to be a component of a Neoproterozoic terrane, based on data presented below.

Recent U-Pb zircon studies from Avalon terranes of the northern Appalachians have identified two periods of igneous activity: circa 620 Ma and circa 560 Ma (Barr and others, 1994, and references therein). Based on the preliminary data set of this study and existing geochronology in the Carolina slate belt (586 Ma Uwharrie volcanic rocks, Wright and Seiders, 1980; 575 Ma metagranite, Glover and Sinha, 1973; 620-650 Ma volcanogenic rocks, Glover and Sinha, 1973, McConnell and Glover, 1982), igneous activity also occurred in two discrete and similar time intervals. These different episodes of magmatism may reflect changes in the tectonic regime, for example from an arc setting at about 620-640 Ma to an extensional, intra-arc basinal regime at 560-590 Ma (*e.g.*, Barr and others, 1994).

### FALLS LAKE MÉLANGE

Muscovite-biotite-quartz-feldspar schist was collected along a tributary of Upper Barton Creek west of NC 50, Bayleaf 1:24,000 quadrangle. A 150 pound sample of feldspathic semi-schist with weakly developed banding was taken from a fresh loose block in an area of recent construction within the Falls Lake mélangé as mapped by Horton and others

(1992). The block is adjacent to outcrop of similar rock containing inclusions of dark-green actinolite-rich ultramafic rock as well as inclusions that differ only slightly in composition and appearance from the schist. The sample is more feldspathic than the typical mélangé matrix of muscovite-biotite schist (J.W. Horton, personal communication).

Two zircon populations are recognized in the schist. The dominant population (>99%) is colorless to light pink, euhedral (mean length:width = 2.5) with well-defined crystal faces (two prisms) and terminations, and is interpreted to be magmatic as opposed to detrital in origin. A second, very small population consists of rounded, multi-faceted grains, which may be inherited and metamorphic in origin. Although the zircon population suggests that the schist is meta-igneous in origin, additional constraints are needed to determine if the schist represents a later intrusion into the Falls Lake mélangé or a recrystallized and deformed meta-igneous block within the mélangé.

U/Pb data for five zircon fractions of the dominant population yield  $^{207}\text{Pb}/^{206}\text{Pb}$  ages ranging from 1117 to 1359 Ma, but plot near a lower discordia intercept of 590 Ma. The preliminary lower discordia intercept is tentatively interpreted as the crystallization age, and is similar to the Avalonian or Pan-African ages reported here for Cary formation metavolcanic rock and the felsic crystal tuff near Spring Hope.

The upper discordia intercept is constrained at  $2.2 \pm 0.2$  Ga. The preliminary data reflect the presence of a significant inherited, mainly post-Grenville (post 1.1 Ga) component in the dominant zircon population, as indicated by the  $^{207}\text{Pb}/^{206}\text{Pb}$  ages.

Muscovite-biotite-quartz-feldspar schist from the Falls Lake mélangé yields a Neoproterozoic (*c.* 590 Ma) lower intercept age, interpreted as the time of crystallization of the protolith, and thus the mélangé appears to contain either fragments or intrusions of magmatic rock similar in age to those in volcanogenic terranes of the Carolina and Eastern slate belts. The data are consistent with either a Neoproterozoic or Paleozoic age for the presumed accretionary wedge (Horton and others, 1986) which formed the Falls Lake mélangé. Reported mélangés from the Potomac terrane of Virginia and Maryland (Pavlidis, 1989) may be coeval.

A 2.2 Ga upper intercept age indicates the presence of an inherited component derived from a Paleoproterozoic source. The Mesoproterozoic  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of 1117 to 1359 Ma may reflect reworking of a Paleoproterozoic crustal source during the Grenville orogeny. Melting of this crustal source in the Neoproterozoic may have produced volcanic and sub-volcanic magmatism of the slate belt. SEM analyses of acid-etched zircons will be performed to test for the presence of inherited cores which could contain the older radiogenic component.

Refinement of the age of the inherited component is planned, as it may be possible to identify a likely source for

the Avalonian magmatism. Archean inheritance in zircon from late Paleozoic granites from the Avalon terrane of southeastern New England was recognized by Zartman and Hermes (1987). They suggested an African source for the Archean inherited component, but South American sources are equally as likely. Ages of circa 2.2 Ga are reported from the West African craton (Sylvester and Attoh, 1992), but also from the Guyana (Montgomery, 1979; Gibbs and Olszewski, 1982) and Rio de la Plata (Dalla Salda and others, 1988) cratons of South America. Keppie (1991) has suggested that the Avalon terrane is of South American provenance, and this connection has been reiterated by Dalziel and others (1994). I suggest that part of the slate belt may be derived from crustal components as old as 2.2 Ga.

### RALEIGH TERRANE

Two samples of biotite-plagioclase-hornblende gneiss were collected in outcrop prior to completion of road construction along I-440 just east of Atlantic Avenue, Raleigh East 1:24,000 quadrangle. U-Pb data for five fractions of euhedral and colorless to light pink zircon and sphene reflect a complex pattern of discordance. A single fraction of sphene yields a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 501 Ma, and is insufficient to resolve whether the sphene records a crystallization or deformation age.  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for zircon range from 461 to 546 Ma. The oldest zircon ages are Neoproterozoic and similar to the  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 544 Ma reported by Horton and Stern (1994) for a single fraction of zircon from the Raleigh gneiss at Raleigh. The zircon data collectively suggest a Neoproterozoic age for the gneiss. Additional analyses are planned.

The Raleigh terrane has been correlated with the Goochland terrane of central Virginia, considered to be of Grenville age (Farrar, 1985b). The oldest  $^{207}\text{Pb}/^{206}\text{Pb}$  zircon ages are Neoproterozoic, and inherited zircon cores have not been identified. Using Nd isotopic data, Coler and others (1994) inferred that Grenville rocks could not be a significant magmatic source component of the Rolesville batholith which intrudes the Raleigh terrane. There is no evidence in the current zircon data to suggest the presence of juvenile Grenville components or Laurentian crust. A similar conclusion was reached by Horton and Stern (1994).

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## THE RALEIGH GRAPHITE SCHIST

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### ABSTRACT

The Raleigh graphite schist, of probable Neoproterozoic age, is a distinctive marker unit that occurs along the western flank of the Raleigh metamorphic belt. Geologic mapping indicates that the graphite schist is exposed on both sides of the projected trace of the Alleghanian Nutbush Creek fault zone with little or no apparent offset. The results of stable carbon isotope analyses are consistent with the hypothesis that samples from both sides of the fault were derived from the same protolith, and that differences in their  $\delta^{13}\text{C}$  values are due to differences in metamorphic temperatures. The carbon is present as crystalline graphite and is of organic origin as confirmed by carbon isotope ratios.

### INTRODUCTION

A distinctive graphite schist along the western flank of the Raleigh metamorphic belt, as mapped by Parker (1979), occurs west of, and extends for some 50 kilometers in the vicinity of Raleigh, North Carolina. In the 19th, and into the early 20th century, the schist was mined for graphite on a modest scale (Parker, 1979). Old mine workings are still encountered occasionally during construction activities in west Raleigh, although most shafts and adits have been filled in or covered up by urban development. The schist is an easily recognized marker unit in a region of complex faulting, folding, and metamorphism, and for this reason alone is deserving of detailed study.

However, there are other important regional problems that further study of the graphite schist will address. First, geologic mapping currently available for the area shows a major discrepancy that needs to be resolved. As shown on the map by Parker (1979), the graphite schist occurs on both sides of the later mapped Alleghanian Nutbush Creek fault zone without apparent offset. According to Druhan and oth-

ers (1988 and this guidebook), the Nutbush Creek fault zone is a regional-scale tectonic feature having up to 160 km of dextral offset. However, if Parker's earlier mapping is even approximately correct, it imposes a severe constraint on the permissible magnitude of fault displacement (Druhan and others, this guidebook). Detailed geologic mapping underway in southern and central Wake County should clarify these relationships. A second major problem concerns the origin of the graphite schist. If its protolith and depositional environment are determined, it will shed light on the tectonic setting of the Crabtree terrane in which it occurs, and perhaps also on its age. This in turn would have important implications for the timing of some of the regional-scale tectonic events on the western flank of the Raleigh metamorphic belt.

### GEOLOGIC SETTING

The western flank of the Raleigh metamorphic belt (Figure 1) includes the Falls Lake melange, the Raleigh terrane, the eastern edge of the Carolina terrane, the southwestern terminus of the Eastern slate belt, and the Crabtree terrane (Stoddard and others, 1991; Horton and others, 1992, this guidebook). Important structural elements, in addition to the Nutbush Creek fault zone, include the Falls Lake thrust, an unnamed thrust fault that separates the Falls Lake melange from the structurally higher Carolina terrane, and possibly another thrust fault separating the Eastern slate belt from the Raleigh terrane (Farrar, 1985; Stoddard and others, 1991, this guidebook; Horton and others, 1992, this guidebook; Druhan and others, 1988, this guidebook).

The Nutbush Creek fault zone was initially identified partly on the basis of a positive linear aeromagnetic anomaly (Casadevall, 1977; Hatcher and others, 1977). As described by Druhan and others in this guidebook, the anomaly is traceable continuously from the type locality of the fault

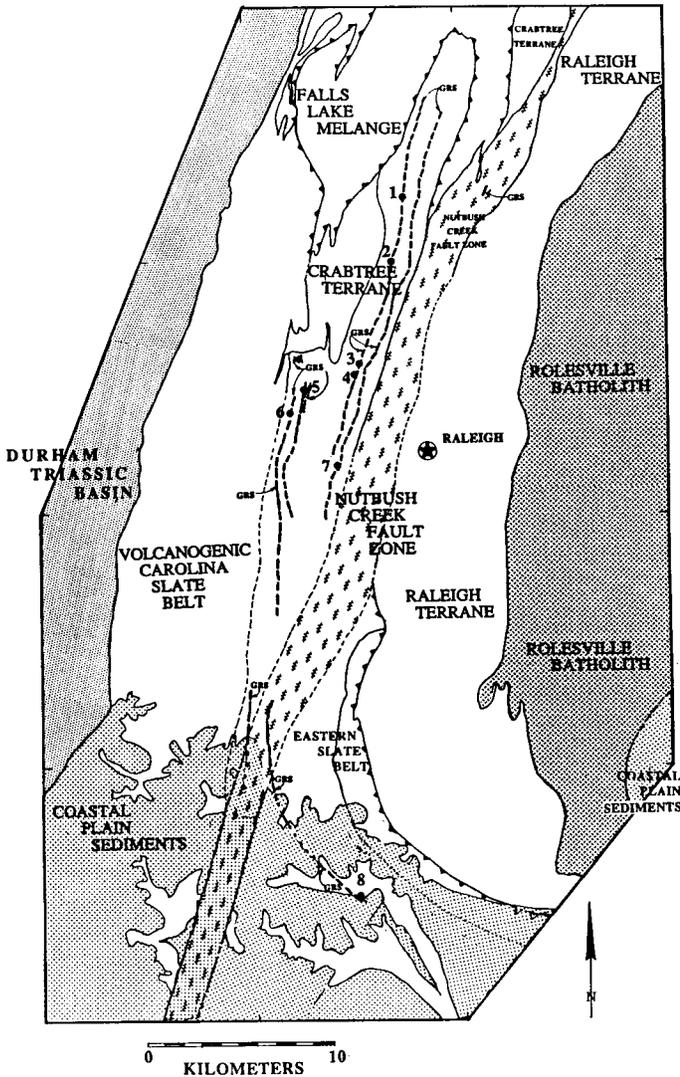


Figure 1. Simplified geologic map of a portion of the western flank of the Raleigh metamorphic belt in Wake County from the mapping of Parker (1979), Druhan and others (1988 and this guidebook), Blake (1993), Butler (1994), Carpenter (1990), Horton and others (1992), and Wylie (1984). Mapped zones of graphite schist (GRS) indicated by the heavy dashed lines. Sample locations referred to in the text and tables are indicated by large numbered dots. In the south, selected geologic features, including the Nutbush Creek fault zone and the graphite schist, are projected beneath Coastal Plain cover. The regions labelled, "Volcanogenic Carolina slate belt" and "Eastern slate belt" belong, respectively, to the Carolina terrane and the Spring Hope terrane (Horton and others, 1991).

zone near the North Carolina-Virginia border southward to central Wake County where it seems to widen, step westward, or bifurcate (Blake, 1993; Blake and Stoddard, 1993; Blake, this guidebook; Butler, this guidebook). The Nutbush Creek fault zone in this region is a zone of highly strained rocks, dominantly of leucogranitic composition. It is characterized in large part by a L>S tectonite fabric and a sub-verti-

cal foliation. The lineation is a subhorizontal, N15-20°E-trending mineral extension lineation (Parker, 1979; Farrar, 1985; Blake, 1986; Druhan and others, 1988; Horton and others, 1992).

### STRUCTURE, STRATIGRAPHY, AND PETROGRAPHY

The graphite schist occurs as at least four major, approximately parallel zones, and numerous thin discontinuous layers. The zones range from 3 to 55 meters thick. It is not known with certainty how many individual stratigraphic horizons are represented, or if they are repeated by folding or faulting. Parker (1979) inferred the repetition of two major horizons to help define the Raleigh antiform. West of the Nutbush Creek fault zone, the graphite schist is interlayered with felsic gneisses and mica schists of the Crabtree terrane (Figure 1) (Parker, 1979; Blake, 1993). In northern Wake County, near Falls Lake, the graphite schist approaches and appears to be truncated by the Falls Lake thrust (Stoddard and others, 1986; Horton and others, 1992). A single occurrence of graphite schist from within the Nutbush Creek fault zone in northern Wake County was reported by Wylie (1984). East of the Nutbush Creek fault zone in southern Wake County, where outcrop is not as good, the graphite schist is part of a phyllite-rich sequence of the volcanogenic Eastern slate belt (Parker, 1979; Carpenter, 1990; Butler, 1994; Wilson and Carpenter, geologic mapping in progress), and appears to sweep northwestward into and across the projected trace of the Nutbush Creek fault zone (Druhan and others, 1988, this guidebook).

Although Parker (1979) reported the black carbonaceous material in these schists as "amorphous graphite," X-ray diffraction analyses on acid-treated samples show well-defined peaks corresponding to crystalline graphite (Figure

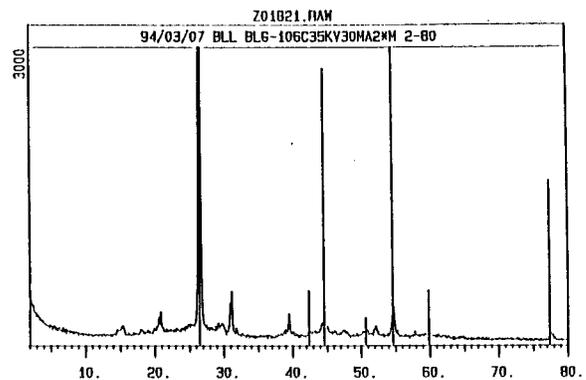


Figure 2. X-ray diffraction pattern acquired from acid-treated sample of graphite schist (Figure 1, locality 1). Vertical lines superimposed on the pattern indicate locations of graphite peaks from the JCPDS file. Extraneous peaks are from incompletely dissolved residue.

## RALEIGH GRAPHITE

Table 1. Mineral assemblages of graphite schist and associated rocks.

<b>Localities</b>	<b>Mineral assemblages</b>
<b>Panther Lake</b> 8	<b>Qtz + Ms + Grp + Grt + Ctd + Chl</b> <b>Ms + Grp + Grt + Tml</b>
<b>West Raleigh</b> 3-7	<b>Ms + Qtz + Grp + Str + Grt ± Ky ± Opq</b> <b>Grp + Ms + Str + Grt</b> <b>Grt + Qtz + Grp</b> <b>Ms + Grp + Qtz + Grt + Str + Bt</b> <b>Qtz + Ms + Grp + Str + Grt</b> <b>+ Bt/Chl ± Tml, Opq</b>
<b>Northwest Raleigh</b> 2	<b>Ms + Grp + Qtz ± Grt, Str, Ky</b> <b>Ms + Qtz + Grt + Grp + Str + Bt + Tml + Opq</b> <b>Grp + Ms + Str + Grt + Tml</b>
<b>Bayleaf</b> 1	<b>Qtz + Ms + Bt + Ky + Str + Grp</b> <b>Qtz + Ms + Grp + Grt + Str + Ky ± Tml</b> <b>Grp + Ms</b>

**Qtz:** quartz; **Ms:** white mica; **Grp:** graphite; **Grt:** garnet; **Ctd:** chloritoid; **Chl:** chlorite; **Tml:** tourmaline; **Str:** staurolite; **Ky:** kyanite; **Opq:** unidentified opaque mineral, possibly ilmenite; **Bt:** biotite

2). This is reasonable in view of the metamorphic temperatures of at least 450°-500°C implied by the staurolite-kyanite zone metamorphism (Parker, 1979; Landis, 1971; Ono, 1972; Grew, 1974; Buseck and Bo-Jun, 1985).

Rocks from other regions called *graphitic* schist typically contain less than two volume percent graphite. In Wake County, the percentage of graphite varies within, and among the zones, from several percent, to above 40%. Because this rock contains so much graphite, it is appropriately referred to as *graphite* schist. Though graphite is abundant in some rocks, its abundance may be overestimated in other rocks where it is finely disseminated in a matrix of white mica. In both hand specimens and thin sections, garnet porphyroblasts commonly have undergone alteration to iron oxides or hydroxides as a result of weathering.

Table 1 lists mineral assemblages of samples of the graphite schist and associated rocks, and Figure 3 shows photomicrographs of thin sections of the graphite schist. The graphite-bearing rocks include several types. One is pelitic schist, rich in quartz and white mica, and containing only two or three modal percent graphite. Such rocks may contain staurolite, garnet, and/or kyanite, but have little or no biotite. As graphite increases in abundance to 10-15%, and quartz decreases, staurolite increases so that some rocks contain as much as 20 modal percent staurolite. Tourmaline is common, while plagioclase has not been identified in these rocks. Besides graphite, other opaque minerals identified include minor pyrite and ilmenite, which seem to increase in graphite-poor samples, and minor rutile. Microstructures include common helicitic texture in staurolite porphyroblasts (Figure 3a), where growth of staurolite occurred post-kinematically.

Kyanite locally is oriented along late cleavage directions (Figure 3b). Garnet, and especially staurolite, have numerous inclusions of graphite. By contrast, kyanite is relatively free of graphite inclusions (Figure 3b). Locally, there is a distinctive rock type associated with the graphite schist which consists of only abundant garnet, staurolite, graphite, and quartz (Figure 3c). At the southern end of the belt, the graphitic rocks are at lower metamorphic grade, as evidenced by the presence of chloritoid and chlorite and the lack of staurolite and kyanite (Figure 3d).

### CARBON ISOTOPES

Analysis of the stable carbon isotopes was undertaken in an effort to place constraints on both the origin and significance of the graphite. First, if the graphite samples occurring on both sides of the Nutbush Creek fault zone represent the same stratigraphic horizon, then their <sup>13</sup>C/<sup>12</sup>C ratios should be the same. If these ratios, expressed as δ<sup>13</sup>C values, differ from horizon to horizon, then they might prove to be an excellent tool for stratigraphic correlation, or they might reveal how many separate horizons exist. This in turn would have implications for the structural geology of the region. Finally, the carbon isotope ratios should help to explain the nature of the protolith of the graphitic carbon.

Table 2 shows results of the isotopic analyses (as well as analyses of bulk weight percent carbon). δ<sup>13</sup>C values range from -22 per mil in the southeast on the east side of the fault (Figure 1, location 8), to -15 per mil to the north and northeast on the west side of the fault (Figure 1, locations 1-7). This shows an enrichment in <sup>13</sup>C clockwise from the southeast to the northeast.

The metamorphic grade is higher to the west and north (Parker, 1979). One explanation for the differences in these isotopic ratios is that the lighter isotope, <sup>12</sup>C, was preferentially lost with methane-producing metamorphic devolatilization reactions as temperature increased (Abelson, 1978; Large and others, 1994). This hypothesis needs to be tested further on the graphite west and south of Raleigh, but in other field studies, a direct relationship has been shown between <sup>13</sup>C enrichment and increasing metamorphic grade (McKirdy and Powell, 1974; Dissanayake, 1981; Large and

Table 2. Carbon and carbon isotope analyses.

<b>Location (Figure 1)</b>	<b>Weight % Carbon</b>	<b>δ<sup>13</sup>C (‰)</b>
1	39.9-40.1	-15.3
2	22.2	-18.9
3	9.4	-16.3
4	8.0	-16.6
5	18.1-20.1	-18.0
6	0.8-1.2	-17.6
7	13.1	-18.7
8	1.7-3.3	-22.2

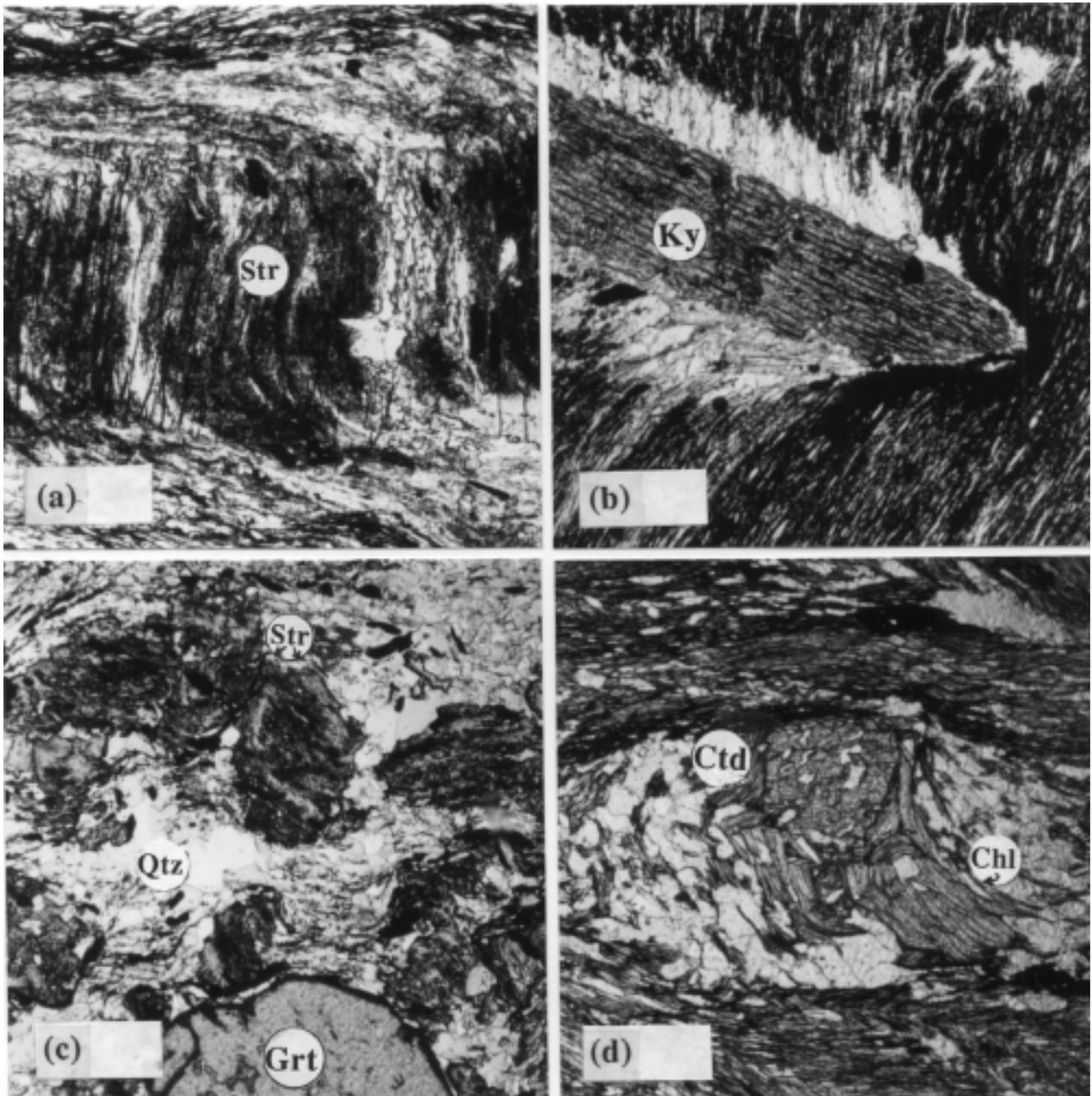


Figure 3. Selected photomicrographs from thin sections of graphite schist. Plane-polarized light; long dimension of white rectangle represents 0.5 mm in all photographs. Photographs contain mineral labels as follows: staurolite, Str; garnet, Grt; quartz, Qtz; chloritoid, Ctd; chlorite, Chl; kyanite, Ky.

(a) Syn- to post-kinematic staurolite porphyroblast with helicitic inclusion trails of graphite defining an early fold. West Raleigh, 1.8 km S21°W from Locality 7, Figure 1. (b) Kyanite porphyroblast which transects schistosity defined by graphite and white mica. Kyanite lies along weak cleavage direction. Northwest Raleigh, 1.2 km N05°E from Locality 2, Figure 1. (c) Mica-poor rock consisting of garnet, staurolite, quartz, and graphite. West Raleigh, 1.25 km S20°W from Locality 7, Figure 1. (d) Phyllite, rich in white mica and quartz, and containing chloritoid porphyroblast, chlorite flakes, and isolated lenticular grains of graphite. Locality 8, Figure 1.

others, 1994).

The observation that  $^{13}\text{C}$  enrichment occurs with increasing metamorphic grade suggests that all the graphite zones may have had similar original  $^{13}\text{C}/^{12}\text{C}$  ratios and a common protolith. Indeed, although the possibility that the differences in  $\delta^{13}\text{C}$  are due to different protoliths cannot be ruled out, the variation seen in the isotope ratios is consistent with a single source. Both petrographic and isotopic data are compatible with either a discontinuous or continuous increase in metamorphic temperatures from the southeast to the northwest across the Nutbush Creek fault zone.

The isotope studies also suggest that the original carbon material was in the form of biologically produced organic matter (Hahn-Weinheimer and Hirner, 1981; Weis and others, 1981). Because of the preferential evolution of the light isotope ( $^{12}\text{C}$ ) during diagenesis and metamorphism, the  $\delta^{13}\text{C}$  value of -22 per mil is a maximum, and the original ratio must have been more negative. Such highly negative ratios are typically found in organic carbon (Strauss and others, 1992; Schidlowski and others, 1983). An organic origin for the carbon is also suggested by the absence of carbonate minerals and the occurrence of rocks having up to 40% carbon that was certainly greater in abundance prior to metamorphism.

If the Crabtree Creek pluton crosscuts the graphite schist in west Raleigh, as indicated by Blake (this guidebook), and if the Neoproterozoic age (544 Ma or older) of the pluton suggested by  $^{207}\text{Pb}/^{206}\text{Pb}$  ages on zircons independently determined by Horton and Wright (1994) and Goldberg (this guidebook) are correct, then the graphite must have a minimum age that is Neoproterozoic, and therefore is likely algal in origin (*e.g.* Schidlowski and others, 1983).

## CONCLUSIONS

The carbonaceous material in the Raleigh graphite is crystalline graphite. The carbon is of organic origin, as suggested by its association with layered rocks of the Crabtree terrane and confirmed by carbon isotope ratios. Because the graphite schist is cut by a pluton that is dated at 544 Ma or older, the carbon is probably algal in origin. Though there is considerable spread in measured  $\delta^{13}\text{C}$  values, they are consistent with the hypothesis that all samples initially had the same low ratio, with their present differences attributed to differences in conditions of metamorphism. Given Parker's (1979) mapping of the graphite schist in southern Wake County, and the projected trace and boundaries of the Nutbush Creek fault zone suggested by Druhan and others (1988 and this guidebook), there is little or no horizontal separation across the fault zone. Alternatively, the ductile strain associated with the Nutbush Creek fault zone may be distributed over a wider area, so that the graphite may be viewed as sweeping into the high-strain zone from the southeast, and becoming transposed into the fault zone orientation. In this

model, all exposures of graphite schist, except for those in the extreme southeast, lie within regions of ductile shear associated with the Nutbush Creek fault zone.

## ANALYTICAL TECHNIQUES

The graphite schist samples were prepared by hand grinding them to a fine powder using a mortar and pestle. For X-ray diffraction analysis, the powdered samples were soaked overnight one or more times in concentrated (48-50%) HF to dissolve the silicate minerals. Though this procedure was successful in concentrating the graphite, some insoluble residue remained for all samples. The carbon contents of untreated powdered samples were determined as the graphitic carbon was combusted to  $\text{CO}_2$  for isotopic analysis using a modified Carlo Erba 1108 C-N-S analyzer (Blair and Carter, 1992). The  $^{13}\text{C}/^{12}\text{C}$  of the  $\text{CO}_2$  was measured on a modified Finnegan MAT Delta E isotope ratio mass spectrometer (Hayes and others, 1977) and is reported as  $\delta^{13}\text{C}$  where  $\delta^{13}\text{C} = [({}^{13}\text{C}/^{12}\text{C})_{\text{sample}} - ({}^{13}\text{C}/^{12}\text{C})_{\text{PDB}}] / ({}^{13}\text{C}/^{12}\text{C})_{\text{PDB}} \times 10^3$ ; given  $({}^{13}\text{C}/^{12}\text{C})_{\text{PDB}} = 0.0112372$ . Both instruments are located in the lab of Neal Blair at North Carolina State University. A graphite standard RM 8541 (USGS-24), with a  $\delta^{13}\text{C}_{\text{VPDM}}$  of  $-15.9 \text{‰} \pm 0.25$ , was used as a reference. Replicate analyses of this standard using the procedure described above in the NCSU lab yielded a value of  $-15.7083 \pm 0.060$ .

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## INTRUSIVE AND DEFORMATIONAL RELATIONSHIPS OF THE CRABTREE CREEK PLUTON IN WEST RALEIGH

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### ABSTRACT

In the northern half of the Raleigh West quadrangle, North Carolina, metamorphic rocks of the volcanogenic Carolina terrane and the Crabtree terrane are separated by a 3 km-wide body of felsic gneiss. The gneiss is a deformed leucogranite to granite, herein referred to as the Crabtree Creek pluton, rather than a clastic metasedimentary rock as previously defined. Plutonic contacts which cut wall rock units of the Carolina terrane and Crabtree terrane, and preservation of relict igneous textures provide evidence for an intrusive origin for the gneiss. The Crabtree Creek pluton is believed to be an intrusion that stitched the two terranes together. The pluton has two mappable facies. The western facies is a foliated leucogranitic orthogneiss; the eastern facies is a foliated to lineated granitic orthogneiss having porphyroclastic disks or rods of quartz. Planar and linear fabrics in the pluton and wall rocks appear to have developed during at least two deformational pulses  $D_2$  and  $D_3$  accompanying an Alleghanian  $M_2$  metamorphism along this segment of the western flank of the Raleigh metamorphic belt. Evidence for  $D_2$  is best preserved in the western facies of the Crabtree Creek pluton and in Carolina terrane and western Crabtree terrane wall rocks.  $D_2$  mineral textures and  $M_2$  mineral assemblages in the pluton and wall rocks are progressively deformed eastward across the quadrangle by  $D_3$  upright, open folds; discontinuous, mesoscopic shear zones; and the right-lateral Nutbush Creek fault zone.  $D_3$  shearing resulted in a mineral stretching lineation that overprints pre-existing fabrics in the discontinuous shear zones and most of the north-central and northeastern parts of the quadrangle. Based upon geometric and kinematic criteria, both oblique and subhorizontal, right-lateral shear are believed to be associated with Alleghanian faulting. In addition, the Nutbush Creek fault zone appears to have affected a wider zone of rocks in west Raleigh than observed elsewhere on the western flank of the Raleigh metamorphic belt.

### INTRODUCTION

This paper documents observations from recent geologic mapping in the northern half of the Raleigh West 7.5' quadrangle in the eastern Piedmont of North Carolina. The mapping was conducted as a part of the North Carolina Geo-

logic Survey STATEMAP project in the Raleigh 1:100,000 sheet. It is also a part of a research agenda to delineate lithologic and structural relationships along the Raleigh segment of the western flank of the Raleigh metamorphic belt, a region of rocks subjected to greenschist to upper-amphibolite facies metamorphism, upright, open folding, and right-lateral shearing along the Nutbush Creek fault zone during the Alleghanian orogeny (Casadevall, 1977; Parker, 1979; Russell and others, 1985; Druhan, 1983; Druhan and others, 1988; Stoddard and others, 1991). Both the Alleghanian metamorphism and deformation affect an assemblage of tectonostratigraphic terranes and overprint pre-metamorphic structural and stratigraphic contacts (Figure 1; Stoddard and others, 1991).

Between 1981 and 1991, detailed geologic mapping on the western flank of the Raleigh metamorphic belt was concentrated on crystalline rocks in northwest Raleigh in the area surrounding Falls Lake State Park (Figure 2). Graduate research by Wylie (1984) and Blake (1986) was combined with unpublished mapping by J. W. Horton, Jr. and E. F. Stoddard to produce a geologic map of the Falls Lake-Wake Forest area (Horton and others, 1991, 1992). A product of this mapping and earlier studies (*e.g.*, Fortson, 1958; Parker, 1968, 1979; Carpenter, 1970; Casadevall, 1977; Moye, 1981; Druhan, 1983; Farrar, 1985; Horton and others, 1986) is the geologic framework which is currently being used to guide studies of the petrologic, structural, and tectonic evolution of the western flank of the Raleigh metamorphic belt. Separate articles in this guidebook by Horton and others and Stoddard and others discuss lithologic units, tectonostratigraphic terranes, and regional fault relationships in the Falls Lake-Wake Forest area; Druhan and others discuss the Nutbush Creek fault zone along the length of the western flank of the Raleigh metamorphic belt in North Carolina and Virginia.

### GEOLOGY OF THE CRABTREE CREEK PLUTON

Unpublished geologic mapping in the west Raleigh segment of the western flank by Blake between 1992 and 1994 has been used to refine the lithostratigraphy of Parker (1979) in Wake County and to extend the tectonostratigraphic terranes delineated by Horton and others (1986, 1991, 1992) in the Falls Lake-Wake Forest area southward into the west

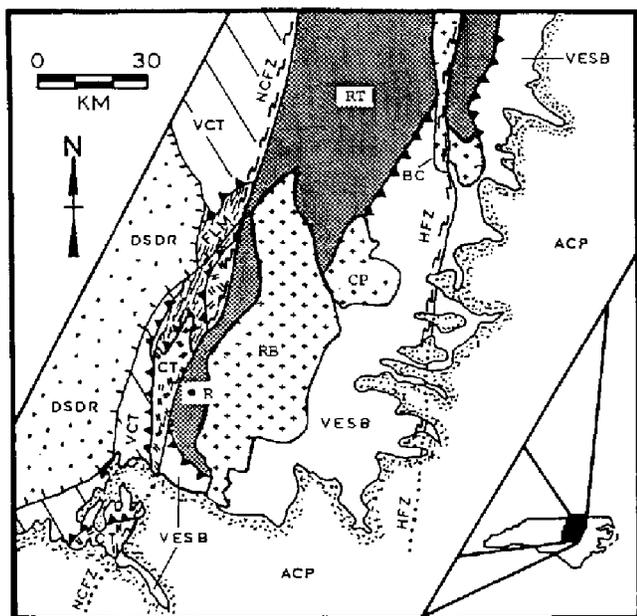


Figure 1. Generalized pre-Mesozoic terrane map of the eastern Piedmont of North Carolina. Lithotectonic terranes include the volcanogenic Carolina terrane (VCT), the volcanogenic Eastern slate belt (VESB), the Falls Lake mélangé (FLM), the Crabtree terrane (CT), and the Raleigh terrane (RT).  $D_2$  thrust faults (hachured lines) separate the Raleigh terrane from the volcanogenic terranes. The  $D_2$  Falls Lake thrust separates the Falls Lake mélangé and Crabtree terrane.  $D_3$  (Carboniferous-Permian) right-lateral zones are the Nutbush Creek fault zone (NCFZ) and the Hollister fault zone (HFZ). Late Paleozoic plutons are the Roleville batholith (RB), the Castalia pluton (CP), and the Butterwood Creek pluton (BC). Mesozoic sedimentary rocks occur in the Durham sub-basin of the Late Triassic Deep River Basin (DSDR). Parts of the Eastern slate belt, Crabtree terrane, and Carolina terrane are covered by sedimentary rocks of the Cenozoic Atlantic Coastal Plain (ACP). The position of downtown Raleigh is indicated by the capital R. Figure modified from Stoddard and others (1991).

Raleigh-Cary area (Figure 2). From west to east across the northern half of the Raleigh West quadrangle, only the easternmost part of the volcanogenic Carolina terrane of Secor and others (1983) and Horton and others (1989), and the Crabtree terrane and Raleigh terrane of Horton and others (1992) crop out. The Falls Lake mélangé of Horton and others (1986) is not exposed. Instead, a large body of felsic gneiss occupies the same relative position as the mélangé (Blake and Stoddard, 1993). The gneiss separates the Cary formation (informal name of Farrar, 1985, for metamorphic rocks of the easternmost part of the Carolina terrane in this area) from the Crabtree terrane. This mapping of metamorphic rocks in the northern Raleigh West quadrangle indicates that the felsic gneiss was an intrusive body prior to metamorphism.

The Crabtree Creek pluton, as originally named by Kish

and Campbell (1986), is a leucogranitic to granitic orthogneiss body (Blake and Stoddard, 1993). It consists of two mappable facies. The western facies is a foliated, medium-grained, leucogranitic orthogneiss. It gradationally changes eastward into the eastern facies which is a foliated to lineated, leucocratic, medium- to coarse-grained granitic orthogneiss. This orthogneiss contains abundant porphyroclastic disks or rods of quartz (Figures 3 and 4). Microscale preservation of relict igneous textural relationships occurs in both the leucogranitic and granitic orthogneisses. Dikes and pluton contacts of these rocks crosscut wall rock units of the Cary formation and Crabtree terrane (Blake, 1992-1994 unpublished mapping; Blake and Stoddard, 1993) These relationships are cited as the primary evidence on which the intrusive origin of the gneiss is based. The focus of the discussion below is the intrusive igneous and deformational relationships recorded by the pluton and its wall rocks in the northern half of the Raleigh West quadrangle.

### Wall Rocks

In the northern half of the Raleigh West quadrangle, Cary formation wall rocks consist of a large mafic unit, the Turkey Creek amphibolite body (informally used by Parker, 1979). This body contains undifferentiated amphibolite, hornblende gneiss, hornblende biotite schist, biotite schist, and metapyroxenite and metagabbro that are thought to represent interlayered basalts and volcaniclastic rocks intruded by gabbroic to pyroxenitic dikes (Figure 3). The significance of a small outcrop of chlorite-actinolite-talc schist is not clear. The metamorphic assemblage of blue-green hornblende + oligoclase  $\pm$  garnet in amphibolitic wall rocks of the Turkey Creek body suggests that both these rocks and the western facies of the pluton achieved lower amphibolite facies conditions during regional metamorphism. The mafic unit is also complexly intruded by a large body of metamorphosed quartz monzonite and subordinate dikes of the metamorphosed equivalent of diorite, trondhjemite to tonalite, and granodiorite to quartz monzonite (informally named Reedy Creek adamellite lens and sills of Parker, 1979). Both the large body and dikes are variably deformed.

Crabtree terrane wall rocks consist of metasedimentary and metavolcanic garnet  $\pm$  staurolite two-mica schist; fine-grained biotite or white mica schist; felsic gneiss; garnet-staurolite-graphite schist and white mica-graphite schist; interlayered, lineated felsic white mica or biotite  $\pm$  garnet gneiss and schist; and lineated biotite  $\pm$  kyanite  $\pm$  garnet schist (Figure 3). Lineated felsic gneiss at the eastern boundary of the Crabtree terrane is equivalent to the Falls leucogneiss of Horton and others (1992). The metamorphic assemblage of garnet  $\pm$  staurolite  $\pm$  kyanite in schist and gneiss wall rocks of the Crabtree terrane suggests that the eastern facies of the pluton and the Crabtree terrane achieved middle amphibolite facies conditions during regional metamorphism.

## CRABTREE CREEK PLUTON

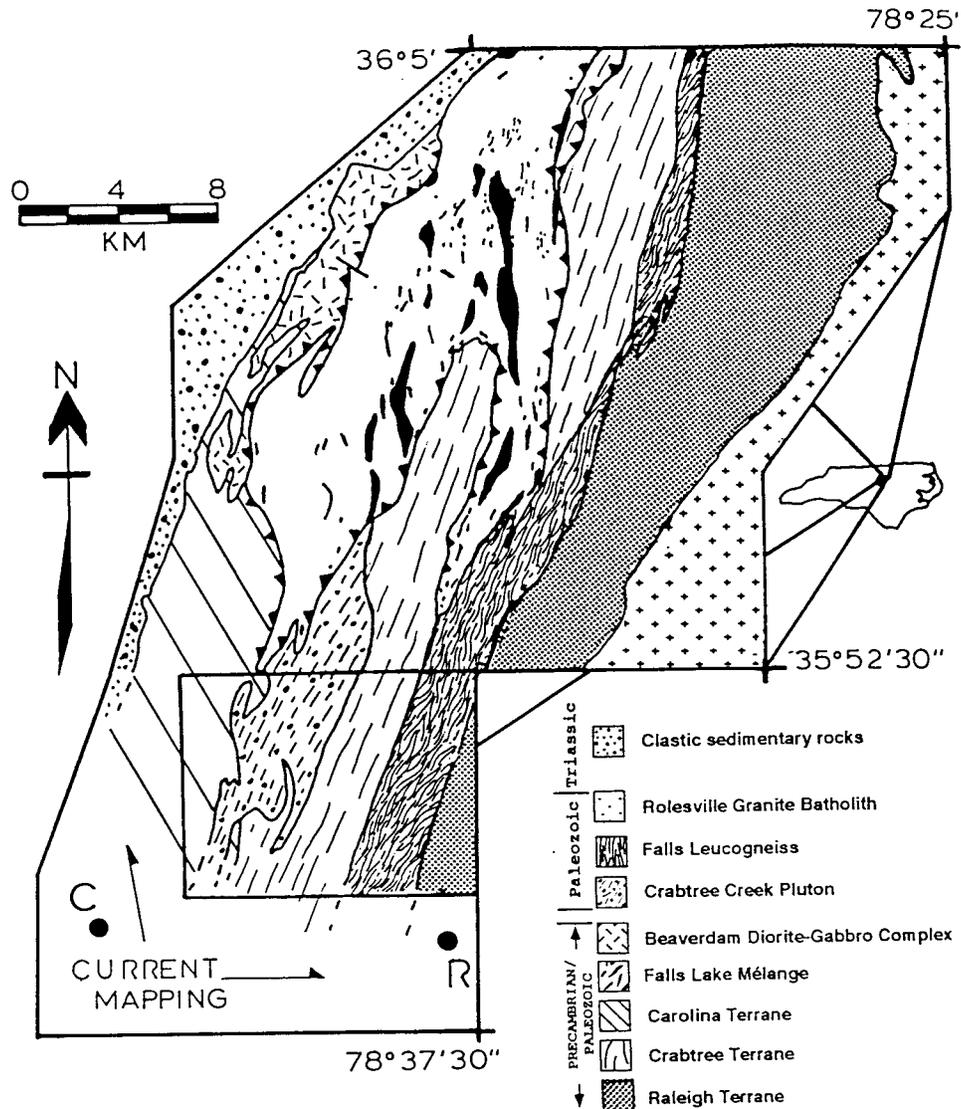


Figure 2. Crystalline terrane map of the western flank of the Raleigh metamorphic belt in the Falls Lake-west Raleigh area compiled from Horton and others (1992) and Blake. The capital C and R locate the positions of downtown Cary and Raleigh, North Carolina, respectively. The box outlines the area shown in Figure 3.

### Leucogranitic Orthogneiss

The smaller, western facies of the Crabtree Creek pluton is a very leucocratic (color index = 0-5), medium-grained, white mica-bearing leucogranitic orthogneiss (Figure 3). It is characteristically exposed as boulder fields on hillsides or as resistant outcrops in stream valleys. The western boundary of leucogranitic orthogneiss is marked by dikes up 0.5 km wide that intrude westward from the main body of the pluton into amphibolite and mafic biotite schist of the Turkey Creek amphibolite body (Figure 3 and 5a). The eastern boundary of leucogranitic orthogneiss is marked by a gradational contact with porphyroclastic granitic orthogneiss of the eastern facies of the pluton. This gradational contact is mapped at the first occurrence of orthogneiss outcrops which do not

contain abundant quartz disks and rods. Mesoscopic dikes of leucogranitic orthogneiss have also been observed north of U.S. Highway 70 in the southern Bayleaf quadrangle where they crosscut coarse-grained biotite-muscovite schist believed to be the southernmost exposure of the Falls Lake mélangé.

Most outcrops of orthogneiss are variably deformed by a regional, west-dipping foliation. This foliation is concordant in all layered amphibolite/orthogneiss outcrops observed. The best exposures of weakly deformed and metamorphosed orthogneiss occur in the southwest part of the mapped area. The western facies of the Crabtree Creek pluton also contains several large xenoliths of amphibolite and biotite schist of the Turkey Creek amphibolite body and garnet two-mica schist of the Crabtree terrane.

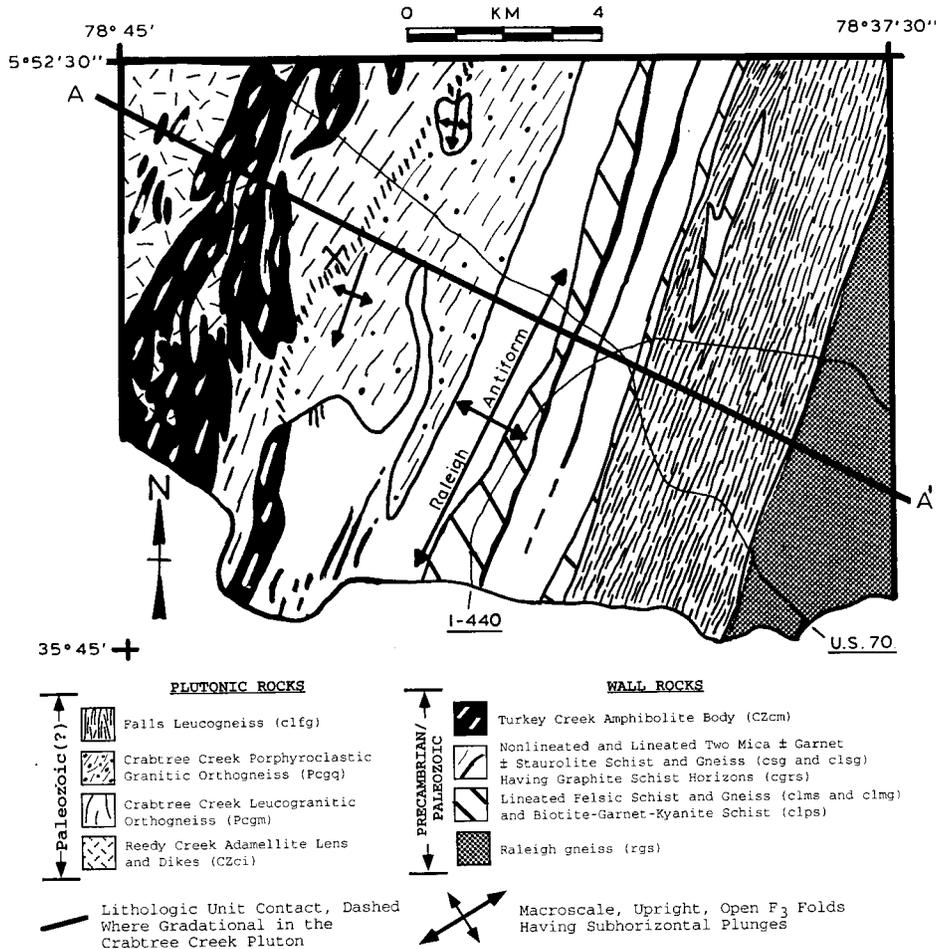


Figure 3. Geologic map of the northern half of the Raleigh West quadrangle, north-central North Carolina, showing the contact relationships between metamorphosed and deformed plutonic rocks and wall rocks of the easternmost Carolina terrane (Cary formation and younger metamorphosed intrusive rocks), the Crabtree Creek pluton, the Crabtree terrane, and the Raleigh terrane. The location of the Crabtree quarry is marked by the X.

Hand samples of weakly deformed leucogranite from the southwestern part of the mapped area display a relict xenomorphic granular to crystalloblastic texture among abundant quartz, K-feldspar, and plagioclase crystals. Average grain size is 5-7 mm. Spaced planes of white mica surround knobby quartz grains and aggregates of quartz, K-feldspar, and plagioclase; the abundance of white mica flakes gives most hand samples a grey-white sheen. Some outcrops display a pink coloration due to an increase in percent of salmon-colored K-feldspar. Locally, biotite and opaque minerals are minor accessory phases.

The relict igneous xenomorphic texture is more apparent at the microscale (Figure 5b). Quartz occurs as polycrystalline aggregates up to 5 mm in length and width. Coarser quartz crystals in large aggregates locally exhibit undulatory extinction, subgrains, and deformation bands. Irregular grain boundaries indicate grain boundary migration. However, no quartz ribbons or sutured grain boundaries are observed in these rocks. Randomly-oriented white mica occurs as coarse

to fine flakes; as discrete selvages in felsic crystal matrix and around larger porphyroclasts of quartz, K-feldspar, or plagioclase; or as polycrystalline masses of small flakes. Randomly-oriented white mica commonly sericitizes plagioclase and less commonly K-feldspar porphyroclasts (Figure 5b). Most of the large sericitized plagioclase crystals exhibit growth twins, and tapered mechanical twins. Microcline occurs as large crystals and polycrystalline aggregates. Where large patches of white mica are locally abundant, plagioclase and microcline show a preference for patchy extinction caused by grain size reduction and formation of an exterior mortar of small, granoblastic feldspar crystals.

Leucogranite in the vicinity of U.S. Highway 70 is more highly strained. The strain increase is indicated by crystalloblastic textures in leucogranitic orthogneiss and local development of composite fabric elements. These orthogneiss outcrops tend to show a more penetrative, closely-spaced, west-dipping white mica foliation. In the foliation plane, a northwest-plunging mineral lineation marked by elongate

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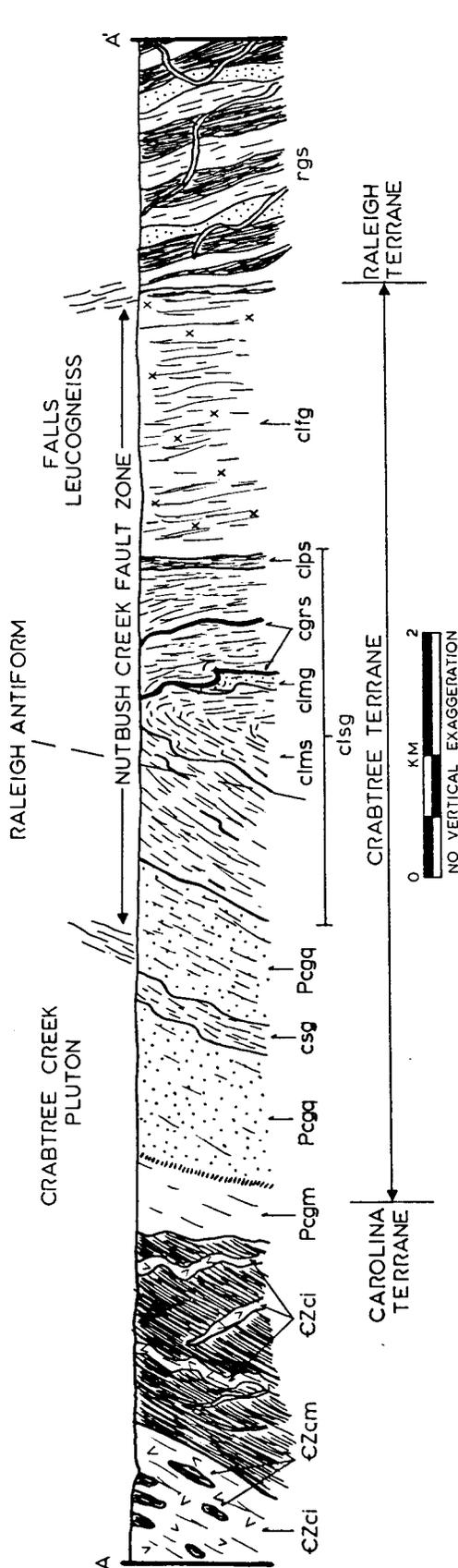


Figure 4. Schematic geologic cross section across the northern half of the Raleigh West quadrangle. The cross section is oriented subparallel to the trace of U.S. 70 and I-440, as shown in Figure 3.

patches of white mica, and quartz and feldspar aggregates is locally weakly developed. Polycrystalline quartz tends to form elongate domains having a 2:1 to 3:1 aspect ratios. Between the domains, microcline and plagioclase are riddled with white mica and small, polygonal granoblastic crystals of feldspar (Figure 5c). Grain size reduction of feldspar porphyroclasts and some quartz aggregates suggest dynamic recrystallization. Larger areas in the matrix, originally porphyroclasts, are marked by the optical continuity of twins in small crystals.

Discontinuous shear zones, up to meters thick, having protomylonitic to phyllonitic dynamic recrystallization textures, shear bands that overprint the regional foliation, and sigma-style quartz augen are also observed (Figure 5d; *e.g.* Simpson and Schmid, 1986). Penetrative strain and subparallel orientations of shear bands and regional foliation produce a thin fissility and schistosity. The mineral lineation is best developed in these shear zones where it plunges obliquely down-dip to the NW in the schistosity. In the phyllonites, polygonal granoblastic quartz domains oriented subparallel to mica fish crosscut larger quartz augen, suggesting syntectonic recrystallization of the quartz augen. Sigmoidal mica fish asymmetry (*e.g.* Lister and Snoke, 1987), shear band shear sense, and the sigma-style quartz augen asymmetry in the phyllonite and associated protomylonite indicate an oblique, tops-to-the NW shear sense in the west-dipping shear zones (Figures 5e and 5f).

Randomly-oriented, large white mica porphyroclasts and large domains of quartz and feldspar crystals having triple junction grain boundary texture suggests local post-tectonic metamorphic mineral growth and annealing of strain textures in leucocratic orthogneiss.

### Porphyroclastic Granitic Orthogneiss

The eastern facies of the Crabtree Creek pluton consists of a leucocratic (color index = 5-10), medium- to coarse-grained, porphyroclastic granitic orthogneiss. The abundance of disk- to rod-shaped quartz porphyroclasts is diagnostic of this main facies of the pluton (Figures 6a and 6b). Cliff outcrops of porphyroclastic granitic orthogneiss are common along most streams in the north-central Raleigh West quadrangle. Sapolite cutbanks in the pluton are distinguished by the abundance of the quartz disks or rods projecting subhorizontally outward from stream banks. In areas lacking outcrop, quartz porphyroclasts are common in the soil profile.

Coarse-grained quartz and finer-grained K-feldspar, plagioclase, and white mica define a crystalloblastic texture in hand samples of this foliated to lineated orthogneiss. Due to variations in the relative abundances of felsic minerals and white mica, the orthogneiss is greenish-gray to pink in color. Accessory phases in the orthogneiss include tourmaline, biotite, epidote, calcite, garnet, zircon, apatite, and magne-

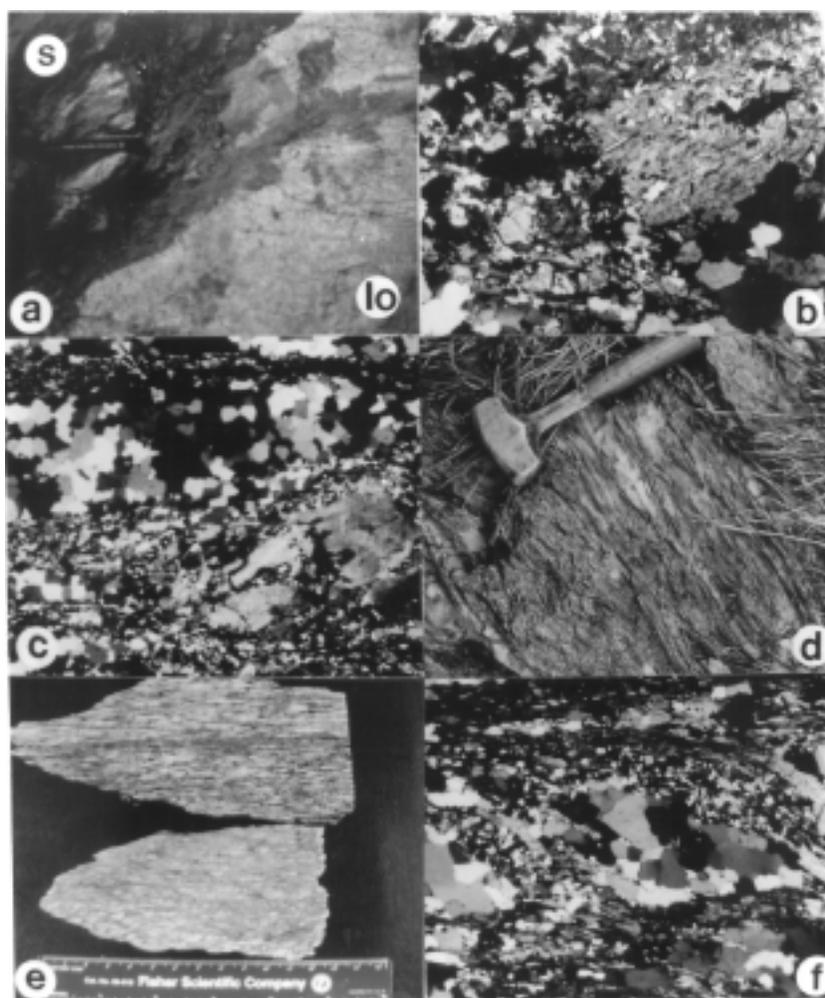


Figure 5. (a) Dike of leucogranitic orthogneiss (lo) intruding biotite schist saprolite (s) of the Turkey Creek amphibolite body along U.S. 70. View to the north. Ruler is 15 cm long. (b-c) Photomicrographs of weakly deformed to more penetratively deformed xenomorphic granular texture in leucogranitic orthogneiss. Note the sericitization of the plagioclase crystal in (b), and the mortar texture of feldspar and the polycrystalline quartz porphyroclast in (c). Width of view of the photomicrographs is 5 mm in cross polarized light. (d) Discontinuous, mesoscopic protomylonitic shear zone cutting  $S_2$  foliation in leucogranitic orthogneiss across from Raleigh Memorial Park on U.S. 70. The 28 cm hammer marks the thickness of the shear zone. View to the south. (e) Hand samples of leucogranitic protomylonite (upper) from the shear zone in (d) and phyllonite (lower) from an adjacent shear zone. Note the regional  $S_2$  foliation cut by shear bands in the upper sample and the quartz augen in a white mica foliation in the lower sample. Both samples show tops to the right (NW) shear sense. Ruler is 15 cm long. (f) Photomicrograph of quartz augen and sigmoidal mica fish from the lower hand sample of (e) showing tops to the left (NW) shear sense. Width of view is 5 mm, in cross polarized light.

tite. Quartz veins in the Crabtree quarry (Teer Aggregates) are reported to contain pyrite, galena, and chalcopyrite, and rare antimony and bismuth minerals including tetrahedrite, bismuthinite, kobellite, jamesonite, cosalite, and aikinite (Parker, 1979). The rare antimony and bismuth minerals have not been observed at the mine for several years (James Izzell, personal communication, 1992).

The porphyroclastic granitic orthogneiss is best exposed in the walls of the Crabtree quarry where it is being mined for crushed stone (Figure 3). Much of the landscape stone and culvert rip-rap in west Raleigh are mined at the quarry. The gradational contact between leucogranitic orthogneiss to

the west and porphyroclastic granitic gneiss to the east can also be observed in the northwest wall of the Crabtree quarry where leucogranitic orthogneiss grades eastward into porphyroclastic granitic orthogneiss containing quartz disks. The quarry will be visited on the 1994 Carolina Geological Society field trip.

In the south-central part of the mapped area, the porphyroclastic granitic orthogneiss contact obliquely truncates a garnet two-mica schist and several interlayered graphite schist horizons in the western part of the Crabtree terrane. Several mesoscopic to macroscopic dikes of the Crabtree Creek pluton also intrude fine-grained biotite quartzofelds-

## CRABTREE CREEK PLUTON

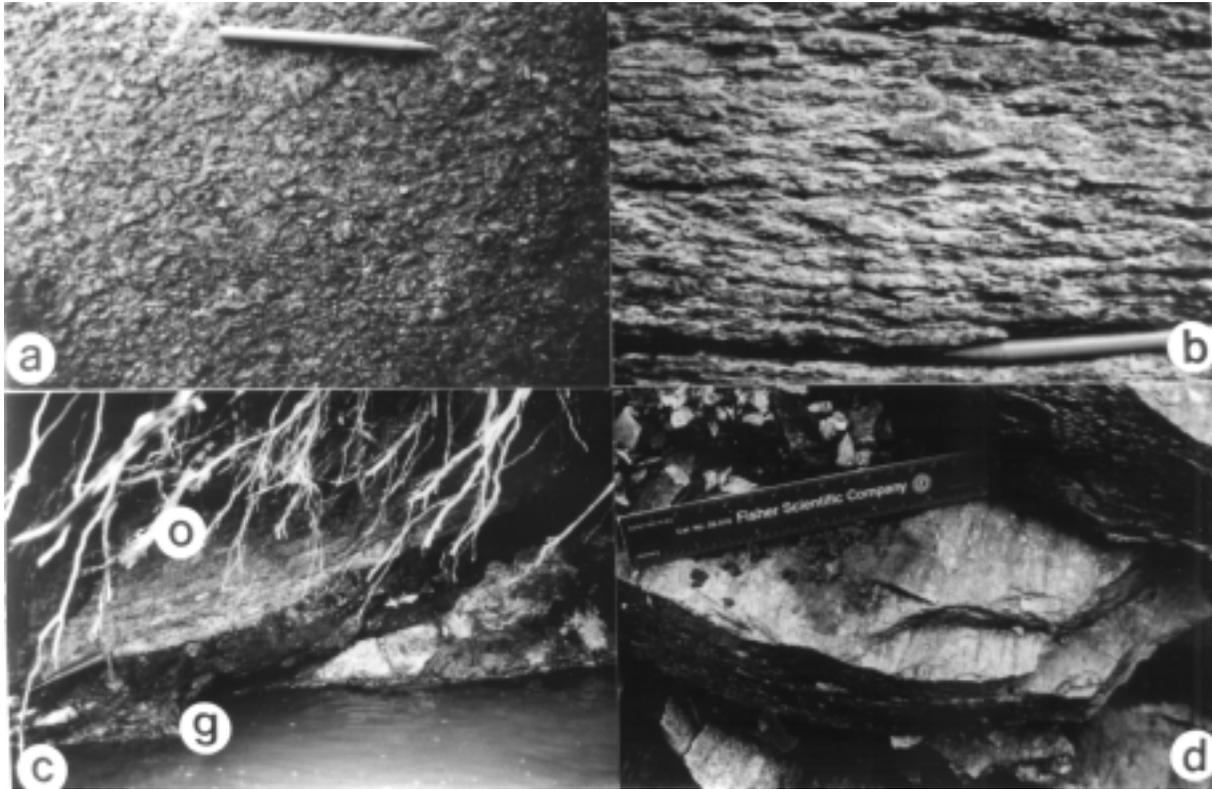


Figure 6. (a) Pavement outcrop of porphyroclastic granitic orthogneiss showing the abundant quartz disks in the  $S_2$  schistosity. The 14 cm long pencil marks the orientation of a weak alignment of quartz disks in the foliation. The matrix is recrystallized K-feldspar and plagioclase (b) Outcrop of quartz disk-bearing porphyroclastic granitic orthogneiss showing the subparallel orientation of the longer axes of the quartz disks and the  $S_2$  schistosity. Pencil is 14 cm long. (a-b) from cliff exposures along Crabtree Creek in the Laurel Hills subdivision of west Raleigh. (c) Stream cut exposing dike relationships of quartz disk-bearing porphyroclastic granitic orthogneiss (o) and biotite gneiss (g) of the western Crabtree terrane. Hammer is 28 cm long. View to the west in the Oak Park subdivision of west Raleigh. (d) Subhorizontal, penetrative  $L_2$  lineation with a  $N14^\circ E$  trend on closely-spaced  $S_2$  foliation planes in quartz rod-bearing porphyroclastic granitic orthogneiss from the east wall of the Crabtree quarry. Lineation is defined by white mica, biotite, quartz-feldspar aggregates, tourmaline prisms, and long axes of quartz rods. View to the southeast. Ruler is 15 cm long.

pathic gneiss of the Crabtree terrane in this area, confirming the intrusive origin of the gneiss (Figure 3 and 6c). West-dipping, regional schistosity in wall rocks and the porphyroclastic granitic orthogneiss are concordant in all outcrops observed along these contacts.

The Crabtree Creek pluton has been traced continuously north to the northern boundary of the Raleigh West quadrangle. The northern termination of the pluton has been mapped in the southern Bayleaf quadrangle (Horton and others, this guidebook). The eastern contact of porphyroclastic granitic orthogneiss grades into fine-grained schists and gneisses of the Crabtree terrane. Locally, the contact appears to be highly sheared. However, due to urbanization, the contact is difficult to trace.

The disks or rods of quartz provide the porphyroclastic granitic orthogneiss with its unique texture. The disks and rods range in size from several mm to 1-2 cm in length and less than 1 cm in width. They typically are aligned in the white mica  $\pm$  biotite regional foliation. Disks define the

quartz morphology on the west side of the porphyroclastic granitic orthogneiss. There they have an approximately 2:1 to 3:1 aspect ratio in sections sliced parallel to the mineral lineation and perpendicular to foliation. Locally, shear bands several centimeters in length overprint the penetrative and closely-spaced white mica schistosity at variable angles. In other mesoscopic exposures, protomylonitic shear zones are developed.

Rod-shaped quartz increases in abundance eastward toward the eastern contact of the porphyroclastic granitic orthogneiss with the Crabtree terrane. There, the orthogneiss is dominated by an  $L>S$  tectonite fabric of rod long axes (Figure 6d). The regional schistosity is strongly overprinted by the lineation. Quartz rod aspect ratios range up to 7:1 in protomylonitic shear zones and the eastern facies of the pluton. In addition, the mineral lineation of quartz rods and white mica flakes has a consistent  $N15^\circ E$  or  $S15^\circ W$  trend and subhorizontal plunge.

At the microscale, disks and rods consist of a polycrys-

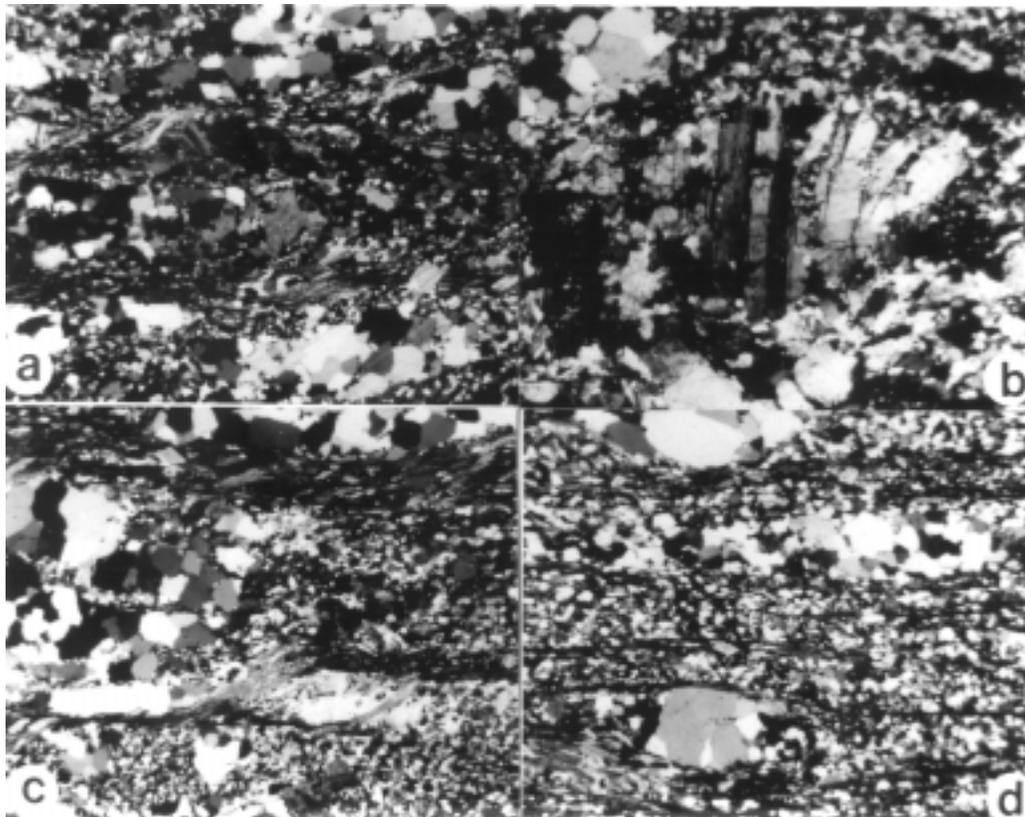


Figure 7. (a-d) Photomicrographs of deformation textures in porphyroclastic granitic orthogneiss to protomylonite. (a-c) show grain size reduction of quartz and feldspar, and polycrystalline quartz disks with undulatory extinction, deformation bands, subgrain development, and curved grain boundaries indicating grain boundary migration. Sigmoidal mica fish surrounding relict feldspar porphyroclasts in (a) and (c) have a tops-to-the right (NW) sense of shear. (d) shows extreme grain size reduction of feldspars with polycrystalline quartz rods remaining as competent porphyroclasts and augen. Width of view of photomicrographs is 5 mm.

talline mosaic of smaller quartz crystals having irregularly-curved to weakly-sutured grain boundaries indicating grain boundary migration. Undulatory extinction, deformation bands, and subgrains are well developed (Figure 7a). Between large polycrystalline domains of quartz, grain size reduction affects a finer-grained microcline, plagioclase, and white mica matrix. Plagioclase and K-feldspar porphyroclasts are locally preserved in rocks showing a less well-developed grain size reduction and penetrative lineation. Plagioclase and K-feldspar exhibit patchy extinction and an exterior mortar of granoblastic feldspar crystals caused by grain size reduction. Relict microcline porphyroclasts are identified by optical continuity of tartan twins in smaller crystals. Randomly-oriented white mica plates sericitize plagioclase and less commonly K-feldspar. Large sericitized plagioclase crystals exhibit growth twins, and tapered mechanical twins. Plagioclase porphyroclasts can have a very disrupted appearance, showing either offset of twin planes along fractures oriented at a high angle to twin planes; separation of the porphyroclasts along fractures oriented parallel to twin planes; or bent twin planes (Figure 7b).

Pressure shadows of recrystallized feldspar and quartz locally form tails around microcline and quartz porphyroclasts. Their shapes define sigma-style augen (Figure 7c; *e.g.* Simpson and Schmid, 1986). White mica fish alignment around ovoid to sigma-style quartz and feldspar porphyroclasts defines an oblique, tops-to-the NW shear sense in closely spaced, west-dipping schistosity. In samples having mylonitic textures, feldspars show extreme grain size reduction. Only quartz porphyroclasts remain in a finer-grained, felsic matrix (Figure 7d). Large domains of quartz and feldspar crystals having triple junction grain boundaries also suggests some post-tectonic annealing of strain textures in the eastern facies of the pluton as well as its western facies.

#### CLASTIC METASEDIMENTARY ROCK VERSUS DEFORMED PLUTON

Felsic gneiss of the Crabtree Creek pluton was originally mapped and defined by Fortson (1958) and Parker (1979) as “quartz-disk or quartz-prism gneiss.” These investigators first documented the lateral extent, mineral assem-

## CRABTREE CREEK PLUTON

blages, textures, and fabrics of this distinctive gneiss. Both Fortson (1958) and Parker (1979) noted the abundance of coarse quartz that forms distinctive flat, disk-shaped to elongate, prism-shaped crystal aggregates. They also noted that larger aggregates are commonly elongate and oriented sub-parallel to each other and to the (001) planes of white mica flakes, thus defining a schistosity and lineation in the gneiss. However, Fortson (1958) and Parker (1979) believed that the protoliths for the quartz-disk gneiss consisted of coarse-grained conglomeratic and arkosic sandstones. They based their interpretation on the large size and number of the quartz disks and rods having a pebble-like appearance, and the high quartz content of the gneiss.

This remapping of rock contacts combined with hand sample analyses indicates that the felsic gneiss located between the Cary formation of the Carolina terrane and the Crabtree terrane is a deformed pluton. In summary, this reinterpretation is based upon: 1) dike contacts of the pluton crosscutting lithologic layering of Cary formation and Crabtree terrane wall rocks at the macroscopic scale; 2) dikes and dikelets of the pluton crosscutting amphibolite and biotite schist of the Turkey Creek body, as well as felsic gneisses and pelitic and graphite schists of the Crabtree terrane at the mesoscopic scale; 3) the relatively homogeneous igneous leucogranitic to granitic bulk composition of orthogneisses at the mesoscopic scale; 4) the lack of well developed layering in orthogneisses at the mesoscopic scale; 3) xenoliths of amphibolite, biotite schist, and pelitic schist in leucogranitic orthogneiss and porphyroclastic granitic orthogneiss at both scales; 4) preservation of relict igneous xenomorphic textures in leucogranitic orthogneiss from the relatively undeformed southwestern facies of the pluton at the mesoscopic and microscopic scale; and 5) local preservation of deformed igneous textures in porphyroclastic granitic orthogneiss of the eastern facies of the pluton at the mesoscopic and microscopic scale.

The origin of the porphyroclastic disks and rods of quartz remains a challenging puzzle. Because the gneiss containing the disks and rods preserves igneous crosscutting relationships with Cary formation and Crabtree terrane wall rocks, as well as relict igneous textures, the ellipsoidal porphyroclasts are not considered to be quartz pebbles in a clastic metasedimentary rock. Instead, the disk- and rod-shaped porphyroclasts of polycrystalline quartz appear to represent phenocrysts in a porphyritic granite that was progressively deformed across its width.

This interpretation is based upon the eastward destruction of relict mesoscopic and microscopic igneous xenomorphic textures and change in porphyroclast aspect ratio across the pluton relative to an increase in microstructure development (*e.g.* undulatory extinction, deformation bands, subgrains, grain boundary migration, grain size reduction of De Paor and Simpson, 1993). It is also based upon the mappable distribution and gradual transition in porphyroclastic tex-

tures eastward across the pluton as evidenced by: 1) quartz crystal aggregates in metamorphosed leucogranite from the southwestern part of the pluton; 2) quartz disks in well-foliated, porphyroclastic granitic orthogneiss from the central part of the pluton; and 3) quartz rods in more highly sheared, lineated porphyroclastic granitic orthogneiss from the eastern facies of the pluton. The porphyroclasts are thought to be active finite strain markers recording a progressive transition from weak deformation to flattening deformation in the western and central parts of the pluton to constriction deformation in the eastern facies of the pluton (*e.g.* Ramsay and Huber, 1983). However, the porphyroclasts must be studied in more detail to confirm or deny their phenocryst origin and their use as measurable strain markers.

Parker also used a high quartz content as evidence that the gneiss had a sedimentary protolith. Based upon microscopic examination, Parker (1979) believed that quartz formed half or more of his quartz-disk to quartz-prism gneiss, and the lineated gneisses of the Falls leucogneiss farther to the east as well. This study of mesoscopic and microscopic textures in the felsic matrix of the leucogranitic and porphyroclastic granitic orthogneisses indicates that white mica alteration, dynamic recrystallization, and grain size reduction preferentially affect feldspars and leave quartz as more competent aggregates in the deforming matrix.

Representative orthogneiss samples from the western and eastern facies of the pluton having variably developed microstructures were also stained for the presence of plagioclase and K-feldspar. These samples show that greater than 50% of the felsic matrix surrounding quartz disks and rods consists primarily of grain size-reduced K-feldspar and plagioclase. Fine-grained quartz forms only approximately 10% to 20% of the matrix; most quartz is confined to the disks or rods. Stained samples indicate that the total quartz content is less than previously believed. In addition, percentages of quartz, plagioclase, and K-feldspar in the variably grain size-reduced orthogneisses are compatible with a leucogranite to granite protolith for these rocks.

## AGE OF CRYSTALLIZATION OF THE PLUTON

Kish and Campbell (1986) originally considered this gneiss to be plutonic based upon Rb-Sr whole-rock isotope studies and geochemistry, and coined the term Crabtree Creek pluton. They determined a Rb-Sr whole-rock date of  $382 \pm 30$  Ma and an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.7065 \pm 0.0006$ , and interpreted the orthogneiss to be part of a suite of Ordovician to Devonian plutons on the western flank of the Raleigh metamorphic belt (Kish and Campbell, 1986). Horton and Stern (1994) reported a discordant 542 Ma U-Pb zircon age for granitic orthogneiss of the Crabtree Creek pluton. Recent geochronologic studies by S.A. Goldberg (this guidebook) show that three discordant zircon fractions from the granitic orthogneiss produced  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of

554, 564, and 566 Ma. These dates suggest that crystallization of the leucogranitic to porphyroclastic granitic pluton occurred in the Neoproterozoic or early Paleozoic.

Because lobes and dikes of the pluton locally display intrusive contacts with metavolcanic and metasedimentary rocks of both the Carolina terrane and the Crabtree terrane, the Crabtree Creek pluton is believed to be an intrusion that stitched the two terranes together. When these observations are combined with the 554, 564, and 566 Ma dates of Goldberg (this guidebook), the data suggest that juxtaposition of the Carolina terrane with the Crabtree terrane must have occurred in the Neoproterozoic. However, a mechanism of formation and source area for the pluton are not yet constrained. Investigations concentrating on the geochemistry of the Crabtree Creek pluton are currently in progress and will address these hypotheses.

### DEFORMATION ACROSS THE PLUTON AND ITS WALL ROCKS

The mesoscopic and microscopic textures in both the leucogranitic orthogneiss and the porphyroclastic granitic orthogneiss indicate that subsequent to crystallization, the Crabtree Creek pluton and its wall rocks were variably deformed. Two deformational pulses defined as  $D_2$  and  $D_3$  accompanying an  $M_2$  Alleghanian metamorphism (Russell and others, 1985; Stoddard and others, 1991) have variably affected the pluton to such a degree that in different structural domains it is a weakly foliated and metamorphosed leucogranite or a well foliated leucogranitic to granitic orthogneiss, protomylonite, or phyllonite.  $D_2$  is the most pervasive deformation pulse in the western facies of the Crabtree Creek pluton and its wall rocks;  $D_3$  is the most pervasive deformation pulse in the easternmost part of the Crabtree Creek pluton and its wall rocks. A structural domain map and equal-area projections showing the orientation of  $D_2$  and  $D_3$  planar and linear fabrics for the northern half of the Raleigh West quadrangle are provided in Figure 8. Evidence for a pre-Alleghanian  $D_1$  deformation and  $M_1$  metamorphism, observed farther north along the Falls Lake mélange-Crabtree terrane contact in the Bayleaf and Grissom quadrangles (Blake, 1986; Blake and Stoddard, 1986; Stoddard and others, this guidebook) have only been locally recognized in Crabtree terrane wall rocks near the Crabtree Creek pluton. The relationship between  $D_1$  deformation and pluton is not clear.  $D_1$  fabrics have not yet been recognized in the pluton.

#### Planar Fabrics

The dominant, penetrative, schistosity is  $S_2$ , the regional foliation formed during  $D_2$  deformation and  $M_2$  metamorphism. Domains I and II show the orientation of the  $S_2$  schistosity in the Crabtree Creek pluton, the Turkey Creek

amphibolite body and Reedy Creek adamellite lens and sills, and western Crabtree terrane.  $S_2$  has a northwest to north strike and a moderate to steep west dip in these rocks reflecting folding of  $S_2$  on the western limb of the  $F_3$  Wake-Warren anticlinorium (Figure 8; Parker, 1979). Local dip reversals indicate that upright, open, mesoscale  $F_3$  folds parasitic to the Wake-Warren anticlinorium re-fold  $S_2$ .

Domain III shows the orientation of  $S_2$  schistosity and  $F_3$  fold axes and axial planes recorded in the eastern Crabtree terrane and western Raleigh terrane (Figure 8). Outcrops in the eastern Crabtree terrane record a dip transition from shallow west-dipping to shallow east-dipping  $S_2$  schistosity. Dip changes reflect overprinting of the schistosity by the subhorizontally-plunging Raleigh antiform, a macroscale  $F_3$  fold that is also parasitic to the Wake-Warren anticlinorium. In the Falls Lake-Wake Forest area, the trace of the contact between the Falls Lake mélange and Crabtree terrane delineates this open, macroscale fold (Figure 2). In the Raleigh West quadrangle, the Raleigh antiform is defined by a series of tight, upright folds having vertical to slightly west-dipping axial planes (Figure 4).

$S_2$  schistosity in leucogranitic to porphyroclastic granitic orthogneiss and wallrocks is also progressively overprinted eastward across the northern part of the quadrangle by thin, discontinuous shear zones and the right-lateral,  $D_3$  Nutbush Creek fault zone. In Domain III, the  $S_2$  schistosity steepens in lineated felsic gneiss (Falls leucogneiss) on the eastern limb of the Raleigh antiform, and is reoriented into the structural grain of the subvertically-dipping Nutbush Creek fault (Druhan, 1983; Druhan and others, this guidebook). This  $D_3$  right-lateral shear zone appears to have transposed the eastern limb of the Raleigh antiform and has reoriented the schistosity of both the easternmost Crabtree terrane and western Raleigh terrane into the N15-20°E striking, subvertically-dipping shear plane.

#### Linear Fabrics

There is an eastward overprinting of  $D_2$  linear fabrics across the northern half of the Raleigh West quadrangle into the  $D_3$  Nutbush Creek fault zone orientation (Figure 8). Domain I shows the orientation of  $L_2$ , a mineral elongation or mineral aggregate lineation west of the Nutbush Creek fault zone. In Domain I,  $L_2$  has a mean vector of 40°, N70°W.  $L_2$  occurs in mesoscopic, discontinuous shear zones crosscutting the Turkey Creek amphibolite body and the Reedy Creek adamellite dikes just west of the Crabtree Creek pluton. There,  $L_2$  is defined by hornblende and biotite aggregates in amphibolite or metagabbro, and by felsic porphyroclasts and aggregates in metamorphosed granitoid dikes.  $L_2$  appears to be a stretching lineation in the mesoscopic shear zones. In metamorphic rocks outside these shear zones,  $L_2$  is rarely developed.

In leucogranitic orthogneiss, the northwest-plunging lin-

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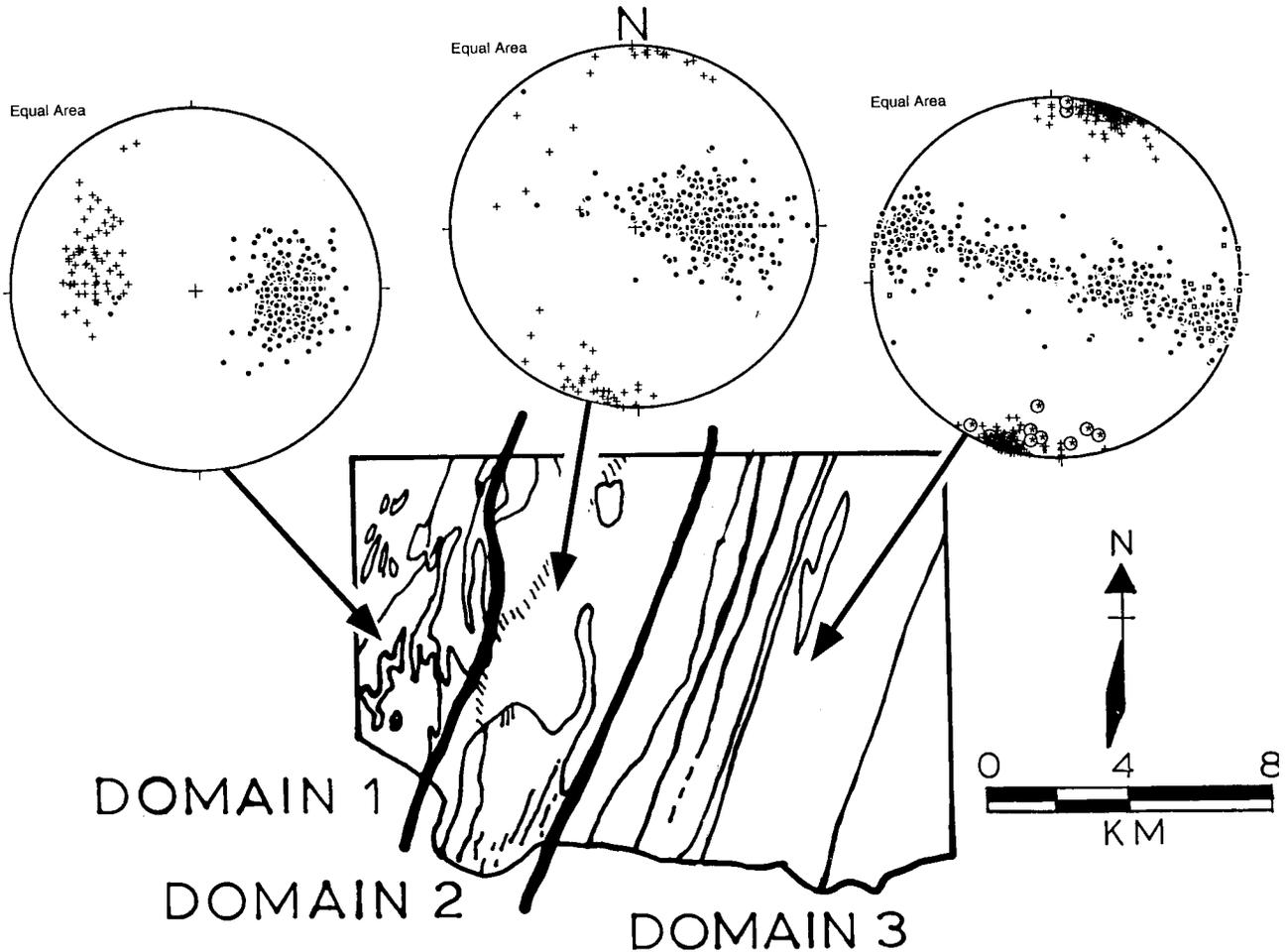


Figure 8. Structural domain map of the orientation of fabric elements across the northern half of the Raleigh West quadrangle. Thin lines are unit contacts. Dark lines are the boundaries for Domains I, II, and III. On the lower-hemisphere, equal-area stereographic projections, poles to  $S_2$  are shown as filled circles, the mineral stretching lineations are shown as pluses,  $F_3$  fold axes are shown as stars surrounded by circles, and  $F_3$  axial planes are shown as open squares. Domain I records 368  $S_2$  foliation and 66  $L_2$  lineation data points, respectively. Domain II records 351  $S_2$  foliation and 61  $L_2$  lineation data points, respectively. Domain III records 539  $S_2$  foliation and 277  $L_2$  lineation data points, respectively, and 21  $F_3$  fold axes and axial planes.

eation of white mica and felsic mineral aggregates defines  $L_2$ .  $L_2$  primarily occurs in the mesoscopic, discontinuous shear zones having thinly banded protomylonite to phyllonite mineral textures, and composite-planar fabrics including shear bands that deform  $S_2$ , sigmoidal mica fish, and asymmetric quartz or feldspar augen. Fabric asymmetry indicates an oblique, tops-to-the NW shear sense in the west-dipping shear zones.

Domain II shows that the northwest-plunging  $L_2$  mineral lineation is also developed in quartz disk granitic orthogneiss and in Crabtree terrane wall rocks south of the pluton (Figure 8). Tourmaline prisms in porphyroclastic granitic orthogneiss, and white mica and felsic aggregates in the orthogneiss and Crabtree terrane schists and gneisses define this lineation. Lineation orientations from Domain II also suggest that there is an eastward transition from northwest-

plunging to a subhorizontally-plunging, N15-20°E to S15-20°W-trending lineation in these rocks. The gradual transition in aspect ratios from oblate disks to prolate rods occurs in porphyroclastic granitic orthogneiss from this domain. Porphyroclastic granitic orthogneiss from the easternmost part of the pluton is an L>S tectonite. This transition is interpreted to represent a progressive change from  $D_2$  flattening deformation to  $D_3$  constriction deformation eastward across the northern half of the Raleigh West quadrangle.

Domain III from the eastern Crabtree and western Raleigh terranes shows that rocks in the entire northeastern half of the quadrangle are dominated by this subhorizontal lineation. In the Crabtree terrane rocks, this lineation is defined by recrystallized quartz, feldspar, magnetite, or phyllosilicate aggregates. Recrystallized hornblende, biotite, quartz, and feldspar define the lineation in the western

Raleigh terrane rocks. Most felsic gneisses in Domain III are classified as L>S protomylonite. The subparallel orientation of this mineral lineation and the mineral stretching lineation observed both north and south of the Raleigh West quadrangle in the Nutbush Creek fault zone (*e.g.* Druhan, 1983; Druhan and others, 1988, this guidebook) suggests that they reflect the same high strains due to D<sub>3</sub> shearing.

### Relationship of Fabrics to the Nutbush Creek Fault Zone

In order to explain the overprinting fabric relationships and shape changes in porphyroclasts of the granitic orthogneiss, the boundaries of penetrative D<sub>3</sub> strain accompanying shearing along the Nutbush Creek fault zone are interpreted to be wider in the northern Raleigh West quadrangle than previously defined from work in the Falls Lake-Wake Forest area (Blake, 1986; Horton and others, 1992). It is hypothesized that linear-dominated rocks in the northern part of the Raleigh West quadrangle are showing the effects of ductile strain partitioning and westward propagation of deformation resulting from oblique to right-lateral shearing contemporaneous with the formation of the D<sub>3</sub> Nutbush Creek fault zone.

Kinematic indicators that are compatible with oblique to right-lateral shearing across the pluton and its wall rocks include: 1) oblique, tops-to-the NW shear bands, sigmoidal mica fish and asymmetric quartz and feldspar augen; 2) the asymmetric swing in map orientation of an elongate, granitic orthogneiss dike in the southeast part of the Crabtree Creek pluton; and 3) the west to east transition from NW-plunging to subhorizontally-plunging, N15°E-S15°W-trending L<sub>2</sub> lineations in Domains I through III. Because mineral lineations cluster around mesoscale F<sub>3</sub> fold axes of the S<sub>2</sub> foliation in Domains II and III, D<sub>2</sub> and D<sub>3</sub> linear fabrics are thought to have been rotated into a subhorizontal orientation parallel to the regional stretching direction during right-lateral shearing.

West of the central part of the Crabtree Creek pluton, D<sub>3</sub> overprinting is interpreted to be confined to the discontinuous shear zones. These zones are believed to represent parasitic, ductile shear zones west of the main Nutbush Creek fault zone. Fabric asymmetry in protomylonitic and phyllonitic rocks in these west-dipping zones indicates an oblique, tops-to-the NW shear sense which is compatible with right-lateral shearing along the Nutbush Creek fault zone. This shear sense is also compatible with Alleghanian oblique-slip faulting observed in the eastern Piedmont of South Carolina (Maher and others, 1991) If this hypothesis is valid, then high strain zones located along the Crabtree Creek pluton-Cary formation contact, the Cary formation-Falls Lake mélange contact, and the Falls Lake mélange-Crabtree terrane contacts may be recording the same D<sub>3</sub> oblique to right-lateral displacements and need further detailed investigation.

## CONCLUSIONS

Recent geologic mapping and detailed study of lithologic contacts, relict igneous xenomorphic textures, and microstructure development demonstrates that the felsic gneiss which occurs along the Carolina terrane-Crabtree terrane boundary is a metamorphosed pluton defined as the Crabtree Creek pluton. This pluton is subdivided into two mappable facies: 1) a foliated, leucocratic, medium-grained, white mica-bearing leucogranitic orthogneiss, and 2) a foliated to lineated, leucocratic, medium- to coarse-grained, white mica ± biotite granitic orthogneiss containing abundant porphyroclastic disks or rods of quartz. This interpretation is primarily based upon plutonic contacts which crosscut wall rock units of the easternmost Carolina terrane and the Crabtree terrane, and the preservation of relict igneous textures in leucogranitic to granitic orthogneisses. The Crabtree Creek pluton is believed to be an intrusion that stitched the Carolina terrane to the Crabtree terrane during Neoproterozoic to early Paleozoic plutonism.

Subsequent to crystallization, the Crabtree Creek pluton was variably deformed and metamorphosed to such a degree that in different structural domains it is a metamorphosed leucogranite to granite, an orthogneiss, a protomylonite, or a phyllonite. D<sub>2</sub> deformation and M<sub>2</sub> metamorphism produced the dominant penetrative schistosity and mineral assemblages in the western facies of the pluton and its wall rocks. D<sub>2</sub> and M<sub>2</sub> are thought to be the components of a regional response to flattening during early to middle Alleghanian orogenesis. Upright, open folds; discontinuous, mesoscopic shear zones; and the L>S tectonite fabric overprint the S<sub>2</sub> schistosity in the eastern facies of the pluton and its wall rocks. These structures are attributed to middle to late Alleghanian D<sub>3</sub> regional folding and oblique, tops-to-the-NW to right-lateral shearing contemporaneous with the formation of the Nutbush Creek fault zone. These data are interpreted to indicate that constriction deformation attributed to this shearing affected a wider zone of rocks than previously observed on the western flank of the Raleigh metamorphic belt. Bulk transposition of pre-existing fabrics in the Crabtree Creek pluton, Carolina terrane and Crabtree terrane wall rocks, and the western Raleigh terrane by folding and right-lateral shearing is compatible with a model of transpression during D<sub>3</sub> deformation along the western flank of the Raleigh metamorphic belt. Late, local, post-tectonic metamorphic mineral growth and annealing of pre-existing strain textures is attributed to the waning stages of M<sub>2</sub> metamorphism during late Alleghanian orogenesis.

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## CRABTREE CREEK PLUTON

# THE FALLS LAKE THRUST: A PRE-METAMORPHIC TERRANE-BOUNDING FAULT IN THE EASTERN NORTH CAROLINA PIEDMONT

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### ABSTRACT

An important contact along the western flank of the Raleigh metamorphic belt in the eastern Piedmont of North Carolina separates two distinctive terranes, the Falls Lake melange, dominantly a two-mica schist containing exotic blocks of ultramafic and other rock types, and the Crabtree terrane, primarily felsic metavolcanic rocks and pelitic schists. Detailed mapping shows that this contact locally truncates structures and units in both terranes. An unusual thinly banded gneiss containing multiple planar fabrics occurs discontinuously along the contact and is interpreted as a metamorphosed and annealed mylonite, with the original mylonitic fabric overprinted by Alleghanian fabrics and porphyroblasts. The contact is inferred to be a thrust fault, the Falls Lake thrust. The thrust may have formed during amalgamation of the Falls Lake melange and the Crabtree terrane prior to Alleghanian deformation and metamorphism.

### INTRODUCTION

Along the western flank of the Raleigh metamorphic belt, the Falls Lake thrust is inferred to mark a suture along which the Falls Lake melange is welded to the Crabtree terrane (Figure 1). This paper outlines the rationale used in interpreting the contact as a thrust, and describes elements of the unique fabrics that are locally present along its trace.

The Falls Lake thrust was first recognized and mapped

as a contact by Parker (1979). On his map of Wake County, it separates "mica and hornblende gneiss and schist" (equivalent to the Falls Lake melange) on the west, from "felsic gneiss and schist" (roughly equivalent to the Crabtree terrane) on the east. Parker recognized "conglomeratic" (block-in-matrix?) texture in the mica and hornblende gneiss and schist near the contact, and also noted the apparent truncation of structures and lithologic horizons in the felsic gneiss and schist at the contact. For these reasons, he interpreted the contact as an angular unconformity, and concluded that the felsic gneiss and schist had suffered an earlier period of deformation prior to deposition of the protoliths of the mica and hornblende gneiss and schist unit. Subsequent mapping by Wylie (1984), Blake (1986), and Horton and others (1992) in the Bayleaf, Wake Forest, and Grissom quadrangles, has extended the contact northward into Granville County and increased the level of detail in Wake County. Another paper in this guidebook, by Horton, Blake, Wylie, and Stoddard, discusses the geologic setting and results of the most recent mapping in the Falls Lake-Wake Forest area.

### EVIDENCE FOR THRUST CONTACT

Some of the observations used by Parker (1979) in his interpretation of the contact as an unconformity may also be used to infer a thrust, as originally suggested by Wylie (1984; see also Wylie and Stoddard, 1984; Stoddard and others, 1985). First, the sharp contrast between distinct rock suites across the contact is more consistent with tectonic jux-

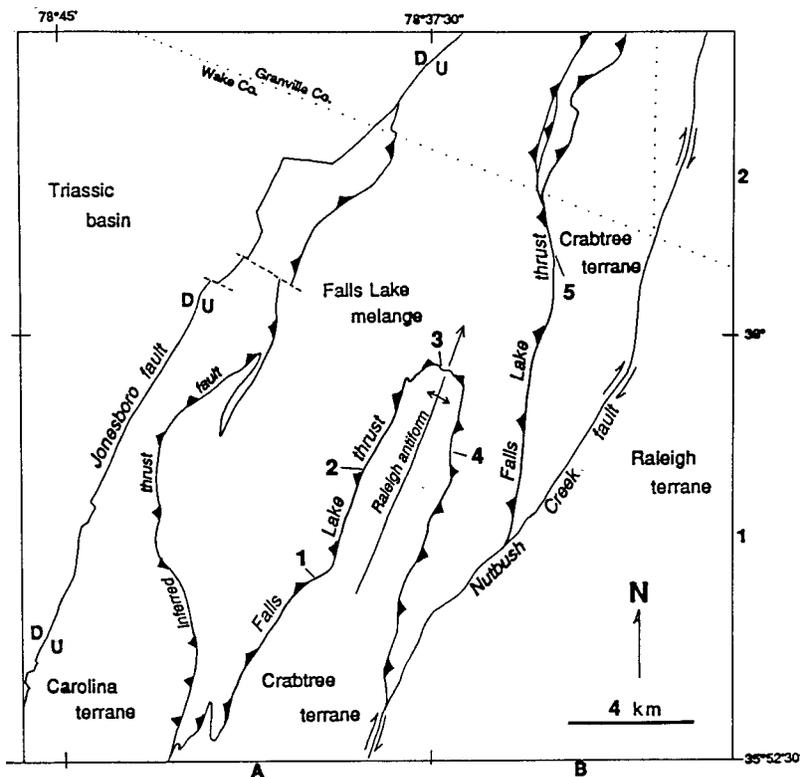


Figure 1. Sketch map of a portion of the western flank of the Raleigh metamorphic belt, after Horton and others (1992), showing the location of the Falls Lake thrust. Localities described in text are indicated. Thrust presumably extends north from area shown, but has not been mapped in detail; south of the area shown, the Falls Lake thrust has not been mapped, but banded gneiss fabrics are even more common (Blake, 1994). Letter-and-number grid indicates 7.5' quadrangles mentioned in text: A1=Bayleaf; A2=Creedmoor; B1=Wake Forest; B2=Grissom.

toposition than a contact within a conformably layered sequence. Second, the abundance of metamorphosed ultramafic and mafic rocks structurally above the contact (in the Falls Lake melange), but not below it (in the Crabtree terrane) as discussed below, suggests that the overlying exotic rocks have been transported. Third, although the truncation of units in the structurally lower Crabtree terrane is critical evidence consistent with either an angular unconformity or a thrust, the local truncation of ultramafic units and metamorphic foliation in the upper plate (as mapped by Horton and others, 1992) requires a fault. The existence of widespread block-in-matrix structure in the Falls Lake melange, which is not restricted to a zone near the contact, given the moderate to steep dips in the area, also argues against Parker's interpretation that it is a basal conglomerate in an unconformably overlying sequence. A final piece of evidence is the existence along the contact of a thinly banded gneiss interpreted as a metamorphosed mylonite.

## TERRANES JUXTAPOSED BY THE FALLS LAKE THRUST

### Rocks of the Falls Lake Melange (Upper Plate of the Falls Lake Thrust)

The Falls Lake melange (Horton and others, 1986; also Wylie, 1984; Blake, 1986; Horton and others, 1985a,b, this guidebook) consists predominantly of metasedimentary two-mica schist enclosing discontinuous pods, blocks, and lenses of exotic rock types ranging from centimeters up to more than a kilometer in longest dimension. Exotic fragments include the metamorphic equivalents of ultramafic and mafic igneous rocks, but also include probable intermediate to felsic igneous rocks and psammitic metasedimentary rocks.

Schist of the Falls Lake melange is distinct from other schists in this part of the eastern Piedmont in that biotite is typically more abundant than muscovite. The schist is commonly rich in sodic plagioclase (up to 20%) and epidote; garnet is common, and staurolite and kyanite occur locally.

Blocks in the melange include serpentinite, talc ± actinolite schist, chlorite schist, hornblende, amphibolite, actinolite ± clinozoisite rock, and chromitite. Relict primary igneous minerals, including olivine and both clino- and

## FALLS LAKE THRUST

orthopyroxene, are sparse but occur locally, especially toward the western, lower grade portion of the area (Parker, 1979; Moye, 1981). Based on whole-rock geochemistry, inferred primary mineralogy, and field relationships, Moye (1981) concluded that these and larger, possibly layered igneous bodies in his “Bayleaf mafic-ultramafic belt” had protoliths similar to rocks of the oceanic lithosphere, and that they represented components of a dismembered ophiolite (see also Stoddard and others, 1982).

The Falls Lake melange is interpreted to be in thrust contact to the west with structurally overlying metavolcanic rocks and metavolcaniclastic phyllites of the Carolina slate belt, as well as slate belt-related metaplutonic bodies, including the informal Beaverdam diorite-gabbro complex (Horton and others, 1992). The melange thus appears to be a thrust-bounded terrane consisting of a sedimentary matrix containing blocks of possible oceanic origin. It has been interpreted to be part of an accretionary wedge formed in a subduction zone accompanying plate movements preceding and during the collision of a slate belt volcanic arc with one or more other terrane(s) (e.g. Horton and others, 1985b, 1986, 1989; Stoddard and others, 1985).

### Rocks of the Crabtree Terrane (Lower Plate of the Falls Lake Thrust)

The Crabtree terrane (Horton and others, 1989; formerly also referred to as “Felsic gneiss terrane”, e.g. Stoddard and Butler, 1989; Stoddard and others, 1991) includes rocks that lie generally east of and structurally below the Falls Lake melange and Falls Lake thrust in northern Wake and southern Granville Counties. Muscovite-bearing, poorly banded quartz-plagioclase-microcline gneiss is the most common rock in this terrane. In thin section, local euhedral plagioclase crystals, interpreted as relict phenocrysts, lend credence to the suggestion that the protolith for some of the felsic gneiss was volcanic. In addition, the Crabtree terrane as mapped by Horton and others (1992) and by Blake (1994) locally contains quartzitic muscovite schist, graphite schist, and muscovite  $\pm$  biotite  $\pm$  garnet  $\pm$  kyanite  $\pm$  staurolite  $\pm$  hornblende schists; these are interlayered with the quartzofeldspathic gneiss. Most of the schists presumably had clay-rich sedimentary protoliths, and the graphite schist had an organic carbon-rich precursor (Lumpkin and others, 1994 and this guidebook).

All rocks in the terrane are strongly foliated, having suffered at least two deformational events and regional metamorphism in the amphibolite facies. Granitoid plutons, now represented by variably deformed orthogneiss, also constitute part of the Crabtree terrane. One such body, the Crabtree Creek pluton, is discussed in detail elsewhere in this guidebook (Blake). Most Crabtree terrane rocks contain very little biotite and hornblende, and the terrane lacks mafic and ultramafic rocks.

Progressively eastward, quartzofeldspathic gneiss of the Crabtree terrane is overprinted by the dominantly linear fabric of the Nutbush Creek fault zone (Druhan and others, 1988 and this guidebook; Blake, this guidebook; Horton and others, 1992 and this guidebook). Although the rocks of the Nutbush Creek fault zone have been described as a separate and distinct unit (Farrar, 1985; Horton and others, 1992; Stoddard and others, 1991), some orthogneiss in the Nutbush Creek fault zone, including the Falls leucogneiss, may belong to the Crabtree terrane. Because of the abundance of granitic material (K-rich compared with typical Na-rich slate belt compositions), lack of mafic or ultramafic rocks, and lithologic suggestions of shallow marine to nonmarine sedimentary environments (e.g. carbonaceous schist), it has been postulated that the Crabtree terrane is of continental affinity (Stoddard and others, 1978, 1991; Horton and others, 1989, 1991), though other interpretations are possible.

### STRUCTURE AND FABRICS ALONG THE FALLS LAKE THRUST

The Falls Lake thrust is folded by the gently north-

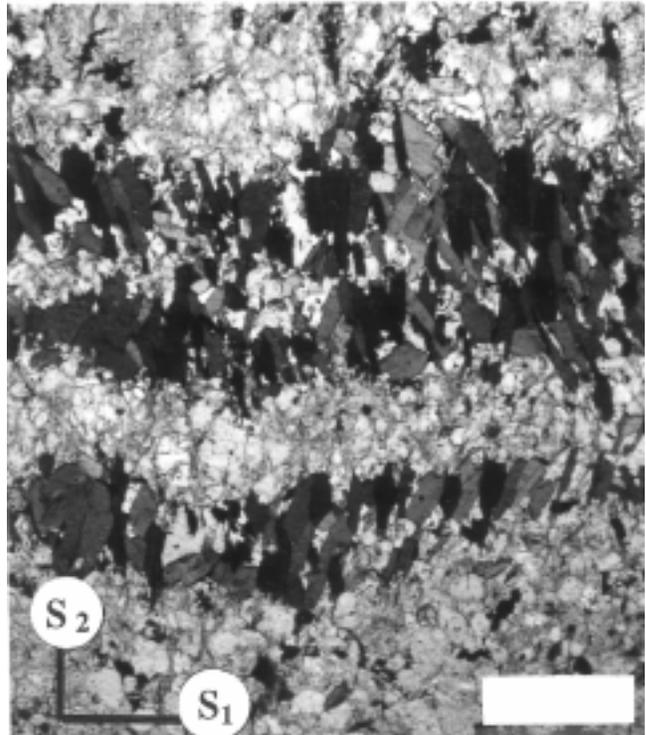


Figure 2. Photomicrograph of typical fabric of ribbon gneiss found along the Falls Lake thrust. Gneissic banding,  $S_1$ , is defined by biotite-free and biotite-bearing layers from 0.2 - 1 cm in width. Preferred orientation of biotite flakes defines a cleavage,  $S_2$ , which typically lies at an angle to  $S_1$ . Plane-polarized light; scale bar represents 0.5 mm. In other rocks from along the thrust, phyllosilicate minerals other than biotite, including muscovite and chlorite, do not always lie along  $S_2$ , and locally appear post-tectonic with respect to  $D_2$ .

plunging Raleigh antiform and is truncated to the east by the Nutbush Creek fault zone (Figure 1). It re-emerges farther north, perhaps on the eastern limb of a truncated synform, and continues northward through southern Granville County (Blake, 1986; Blake and Stoddard, 1986; Horton and others, 1992; Horton and others, this guidebook). To the south, the thrust has been mapped to the southern edge of the Bayleaf quadrangle, where it is interrupted, perhaps intruded, by the Crabtree Creek pluton (Blake and Stoddard, 1993; Blake, this guidebook; Horton and others, this guidebook). Hopefully, 1:24,000-scale mapping will determine if the fault continues into central and southern Wake County, as suggested previously (*e.g.* Stoddard and others, 1991).

The Falls Lake thrust is marked by a discontinuous and narrow (less than 10 m thick) zone of thinly layered biotite ribbon gneiss and quartz ribbon gneiss, which we interpret as metamorphosed and annealed mylonite (Figure 2; see also Stoddard and others, 1985). An early foliation, defined as  $S_1$  in this discussion, consists of thin laminations in the ribbon gneisses. In biotite ribbon gneiss  $S_1$  is represented by one to five mm thick black, biotite-rich laminae alternating with white, quartzofeldspathic laminae of similar thickness.  $S_1$  in quartz ribbon gneiss is defined by polycrystalline aggregates of quartz two to five mm thick and up to several cm long, in a quartzofeldspathic matrix (Blake, 1986). Both gneisses lack evidence for sedimentary origin, such as relict clastic textures or grading. On the other hand, the laminae are similar in appearance to small-scale layering in mylonite from known shear zones (*e.g.* Simpson, 1983). We interpret the laminae to be tectonic in origin, formed during intense shearing. The ribbon gneiss is therefore interpreted to be a metamorphosed mylonite.

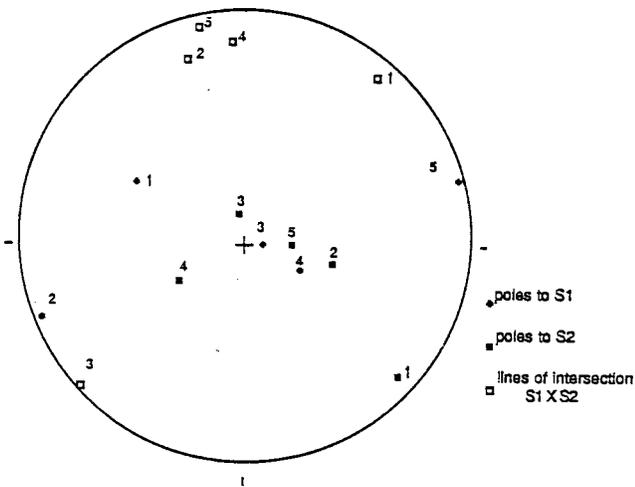


Figure 3. Equal area, lower hemisphere stereographic projection of poles to  $S_1$  and  $S_2$  foliations from the five exposures of the Falls Lake thrust described in the text, with the lines defined by their intersections (open boxes). The effects of deformation associated with the  $F_3$  Raleigh antiform and the Nutbush Creek fault are evident.

A later foliation,  $S_2$ , is defined by the preferred orientation of the biotite plates (Figure 2). In some rocks, white mica shares the biotite  $S_2$  orientation; in others, unoriented flakes of white mica and chlorite appear to have crystallized after the event responsible for  $S_2$ .  $S_2$  is the regionally dominant planar fabric, and is folded into map-scale structures in the area, specifically by the Raleigh antiform; the Raleigh antiform is thus an  $F_3$  fold. In most of the Falls Lake melange and Crabtree terrane, compositional layering (presumably  $S_1$ ) and mica schistosity (presumably  $S_2$ ) have been observed to be parallel or nearly so, or have not been separately indicated (Parker, 1979; Wylie, 1984; Horton and others, 1992). However, in the biotite ribbon gneiss along the Falls Lake thrust, micro- and meso-scale  $S_1$  and  $S_2$  foliations are commonly oblique to one another. For example, in the southern Grissom quadrangle, Blake (1986) measured both planar fabrics in biotite ribbon gneiss along the thrust. While both fabrics strike consistently within  $20^\circ$  of north, the  $S_2$  biotite schistosity dips variably ( $15^\circ$ - $76^\circ$ ) to the west, whereas the  $S_1$  compositional banding dips moderately to steeply east (dips range from  $49^\circ$  to vertical). More detailed structural analysis is needed to sort out the significance of these fabrics.

### Fabric Orientations from Selected Exposures Along the Trace of the Falls Lake Thrust

The following paragraphs provide brief descriptions of exposures of rocks and fabrics of the thrust zone, keyed to Figure 1, and show variations in the attitudes of  $S_1$  and  $S_2$ . Variation in  $S_2$  can be attributed to the effects of  $F_3$  folds, notably the Raleigh antiform (Figure 1), which the exposures traverse. However, because the  $S_1$  mylonitic(?) banding has been folded by microscopic and mesoscopic  $F_2$  folds, and subsequently refolded by the  $F_3$  structures, the original structural geometry of the thrust itself is difficult to discern, especially with such a small amount of data (Figure 3). Most of the reported measurements were taken from sawed oriented samples or thin sections because the  $S_2$  fabric is best seen on two surfaces intersecting at a high angle with the aid of hand lens or microscope. For more precise location of these exposures, the interested reader is referred to the 1:24,000 scale map (Horton and others, 1992).

#### 1. Tributary of Lower Barton Creek south of Mount Vernon Church Road

This outcrop of biotite ribbon gneiss lies along a west-flowing tributary of Lower Barton Creek, south of Mount Vernon Church Road (SR 1844) and west of Six Forks Road (SR 1005), in the east-central Bayleaf quadrangle. To the east and southeast, outcrops of quartzitic muscovite schist and quartzofeldspathic gneiss of the Crabtree terrane are sparse, but can be found in drainages in residential developments west of Six Forks Road. Graphite schist occurs about

## FALLS LAKE THRUST

1.5 km south along Baileywick Road (SR 1830) at the YMCA (see photograph in Stoddard and others, 1991). Traversing the creek downstream from the biotite ribbon gneiss toward the west, one encounters a large ultramafic body at the confluence with a larger north-flowing creek. The first outcrops of the ultramafic body are dominantly chlorite schist. An oriented sample of the biotite ribbon gneiss gave the following attitudes:  $S_1$ , N30°E, 45°SE;  $S_2$ , N40°E, 75°NW.

### 2. Adam Mountain area

North of the community of Bayleaf (Bayleaf quadrangle) and just west of Six Forks Road (SR 1005), a hill called Adam Mountain is underlain by a large body of metamorphosed ultramafic rock within the Falls Lake melange. A north-flowing creek along its eastern margin marks the approximate position of the Falls Lake thrust (Stoddard and others, 1986). East of the thrust, rocks of the Crabtree terrane, including quartzofeldspathic gneiss of probable volcanic origin, and interlayered graphitic muscovite schist of sedimentary origin, are exposed in the creek, along its smaller tributaries, and in the hillslopes. In addition, beginning around 1985, excavation associated with a new subdivision resulted in new exposures. Ditches along the new road just west of the creek on the flank of Adam Mountain showed saprolite of biotite-muscovite schist in contact with chlorite ± actinolite rock belonging to the ultramafic body. Along the same road just east of the creek, biotite ribbon gneiss may still be visible in loose blocks or small ditch exposures. The same rock may be seen in one or more outcrops along the creek. As reported by Stoddard and others (1986), the attitude of  $S_1$  ranges in strike from N8°E-N31°E, having steep dips (69°-82°) toward the southeast. The later foliation,  $S_2$ , strikes N15°W-N20°E and dips 16-60°W at this locality. [Errata note: Strike and dip ranges reported in Stoddard and others (1986, p. 225, lines 20-21) are erroneous; the authors' correction submitted prior to publication was unfortunately not incorporated]. More recent measurements, made from an oriented sample, yielded  $S_1$  of N20°W, 82°NE, and  $S_2$  of N10°E, 31°NW. As mapped by Parker (1979), Wylie (1984), and Horton and others (1992), the graphitic schist horizon near Adam Mountain approaches the Falls Lake thrust at an oblique angle, and appears to be truncated by the thrust.

### 3. Rocky Branch

Rocky Branch (northeasternmost Bayleaf and adjacent northwesternmost Wake Forest quadrangles) is a west-flowing creek that transects the hinge area of the shallowly north-plunging Raleigh antiform and empties into Falls Lake north of North Carolina Highway 98. Exposures are good in the creek, and the prominent  $S_2$  foliation is nearly flat-lying. At its east end, near Stony Hill, the creek begins in quartzitic and muscovite-bearing quartzofeldspathic gneisses and

quartzose muscovite schist of the Crabtree terrane. Traversing downstream toward the west, one encounters outcrops of biotite-muscovite schist of the Falls Lake melange, and the creek apparently snakes back and forth across the thrust zone. No ultramafic rocks are encountered except for float of actinolite-chlorite rock near the mouth of Rocky Branch at Falls Lake. Biotite ribbon gneiss is not abundant. A single oriented sample yielded  $S_1$  of N-S, 07°W; and  $S_2$  of N81°E, 10°SE, but  $S_2$  foliations measured near the thrust contact along this traverse commonly dip 10°-15°N as shown on geologic maps by Wylie (1984) and Horton and others (1992).

### 4. Falls Lake

In the northwest-central Wake Forest quadrangle, outcrops along the thrust on the south side of Falls Lake north of Possum Track Road (SR 2002) lie on the eastern limb of the Raleigh antiform. A good transect of the Falls Lake thrust and rocks of both plates can be seen by traversing the lakeshore at low water, from Cedar Creek to the western edge of the Wake Forest quadrangle. An oriented sample gave  $S_1$  of N24°E, 22°NW, and  $S_2$  of N26°W, 26°NE.

### 5. Tributary of Mill Creek

An unnamed tributary (informally termed Mosquito Creek by Blake, 1986) flows northward into Mill Creek at the Wake-Granville County line in the southern Grissom quadrangle. Outcrops of biotite-ribbon gneiss display a strong subhorizontal and north-trending intersection (and extension?) lineation. This exposure of the Falls Lake thrust is located east of the others, and closer to the Nutbush Creek fault zone. The linear fabric of the Nutbush Creek fault zone has a similar orientation (Blake, 1986; Druhan and others, 1988 and this guidebook). An oriented sample of biotite ribbon gneiss gave a steeply dipping  $S_1$  of N17°W, 86°SW and a gently dipping  $S_2$  of N-S, 15°W. At a nearby outcrop, Blake (1986) reports  $S_1$  of N10°W, 52°NE and  $S_2$  of N40°W, 15°SW.

## SIGNIFICANCE

It has been proposed (*e.g.* Stoddard and Butler, 1989; Stoddard and others, 1985; Horton and others, 1989, 1991) that the Falls Lake thrust, and associated thrusts along the western flank of the Raleigh metamorphic belt constitute a suture between “oceanic/volcanic” terranes, including the Carolina slate belt and the Falls Lake melange, and “continental/continental margin” terranes, including the Crabtree terrane. Evidence for this conclusion includes: (1) the presence of fault-bounded ophiolitic melange, probably representing part of an accretionary wedge; (2) the distinction between the lithologic types and inferred histories on either side of the zone (separate terranes); and (3) suggestions that this corridor along the western flank of the Raleigh meta-

morphic belt is a region of fundamental crustal weakness, because it lies within a major gravity gradient, and it has experienced later faulting during the Alleghanian orogeny and early Mesozoic rifting.

In the composite Potomac terrane of Virginia and Maryland, Drake (1985, 1987, 1994; see also Pavlides, 1989) has described “tectonic motifs” of paired thrust sheets and precursory sedimentary melanges which locally contain fragments of mafic and ultramafic rocks. There, the overlying sheets were deformed and metamorphosed prior to thrust emplacement, and the melanges contain clasts derived from the overlying thrust sheet. Although further study is needed, the Falls Lake melange and tectonically overlying volcanic arc (Carolina terrane) may be analogous to these “tectonic motifs” of the Potomac terrane.

Although the age of the Falls Lake thrust is unknown, it has been strongly overprinted by demonstrably Alleghanian amphibolite-facies metamorphism (Russell and others, 1985), upright open folding (*i.e.* Raleigh antiform), and right-lateral strike-slip faulting (*i.e.* Nutbush Creek fault zone; Horton and others, 1986; Stoddard and others, 1991). It has been suggested that the Falls Lake thrust is of early or middle Paleozoic age (Taconic or Acadian; *e.g.* Stoddard and others, 1991). However, if the fault is transected by intrusion of the Crabtree Creek pluton (Blake and Stoddard, 1993), and if the pluton was emplaced during the Late Proterozoic or Early Cambrian, as suggested by preliminary, discordant  $^{207}\text{Pb}$ - $^{206}\text{Pb}$  ages of 542-566 Ma (Goldberg, this guidebook; Horton and Stern, 1994), then the thrust must be pre-Taconic. More definitive geochronologic work is needed to determine if the timing of events in the Falls Lake region is similar to that in the central Appalachian Piedmont of Virginia and Maryland. There, the formation of melanges and emplacement of thrust sheets preceded emplacement of the Occoquan Granite (479 Ma) and Falls Church Intrusive Suite (481 Ma), and have been attributed to a Late Proterozoic or Cambrian (Penobscot or Cadomian) orogeny (Drake, 1987, 1994).

This scenario is consistent with the hypothesis that the Crabtree terrane represents material exotic to Laurentia, perhaps a continental margin or arc sequence of proto-African or proto-South American origin, which collided with the eastern edge of a slate belt volcanic arc during the Cambrian. On its western side, docking of the slate belt with the Laurentian margin came later, during the Taconic. The Piedmont terranes were later shuffled by dextral faulting during the late Paleozoic, when the Raleigh terrane and Eastern slate belt were transported southward to their present outboard locations. If the Crabtree Creek pluton does not stitch the thrust contact, then the thrust and, by implication, the suturing event, could be as young as early Alleghanian.

## ACKNOWLEDGMENTS

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## THE NUTBUSH CREEK FAULT ZONE, EASTERN PIEDMONT OF NORTH CAROLINA AND VIRGINIA

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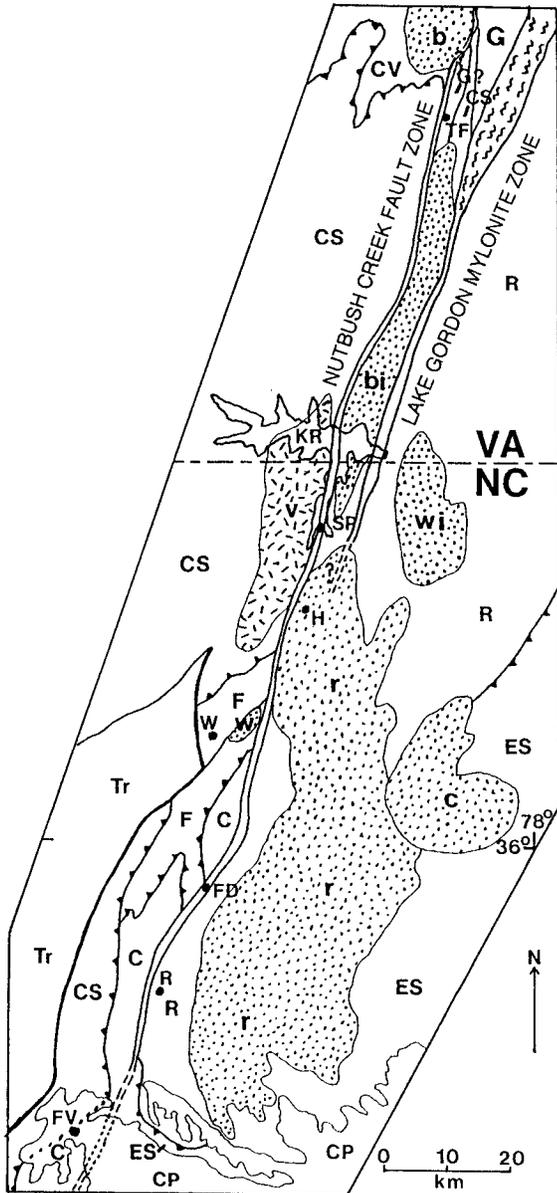
### ABSTRACT

The Nutbush Creek fault zone is part of a regional system of right-lateral Alleghanian faults in the Southern Appalachian orogen that includes the Eastern Piedmont fault system and several other faults as far west as the Brevard zone. In most of the area studied on the western flank of the Raleigh metamorphic belt, the Nutbush Creek fault zone juxtaposes different rock units. It trends north-northeast and is typically about one km wide. The fault zone has been traced by the authors for a total of 200 km, 135 km in north-central North Carolina and 65 in southern Virginia. Linear magnetic anomalies are associated with the exposed Nutbush Creek fault zone. Similar magnetic anomalies along strike beneath Coastal Plain sediments suggest that the fault zone extends farther to the southwest. Whole-rock Rb-Sr geochronology from sheared and unsheared granite plutons brackets the time of shearing between about 312 and 285 Ma. The sense of shear on the Nutbush Creek fault zone is consistently right-lateral, as determined from S-C mylonites, shear bands, asymmetrical porphyroclasts, minor-fold vergence, and asymmetrical boudinage. Horizontal motion is further supported by subhorizontal lineations and steep to vertical crenulations. Amount of displacement along the fault zone is uncertain, with estimates ranging from 160 km to no measurable offset.

### INTRODUCTION

The Nutbush Creek fault zone is part of a major system of Paleozoic faults in the eastern Piedmont. First recognized by Hatcher and others (1977), the Eastern Piedmont fault system extends along the southeastern exposed part of the southern Appalachians and beneath the adjacent Coastal Plain from Alabama to Virginia. Recent studies indicate that the Eastern Piedmont fault system is part of an extensive system of Alleghanian right-lateral strike-slip faults that affects the entire Piedmont, from the Brevard zone to the basement beneath the Coastal Plain overlap (Bobyarchick, 1981; Gates and others, 1986; Gates and Glover, 1989; Edelman and others, 1987; Lawrence and Hoffman, 1993).

Hadley (1973) mapped a fault on the western flank of the Raleigh metamorphic belt, but he did not discuss the evidence for or significance of the proposed fault. The regional extent of the Nutbush Creek fault zone was first recognized and the zone was named by Casadevall (1977), who reinterpreted a strip of mylonites and phyllonites mapped earlier as phyllites by Parker (1963, 1978) in the Kerr Reservoir area near the North Carolina - Virginia border (Figure 1). The phyllonites and mylonites coincide with a linear aeromagnetic anomaly and a topographic lineament, visible on LANDSAT images as well as on topographic maps and aerial photographs. Casadevall (1977) suggested that the fault zone extends for about 120 km into North Carolina and 60 km into Virginia. Druhan (1983) initiated the present study and mapped the Nutbush Creek fault zone in North



## EXPLANATION

### Terrane Names, listed from north to south

- CV** Gneiss terrane of the central Virginia Piedmont
- CS** Volcanogenic terrane of the Carolina slate belt
- G** Goochland terrane
- R** Raleigh terrane
- ES** Volcanogenic terrane of the Eastern slate belt
- F** Falls Lake melange
- C** Crabtree terrane

### Geologic Units

- CP** Coastal Plain sediments, Mesozoic and Cenozoic
- Tr** sedimentary rocks of Durham Triassic basin



- Granite plutons, Late Paleozoic
  - b** Burkeville pluton
  - bi** Buggs Island pluton
  - wi** Wise pluton
  - r** Rolesville pluton
  - c** Castalia pluton
  - w** Wilton



- Vance granitoid pluton, late Proterozoic

### Geographic Locations, listed from north to south

- TF** The Falls
- KR** Kerr Reservoir
- SP** Satterwhite Point
- H** Henderson
- W** Wilton
- FD** Falls Dam
- R** Raleigh
- FV** Fuquay-Varina

Figure 1. Generalized tectonic map of north-central North Carolina and south-central Virginia, showing the Nutbush Creek fault zone and nearby features. Modified after Druhan (1983), North Carolina Geological Survey (1985), Horton and others (1989, 1991, 1992), and Virginia Division of Mineral Resources (1993).

Carolina. Farrar (1985a) shows the Nutbush Creek fault zone in the Raleigh area as a diffuse zone as much as 10 km wide, located generally to the west of where we and others have mapped the main part of the zone (Wylie, 1984; Blake, 1986; Horton and others, 1986, 1991, 1992). Recent maps of the southern Virginia Piedmont show the geologic setting of the Nutbush Creek fault zone and the nearby Lake Gordon mylonite zone to the east (Virginia Division of Mineral Resources, 1993; Horton and others, 1993a, 1993b).

This paper describes and evaluates the geologic characteristics and tectonic significance of the Nutbush Creek fault zone. We have traced the zone for 200 km from Lillington,

North Carolina, where it disappears beneath the Coastal Plain, northward into southern Virginia, where it loses many of its typical aspects (Figure 1). Several geological features are consistently observed along the length of the fault zone and include: (1) intensely deformed mylonites, phyllonites, and L-tectonites in a north-northeast-trending zone with an average width of about one km; (2) mesoscopic and microscopic structures indicating subhorizontal, right-lateral shear sense; (3) juxtaposition of different rock suites and terranes on opposite sides of the fault zone along most of its length; and (4) a linear, positive aeromagnetic anomaly that coincides with the outcrop pattern. The evidence for the amount

## NUTBUSH CREEK FAULT ZONE



Figure 2. Photograph of composite fabric in phyllonite, Satterwhite Point on Kerr Reservoir. Photograph is taken directly downward, with north to the right. Diameter of coin is 2.2 cm.

of displacement on the fault zone is inconclusive, and some critical areas along the fault zone are still poorly understood.

The Nutbush Creek fault zone will be visited at two localities during the 1994 Carolina Geological Society field trip, the “type locality” of the fault zone at Satterwhite Point on Kerr Reservoir, just east of Nutbush Creek (Field Trip, Stop 10) and exposures of the L- and LS- tectonite that constitute the fault zone in Wake County (Stops 9 and 9A).

### GEOLOGIC SETTING

The Nutbush Creek fault zone is tectonically related to several different terranes (Figure 1). Large tectonic units in the northeastern North Carolina Piedmont include the Raleigh terrane, flanked on the west by the volcanogenic terrane of the Carolina slate belt (Carolina terrane) and on the east by the volcanogenic terrane of the Eastern slate belt, which is also called the Spring Hope terrane (Farrar, 1985a; Horton and others, 1986, 1989, 1991; Stoddard and Butler, 1989; Stoddard and others, 1991). The smaller but tectonically significant Falls Lake melange and Crabtree terrane occur just west of the Nutbush Creek fault zone, between the Raleigh terrane and the volcanogenic terrane of the Carolina slate belt. Horton and others (1989, 1992, this guidebook) and Stoddard and others (1991) discuss nomenclature and characteristics of the terranes, so only a brief summary is given here.

The Raleigh terrane is mainly well-banded, locally migmatitic, biotite- and hornblende-bearing gneiss, felsic gneiss,

and mica schist of high metamorphic grade (kyanite and sillimanite zones), intruded by granitic plutons (Blake, 1986; Stoddard and others, 1991). The Raleigh metamorphic belt has a general antiformal structure (Wake-Warren anticlinorium of Parker, 1968) that plunges south-southwest. The flanking volcanogenic terranes of the Carolina and Eastern slate belts have many similarities to each other and may have been laterally continuous before Paleozoic and early Mesozoic faulting. Low-grade metamorphic rocks (chlorite and biotite zones) of these belts have a wide range of volcanic, sedimentary, and intrusive protoliths, and are generally considered to have formed in a magmatic arc environment (Kish and Black, 1982; Feiss, 1982; Rogers, 1982). Recent interpretations consider the Raleigh terrane to be a tectonic window through a large thrust sheet that includes the volcanogenic terranes of the Carolina and Eastern slate belts, although the location and existence of the thrust zone are disputed (Druhan, 1983; Wylie, 1984; Farrar, 1985a; Blake, 1986; Horton and others, 1986, 1989).

### NATURE OF THE NUTBUSH CREEK FAULT ZONE

The Nutbush Creek fault zone is defined by a zone of mylonites, phyllonites, and lineated gneiss generally about one km wide, but locally as wide as three km. Cataclastic rocks are rare in the Nutbush Creek fault zone; narrow breccia zones (one to three meters thick) of limited extent have been found. Near Wilton, North Carolina, Triassic or

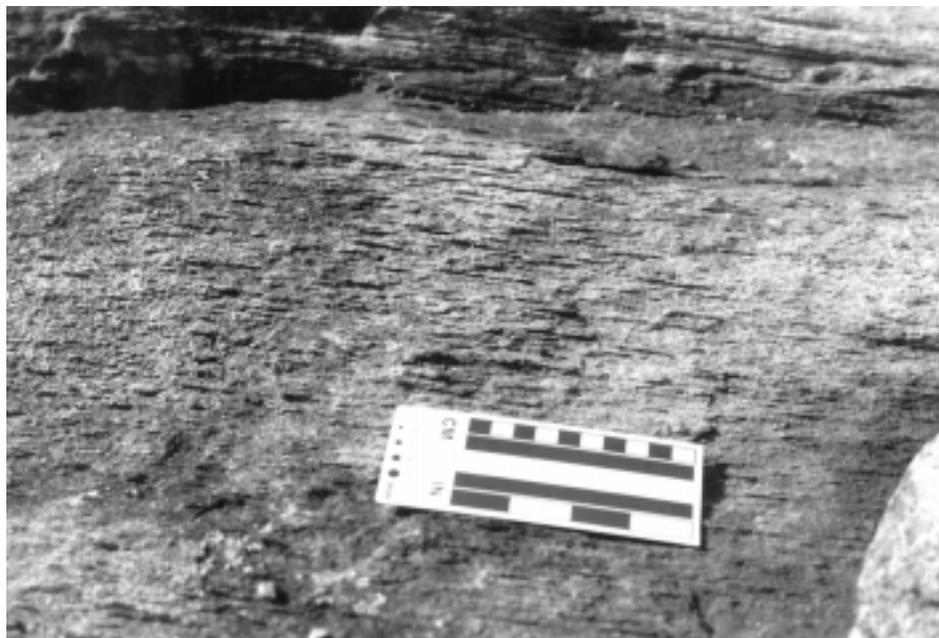


Figure 3. Photograph of lineated gneiss (L-tectonite), just west of emergency spillway at Falls Dam on the Neuse River, north of Raleigh. View toward east, north is to the left, and the lineations plunge about  $3^\circ$  south. Differential weathering makes the elongate quartz aggregates stand out.

younger brittle faults cut older mylonitic rocks in the Nutbush Creek fault zone, but do not noticeably offset the fault zone or extend beyond it to the east (Druhan, 1983).

Metamorphic mineral assemblages and textures indicate that the sheared rocks in the Nutbush Creek fault zone formed under metamorphic conditions ranging from the lower greenschist to amphibolite facies. At many localities, the fault zone is characterized by mylonite and phyllonite and composite S-C fabrics are common (Figure 2). From north of Wilton southward to Fuquay-Varina, the main rock in the Nutbush Creek fault zone is lineated leucocratic granitoid gneiss (Figure 3). This unit, referred to by Farrar (1985b) and Horton and others (1992) as the Falls leucogneiss (informal name) is a spectacular L- and LS-tectonite. We have found strongly lineated gneiss only in zones of high strain, such as the Nutbush Creek fault zone and Lake Gordon mylonite zone. The lineated gneiss is shown on the North Carolina geologic map (North Carolina Geological Survey, 1985) as a narrow unit 75 km long and no more than 3 km wide. Lineated gneisses also are present in the Nutbush Creek fault zone north of The Falls, Virginia, and south of Raleigh near Fuquay-Varina, North Carolina. The lineations are elongate aggregates of microcline, quartz, and magnetite crystals; axial ratios of the aggregates are commonly as much as 15:1. The lineations are subhorizontal and trend consistently N  $15\text{--}20^\circ$  E or S  $15\text{--}20^\circ$  W, parallel to the boundaries of the Nutbush Creek fault zone. We interpret the lineations to have formed by stretching parallel to the direction of movement along the fault zone, coincident with recrystalli-

zation under amphibolite-facies conditions.

Mineral assemblages and metamorphic textures suggest that the lineated gneiss near Raleigh was probably deformed under relatively high temperature conditions at lower to middle amphibolite facies conditions, based on the ductile behavior of both quartz and microcline, and on extensive recrystallization and recovery of the deformed minerals. North of Wilton and in the Lillington area, deformation was probably at greenschist-facies conditions, as indicated by finer grain size in the mylonitic rocks and by the abundant low-grade minerals such as chlorite, epidote, actinolite, and albite that define the mylonitic fabric.

## GEOLOGY OF SELECTED AREAS

### General Statement

Our studies have concentrated on selected areas along the Nutbush Creek fault zone, where it is best exposed and has features critical to interpretation of the tectonic history of the zone. Several of these areas are discussed below. Some critical areas have not been mapped in detail, including the northern part of the zone in the Virginia Piedmont, and in the North Carolina Piedmont just south of Raleigh.

### Southern Virginia

In southern Virginia (Figure 1), the Nutbush Creek fault zone is located along the western side of the Buggs Island

## NUTBUSH CREEK FAULT ZONE

granite pluton and locally is the boundary between the pluton and the volcanogenic terrane of the Carolina slate belt to the west (Virginia Division of Mineral Resources, 1993; Horton and others, 1993a). The eastern boundary of the pluton is the recently recognized Lake Gordon mylonite zone (Horton and others, 1993b), which apparently extends southward to the vicinity of Henderson, North Carolina, in an area that is not yet adequately mapped.

The Buggs Island pluton is a 55-km-long granite intrusion, having a maximum width of 6 km (Horton and others, 1993a; Virginia Division of Mineral Resources, 1993). The pluton is located between the Nutbush Creek and Lake Gordon mylonite zones, and as a consequence it is moderately to strongly sheared on both its western and eastern boundaries (Horton and others, 1993a, 1993b). Parts of the granite have composite S-C fabrics that consistently indicate right-lateral shear. The granite locally has mylonitic fabric (Horton and others, 1993b) and evidence of high-temperature deformation and recrystallization. All of the granite is deformed, but the deformation is progressively more intense near the boundaries of the pluton. We conclude that the emplacement of the Buggs Island granite is at least partly contemporaneous with movement along the two mylonite zones.

Near The Falls, Virginia, several changes in geologic relationships are observed, summarized as follows: (1) the Nutbush Creek fault zone narrows, is difficult to trace, and loses its characteristic positive magnetic anomaly; (2) the northern end of the Buggs Island pluton is mapped just south of The Falls; (3) the volcanogenic terrane of the Carolina slate belt ends at a sinuous northwest- to west-trending tectonic contact, along which metavolcanic rocks of the slate belt, to the south, are in contact with a gneissic terrane (lithologically similar to the Raleigh terrane but of uncertain affinity) to the north (Figure 1), that includes migmatitic paragneiss, granitic gneiss, mica schist, and thin amphibolite bodies (Virginia Division of Mineral Resources, 1993; Rader and Evans, 1993); and (4) the Lake Gordon mylonite zone widens, changes strike from N 20° E to N 30° E and continues north-northeast to join with the Hylas mylonite zone near Richmond, Virginia (Horton and others, 1993b; Virginia Division of Mineral Resources, 1993).

Based on the above observations, our interpretation is that displacement on the Nutbush Creek zone in southern Virginia decreases northward and displacement is transferred to the Lake Gordon zone. The Buggs Island pluton is emplaced in a releasing bend or step in the dextral fault system, where the major displacement is transferred in a right-stepping *en echelon* pattern to the Lake Gordon zone (Figure 1).

Our geologic reconnaissance west of The Falls indicates that metavolcanic rocks of the volcanogenic terrane of the Carolina slate belt overlie the gneissic terrane along a contact that may be a pre-metamorphic thrust fault. The contact zone is defined by several tens of meters of laminated schis-

tose rocks that we interpret to be metamorphosed mylonite. The contact between the terranes is truncated to the east by the Nutbush Creek fault zone.

### Satterwhite Point, North Carolina

The Nutbush Creek fault zone was first identified in the region of Satterwhite Point, North Carolina by Casadevall (1977). This location (Figure 1) is one of the best places to study progressive fabric development with increased shearing at the western contact of the fault zone. A geologic map of Satterwhite Point and further descriptions of the rocks are given in the information on field trip stops in this guidebook. Most of the mylonites and phyllonites at Satterwhite Point were derived from rocks of the Carolina slate belt to the west of the fault zone. The Vance pluton is a granitic batholith west of Satterwhite Point that intrudes metavolcanic rocks of the Carolina slate belt. The pluton, also called the Vance County pluton (Casadevall and Rye, 1980), has a zircon U-Pb age of  $571 \pm 17$  Ma (LeHuray, 1989). The eastern part of the Vance pluton is sheared by the Nutbush Creek fault zone. At Satterwhite Point, a traverse can be made eastward from the relatively undeformed granitoid rocks of the pluton into their mylonitized equivalents in the fault zone. East of the mylonites derived from rocks of the Vance pluton, phyllonites are the sheared equivalents of metavolcanic rocks from the volcanogenic terrane of the Carolina slate belt. Phyllonites commonly show S-C composite fabric having right-lateral sense of shear (Figure 2).

Mylonitic rocks in the eastern part of the Nutbush Creek fault zone were derived from rocks similar to those in the adjacent Raleigh terrane east of the fault. On the eastern side of Satterwhite Point, mylonitized biotite gneiss and granitic gneiss, and strongly sheared pegmatite dikes occur in saprolite exposures. Rocks of the Raleigh terrane that are not mylonitized are exposed on the lakeshore about 1100 m east of Satterwhite Point, but the boundary of the fault zone is poorly exposed.

### Falls Lake Area, North Carolina

The Falls Lake area northwest of Raleigh is a key area where relationships of several major tectonic features can be determined (Parker, 1979; Stoddard and others, 1986, 1991, this guidebook; Horton and others, 1986, 1992, this guidebook). These features are a focus of the 1994 Carolina Geological Society field trip. West of the Nutbush Creek fault zone, the Crabtree terrane is structurally overlain by the Falls Lake melange and rocks of the volcanogenic terrane of the Carolina slate belt. Contacts between these terranes are interpreted to be thrust faults, the Falls Lake thrust and an inferred higher thrust (Horton and others, 1992, this guidebook; Stoddard and others, this guidebook). The terranes and intervening fault zones were folded and metamorphosed dur-

ing the Alleghanian orogeny. The Falls Lake thrust is truncated on the east by the Nutbush Creek fault zone. These features are shown on the 1:24,000 scale geologic map of the Falls Lake area (Horton and others, 1992).

In this area, the Nutbush Creek fault zone is defined by lineated leucocratic granite gneiss (Figure 3), an early Paleozoic granitoid strongly deformed during the late Paleozoic. The lineated leucocratic gneiss generally does not show prominent shear-sense indicators. Locally, mica-rich zones in the lineated gneiss have composite S-C fabric indicating right-lateral shear sense.

### South of Raleigh, North Carolina

The southernmost exposures of the Nutbush Creek fault zone occur 40 km south of Raleigh (Figure 1). Farther south, crystalline rocks of the Piedmont are covered by sediments of the Coastal Plain. West of the Nutbush Creek fault zone, the gneiss at Raven Rock (as used informally by Stoddard and others, 1991, p. 84), which is correlated with the Crabtree terrane, lies structurally below rocks of the volcanogenic terrane of the Carolina slate belt. The boundary between the two terranes is a thin-layered schist with a thickness of 30 to 50 m. This boundary is interpreted to be a thrust fault analogous to the Falls Lake thrust (Stoddard and others, 1991).

East of the Nutbush Creek fault zone are rocks of the volcanogenic terrane of the Eastern slate belt. They structurally overlie rocks of the Raleigh terrane. The boundary between these two terranes, 13 km south of Raleigh, is inferred to be a thrust fault and is apparently truncated to the west by the Nutbush Creek fault zone. Along the boundary, low-grade metavolcanic rocks to the southwest overlie the Raleigh terrane, which includes migmatitic gneiss, granitic gneiss, mica schist, and layers of amphibolite. The boundary strikes northwest and dips moderately southwest. Druhan and others (1988) speculated that this northwest-trending thrust(?) contact is truncated by the Nutbush Creek fault zone and displaced by 160 km of right-lateral movement. According to this model, the correlative contact *west* of the Nutbush Creek fault zone is the northern end of the volcanogenic terrane of the Carolina slate belt near The Falls, Virginia. In that area, metavolcanic rocks also structurally overlie a gneissic terrane along a northwest-trending, southwest-dipping contact (Figure 1).

In central and southern Wake County, at least four thin layers of graphite-rich mica schist, belonging to the Crabtree terrane, can be traced for tens of kilometers and are excellent markers helping to define the folds and faults (Parker, 1979; Horton and others, 1992, this guidebook; Lumpkin and others, 1994, this guidebook). Such continuous graphite schist layers are restricted to the Crabtree terrane, as they are unknown in the Raleigh terrane and volcanogenic terrane of the Carolina slate belt. Near Fuquay-Varina, south of Raleigh, several graphite-rich layers are exposed west of the

projected trace of the Nutbush Creek fault zone and at least one graphite-rich horizon is exposed east of the trace in rocks considered to be part of the volcanogenic terrane of the Eastern slate belt. Thus, the graphite horizon appears to cross the fault zone without offset. Most of this critical area is obscured by sediments of the Coastal Plain, and the few exposures are small and deeply weathered, so resolution of the problem will be difficult. Existing geologic maps are inadequate to resolve the problem, and the area is being remapped.

In this area, the positive magnetic anomaly marking the position of the Nutbush Creek fault zone is offset *en echelon* to the right, suggesting a corresponding offset in the Nutbush Creek fault zone. The Nutbush Creek zone may be displaced by a brittle fault (Triassic?) or some other structure.

### MYLONITIC FABRIC AND KINEMATIC INDICATORS

The mapped contacts of the Nutbush Creek fault zone strike N-S to N 25° E. Within the fault zone, mylonitic foliation and compositional layering are nearly ubiquitous, except in the lineated gneiss (L-tectonite). The strike of the mylonitic foliation and of the compositional layering is essentially parallel to the contacts of the zone, and foliation and layering generally dip steeply to the east or west. Structures in the Nutbush Creek fault zone are consistent in their appearance and orientation along the entire length of the zone. The variation in orientation of planar and linear structures in a single large outcrop (*e.g.*, emergency spillway at Falls Dam) is illustrated by data from Mims (1988; Mims and others, 1990; see field trip stop description). Figure 4A shows consistency in foliation orientations from southern Virginia to the Lillington area of North Carolina. There is some dispersion of foliation orientation caused mainly by slight changes in strike of the Nutbush Creek fault zone. Along most of the fault zone, foliation dips steeply to the NW, but in the Falls Lake and western Raleigh areas, the dips are mainly to the SE (Figure 4A). Lineation orientations along the length of the fault zone are consistent; the plunge of lineations fluctuates slightly along the fault zone, but it is everywhere horizontal or nearly so (Figure 4B).

Along the entire mapped length of the Nutbush Creek fault zone, the following fabric elements indicate a right-lateral, subhorizontal sense of shear: (1) S-C composite fabrics (Figure 2); (2) shear bands (C'); (3) rotated porphyroclasts; (4) asymmetry of steeply plunging mesoscopic and microscopic folds; and (5) orientation of elongate mineral aggregates in the lineated gneiss (Druhan, 1983; Bartley and others, 1984; Wylie, 1984; Blake, 1986). Kinematics were interpreted using the methods of Simpson and Schmid (1983), Lister and Snoke (1984), and Dennis and Secor (1990). Mylonitic foliation is considered to be a C-plane, as it is generally parallel to the boundaries of the zone. Slip

## NUTBUSH CREEK FAULT ZONE

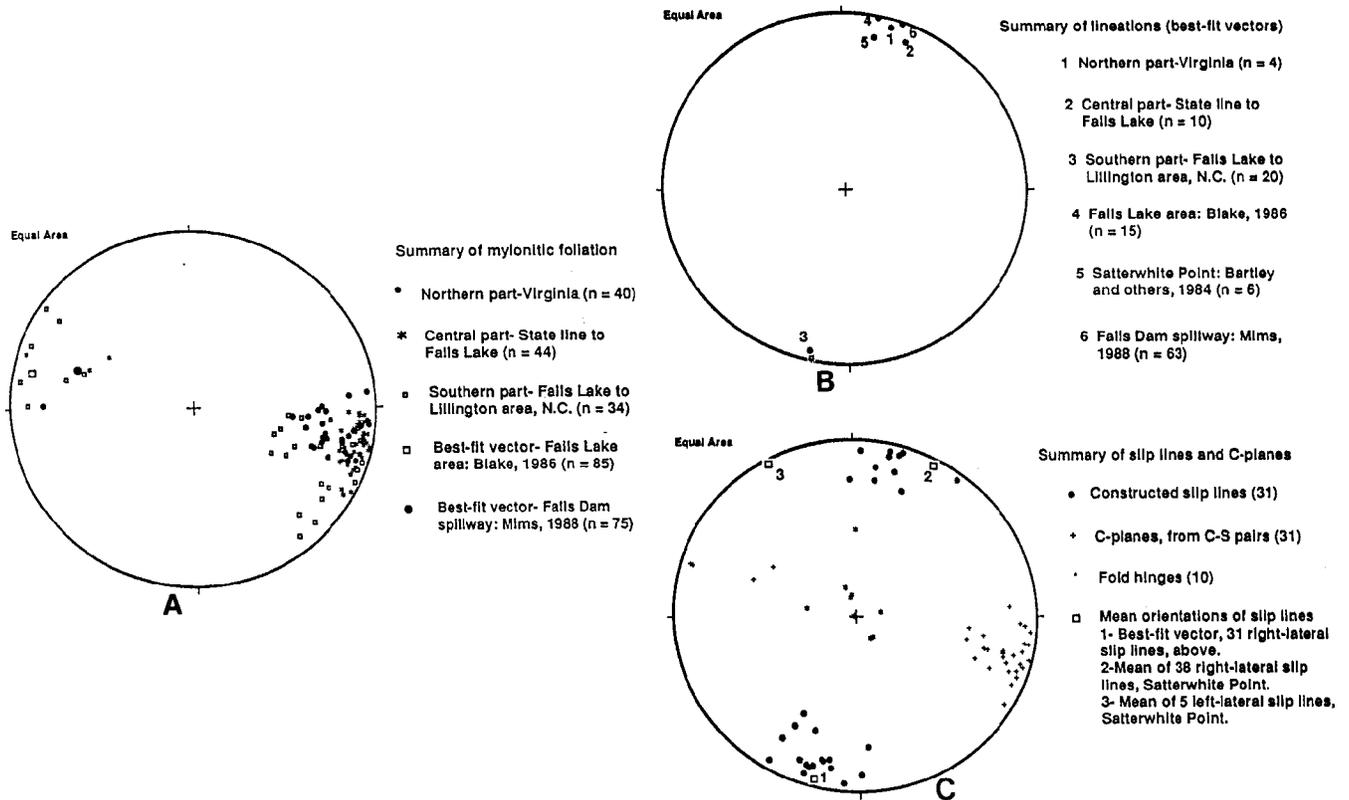


Figure 4. Stereographic projections (equal-area net, lower hemisphere) of structural features along the Nutbush Creek fault zone in North Carolina. A. Poles of foliations from three segments of the NCFZ (small dots- Virginia segment, n=40; stars- VA-NC state line to Falls Lake area, n=44; small boxes- south of Falls Lake area, n=34) and two areas mapped in detail (large dot- Falls Dam, n=75, Mims, 1988; box- Falls Lake area, n=85, Blake, 1986). B. Summary of lineations (best-fit vectors) from three segments of the NCFZ and three areas mapped in detail. 1- Virginia segment, n=4; 2-VA-NC state line to Falls Lake area, n=10; 3-south of Falls Lake, n=20; 4-Falls Lake area, n=15, Blake, 1986; 5-Satterwhite Point, n=6, Bartley and others, 1984; 6-Falls Dam, n=63, Mims, 1988. C. Constructed slip lines, mean orientations of slip lines, and poles of C-planes. Data from Satterwhite Point are from Bartley and others (1984) and J.W. Mies (unpublished data).

lines are obtained from S-C composite fabric, assuming that the S-planes approximate the XY plane of the finite strain ellipsoid and the C-planes are simple shear planes. The constructed slip lines lie in the C-plane and are perpendicular to the intersection of the S and C planes. Dennis and Secor (1990) showed that slip direction is not necessarily orthogonal to the intersection of S and C planes; however, when stretching lineations are perpendicular to crenulation axes, the overall transport direction is approximately perpendicular to the crenulation axes. In data from the Nutbush Creek fault zone (Figure 4C), the lineations are approximately perpendicular to the crenulation and small fold axes and we conclude that it is valid to construct slip lines from S-C composite fabric.

Slip lines were constructed for 31 of the best developed S-C pairs (Figure 4C) at outcrops in the Nutbush Creek fault zone from southern Virginia to the Lillington area, North Carolina. Scatter in the constructed slip lines reflects variations in strike and dip of the fault zone over a distance of 200 km, as well as errors in constructing the intersections of

planes that subtend a relatively small acute angle. The best-fit vector of the 31 slip lines plunges 4° SSW. (Figure 4C). In detailed structural studies at a single locality (Satterwhite Point), Bartley and others (1984; J. W. Mies, unpublished data) found that the mean orientation for 38 constructed S-C slip lines plunges 4 degrees NNE (Figure 4C). They also determined slip lines for five minor, antithetic left-lateral shear zones (Figure 4C). Small-scale folds (amplitudes less than 30 cm) and crenulations that fold the mylonitic foliation consistently have hinges that plunge steeply and show a clockwise sense of rotation, indicating right-lateral shear (Figure 4C).

In summary, the fabric data indicate highly consistent right-lateral, essentially horizontal slip along the Nutbush Creek fault zone. There are no significant changes in the appearance of the mylonitic fabric, its orientation, or the sense of displacement along the 200 km segment of the Nutbush Creek fault zone discussed here.

## AGE OF FAULTING

The main episode of shearing along the Nutbush Creek fault zone is bracketed by whole-rock Rb-Sr ages of two granite plutons. The older constraint is the age of Buggs Island pluton that is located between the Nutbush Creek and Lake Gordon fault zones in southern Virginia (Figure 1). The Buggs Island pluton has a whole-rock Rb-Sr age of  $312 \pm 15$  Ma and an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.7046 \pm 0.0002$  (Kish and Fullagar, 1978; Kish, 1983). Fabrics indicative of crystal-plastic deformation demonstrate that the Buggs Island pluton was emplaced before the latest stages of shearing along the two fault zones. The Buggs Island pluton therefore provides an older age limit for at least part of the ductile deformation in the Nutbush Creek fault zone and the Lake Gordon mylonite zone.

The younger age bracket is provided by the Wilton pluton, which intrudes strongly sheared rocks along the western contact of the Nutbush Creek fault zone (Druhan, 1983). The granite of the Wilton pluton (Figure 1) is mostly massive, but locally has a faint biotite foliation. In thin sections, quartz has moderate to strong undulatory extinction (Carpenter, 1970; Farrar, 1985a), but neither quartz nor feldspar has a readily visible shape fabric that can be attributed to ductile deformation. The granite intrudes highly deformed rocks but contains little evidence of strain. Samples of granite from the Wilton pluton have a whole-rock Rb-Sr model age of  $285 \pm 10$  Ma (Klinge, 1977; Fullagar and Butler, 1979). All samples had high  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{87}\text{Rb}/^{86}\text{Sr}$  ratios; therefore, an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.705 was assumed in calculating the age. The assumed ratio is slightly higher than the median initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio for 17 late Paleozoic granites in the southern Appalachians (Fullagar and Butler, 1979). Use of a lower initial ratio would result in a greater model age for the pluton. The assumed initial ratio of 0.705 gives the best fit to the isotopic data; however, use of other initial ratios reported by Fullagar and Butler (1979), excluding the extreme values, would change the age only about 10%. We consider the model age of  $285 \pm 10$  Ma to be an approximate younger limit on the age of ductile deformation and movement along the Nutbush Creek fault zone. The ages and field relationships of the Buggs Island and Wilton plutons therefore closely constrain the major faulting to about 312-285 Ma (Pennsylvanian). Evidence for significant earlier deformation is lacking, although the possibility has not been eliminated.

Mineral dates by Rb-Sr and conventional K-Ar methods on samples from the lineated gneiss and western Raleigh terrane indicate that these rocks did not cool through a temperature of about  $300^\circ\text{C}$  until 250-240 Ma (Russell and others, 1985), 40 to 60 Ma after the main movement on the Nutbush Creek fault zone.

## CONSTRAINTS ON DISPLACEMENT

Druhan and others (1988) speculated that right-lateral displacement along the Nutbush Creek zone is about 160 km, based on right-lateral separation of a metavolcanic rock/gneiss contact and on the fabric evidence for horizontal displacement discussed above. One contact is between rocks of the volcanogenic terrane of the Eastern slate belt and underlying gneisses of the Raleigh terrane (south of Raleigh and east of the Nutbush Creek zone) and the other contact is between rocks of the volcanogenic terrane of the Carolina slate belt and underlying gneisses near The Falls, Virginia (west of the Nutbush Creek zone) (Figure 1).

At both localities, rocks along and adjacent to the contact are similar (metavolcanic terrane structurally over gneissic terrane) and probable metamorphosed mylonites nearest to the Nutbush Creek zone have foliations that strike northwest and dip southwest. Structural fabrics within the Nutbush Creek fault zone discussed above indicate horizontal movement during ductile deformation, so the strike separation of the contact may approximate the true displacement on the fault zone. The critical areas near The Falls, Virginia, and south of Raleigh, North Carolina, must be studied in detail to test this hypothesis.

On the other hand, if individual graphite schist marker beds are demonstrated to extend across the full width of the Nutbush Creek fault zone without offset, then right-lateral slip along the fault zone would be negligible (Lumpkin and others, 1994, this guidebook), at least in the segment south of Raleigh. The amount of slip along the fault zone may vary along strike, and the zone is part of a regional system, so movement may be transferred to other faults in the system. The Nutbush Creek fault zone is clearly an important member of the Alleghanian fault system in the southern Appalachian Piedmont, but many questions remain about its tectonic history and relationships to other segments of the fault system.

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## NATURE OF THE ROLESVILLE BATHOLITH, NORTH CAROLINA

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### ABSTRACT

The Rolesville batholith is a composite body, 2000 km<sup>2</sup> in area, comprised of a north-northeast trending cluster of elongate granitoid plutons. It is emplaced in the Eastern slate and Raleigh metamorphic belts of northeastern North Carolina. The component granitoids are strongly similar in composition, mineralogy, and texture. The plutons of the batholith are identifiable by intervening trains of enclaves, either wall-rock xenoliths or granitoid autoliths. Many of these internal intrusive contacts extend to cusped reentrants in the batholith contact. These multiple plutons can be further substantiated in some instances by differences in mineralogy and texture of the granitoids on either side of the internal contacts. Individual bodies are elongate parallel to and centered on the southern termination of the Macon mylonite zone. The Rolesville batholith is comparable to cryptically sheeted plutons that have been emplaced by repeated diking in active shear zones. An important difference is that the Rolesville batholith is neither as tabular nor as deformed as is usual for sheeted plutons. The magmatic event either outlasted or moved beyond the limits of the controlling Alleghanian deformation event confined within the shear zone.

### INTRODUCTION

The outcrop shapes of late Paleozoic granitoid plutons emplaced during the Alleghanian Orogeny in the southern Appalachians range from nearly circular away from Alleghanian ductile shear zones through elliptical to elongate adjacent to and within these shear zones (Speer and others, 1994). Most are composite bodies, that is, they are built up of several magma pulses. For most of the Alleghanian plutons in the southern Appalachians, it is a straightforward effort to discover and work with the composite nature of these bodies. The differing magmas have crystallized to form easily distinguishable units based on either or both texture and mineralogy. These features are readily mappable and their field differences can be observed in mineral and rock compositional differences as well. However, there is a set of granites for which this is not true. These are the larger elliptical and elongate bodies that occur in deformation zones. The initial efforts to unravel the intrusive history of one such group of granites, the Rolesville batholith, are described here.

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The Rolesville batholith, located in the Eastern slate and Raleigh metamorphic belts of North Carolina, is a north-northeast trending cluster of elongate to elliptical granitoid bodies. The geographic distinctiveness of this cluster was first recognized by Watson (1904), and they formed one part of his northeastern Carolina granite belt. The general extent of the batholith was shown on the 1958 Geologic map of North Carolina (N. C. Division Mineral Resources, 1958). Stuckey (1965) termed the rocks the Rolesville granite. Regional maps of the Rolesville batholith, defined here to include the Castalia body as done by earlier workers, were presented by Parker (1968), and later by Farrar (1985a,b). More detailed mapping of portions of the batholith are presented by Julian (1972), Parker (1979), McDaniel (1980), Carpenter (1990), Horton and others (1992), and Stoddard (1993). The later three references, as well as the work reported here, are part of a program of the North Carolina Geological Survey and U. S. Geological Survey to map the Raleigh 1:100,000 Sheet. Figure 1 is a compilation of these maps. For a discussion of the regional geology and wall rocks of the Rolesville batholith, see Horton and others (this guidebook).

### Composite Nature

The Rolesville batholith is the largest single pluton in the southern Appalachians, covering over 2000 km<sup>2</sup> in outcrop. The size makes it unlikely that it represents a single magma pulse. Granitoids within the pluton differ in texture, mineralogy, and modal abundances. This is also an indication that the Rolesville batholith is a composite pluton assembled from differing magmas. Farrar (1985a,b) mapped four texturally-defined and geographically distinct granite facies within the Rolesville batholith. However, one of these, the Rolesville main facies granite, comprises most of the pluton. It is also large, suggesting it might be a composite pluton as well. It is variable in texture, but the presence of multiple granites within it can be readily confirmed by the cross-cutting and inclusion relationships in fresh, large exposures. This will be evident at the pavement outcrop at the fieldtrip stop on Norris Creek during the 1994 Carolina Geological Society meeting. Here the juxtaposition makes the differences readily apparent. However, the rocks are so similar that it is easy to understand the difficulty of mapping different granite facies if the exposures were separated, had

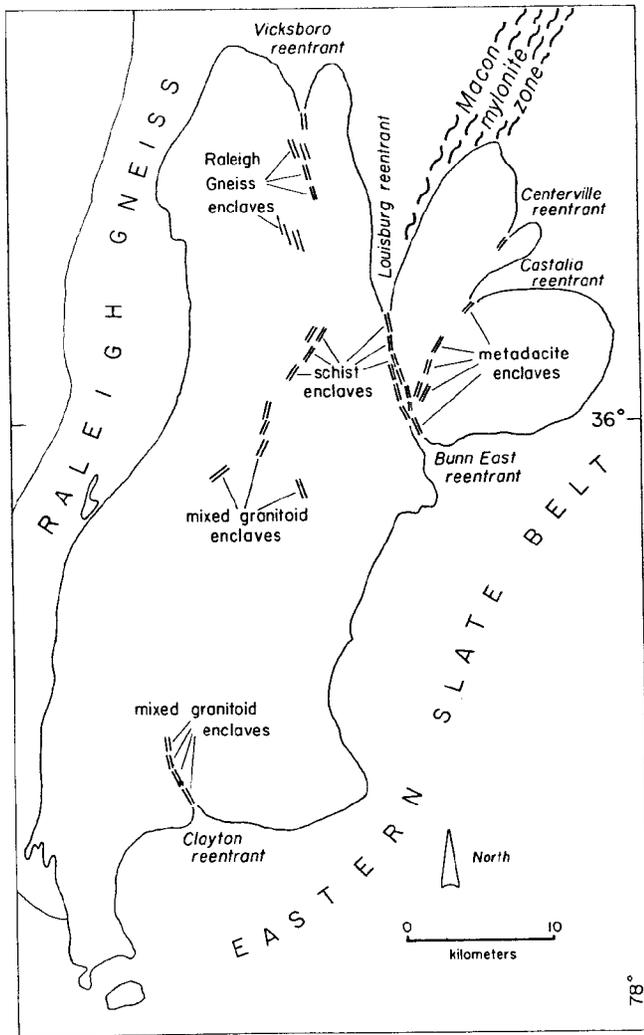


Figure 1. Sketch map of the Rolesville batholith, North Carolina showing some of the wall rock features, the enclave train locations, and reentrants at the pluton contact. The map is compiled from mapping by Farrar (1985b), Carpenter (1990), Horton and others (1992), and unpublished mapping by T. L. Clark, P. A. Carpenter III, R. H. Carpenter, J. A. Speer and E. F. Stoddard.

differing weathering and viewing conditions, and were examined several hours, days, weeks or years apart. With petrographic differences too subtle to be easily used in field mapping, how can we determine if the remaining portion of the Rolesville batholith comprises many individual plutons?

One approach would be to look for contacts between granites within the batholith. This can be done on the basis of map geometry and intrusive contacts. Parker (1968) recognized the somewhat circular and detached northeast portion of the batholith as distinct. This portion had largely discordant contacts, as opposed to concordant contacts in the rest of the batholith. Further, this detached portion is connected to the rest of the batholith by an area containing a

large portion of “gneiss”. He suggested that it was a separate pluton. Using similar criteria, Julian (1972) also interpreted this broad protrusion of the Rolesville batholith as a separate pluton and termed it the Castalia adamellite. Julian (1972) found that the Castalia pluton has two lobes separated by a belt of mixed gneisses, granitic rocks, and pegmatites. The granite of the northern lobe was found to be finer-grained than that in the southern lobe, but he treated the two lobes as products of the same magma.

Tyler Clark (unpub. map) re-examined the contacts between the Rolesville portion of the batholith west of the Castalia and Castalia plutons and between the northern and southern lobes of the Castalia. He confirmed that these were zones of relatively abundant enclaves of granitic and metamorphic rocks. But, more importantly, he found that the metamorphic enclaves comprised distinctive country rocks and could be traced back out of the pluton to their occurrence in cusped reentrants in the pluton wall. There is one zone between the Rolesville pluton and northern lobe of the Castalia pluton of muscovite schist xenoliths that can be traced northward into the Louisburg reentrant that contains the biotite-muscovite schist of the Macon Formation and mylonite zone (Figure 1). Between the Rolesville and southern lobe of the Castalia is a zone of xenoliths of fine-grained, laminated metadacite that can be traced southward into comparable wall rocks described and mapped in the Bunn East reentrant by Stoddard (1993) (Figure 1). This zone of metadacite enclaves also extends to the northeast between the northern and southern lobes of the Castalia, eventually joining up with the Castalia reentrant (Figure 1). A previously unrecognized small body of finer-grained granite lies within this zone. Significantly, these enclave zones separated what had been previously suspected to be differing granites based on minor textural differences.

Elsewhere in the batholith there are wall rock cusped reentrants and zones of enclaves (Figure 1). Raleigh gneiss xenoliths extending southward from the Vicksboro reentrant were recognized by Farrar (1985a,b). The schist, siltstone, and gneiss xenoliths adjacent to the Louisburg reentrant were mapped by McDaniel (1980). In each case the enclave lithology is that of the adjacent wall rocks. The enclave zones recognized south of the 36° parallel for this study (Figure 1) more commonly comprise texturally distinct granitoid autoliths, rather than country rock xenoliths. These are interpreted as internal intrusive contacts. One zone extends northward from the Clayton reentrant. The other zones are isolated well within the interior of the pluton. These granitoid enclave zones are similar to, but a more subtle feature than the xenolith zones described above. This feature may seem rather trivial in a body so large, but it provided a starting point for a closer examination of granite petrography throughout the Rolesville batholith.

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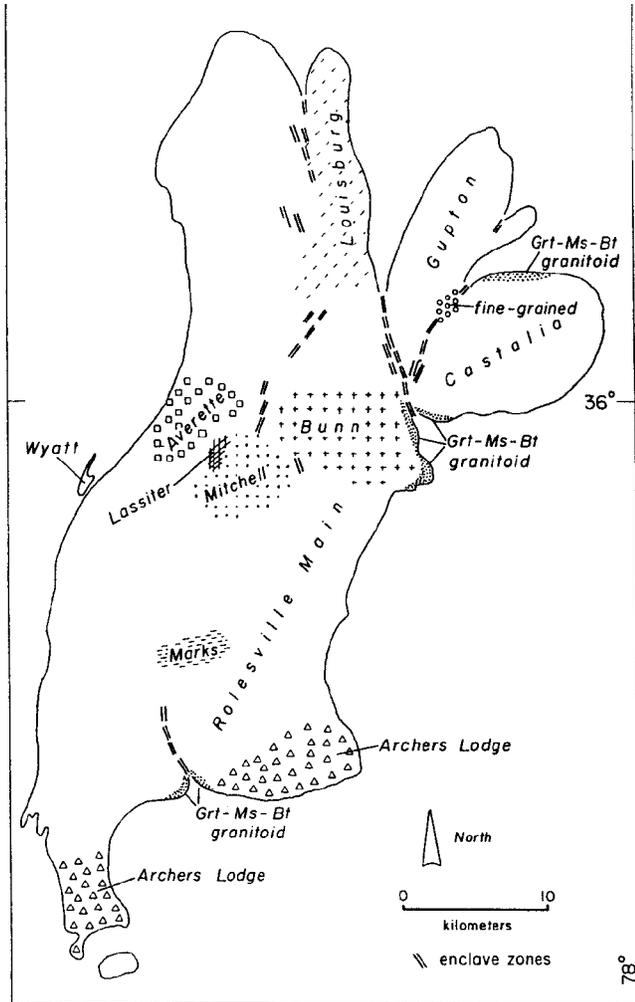


Figure 2. Sketch map of the Rolesville batholith, North Carolina showing areal extent of the identified component granitoid facies. The granitoids are described in the text.

### Granitoids of the Rolesville Batholith

Differing granitoid facies occur on either side of the enclave zones in the Rolesville batholith. Volumetrically minor but distinct granitoid facies also occur within these zones. About sixteen texturally and mineralogically distinct granitoid facies have been recognized (Figure 2). These granitoids are more similar than different. They are dominantly monzogranites (Figure 3), with the varietal minerals biotite + muscovite. The distinction among them is mostly textural as described below. These facies are geographically limited within the pluton but are seldom continuous within those areas. Rather they are disrupted and intruded by or contain abundant enclaves of the Rolesville main granitoid facies, the most widespread and abundant rock type.

*Archers Lodge granitoid*: a coarse-grained biotite monzogranite with alkali feldspar megacrysts up 3 cm long.

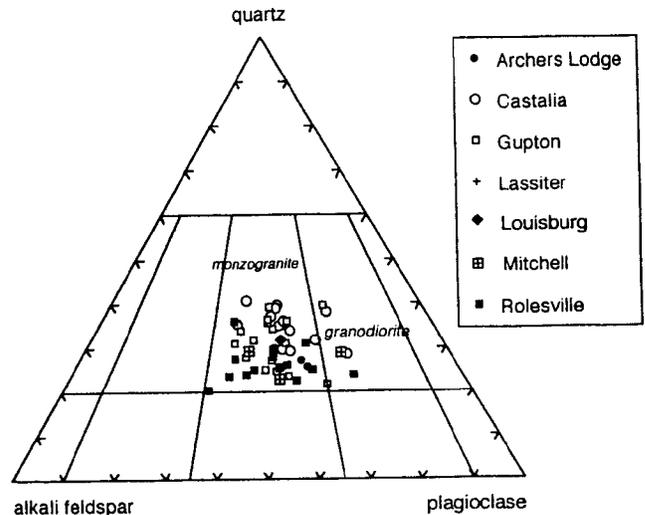


Figure 3. Modal distribution of quartz, alkali feldspar, and plagioclase for the Rolesville batholith, North Carolina. Modal classification used is the IUGS-approved system (LeMaitre, 1989). Data are from Becker and Farrar (1977) and Julian (1972).

It was first recognized by Farrar (1985a,b) who mapped two separate areas of this rock type (Figure 2). In the southeast recess of the batholith, the Archers Lodge granite has what is interpreted as a subsolidus deformational fabric and occurs as large enclaves within other, undeformed granitoids. These features indicate that the Archers Lodge granitoid here formed part of an earlier pluton disrupted and deformed by the intrusion of younger magmas. The Archers Lodge granitoid in the southern tip of the batholith is unfoliated.

*Averette granitoid*: a massive, coarse-grained biotite + muscovite granitoid at the west central margin of the batholith. This granitoid is newly recognized. It is distinguished by an abundance of subhedral, orange alkali feldspar megacrysts to 1 cm. To the south and east of its outcrop, the alkali feldspar megacrysts become less abundant and the Averette granitoid appears to have a gradational contact with the Rolesville main granitoid. Foliation is developed near the external contact of the batholith.

*Border, peraluminous granitoids*: fine to coarse grained garnet + muscovite + biotite granitoids that occur in narrow zones, less than 1 kilometer wide, at four separate places on the batholith contact. All are adjacent to reentrants (Figure 1). Two are on either side of the Bunn East reentrant in the Rolesville and Castalia plutons (Stoddard, personal communication). One is at the northern margin of the Castalia pluton within the Castalia reentrant. As this is the location of the only quarry in the Castalia pluton, it has given an erroneous impression that the entire pluton is peraluminous. Lastly, there is one bordering the Clayton reentrant at the southern border of the pluton. This granitoid is the only fine-grained peraluminous granitoid and it has a strong lineation.

*Bunn granitoid*: a massive, medium- to coarse-grained biotite + muscovite granitoid identified in this study. It is

identical to the Rolesville main granite but is distinguished microscopically by the accessory mineral monazite. The rare earth element mineral in the rest of the batholith is allanite. The area of the Bunn granitoid is also characterized by zoned pegmatites containing smoky quartz that are more abundant as compared to elsewhere in the Rolesville pluton.

*Castalia granitoid*: a medium- to coarse-grained biotite monzogranite occupying the southern lobe of the Castalia pluton. The Castalia pluton was originally distinguished from the rest of the Rolesville batholith by Parker (1968), Julian (1972), and Farrar (1985a) on the basis of its separation from the main pluton and discordant relationship with the country rock. This granitoid differs from other rocks of the Rolesville pluton by slightly more uniformity in grain size, lower color index, and by blocky alkali feldspars 2 cm in size. Local inclusions of amphibole in quartz indicate amphibole was an early crystallizing phase.

*Gupton granitoid*: a fine- to medium-grained biotite granite occupying the northern lobe of the Castalia pluton. Julian (1972) recognized it as finer grained than the Castalia granitoid. It lacks the distinctive alkali feldspars of the Castalia granite and is locally intruded by garnet-bearing pegmatites up to 10 meters across.

*Lassiter granitoid*: a fine grained, light gray biotite + muscovite monzogranite. It is distinguished from the other granitoids by a higher color index of 10 and a finer grain size. Average grain size is 1.5 mm, though some anhedral feldspars range up to 10 mm. It is the earlier finer-grained, medium dark quartz monzonite of Parker (1968), the fine- to medium-grained biotite quartz monzonite of Dalheim and Kuryvial (1980), and the fine- to medium-grained, light-gray biotite granite of Horton and Stern (1994).

*Louisburg granitoid*: a foliated, fine- to medium-grained biotite monzogranite with quartz and feldspar grains of 1-2 mm (Farrar, 1985a). Unlike the other facies of the Rolesville pluton, it has sharp contacts with the other granitoids.

*Marks granitoid* is a massive, medium-grained (1-3 mm) biotite + muscovite granitoid with a color index of 3. It contains alkali feldspar up to 5 mm.

*Mitchell granitoid*: a massive, medium-grained (1-4 mm) biotite + muscovite monzogranite to granodiorite with a color index of 5. The distinguishing feature of this granitoid is its color. The feldspars are white and the quartz light gray, giving the rock a white color rather than the light orange of the remainder of the batholith. The Mitchell granitoid is the later coarser-grained granite with less biotite of Parker (1968), the lighter, coarser-grained biotite granite of Dalheim and Kuryvial (1980), and medium to coarse grained, very light grey biotite granite of Horton and Stern (1994).

*Rolesville main granite*: a medium- to coarse-grained biotite + muscovite monzogranite with a color index of 2-10 named by Farrar (1985a). The Rolesville main granite varies in appearance, with a range in color index and grain size, development of a foliation, as well as the presence or

absence of subhedral alkali feldspar megacrysts. This variation may result from a number of still unrecognized granitoid facies. It is notable for its friable nature. This granitoid is ubiquitous in the Rolesville pluton, and occupies the largest surface area at the present level of erosion.

*Wyatt granitoid*: a medium- to coarse-grained garnet + biotite + muscovite granitoid. It was distinguished by Parker (1979) both by its mineralogy and by its occurrence in a satellite pluton separated from the main pluton.

## Age

The Rolesville batholith is interpreted to be a late Paleozoic intrusion (Farrar, 1985 a,b). There have been many attempts to date the granites, but success appears to have been hampered by the composite nature of the pluton. The northern peraluminous border granitoid of the Castalia pluton has a Rb-Sr whole rock age of  $313 \pm 13$  Ma (Fullagar and Butler, 1979). Horton and Stern (1994) reported  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of bulk zircon splits for several granitoids within the Rolesville pluton: 312 Ma for the Lassiter granitoid, 298 Ma for the Mitchell granitoid, and 286 Ma for what may be the Rolesville main granitoid at the northernmost tip of the batholith. An  $^{40}\text{Ar}/^{39}\text{Ar}$  biotite cooling age of 255 Ma from the Rolesville main granitoid in the southwestern corner of the batholith was determined by J. Sutter (unpublished data).

## DISCUSSION AND SIGNIFICANCE

Large granitoid plutons having the features similar to those found in the Rolesville batholith have been described elsewhere. Most notable is the Main Donegal granite of Ireland (Pitcher and Read, 1959). These authors described a stratigraphic arrangement within the granite of country rock xenoliths they termed "ghost stratigraphy" or "raft-trains". The interpretation was that magma was emplaced in a sequence of pulses that wedged apart the wall rocks, leaving partially disrupted septa separating granite sheets. The multiple sheets coalesced to form a massive, relatively homogeneous pluton. It appears that a synchronous deformation emphasized the structural concordance of the Main Donegal granite (Pitcher and Read, 1959). Hutton (1992) in a study on the Great Tonalite Sill of Alaska and British Columbia and in a review of other plutons, emphasized these features and observed that plutons constructed in this way exhibit little in the way of petrographic variation to help identify individual sheets. This cryptic sheeting may result from physical and chemical mixing. The existence of "ghost stratigraphy" or "raft trains" may be one of the few clues to the identity of this type of pluton.

The Rolesville pluton is a composite body. It is assembled from a number of magma pulses arriving in the same place about the same time. This may be the only genetic connection these granites have with one another. The Rolesville

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pluton is comparable to cryptically sheeted plutons. A sequence of magma pulses has wedged open the country rocks or earlier granitoids. The multiple sheets coalesced to form a massive, relatively homogeneous pluton. They are separated by internal contact zones indicated by a ghost stratigraphy of country rock xenoliths or zones of granitoid autoliths. These cryptic contacts are also the locations of additional intrusive rocks of minor volume.

If the Rolesville pluton is identical to sheeted plutons described from elsewhere, the implication is that the magmas of the constituent granitoids were emplaced by repeated diking in active shear zones. The Rolesville pluton is emplaced on the present southern terminus of the Macon Mylonite zone (Farrar, 1985b), which is thus the most likely candidate. The structures and timing described by Farrar (1985b) for the mylonite zone and Alleghanian plutons in the Raleigh block permit this interpretation. Farther north, near the North Carolina-Virginia border, the Macon mylonite zone intersects the Hollister fault zone. Here the Butterwood Creek, Alberta, and a number of unnamed, syn- to post-kinematic, tabular granitoid plutons are emplaced into or bridged across these deformation zones (Farrar, 1985b; Boltin and Stoddard, 1987; Horton and others, 1993).

The Rolesville pluton is less tabular than the Great Tonalite Sill, and more comparable to the Donegal granites. The magmatic event either outlasted or, with time, moved outside the limits of the Alleghanian deformation in the mylonite zone. The earliest to latest granitoids are: (1) the highly deformed granites occurring as disrupted enclaves within later granitoids, (2) granitoids concordant with the wall rocks, (3) granitoids discordant to structures and fabrics in the country rocks. Concordant granitoids have little post-crystallization deformation, indicating that movement occurred in the presence of deformation-absorbing melt and ceased for the most part once the magma crystallized.

### ACKNOWLEDGMENTS

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# TRIASSIC SEDIMENTARY ROCKS OF THE CENTRAL DURHAM BASIN, NORTH CAROLINA

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## ABSTRACT

The Durham basin is filled with non-marine, primarily fluvial, clastic deposits of the Late Triassic Chatham Group. The Chatham Group rocks are intruded by Early Jurassic diabase as dikes and sheets. Bordering rocks consist of pre-Mesozoic intrusive, metavolcanic and metasedimentary rocks of the Carolina slate and Raleigh belts. Mapping of the Southeast and Southwest Durham 7.5-minute quadrangles delineated three lithofacies associations within Triassic sedimentary rocks. The three associations are comprised of seven distinct lithofacies and form three belts that generally conform to the trend of the basin. The western most association (Lithofacies Association I) consists of mud-clast-rich, trough crossbedded, arkosic sandstone interspersed with locally thick siltstone beds. This unit is interpreted to represent sandy braided stream deposits flowing within an anastomosing drainage system cut into fine-grained interstream areas. The central association (Lithofacies Association II) consists of sandstone with interbedded siltstone and siltstone with interbedded sandstone. The sandstone/siltstone facies consists of arkosic, fining-upward, meandering stream deposits that grade southward to the siltstone/sandstone facies, where fine-grained fluvial overbank fluvial and lacustrine deposits dominate. The eastern association (Lithofacies Association III) is comprised of four lithofacies. Conglomerates along the border fault grade basinward through interbedded sandstone and conglomerate to pebbly sandstone and then to muddy sandstone. Adjacent facies exhibit both intertonguing and gradational relationships. This lithofacies association is interpreted to represent basin-margin alluvial fan deposits that prograded westward from a southeastern highland.

## INTRODUCTION

The Durham basin is one of a series of extensional basins in eastern North America that developed during rifting in the early Mesozoic that resulted in the separation of the North American and African plates. Approximately 20 "synrift" basins, collectively identified as the Newark rift system, are exposed along the North American continental margin from South Carolina to Nova Scotia. Many other, presumably coeval, basins have been interpreted to lie

beneath the late Mesozoic and Cenozoic sediments of the Atlantic Coastal Plain and adjacent continental shelf (for example, Benson, 1984).

Newark rift system basins contain Late Triassic and Early Jurassic non-marine clastic deposits of fluvial and lacustrine origin with interbedded evaporites and basalt flows. These rocks form the Newark Supergroup (Froelich and Olsen, 1984). Interbedded basalt flows belonging to the Newark Supergroup are limited to basins from Virginia northward. A second Early Jurassic episode of intrusion by diabase dikes, sheets, and sills occurred. These intrusions are concentrated mainly in the Carolinas and are sparse to absent in the more northern basins (Manspeizer and Cousminer, 1988). Due to their cross-cutting relationships and post-depositional emplacement, these rocks are not included in the Newark Supergroup.

The Durham basin is a half-graben structure within crystalline rocks of the Piedmont region. It is down-faulted along the southeastern margin; but on the west, Mesozoic sedimentary rocks nonconformably overlie Piedmont rocks (well exposed at Teer Aggregates' Durham Quarry). Locally, the western border is formed by minor southeast dipping high-angle normal faults. The eastern border fault, which dips northwestward at a high angle, was named the Jonesboro fault by Campbell and Kimball (1923) for an exposure in Lee County.

The Durham basin, and the Sanford and Wadesboro basins to the south, form a 240-kilometer-long by up to 26-kilometer-wide structure known as the Deep River basin. The individual basins are separated by cross-trending structural highs named the Colon cross structure (between Durham and Sanford basins) and the Pekin cross structure (between Sanford and Wadesboro basins). Sedimentary rocks of the Deep River basin of Chatham County were named the Chatham series by Emmons (1857). Subsequently, the term Chatham Group has been used to include all the Late Triassic (Carnian) rocks of the Deep River basin (Froelich and Olsen, 1984; North Carolina Geological Survey, 1985).

## GEOLOGY

Hoffman and Gallagher (1989a, b, c) mapped and reported on the geology of the Southeast Durham and South-

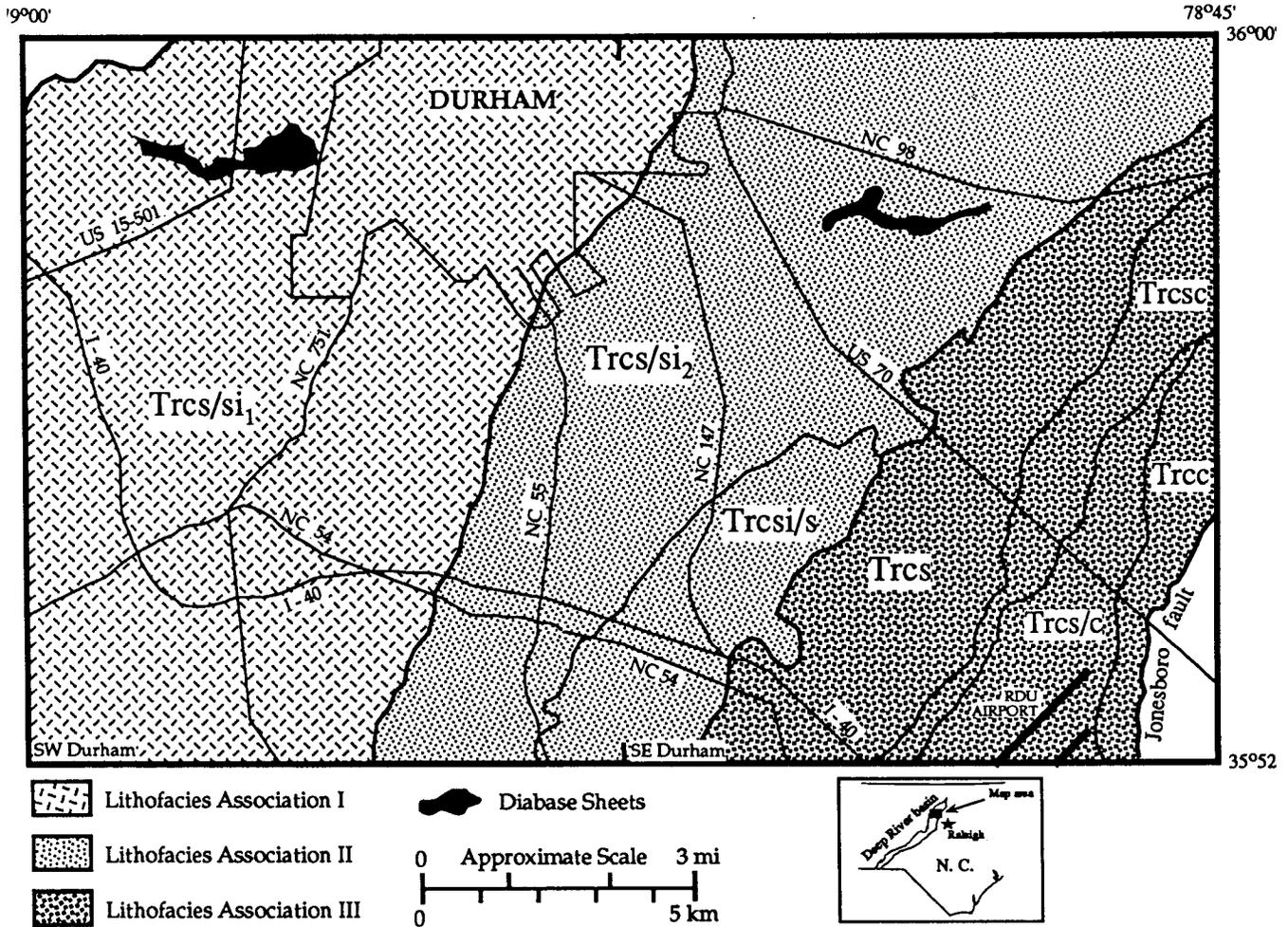


Figure 1. Geologic map of the Southeast Durham and Southwest Durham 7.5-minute Quadrangles (from Hoffman and Gallagher, 1989a).

west Durham 7.5-minute Quadrangles, an area of approximately 300 square kilometers that includes a 26 kilometer transect across the central Durham basin. The area extends from the Jonesboro fault in the southeastern corner to the bounding unconformity on the northwestern side of the basin west of Durham (Figure 1). The following descriptions are based largely on this earlier work.

Triassic sedimentary rocks of the central Durham basin can be divided into seven mappable lithofacies (identified by age (Tr), group name (c-Chatham) and lithology (c-conglomerate, s-sandstone, sc-pebbly sandstone, si-siltstone). These lithofacies are then organized into three lithostratigraphic groups, termed lithofacies associations, each of which define a depositional system that operated through the basin's history. The three associations form three belts that generally conform to the trend of the basin (Figure 1).

The basal association (Lithofacies Association I) that crops out along the western margin of the map area consists of sandstone with interbedded siltstone (Trcs/si<sub>1</sub>). The central association (Lithofacies Association II) is comprised of sandstone with interbedded siltstone (Trcs/si<sub>2</sub>) and siltstone

with interbedded sandstone (Trcsi/s). The eastern association (Lithofacies Association III) is comprised of sandstone (Trcs), pebbly sandstone (Trcsc), sandstone with interbedded conglomerate (Trcs/c), and conglomerate (Trcc).

Strike and dip measurements of bedding are difficult to obtain from the generally poor and highly weathered exposures of the Durham basin. Regional strike of bedding is about N40°-50°E with a 7-10° southeast dip. Intrabasinal block faults have been demonstrated within the basin (Bain and Brown, 1980) through extensive geophysical investigations. Minor (outcrop scale) high-angle normal faults are not uncommon.

Using a 7°-10° southeast dip, a 26 kilometer width of the basin, and a 65° dip for the eastern border fault, the projected maximum thickness for the rocks of the Durham basin is 3 to 4 kilometers. Given that the eastern border is step-faulted (Bain and Brown, 1980), the maximum thickness could be considerably less than this value. Bain and Brown (1980), on the basis of gravity and aeromagnetic modeling, estimated the maximum thickness of the Durham basin to be about 2 kilometers.

## Lithofacies Association I

### Trcs/si<sub>1</sub>

Lithofacies Association I (LA I) consists of a single mappable unit identified as the Trcs/si<sub>1</sub> facies. This unit consists of fine- to medium-grained feldspathic sandstone and bioturbated siltstone and mudstone. Fine-grained biotite is a common accessory mineral that helps to distinguish the sandstones of this facies from sandstones of the other lithofacies. Muscovite is also common, though it is not distinctive to this lithofacies. Widespread red clayey soils, abundant and large mud clasts in sandstone channel deposits, and some exposures which contain thick siltstone sections indicate that siltstone is a significant component of this facies.

Sandstone preferentially crops out and thus is the dominant lithology exposed through the area underlain by this facies. Sandstone sequences are usually thick (5 meters or more) and are composed of individual depositional units that are characterized by abrupt vertical and lateral changes. The basal portions of sandstone beds, immediately overlying basal scours, are very coarse grained to pebbly and contain abundant mudstone clasts. Mudstone clasts ranging up to 50 centimeters in diameter are commonly scattered along scour surfaces. Where preserved, the upper portions of fining-upward sequences consist of bioturbated siltstone and mudstone.

Trough crossbedding is abundant in the sandstones of this facies. Individual sets decrease in thickness from the base of a sequence to the upper portions. Tabular foresets are less abundant, but occur near the tops of fining-upward sequences in a few outcrops.

Bioturbation is extensive in the finer grained portions and within the thinner sandy beds of this facies. Both root structures and *Scoyenia* (crawfish burrows) occur. Locally, thin zones of nodular carbonate also occur in the muddy portions of the Trcs/si<sub>1</sub> facies. Voids within the basal portions of some sandstones are interpreted as weathered-out carbonate and/or mud clasts that were reworked from underlying mudstone.

Sandstone sequences within this facies resemble those of sandy braided rivers described by Cant (1978) in that 1) large scale, poorly defined, mud-clast-rich trough crossbeds grade vertically to smaller scale trough crossbeds, 2) fining-upward sequences are poorly developed, 3) intercalated sets of tabular crossbeds have paleocurrent directions at high angles to the directions indicated by the trough crossbeds, and 4) ripple cross-laminated, fine-grained sandstone and siltstone beds are thin to absent at the tops of fining-upward sequences. By this model, the tabular foresets represent mid-channel sand sheets and bars deposited in waning flow conditions over the trough crossbeds formed by dunes during high flow stages.

Unlike Cant's model, however, the Trcs/si<sub>1</sub> facies sandstones are surrounded by apparently thick sequences of

heavily bioturbated siltstone and mudstone. The sparse but well-developed character of sandstone outcrops suggests that onset and termination of braid channel sedimentation happened suddenly, that is by avulsion as opposed to lateral migration. Smith and Smith (1980) description of channel avulsion of anastomosing streams on a muddy floodplain may be a modern analog to early Durham basin sedimentation.

## Lithofacies Association II

Lithofacies Association II (LA II) is comprised of two units, a dominantly sandstone facies (Trcs/si<sub>2</sub>) and a dominantly mudstone facies (Trcsi/s). In the south-central portion of the map area, the Trcs/si<sub>2</sub> facies grades upward into the Trcsi/s facies. The contact between LA I and LA II appears to be gradational. This change occurs through a zone wherein the lithologic and sedimentary characteristics of both associations occur. Some outcrops or individual beds within this zone are more distinctly like one facies or the other, but there is no apparent systematic vertical change.

### Trcs/si<sub>2</sub>

The Trcs/si<sub>2</sub> facies is typified by well developed, cyclical, fining-upward sequences. Coarse- to very coarse-grained pebbly sandstone with very coarse-grained muscovite generally marks the base of cycles. Both flattened and rounded mud clasts (1 to 2 cm thick) commonly overlie scour surfaces. These pebbly, trough crossbedded basal sandstones grade upward through finer-grained, ripple- to parallel-laminated sandstone into rooted and burrowed, sometimes calcareous, siltstone and mudstone. Depositional sequences in this facies are typically 2 to 5 meters thick. The few exposures where trough crossbeds provide paleocurrent data indicate a southwest flow direction.

Sandstones of the Trcs/si<sub>2</sub> facies are very feldspathic. Muscovite mica is a very common accessory mineral. Sandstones of this facies are distinguished from the Trcs/si<sub>1</sub> sandstones by their generally coarser grain size, noticeably abundant pink potassium feldspar which gives these sandstones a slightly different hue (more red), and relatively less biotite. A better developed and more consistent rhythmic character of fining-upward sequences also helps distinguish the Trcs/si<sub>2</sub> facies from the Trcs/si<sub>1</sub> and other facies of the study area.

Thin, discontinuous lenses of laminated to thin-bedded shale containing the fossil branchiopod conchostracan (*Cyzicus*) occur locally within the Trcs/si<sub>2</sub> unit. In many outcrops of this facies, nodular and "bedded" limestone zones occur in the thicker mudstone and siltstone horizons. Limestone nodules are commonly associated with root structures. The "bedded" limestone occurs as discontinuous stringers up to several centimeters thick, is usually dense, and has a laminated structure. Although these stringers appear to be pri-

mary features within massive mudstone, they rarely yield a strike and dip conformable with those obtained for enclosing sedimentary strata. It would thus seem that they are possibly diagenetic features, perhaps related to pedogenic processes.

Characteristics observed in the Trcs/si<sub>2</sub> facies are consistent with lateral point bar aggradation within a meandering fluvial system surrounded by a vegetated floodplain (Cant, 1982; Walker and Cant, 1984). The carbonates appear to be pedogenic and are partially replaced by chert. The abundant potassium feldspar and mica, along with the coarse to very coarse grain size of the Trcs/si<sub>2</sub> facies, especially in the more northern portion of this facies, suggests a felsic-rich source area.

### Trcsi/s

The upper part of the Trcs/si<sub>2</sub> facies grades southward into the Trcsi/s facies. Outcrops of this facies are particularly sparse. Siltstone of the Trcsi/s facies is typically reddish brown with light-green to whitish-gray mottling along both fossil and modern root structures. Bedding is usually massive; this is likely due to intense bioturbation which has destroyed primary structures. Scoyenia burrows are very abundant. Laminated to thin-bedded reddish-brown shale containing conchostracans and ostracods occurs at several localities.

Sandstones within this facies are fine- to medium-grained and are usually less than a meter thick. Sandstone composition is difficult to discern in the field because of the relatively fine grain size. In coarser lenses, sandstones are clearly feldspathic. In a few exposures the sandstones exhibit small-scale planar crossbedding and ripple cross lamination. Otherwise, flow structures were not observed. Fining or coarsening trends within individual sandstone beds are usually very subtle or absent.

Nodular and "bedded" carbonate horizons as described above for the Trcs/si<sub>2</sub> facies are extensive within the Trcsi/s facies. Most outcrops contain some carbonate either in this form or as cement within siltstone beds. Chert, also more abundant in this facies than others, is most often found as float; however, a number of outcrops contain in-place chert stringers or nodular-like "bedded" masses. These are nearly always associated with carbonate. The major difference between the Trcsi/s and Trcs/si<sub>2</sub> facies with respect to carbonate and chert is the relative abundance rather than any characteristic related to depositional setting.

The Trcsi/s facies is interpreted as representing mostly fluvial overbank deposits with locally developed, areally limited, ephemeral, shallow, freshwater lakes. Abundant root structures and carbonate nodules suggest that exposed surfaces were vegetated and that soils developed on them. The Trcsi/s facies may represent a local lowland away from the main fluvial belt of the Trcs/si<sub>2</sub> facies or it could represent a change to muddier conditions in the later part of deposition of LA II. The change could be due to basin filling or an

increased input of fine-grained sediment from another source area (possibly the east). Another consideration is that the drainage system of this lithofacies association may have flowed into a large lake to the south. A relative rise of that lake's level would tend to decrease stream gradients within its feeder fluvial system.

### Lithofacies Association III (LA III)

Lithofacies Association III (LA III) is comprised of four units that are texturally and mineralogically distinct from the sedimentary rocks of the first two lithofacies associations. Namely, muscovite, which is very common in the rocks of LA I and LA II, is absent from these rocks. Also, lithic fragments are more common. Matrix is a more significant component and matrix-supported textures are common. The facies of this association progress from massive, boulder-dominated deposits (Trcc) adjacent to the Jonesboro fault through gradually finer grained cobble, pebble, and sandstone deposits (Trcs/c and Trcsc) to muddy sandstone (Trcs) toward the central portion of the basin.

### Trcs

A dominantly sandstone facies (Trcs) comprises the most distal and finest grained facies of LA III. This facies generally consists of reddish-brown, poorly to moderately sorted, fine- to medium-grained sandstone and muddy sandstone. Matrix-supported granules and coarse sand grains are common. Locally, some beds and lenses are moderately well sorted and relatively low in mud content, but siltstone and mudstone are typically minor constituents.

Depositional units are typically 1 to 2 meters thick and are commonly tabular bodies that display good lateral continuity. Relatively thin (5 to 20 centimeters), sometimes burrowed, muddy sandstone zones usually cap the sequences. Gradation from cleaner sandstone to these fine-grained zones is usually abrupt. A lack of internal stratification may be due to (poorly preserved) bioturbation.

The Trcs facies appears to reflect deposition in broad shallow channels incised into muddy flats. The eradication of internal stratification by bioturbation indicates relatively thin depositional units or relatively long periods of non-deposition between sedimentation events or both. Muddy, matrix-supported sandstones may also represent distal debris flow deposits or hyperconcentrated stream flow deposits (Nilsen, 1982; Pierson and Scott, 1985).

### Trcsc

Sandstone of the Trcs facies grades upsection and south-eastward to pebbly sandstone of the Trcsc facies. The Trcsc facies consists of reddish-brown, poorly sorted sandstone with at least 5 percent gravel (chiefly granules with subordinate amounts of pebbles and cobbles). Coarse clasts are generally matrix supported and scattered throughout sandstone

## TRIASSIC ROCKS OF CENTRAL DURHAM BASIN

beds. Siltstone and mudstone are minor components in this facies.

Bedding on the order of 1 to 3 meters thick is defined by concentrations of pebbles and cobbles along basal contacts. These contacts are usually scour surfaces with conglomeratic zones that range up to 50 cm thick. The conglomeratic portions grade rapidly upward into poorly sorted sandstone. Internal stratification is limited to rare occurrences of pebble and cobble trains, commonly only one or two clast diameters thick, which define flat to slightly inclined lenses within sandstones.

The Trcsc facies appears to have been deposited in broad, shallow channels. The poor sorting and general lack of stratification within the sandstones may indicate deposition by streams with high sediment concentrations (hyperconcentrated flow) or it could be due to bioturbation disrupting previously better stratified deposits. Some of the deposits may also have been formed by low-viscosity debris flows (Nilsen, 1982). The coarser grain size and paucity of muddy interbeds suggest a closer proximity to source and higher energy flow conditions for this facies versus the Trcs facies.

### **Trcs/c**

Pebbly sandstone of the Trcsc facies grades southeastward toward the basin margin into a coarser grained facies consisting of sandstone with interbedded conglomerate (Trcs/c). The presence of well defined conglomerate beds, as opposed to basal conglomeratic lags, distinguishes this facies from the Trcsc facies.

Rock fragments are a noticeable component of the pebbly sandstone facies. Sorting is poor and matrix-supported granule and larger size clasts are very abundant in the sandstone beds. Within the conglomerate beds, both matrix- and clast-supported textures occur. Conglomerate clasts, generally coarser than in the Trcsc facies, are mostly cobble size.

The Trcs/c facies appears to have been deposited in broad, relatively shallow channels by streams with high sediment concentrations or as debris flows or both. Streams that deposited this facies were apparently larger and deeper than those that deposited the Trcsc facies.

### **Trcc**

The Trcs/c facies grades southeastward toward the border fault into a dominantly conglomerate facies (Trcc). The Trcc facies is composed mainly of cobble- to boulder- size clasts that occur in thick to massive beds with a subordinate amount of very coarse-grained to gravelly sandstone as matrix, beds, and lenses. Both clast-supported and matrix-supported textures are found within the conglomerates of this facies. Clasts are generally rounded and their size and composition are highly variable.

The Trcc facies, with its poor sorting and matrix-supported character, is interpreted as primarily representing

debris flow deposits. Lenses of grain-supported conglomerate are interpreted as deposits of small channels. These channels either were incised into debris flows or flowed around them. To the north, channel deposits are more dominant in this facies.

The Trcsc, Trcs/c, and Trcc facies are interpreted as the deposits that developed adjacent to the eastern border fault as alluvial fans extending northwestward into the basin. Several paleocurrent measurements based on imbricated pebble orientations indicate northwestward flow. This information, together with the consistent eastern source or provenance, the gradational fining of the facies away from the eastern border fault, the basinward transition from debris-flow-dominated to fluvial-dominated deposition, and the basinward transition from thicker channel conglomerates to thinner, sheet-like sandstones are all consistent with an alluvial fan model (Nilsen, 1982). Systematic lithologic change of the conglomerate deposits along strike suggests that there were multiple feeder systems operating along the border fault to produce a complex deposit.

## DISCUSSION

The three lithofacies associations define three belts of different provenance and depositional style: a western belt of arkosic anastomosing stream deposits, a central belt of arkosic meandering stream deposits, and an eastern belt of conglomeratic alluvial fan deposits with distal sandstones. Subsurface data are lacking for this central portion of the Durham basin, so the stratigraphic relationship between the western (LA I) and central (LA II) lithofacies associations at depth is unknown. A question remains as to whether these two facies persist vertically as stratigraphic equivalents through the depositional history of the basin or if the western facies represents an earlier stage of basin development and the central facies was deposited subsequently. In the second scenario, the western belt rocks would extend southeastward beneath the central belt rocks (Figure 2).

Evidence to support the second scenario exists to the south of the map area, near Apex in the southern part of the Durham basin. Limited seismic reflection data provided to the North Carolina Geological Survey by Texaco, Inc. show basal sediments prograding from the west and persisting across the extent of the basin (Almy, personal communication). The extent to which these sediments intertongue with early stage alluvial fan deposits of LA III is not readily apparent from the data.

Integration of subsurface data, particularly the available seismic-reflection profiles, with surface geological mapping is sorely needed to provide better resolution to the stratigraphy and structure of the Durham basin. Likewise, continued surface mapping in additional quadrangles is required to test, refine, and extend as appropriate the model developed from mapping of the Southeast and Southwest Durham quadrangles.

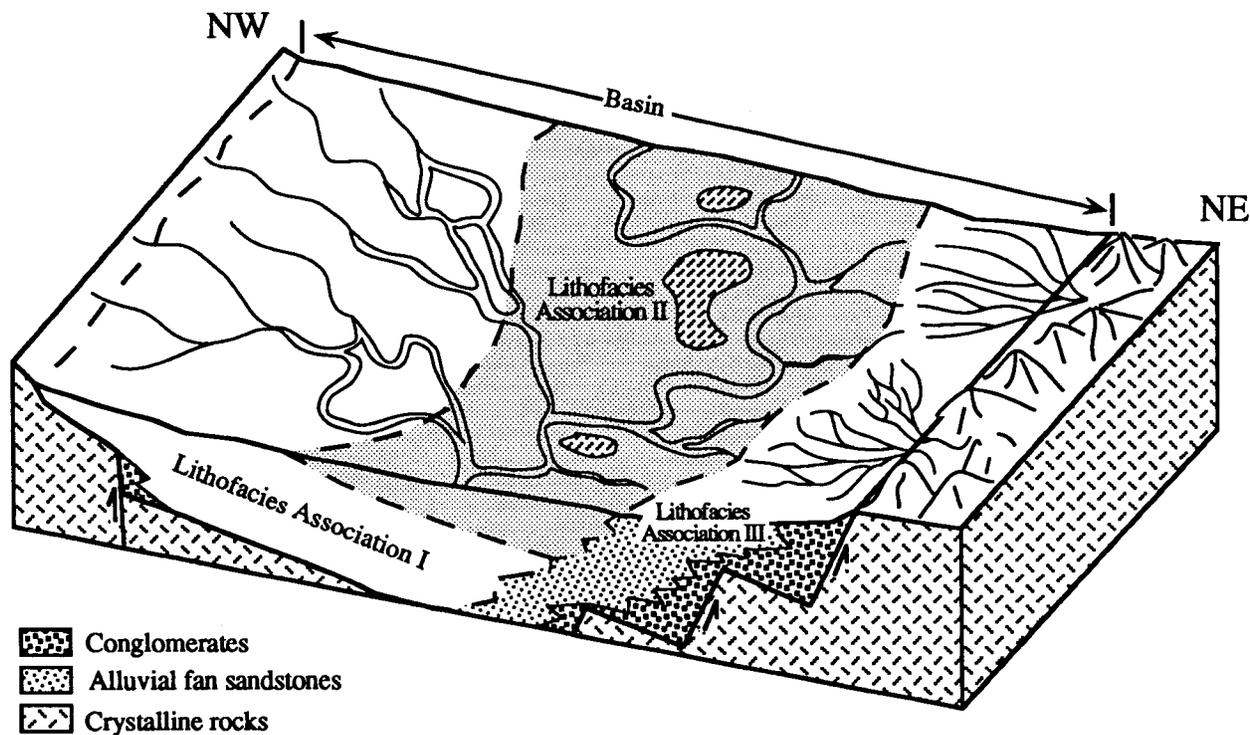


Figure 2. Schematic block diagram illustrating conceptual model of central Durham basin stratigraphy (from Hoffman and Gallagher, 1989a).

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## STRUCTURAL FEATURES ASSOCIATED WITH THE JONESBORO FAULT WHERE IT CROSSES U.S. HIGHWAY 70, WAKE COUNTY, NORTH CAROLINA

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### ABSTRACT

The segmented, basin-bounding Jonesboro fault forms the eastern side of the Triassic Deep River Basin, North Carolina. The ~56 km-long Durham segment is the longest major segment and trends northeastward from near Raleigh to the vicinity of Creedmoor. Road construction in 1993 exposed new structural features in the vicinity of the Angus Barn Restaurant which is near the midpoint of the Durham segment where it crosses U.S. Highway 70. Here, zones of vertically oriented cobbles in conglomerates are indicative of major paleoseismic events accompanying Triassic deposition. Here also, a monocline with associated low-angle, SE-dipping extensional faults suggests that a graben may have existed adjacent to the Durham segment. Sheared cobbles and clay gouge zones along minor faults indicate that brittle extensional faulting also continued at depth after the strata were indurated. Sheared cobbles, offset contacts, and slickensides on minor faults collectively indicate that displacement on the Durham segment of the Jonesboro fault was primarily sinistral-oblique normal (down-to-the-W); thus the Durham segment is *unfavorably oriented* (Sibson, 1990) with respect to the Triassic regional paleostress field which fault slip directions and mode I joints indicate had an ~E-W extension direction. The apparent basinward (westward) deflection of the Durham segment at the Angus Barn locality may have resulted either from the segment actually being a *misoriented* (Sibson, 1990) fault or from a large (~300 x 700-m) paleolandslide of metamorphic rock of the volcano-genic Cary Formation which slid along the main fault (or along regionally aligned foliation surfaces) into the basin bounded by the Jonesboro fault. If this is a slide-block, then subsequent faulting along the Durham segment reactivated secondary faults, characterized by very steep dips, oblique

strikes (relative to pre-existing foliation) and siliceous fluids, that propagated across this block of crystalline rock.

### INTRODUCTION

The W-dipping, basin-bounding, Jonesboro fault forms the eastern border of the ~240-km long, Triassic age Deep River basin (*e.g.*, North Carolina Geological Survey, 1985; Burt and others, 1978; Olsen and others, 1991). The northern part of the Jonesboro fault is divisible into four major structural segments (Figure 1) which are marked by abrupt, 30°-60° changes in trend of the main fault surface. By analogy with active basin-bounding faults in the Basin and Range Province of the western U.S.A., each major segment of the Jonesboro fault is probably made up of structurally distinct shorter subsegments that were capable of moving independently of adjacent subsegments and yet periodically linked together during major seismogenic events (*e.g.*, Crone and others, 1987; Machette and others, 1987; Stickney and Bartholomew, 1987).

The focus of this paper is on a locality along the longest major segment, the ~56-km long Durham segment. The Durham segment extends from the abrupt (E-NE to N-NE) deflection point near Holly Springs to the abrupt (NE to N-NW) deflection point ~11 km east of Creedmoor (Figure 1). In 1993, new road construction temporarily exposed structural features near the Angus Barn Restaurant which is a local landmark located about midway between Raleigh and Durham where the Jonesboro fault crosses U.S. Highway 70 (Parker, 1979). This is also the approximate midpoint along the Durham segment (Figure 1) of the Jonesboro fault.

At this locality, adjacent *en echelon* subsegments (Parker, 1979, his Plate 1) appear to be linked along an anomalous, basinward deflection of the Durham segment of

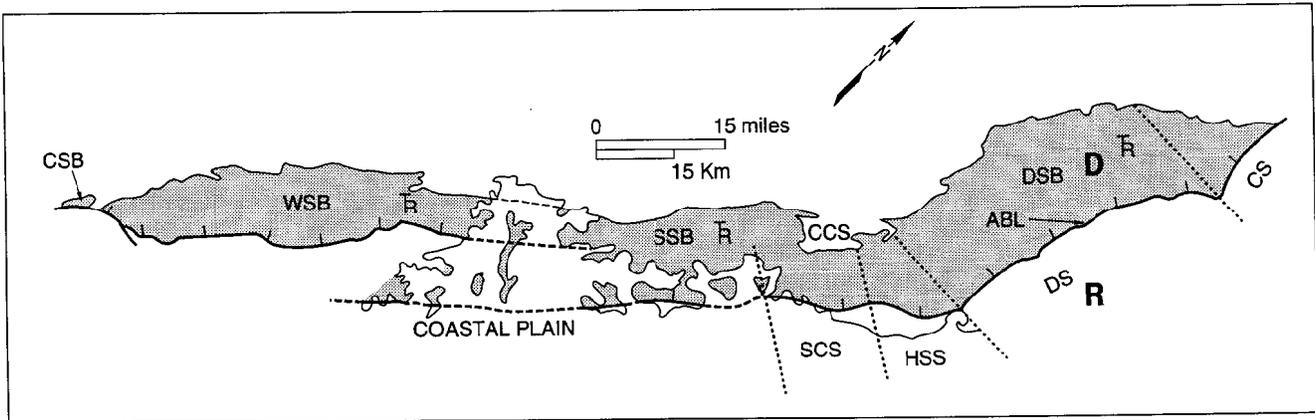


Figure 1. Generalized map of the Deep River basin (modified after Olsen and others, 1991) showing the Angus Barn locality (ABL) and major segments of the basin-bounding Jonesboro fault: CS-Creedmoor segment; DS-Durham segment; HSS- Holly Springs segment; SCS-Sanford composite segments. DSB-Durham sub-basin; CCS-Colon cross-structure; SSB-Sanford sub-basin; WSB-Wadesboro sub-basin; CSB-Crowburg sub-basin; **D**-Durham; **R**-Raleigh; shaded area is underlain by Triassic strata; dotted lines delineate approximate segment boundary zones separating structural domains related to each segment.

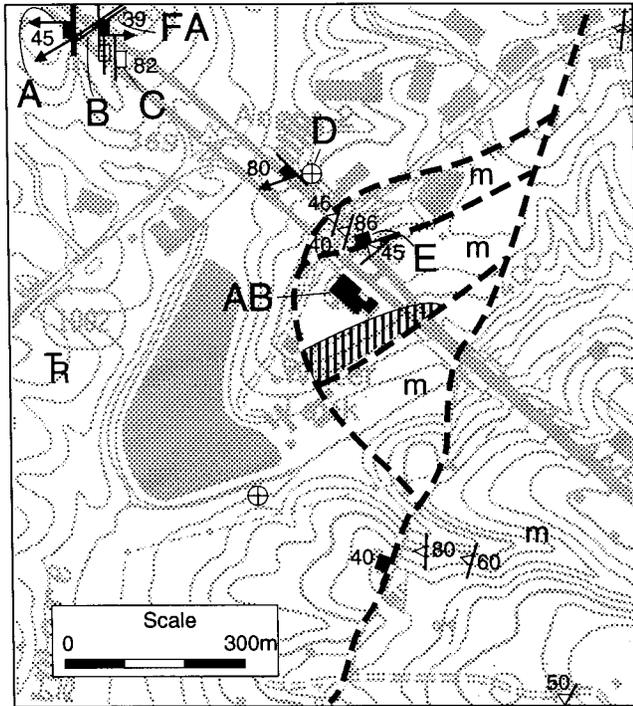


Figure 2. Geologic map of the Angus Barn locality with our data added to Parker's (1979) data and with his locations of contacts where they cross the roads all fitted to an enlarged 7.5-minute topographic base; m- metamorphic rocks; ruled area has float of siliceous cataclasite; AB-Angus Barn Restaurant; FA-monocline axis (double line); A, B, C, D, & E-localities mentioned in text; bar with open triangle -strike and dip of foliation; bar with open square -strike and dip of joint; bar with solid square -strike and dip of fault; arrows indicate slip-directions of hanging walls of small faults; north is toward the top of the page.

the Jonesboro fault around an ~300 x 700-m block of phyllite of the Cary Formation (Farrar, 1985) of the Carolina slate belt which protrudes northwestward from the overall trend of the fault (Parker, 1979, his Figure 8). Float of siliceous cataclasite, similar to fault rocks described by Garihan and Ranson (1992), occurs within the area underlain by phyllite both across the highway from, and on the gentle slope south of the Angus Barn Restaurant (Figure 2). The siliceous cataclasite is characteristic of Mesozoic brittle fractures and faults in crystalline rocks in other parts of the Piedmont (Garihan and Ranson, 1992) and is inferred to indicate Mesozoic faulting here as well.

Severe seismic shaking of nonindurated sediment during Triassic deposition is suggested by pillar structures (e.g., Geer Street and U.S. 70, Durham) and numerous, locally abundant, sediment-filled (clastic) dikes (e.g., quarries near SE Durham, Bethesda, and Genlee) throughout the basin from Creedmoor to Sanford. At the Angus Barn locality, however, we observed (localities A and C, Figure 2) a less common type of soft-sediment deformational feature associated with liquefaction that has not been noted elsewhere in this basin before. Here also, is the northwest margin of a possible wide graben (locality B, Figure 2) within the Triassic sediments adjacent to the basin-bounding fault. Subsequent brittle faulting, when the strata were more deeply buried, are suggested by other features such as sheared and fractured clasts (locality A, Figure 2) and clay gouge zones along faults (localities A and E, Figure 2).

**STRUCTURAL FEATURES**

At the Angus Barn locality, the effect of soft-sediment deformation is most apparent in vertically oriented cobbles in beds of Triassic alluvial fan gravels (Figure 3A; locality

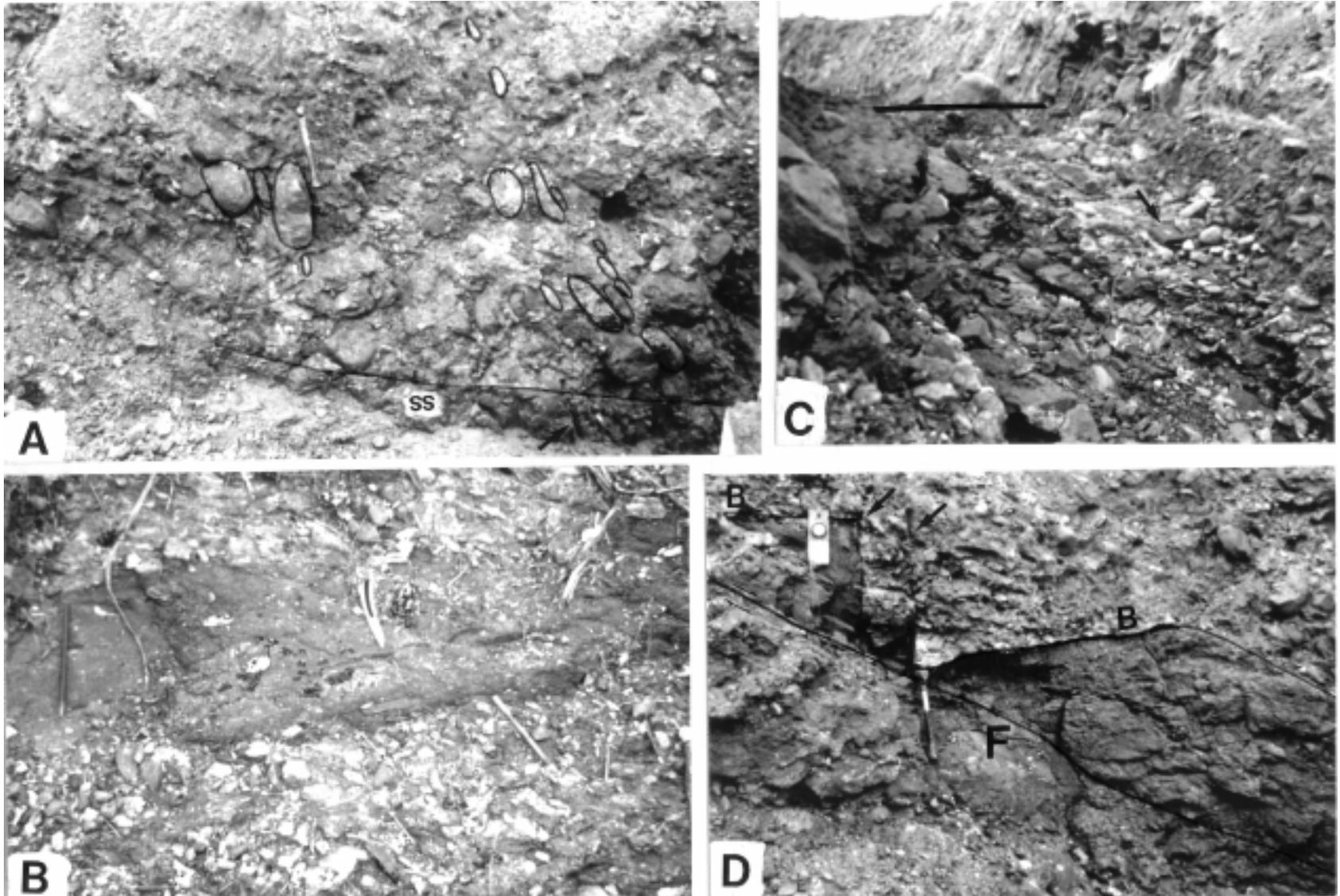


Figure 3. A: Zones of vertically oriented cobbles within conglomerate above red sandstone bed (SS) with vertical joints (arrow) in W-facing cut at locality C, Figure 2. B: Cusped, near-vertical, slickensided surfaces (at point of 12 cm knife) in subhorizontal, reddish brown sandstone interbedded with conglomerate exposed in W-facing outcrop at locality D, Figure 2. Pencil and pencil eraser indicate directions of slip on these surfaces. C: NE-trending horizontal monocline axis (heavy line) at locality B, Figure 2. Silva compass (arrow) on SE-dipping bedding surface whereas bedding is horizontal in trench in background to NW behind fold axis. D: Low-angle extensional fault (above F) sub parallel to SE-dipping bedding at locality B, Figure 2. Extension above low-angle fault in W-facing cut is accommodated by near-vertical joints (arrows) reactivated as slip-surfaces, similar to cusped surfaces in Figure 3B, which offset bedding surface (B).

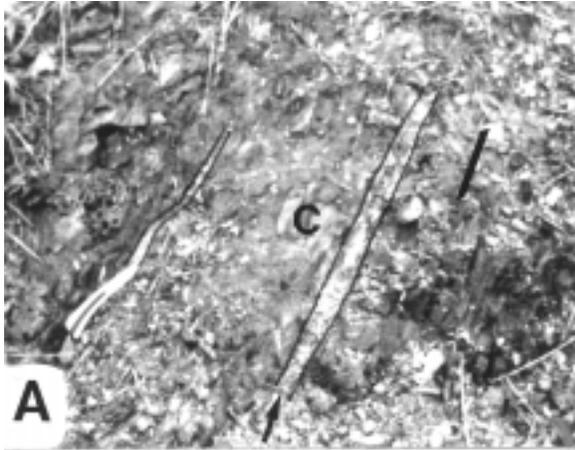


Figure 4. A: Fault zone exposed in W-facing roadcut at locality E, Figure 2 with breccia of angular phyllite clasts (C) between clay-gouge zones (outlined in ink above 12 cm knife and arrow). Long axes of clasts generally are subparallel to dip direction of fault surface. Knife marks top of breccia. Basal clay-gouge zone (arrow) is subparallel to foliation (heavy line) in subjacent phyllite. B: Photomicrograph (width of large clast is 2 cm) of breccia in Figure 4A showing unsorted phyllite clasts and matrix cut by conjugate shear surfaces (parallel arrows mark individual shear surfaces).

C). Such re-orientation, which occurs as large cobbles rapidly gravitate downward through finer material, is common in gravel deposits adjacent to active faults (e.g., Bartholomew and others, 1990, their Figure 3) and is attributed to severe shaking of unconsolidated gravels. Vertically oriented cobbles also occur in a nearby deformed channel deposits just west of locality A.

As noted by Parker (1979), the Triassic strata proximal to the fault (Figure 3B ; locality D, Figure 2) are horizontal. However, ~500 m NW of the fault (locality B, Figure 2), a horizontal monoclinial hinge (Figure 3C) trends N50°E separating horizontal strata (to the NW) from 20°-30° SE-dipping beds. Along this SE-dipping limb, a small, low-angle (39° SE), extensional fault (Figure 3D) is sub parallel to bedding. Slickensides and offsets along the fault indicate hanging-wall transport (down-to-the-ESE) toward the Jonesboro fault. Monoclines and transport toward the fault along low-angle extensional faults are features found along grabens that are commonly observed adjacent to active and inactive faults (e.g., Stickney and Bartholomew, 1987; Crone and others, 1987).

A fault (N70° E, 86° NW), within Cary Formation phyllite, crops out in the roadcut across from the Angus Barn (locality E, Figure 2). Large blocks of siliceous cataclasite occur along the NE-projection of this fault for ~100 m from this locality. Another zone of siliceous cataclasite float which occurs south of the Angus Barn suggest a sub parallel fault ~100 m south of this exposed fault (Figure 2). Within the outcrop, the dip of the fault steepens upward from 86° to 90° and the fault surface is marked by 1-2 cm of clay gouge beneath a breccia zone. The breccia zone is ~30 cm thick and has a thinner clay-gouge zone above it (Figure 4A). Although folded, the foliation in the phyllite SE of the fault dips NW and strikes consistently sub parallel to the fault zone, whereas phyllite that was exposed in the road bed NW of the fault zone was more contorted. The breccia between the two seams of clay gouge is composed of poorly sorted, angular phyllite clasts that range in size up to ~10 cm (C on Figure 4A). Although minor fault surfaces are visible in the breccia, both in the exposure and in thin section (Figure 4A and B), larger clasts are generally not bounded by obvious shear-surfaces. The matrix consists of similar, but smaller, clasts of phyllite with very fine-grained matrix of aligned clasts occurring both along larger shear surfaces and near the intersection of conjugate shear surfaces (center of Figure 4B). Although some small clasts are bent and fractured (c on dark clasts in Figure 4B), larger phyllite clasts are more randomly oriented and are not consistently bounded or offset by shear-surfaces. This suggests that this breccia may have a complex origin. It may even be a sedimentary breccia associated with, and cut by a fault rather than a tectonic breccia in which all clasts formed by fracturing and shearing. Along active faults, colluvial wedge material in the hanging wall often separates from the free face forming a crevasse which

## JONESBORO FAULT

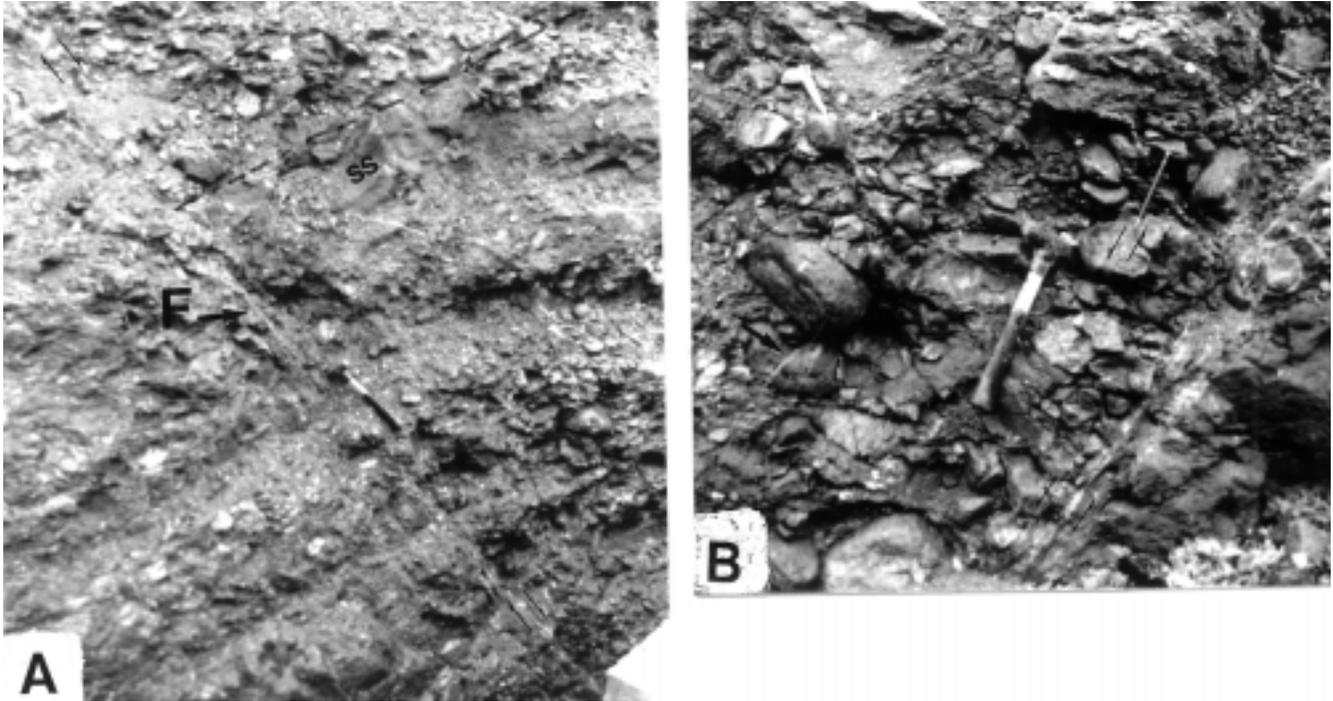


Figure 5. A: W-dipping fault (F), marked by clay gouge, exposed in N-facing cut at locality A, Figure 2. Dashed line marks contact between reddish brown sandstone (SS) and conglomerate and overlying gray conglomerate. B: the same W-dipping fault exposed in S-facing cut where sheared pebbles (*e.g.*, pencil & arrow) show down-to-the-W displacement. Pencil is parallel to slickensides on shear surfaces cutting cobbles; knife (12 cm) marks upper limit of zone of sheared cobbles near fault.

is filled by new colluvial material and is successively cut by younger displacement along the fault (*e.g.*, Bartholomew and others, 1990, their Figures 3 and 5). The fault and associated breccia at locality E are ~100 m from the nearest Triassic conglomerates (locality D, Figure 2) which consist primarily of poorly sorted, subangular phyllite and metasandstone clasts, rounded quartz pebbles, and some rounded granitoid clasts. The mixture of quartz pebbles and granitoid clasts in these Triassic beds suggests that they are not colluvial wedge material, *per se*, but are fluvial deposits in part derived from wedge material as well as from granitoids to the NE or NW.

The large block of phyllite, cut by high-angle faults, which protrudes into the basin around the Angus Barn (Figure 2), suggests the presence of one or more large rock-block paleo-landslides which are actually part of the colluvial material adjacent to the Jonesboro fault and thus are not basement beneath the Jonesboro fault as interpreted by Parker (1979). Thus the trace of the actual Jonesboro fault may, in fact, not be deflected northwestward around the Angus Barn, but may continue northeastward approximately along the dashed trace shown on Figure 2. Minor siliceous cataclasite was found at one place during reconnaissance along this projected trace northeast of US Highway 70.

At locality A (Figure 2), a fault (F on Figure 5A) with

more than 5 m of displacement strikes  $N2^{\circ} W$  and dips  $45^{\circ}$  SW. The fault surface is marked by 1-2 cm of clay gouge (Figure 5B) with slickensides trending  $N80^{\circ} W$  and  $S65^{\circ} W$ . Fractured pebbles (Figure 5B) in the hanging wall within ~60 cm of the fault surface indicate that at least some of the movement took place when the rocks were buried deep enough and/or lithified enough to deform brittlely. Shear-surfaces offsetting clast-surfaces (Figure 5B) show normal, down-to-the-NW displacement and slickenside trends on these surfaces are consistent with slickensides on the fault surface indicating normal to sinistral-oblique normal displacement.

## DISCUSSION

Vertically aligned cobbles at the Angus Barn locality, as well as clastic dikes and pillar structures elsewhere in the basin, are consistent with the interpretation that ground shaking and liquefaction accompanied some large paleoseismic events along the Jonesboro fault during deposition of Triassic sediments in the adjacent basin. In contrast, sheared cobbles and gouge zones indicate subsequent brittle fracturing of indurated rock at depth. Triassic movement on the central part of the Durham segment of the Jonesboro fault was primarily sinistral-oblique normal as indicated by slip direc-

tions on nearby smaller faults. The overall Triassic extension direction, inferred from these slip-directions and from the orientation of mode I joints (Figure 2), was ~E-W, suggesting that the N-trending Creedmoor segment of the Jonesboro fault is *favorably oriented*, whereas the Durham segment is *unfavorably oriented* (Sibson, 1990) with respect to the regional stress field in which this rift basin formed.

The overall strike of the pre-existing foliation in the subjacent Cary Formation phyllite is sub parallel to the trend of the Durham segment of the Jonesboro fault and may have been a contributing factor in the development of the *unfavorably oriented* Durham segment. At the Angus Barn locality, the *unfavorably oriented* Durham segment may have been deflected even more, perhaps by this pre-existing foliation, thus producing N70° E-trending, 85°-90°-dipping *misoriented* (Sibson, 1990) faults in a small block of phyllite that protruded into the basin. If such a severe deflection of the main fault occurred here (as mapped by Parker, 1979) then this would act as a segment boundary (e.g., Susong and others, 1990). Alternatively, a large landslide-block of phyllite may have slumped into the edge of the basin on a slip-surface parallel either to the main fault or to the pre-existing foliation (similar to the slip-surface of the Hebgen landslide which occurred during the 1959 Hebgen Lake, Montana earthquake, e.g., Hadley, 1964). If the slide-block remained relatively intact (unlike the Hebgen landslide) or moved gradually, then subsequent reactivation of slip-surfaces in this landslide-block could account for the apparent *misoriented* faults which deviate significantly from the overall N25°-35° E trend and 40°-45° dip of the already *unfavorably oriented* Durham segment of the Jonesboro fault (Parker, 1979) (Figure 2). If a landslide block is present here, then the Angus Barn deflection is of minor significance and probably did not act as a segment boundary during major paleoseismic events along the Durham segment of the Jonesboro fault.

#### ACKNOWLEDGMENTS

Our ongoing work on the structural characterization and analysis of the Wake/Chatham County potentially suitable low-level nuclear waste site, as well as our work in other parts of the Deep River basin, has provided valuable insights into the development of Mesozoic structures such as those near the Angus Barn. The work for the site has been supported by LAW Engineering and Environmental Services. We sincerely appreciate the helpful questions and suggestions about this paper from Bob Butler, Dave Blake, Bill Hoffman, Wright Horton, Sharon Lewis and Skip Stoddard. Discussions with Tim Davis about Mesozoic structural features have also been of value in formulating our ideas.

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## GROUND-WATER RESOURCES OF WAKE COUNTY, NORTH CAROLINA

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### ABSTRACT

Ground water in Wake County comes chiefly from the saprolite overlying the crystalline rocks and from the crystalline rocks themselves. Fracture porosity and permeability dominates the movement of the water. Knowledge of the geology and fracture patterns aids in evaluating the potential for ground water. Recharge to the saturated zone is estimated to be approximately 10 to 15 percent of the annual precipitation. With use of recharge values and knowledge of the production obtained from various rock types, it has been possible to identify regions of the county where reliance on ground water is feasible for certain maximum residential densities and industrial uses. The principles have been indirectly applied by governmental agencies in zoning protection zones around the water supply lakes in the county.

### INTRODUCTION

The following discussion reviews briefly the ground-water resources of Wake County in terms of ground-water occurrence and general availability. The discussion focuses on ground water in the crystalline rocks of the county and considers only in passing the problems associated with finding and use of ground water in the Triassic rocks of western Wake County. However, many of the observations considered below also apply to the Triassic Basin rocks.

Although ground water is generally available throughout the county, local bedrock geology influences its distribution and its use for domestic and industrial purposes. The ability to produce significant quantities of ground water in key places influences the economic growth of the county, at least as defined by placement of housing developments and suburbanization of once rural areas. Reliance upon ground water as part of a land-use policy is a decision embraced by both the City of Raleigh and Wake County for environmentally sensitive portions of the county surrounding the Falls of the Neuse Reservoir (Falls Lake). Large lot residential zoning designed to protect the Falls Lake from water quality degradation associated with surface runoff relies upon ground water for water supply. This arrangement can contribute indirectly perhaps as much as a million gallons of water per day to the water supply of the county. The following discussion describes the hydrogeology of Wake County and discusses application of a knowledge of the county's hydrogeology to land-use planning decisions.

### HYDROGEOLOGY

The bedrock of the county as depicted in Parker (1979) consists of a series of metamorphic rocks, granitic masses, and the sedimentary rocks of the Triassic basin. Various attempts have been made to associate ranges of ground-water yields with rock types. Also there have been attempts to find a statistically significant relationship between topographic settings and water well yields. Although some general trends may seem present, it is difficult to state with any degree of assurance that a particular combination of circumstances will lead to water well yields of a certain minimal value. Figure 1 summarizes the bedrock geology of Wake County for the purposes of the present discussion.

One can view the ground-water systems in the metamorphic and igneous rocks of the Raleigh area as a sponge or tank connected to a series of pipes. The sponge or tank represents the saprolite while the pipes represent the fractures and fractured quartz veins in the crystalline rocks. Figure 2 illustrates this concept. Because of the nature of the weathering process a relatively thin zone exists between the better-weathered, clay-rich portion of the saprolite and the unweathered bedrock. In this zone ground water may move horizontally because of the zone's general coarse texture and associated greater hydraulic conductivity compared to that found in the overlying more intensely weathered saprolite. The bulk of the storage occurs in the saprolite overlying the crystalline rocks. Also, observations in quarries and road cuts demonstrate that not all fractures receive water from the saprolite; some receive none. A laboratory model demonstrated the importance of topography and permeability of the saprolite in controlling recharge to fractures in the bedrock (Welby, 1977).

Ground-water yields from wells drilled into the crystalline rocks vary according to the size of the fractures, the lateral and vertical extent of individual fractures, and the nature of the fracture interconnections. Daniel (1990) has described a major experiment dealing with site selection criteria and well design for the crystalline rocks of the Piedmont. The study site was in Cary, a short distance west of Raleigh.

The investigation confirmed for the test site that geologic controls on large-yield wells include rock type, thickness of saturated regolith based upon topographic features, and placement of a well with regard to drainage lineations which can be interpreted as indicating the position of fractures or joints in the bedrock. Two of 13 wells were drilled at

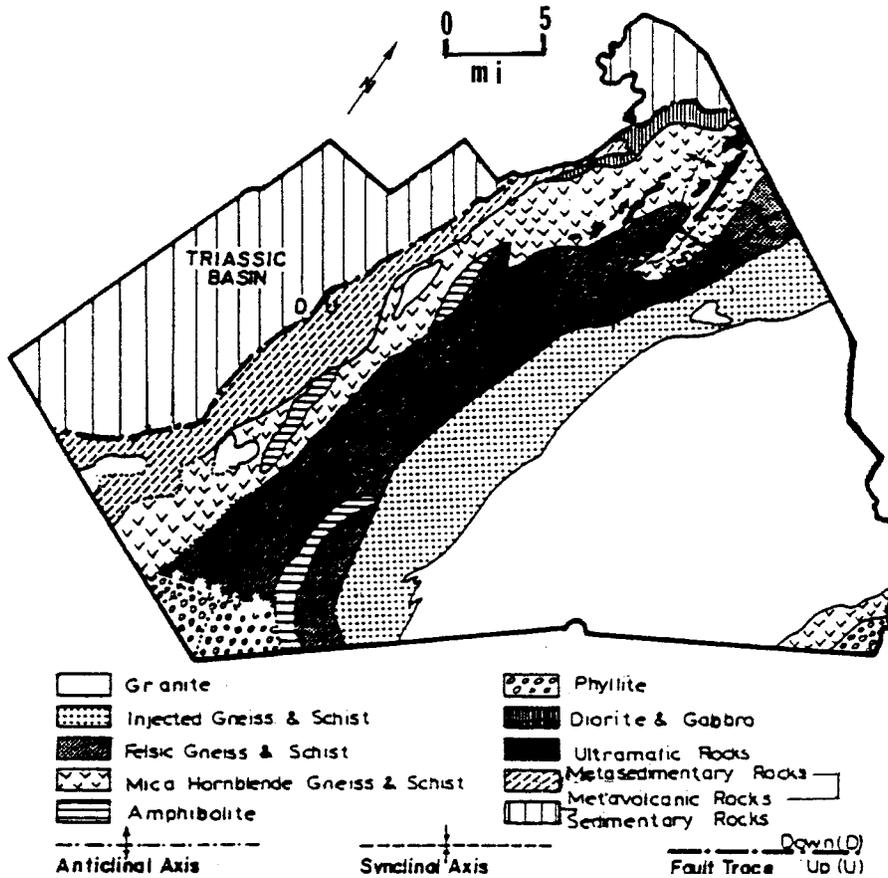


Figure 1. Generalized geologic map of Wake County (after Parker, 1979).

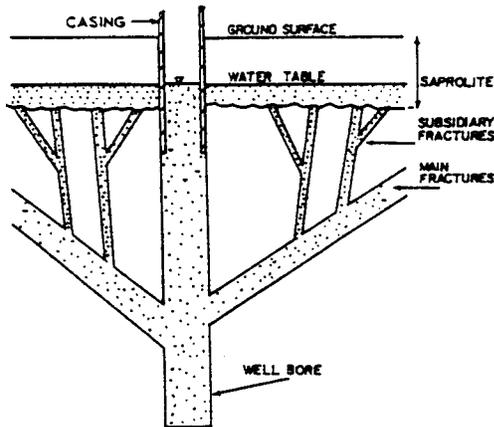


Figure 2. Conceptual model of ground water in saprolite and fractured rocks.

“ideal” sites, and each had reported yields of about six times the average yield determined from wells drilled haphazardly in the same hydrogeologic unit. Nine wells drilled at what were considered less than ideal sites had yields ranging from slightly above average to approximately six times the average yield for the respective rock unit. The locations of these wells were chosen with consideration of the above-cited geo-

logic controls in mind. Other, nongeologic factors controlled their actual siting. Over the years investigators have attempted to relate the yields of bedrock wells in the crystalline rocks of the Piedmont to various geomorphologic and lithologic factors. Positions on hills, on slopes, and in swales all have been evaluated as have rock types. The studies have met with limited success in establishing good correlations between these factors and the ultimate sustained yields of individual wells. Figure 3 illustrates yield probability by lithology for the rock types found in Wake County (Welby and Wilson, 1982). Well yields in Wake County seem controlled more by lithology than by topographic position, although thickness of saprolite probably plays an important role in the long-term availability of ground water. In the Falls Lake basin a number of potential water well sites for use with planned public facilities were selected using topographic and lineament criteria. At 12 of these sites little or no ground water was found.

Theoretically the better location for a water well in the crystalline rocks of the Piedmont is at the intersection of two or more fractures. The question is how to identify the position of a fracture or fractures from the surface. Drainage patterns are often assumed to provide evidence about fracture distribution (see Daniel, 1990). Lineaments mapped on topo-

## WAKE COUNTY GROUNDWATER

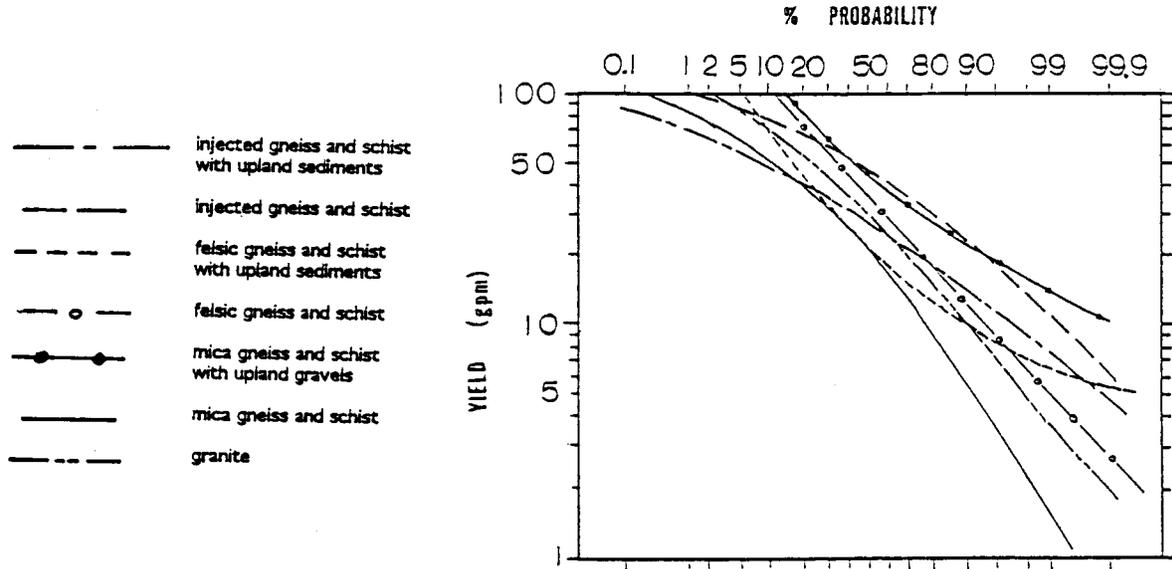


Figure 3. Yield probability by lithology.

graphic maps, aerial photographs, and on satellite imagery have been utilized in attempting to understand ground water in the crystalline rocks. Welby and Wilson (1982) found that in a semi-quantitative fashion specific capacities of wells associated with the intersection of two or more linears one of which exceeded 2000 ft is greater than the specific capacities of wells not associated with linears or associated with only one linear.

Evaluation of specific capacities of wells in Wake County in terms of well depths shows that the specific capacity values tend to stabilize at a specific capacity value of 0.1 gpm/ft at well depths of between 250 and 300 ft. As a general economic rule of thumb it appears that extension of a well below 250 to 300 ft results in an increased cost per additional gallon of water obtained. Most of the wells used in the study described by Welby and Wilson (1982) had specific capacities of 0.5 gpm/ft or less. The work of Daniel (1990) emphasized the anisotropy of the cones of depression around pumping wells. The anisotropy is related to the foliation and fracture orientation in the bedrock. From a wellhead protection regulation standpoint, the anisotropy is a difficult issue with which to deal.

### Baseflow as an Inventory Tool

The technique whereby stream low flow conditions are used to estimate the volume of ground water available for use is described in Welby (1984). Low flow conditions for one-year return and seven-year return conditions are utilized in the technique. Water budget computations suggest that approximately 10 to 15 percent of the annual average precipitation of about 45 inches reaches the water table.

### Ground Water in the Triassic Basin

A word about ground water in the Triassic Basin seems in order. Briefly, the Triassic Basin is notorious for the ground-water supply problems it presents. Although no statistical computations have been prepared for this paper, it is possible to observe that location and continuous production from high-yield wells (20 gpm or greater) in much of the basin can be considered a relatively high risk venture. People have bought five and ten acre homesites and have been unable to find adequate water supplies for minimal household usages. Owners of smaller parcels often have to "nurse" their water supply to provide for household purposes.

Diabase dikes cutting through the Triassic Basin sediments provide fracture porosity and permeability and locally some rather large well yields. However, they are like pipelines, and ground water can move along them laterally. In one instance a shopping mall tapped a diabase dike for a reported yield of 50 gpm. The developers of the mall, thinking they had a good thing going, then drilled a second well about a quarter of a mile along the strike of the dike. When the second well was tested, the first well became dry. In another case leaky sewer lines crossed a diabase dike or dikes and became sources of contamination to a water supply well drilled into the dike some distance away from the crossing.

Growth in the Triassic Basin of western Wake County has been limited because of the difficulty of obtaining adequate ground-water supplies in any systematic fashion. The development of the Wake County portion of the Research Triangle has had to await the extension of water lines as ground water could not be relied upon as a water source. (see also Trexler and White, this volume.)

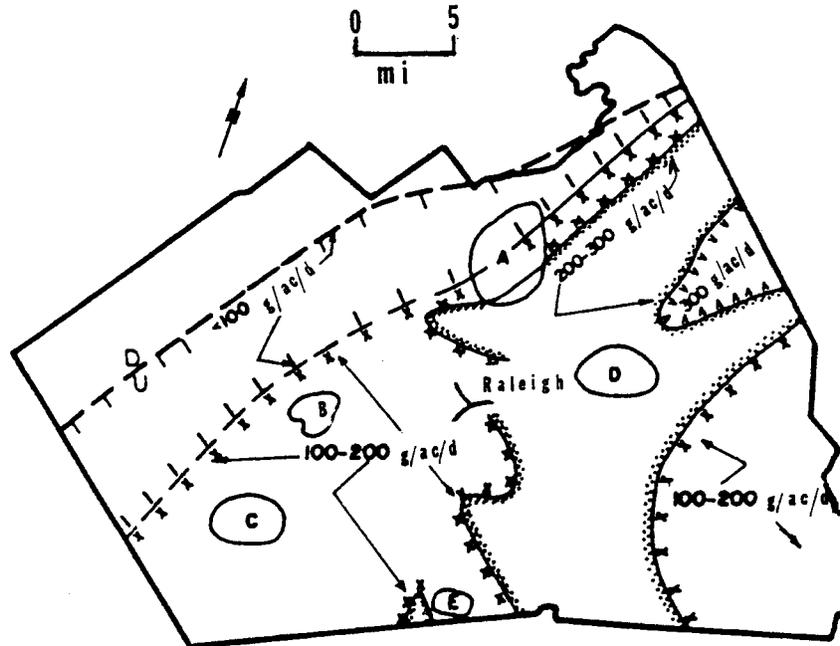


Figure 4. Ground-water availability (g/ac/day) distribution for annual seven-day low flow period. A,B,C,D,E=areas where fracture coefficients are low (after Welby, 1984).

## GROUND WATER AND LAND-USE PLANNING

It is important, of course, to understand the hydrogeology of the crystalline rocks. But to be of more than passing interest in a changing society, the knowledge needs to be put to use in a land-use planning context. The following discussion will summarize some ideas which have been used, for better or worse, in attempting to make ground water an effective tool in land-use policy and land-use planning.

There are two aspects to the question. One is related to what can be produced from a given well over the long term. The second is related to the question of inventory; that is, how large is the ground-water reserve and how much is available for consumptive use? It is common knowledge that worldwide there are many areas where consumption exceeds recharge. Antidotal evidence exists for Wake County about municipal water supply wells constructed in the crystalline rocks of the county that have gone dry even though when originally developed and tested according to state regulations the wells displayed adequate yields. More than one home owner has had to drill additional wells when the rocks have not contained an adequate supply for the demand placed upon them. The plumbing system described in Figure 2 is not infallible, and there may be a limited reserve available.

There is no easy way to determine the inventory of ground water beneath a given acre of land. However, if one assumes that the crystalline rocks have 0.2 percent effective porosity down to a depth of 300 ft. and a 20 percent effective porosity in 30 ft of saprolite (Figure 2), about 2 million gal-

lons of water are stored beneath an acre of land. To emphasize the effects of ground-water withdrawal on the inventory, a well pumping constantly at 10 gpm can withdraw 500,000 gallons in about 35 days. At a residential density of four residential units (Ru) per acre and an average water use of 300 gal/day/Ru, 500,000 gallons will be used in 1.14 years, or 2 million gallons can be pumped out in about 4.5 years.

Consideration of the nature of the fracture pattern and the abundance of fractures together with recognition of a fracture coefficient (Jenkins and Prentice, 1982) helps outline areas more and less favorable for various levels of ground-water development. Figure 4 outlines areas where ground-water availability is adequate for residential densities of about one residential unit per acre.

It is also possible to estimate a maximum permissible residential density which does not overdraft the ground water. Similar calculations can be made for other land uses. The estimated recharge values determined from water budget calculations and the ground-water inventory values determined from the low flow calculations provide the basis for this estimate. Figure 5 shows the relationships between the amount of water required for a 50-acre subdivision at various residential densities and the required volume of water and the number of acres required to provide that water on the assumption of 300 and 403 gallons/acre/day recharge. The larger value represents the total probable annual recharge based upon water budget calculations and stream low flow calculations. Thus if a planning decision is made to allow one-quarter acre lots (4 Ru/Ac) in the 50 acre subdivision and if the ground-water recharge is 300 g/ac/d, then a

## WAKE COUNTY GROUNDWATER

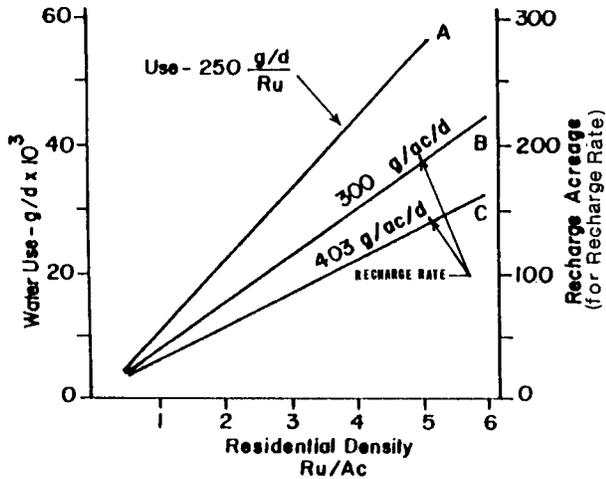


Figure 5. Residential densities, water use and required recharge acreage for a 50-acre subdivision. Curve A=water use, g/d/Ru; Curves B and C based upon indicated recharge rate and required recharge acreage. Thus for 3 Ru/ac in a 50 ac subdivision, 37,500 g/d are required. At a recharge rate of 300 g/d, 125 ac are required to provide the required water. The figure does not take into account the seasonality of recharge (after Welby, 1984).

total of approximately 160 acres will be required to supply the water to the approximately 200 units in the subdivision.

### Falls Lake Watershed

It has become established in recent years that the less development around water supply lakes the better. The Falls Lake in northern Wake County can serve as an example of the use of ground-water inventory data as a guide for land-use decisions.

Regulations and rules about development around Falls Lake require a minimum residential lot size of one acre for much of the basin and of at least two acre lots in a band extending about 2500 feet from the lake. Essentially there is no commercial development allowed within the basin except for businesses that existed prior to implementation of the zoning regulations. Based upon the evaluation of the ground-water resources summarized above, it appears that the one acre zoning is a density which maximizes the use of ground water or slightly overdrafts the ground-water supply on a long term basis. Greater density can be expected eventually to cause overdrafting of the ground-water resource. Some of this overdrafting can be expected to show up when wells drilled on individual residential lots eventually drain the aquifer or yields begin to decline in the wells of community water systems. In those portions of the basin where the recharge is greater than that required by the density of development, ground water can continue to be a suitable source for residential use.

When wells go dry in a consistent pattern, political pressures can be expected to develop for extension of municipal

water lines into the basin. Politically, costs of the extensions can be anticipated to bring pressures to bear for lowering the one and two acre minimum lot sizes as a way of increasing the residential density to recover the costs of the extensions. Two new problems then arise and have to be confronted in the political arena: (1) increased urban runoff with concomitant increased loading from pollutants and (2) decrease in ground-water recharge due to the additional impermeable surfaces.

For Wake County and Raleigh there is often lost in the question of the use of ground water the issue of total water supply to an urbanizing county. Shortly after the closure of the Falls Dam and the first withdrawal of water from the Falls Lake by the City of Raleigh, it was discovered that the amount of water available was about 20 percent less than that contracted for originally by the City. Even though the City and the Corps of Engineers have recently concluded an agreement to raise the Falls Dam to correct for the shortage of storage, the systematic and planned use of ground water in the Falls Basin provides additional water to Wake County's overall supply. This contribution is estimated to be on the order of one million gallons per day when the basin is fully developed at its present zoning density.

### SUMMARY

Ground water found in Wake County comes from the saprolite overlying the crystalline rocks and from the crystalline rocks themselves. The relationship between rock types and ground-water yields is not entirely clear cut. The plethora of factors that affect fracture development in the bedrock combined with the lack of detailed knowledge of recharge patterns leads to less than precise knowledge of the hydrogeology of a given site. However, some broad trends relating rock types, regolith thickness, topography and presumed indicators of fractures are present. These trends and the associated details that point to them provide a basis for using the understanding of Wake County's hydrogeology as a basis for land-use planning.

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## **HYDROGEOLOGY OF THE TRIASSIC DURHAM SUB-BASIN**

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### **INTRODUCTION**

Early Mesozoic rift basins containing non-marine sedimentary rocks occur in a discontinuous belt that parallels the Atlantic continental shelf and extends north from the Gulf of Mexico to Nova Scotia (Olsen and others, 1991). The exposed basins are of hydrogeologic concern because the availability of water influence the potential for development. In North Carolina, ground-water resources have been thought to be virtually nonexistent in the Triassic Durham sub-basin with many stories of dry wells. Development has been limited to areas where surface water could be supplied. This paper reviews the hydrogeology of the Durham sub-basin in terms of available water and water quality.

### **GEOLOGY**

The following discussion is a brief summary of the geologic characteristics of the Durham sub-basin. The intent of this summary is to present the information necessary so a reader unfamiliar with the Durham sub-basin can easily follow the preceding hydrogeologic discussion. The geology of the Durham sub-basin is described in greater detail by Hoffman (this volume), Hoffman and Gallagher (1989), Olsen and others (1991) and Parker (1979). The following geologic discussion was developed from a review of these works.

There are three Triassic basins exposed in North Carolina- the Dan River, Davie, and Deep River basins. The Deep River basin extends from the South Carolina line near Wadesboro northeastward to near Oxford. The Deep River basin has been divided into the Wadesboro, Sanford, and Durham sub-basins by northwest-southeast trending structural highs. The Colon cross structure separates the Durham and Sanford sub-basins, the Pekin cross structure separates the Sanford and Wadesboro sub-basins. This discussion is limited to the hydrogeologic conditions observed in the Durham sub-basin.

The Durham sub-basin is bounded to the east by the Jonesboro fault, which separates the basin and crystalline rocks generally belonging to the Raleigh belt, and to the west by an unconformity on the metamorphosed volcanic and sedimentary rocks of the Carolina Slate belt. The basin is comprised of the non-marine, Late Triassic sediments of the Chatham Group that have been intruded by Early Jurassic intrusives.

Bedding of the Late Triassic sedimentary rocks strikes

north-northeast and commonly dips gently southeastward towards the Jonesboro fault. The sedimentary rocks consist of a wide range of poorly sorted sediments lithified by diagenetic processes. The sedimentary lithologies range from siltstones to conglomerates.

Early Jurassic diabase dikes and sheets were emplaced throughout the region. Dikes generally trend north-northwest, dip vertically or steeply to the northeast and vary in thickness and length, though individual dikes generally maintain uniform thickness. They show a high degree of spheroidal weathering and can be traced overland by the presence of discontinuous spheroidal boulder trains.

Dike contacts are sharp and baked zones generally tend to be confined to a zone within twice the dike width away from the dike. The baked zones are usually highly fractured zones with the intensity of the fractures decreasing as the distance from the dike increases. The typical red colors of the sandstones, siltstones, and shales are usually changed to black in the baked zone.

For the purposes of this paper, the lithology of the basins has been divided into two general groups, the unmetamorphosed clastic sediments and the diabase intrusives. The diabase intrusions and the adjacent baked sedimentary zones are collectively referred to as diabase zones

### **HYDROGEOLOGY**

Hydrogeologic data available from two sites in the Durham sub-basin are used in this paper to demonstrate the availability of ground water in the basin. These data are available as public information from the North Carolina Department of Environment, Health, and Natural Resources, Division of Solid Waste Management, Hazardous Waste Section and the Division of Land Resources, Geological Survey Section.

#### **Site One**

Site one is located in the central portion of the Durham sub-basin at Research Triangle Park, North Carolina and consists of both consolidated and unconsolidated Triassic sands and sandstones grading into silts and siltstones with occasional thin beds of shale. The effective porosity of the sediments is very low. Diabase dikes and sheets cut these sediments. Three major intersecting dikes cut the site for a total known distance of 11,440 feet (ft). In addition, diabase

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Table 1. Pumping Test Data Summary

Site	Test ID	Duration (Days)	Pumping Rate (GPM)	No. Wells Showing Drawdown	Average Transmissivity*	Average Coefficient of Storage*
Site 1	Test No. 1	1	57.5	13	800	$1.3 \times 10^{-2}$
	Test No. 2	1	9.6	9	370	$1.2 \times 10^{-3}$
Site 2	Test No. 1	5	0.85	8	38	$1.7 \times 10^{-4}$
	Test No. 2	7	0.06	15	6.6	$1.1 \times 10^{-3}$
	Test No. 3	11	2.95	5	114	$7.0 \times 10^{-4}$
	Test No. 4	17	0.7	10	15	$9.5 \times 10^{-5}$

*\*These values reflect the aquifer parameters of either metamorphosed sedimentary rocks or the diabase bodies and should not be considered representative of the unmetamorphosed sedimentary rocks.*

sheets underlie a portion of the site and are connected to one or more of the dikes. The secondary porosity of the fractured diabase zones controls the availability of ground water.

A total of 51 recovery (38) and packer (13) tests were conducted at the site. The average hydraulic conductivity (K) for the 51 tests was  $7.8 \text{ E-2}$  ( $7.8 \times 10^{-2}$ ) feet per day (ft/d). Sixteen of the tests were conducted in wells completed in the unmetamorphosed silts and siltstones, and resulted in an average K-value of  $2.3 \text{ E-2}$  ft/d. Seven of the tests were conducted in wells completed in the sands and unmetamorphosed sandstones and resulted in an average K-value of  $7.7 \text{ E-2}$  ft/d.

Two 24-hour pumping tests were conducted. The first test was conducted in May 1981 at a rate of 55 to 60 gallons per minute (gpm). The well encountered diabase at 18 ft below ground surface, continued through the diabase and baked zone of siltstone to 110 ft, and through siltstone to 147 ft. Thirty observation wells were monitored; 13 wells had observable drawdown (Table 1). Drawdown was observed in wells which penetrated the diabase zones; drawdown was not observed in the wells penetrating the unmetamorphosed sedimentary rocks. Transmissivities (T) ranged from 85 feet<sup>2</sup> per day (ft<sup>2</sup>/d) to 2,510 ft<sup>2</sup>/d and averaged 800 ft<sup>2</sup>/d. The coefficient of storage (S) ranged from  $8.0 \text{ E-2}$  to  $5.6 \text{ E-6}$  and averaged  $1.3 \text{ E-2}$ . The average K for the wells associated with the pumping test was  $7.4 \text{ E1}$  ft/d.

The T-values are expressed in this paper as ft<sup>2</sup>/d, but T-values are also commonly referenced as gallons/day-foot (gal/day-ft). The units can be converted by multiplying the ft<sup>2</sup>/d by 7.48 gallons per cubic foot, resulting in gal/day-ft. T is defined as the rate of flow of water through a vertical strip of aquifer one unit wide, extending the full saturated thickness of the aquifer, under a hydraulic gradient of one foot per

foot.

The second pumping test was conducted in December 1986 in a well drilled to 240 ft below ground surface. Diabase was encountered from between 0.5 and 43 ft and from between 163 and 203 ft. The diabase was very fractured between 165 to 170 ft, at 187 ft, and between 198 to 203 ft. The 24-hour pumping test was conducted at 9.6 gpm. Twenty-nine wells were monitored; 9 wells had observable drawdown (Table 1). T values ranged from 105 ft<sup>2</sup>/d to 860 ft<sup>2</sup>/d and averaged 365 ft<sup>2</sup>/d; S values ranged from  $4.9 \text{ E-3}$  to  $1.2 \text{ E-6}$  and averaged  $1.2 \text{ E-3}$ . The K for the wells associated with the second pumping test was  $1.8 \text{ E1}$  ft/d.

It was observed during the pumping tests that the fracture system associated with the dike was of limited storage. The large drawdowns observed and the failure of the pumping wells to stabilize over the 24-hour period indicated that the fracture system was being dewatered and that high withdrawals could not be sustained for extended periods. The pumping well utilized in the first pumping test was continuously pumped from 1981 to 1986. The 1981 pumping rate of 55 to 60 gpm declined to a sustained flow of 5 to 7 gpm.

**Site 2**

The second site is located in the southern portion of the Durham Sub-Basin near New Hill, North Carolina and is underlain by the typical sedimentary sequences, diabase intrusives, and faults indicative of the Durham sub-basin (Chem-Nuclear, 1993).

Four pumping tests were conducted to determine the aquifer parameters of the formation under the following conditions:

- Test No. 1 - stratigraphically controlled high K-zone,

## HYDROGEOLOGY OF THE DURHAM SUB-BASIN

- Test No. 2 - shallow hydrogeologic system associated with a poorly drained area,
- Test No. 3 - hydrogeologic system associated with a diabase dike, and
- Test No. 4 - hydrogeologic system associated with a high angle fault.

Generally speaking, the tests were conducted in areas where structural features may have enhanced the K of the formation. The information obtained from the pumping tests was summarized to determine the general nature of the aquifer characteristics in these areas of structural enhancement (Table 1).

Thirty-eight wells had observable drawdown from the four pumping tests conducted at this site. The values of T from the tests covered four orders of magnitude, from tenths to hundreds of ft<sup>2</sup>/d; values of S ranged three orders of magnitude, from 1 E-6 to 1E-3.

Pumping Test No. 3, which was conducted in the diabase zone, resulted in the highest T-values relative to the other pumping tests and is in the same order of magnitude as T-values from the Site No. 1 pumping tests. The average T-values for the four tests conducted at Site No. 2 ranged from 6.6 ft<sup>2</sup>/d to 114 ft<sup>2</sup>/d (Table 1).

### WATER QUALITY

Water quality data available for the Durham sub-basin are summarized in Table 2. The water is neutral in terms of pH and moderately hard to hard. Often the iron and manganese may exist at concentrations sufficiently high to be objectionable. The problems associated with the presence of these compounds, especially iron, are complicated due to the length of time required for them to form insoluble compounds and precipitate from solution. The rate of precipitation of iron is controlled by a complex relationship between the level of dissolved oxygen (DO), Eh, and pH, with pH being the most influential parameter. Using the reported average pH of 7.2 and an assumed DO of 3 mg/L, 20 minutes will be required for half of the iron to precipitate (Applin and Zhao, 1989). Depending on the holding times associated with the pumping system components, chemical precipitates will begin to form in the well and continue throughout the handling of the extracted ground water.

### GROUND WATER SUPPLIES

#### Common Scenario

Generally speaking, adequate quantities of ground water can be difficult to obtain, and should be addressed in the planning stages of both residential and industrial development. Wells to depths of 300 feet producing 1 gpm or less are common. In the event a low yielding well is the only means

of obtaining water, it can be a satisfactory method of supply if the well is equipped with a storage system and is regularly maintained. If allowed to pump for a 24-hour period, a well yielding 1 gpm can produce 1,440 gpd, which is an adequate quantity for many residential needs.

The storage system should be sized according to the demand of the service and the yield of the well. Since the well will be pumping in a manner that results in the accelerated accumulation of chemical deposits, periodic removal of the deposits will be required. The well maintenance program should consist of monitoring water levels and yield records to indicate the gradual decline in production and the water table.

#### Best Case Scenario

The diabase intrusives and associated baked zones are preferred locations for water supply wells. Wells installed in these areas can typically yield from 5 to 50 gpm depending upon the length of the dikes and sheets exposed to recharge from the surrounding sediments. These areas can be located by conducting magnetic surveys; the diabase can produce localized total magnetic field anomalies of 1,000 gammas and can be traced on aeromagnetic maps. The problem with this scenario is the limited occurrence of the diabase.

#### Worst Case Scenario

The worst case is a dry well. This is a condition that occurs with enough frequency in Triassic sedimentary rocks that addressing water supply issues in the planning stages of residential and industrial development is strongly recommended. Unless a well intersects a diabase zone, increasing its depth below ground surface does not increase the probability of obtaining water. In the event ground water is not encountered within 300 feet of the surface, drilling should be terminated and relocated.

### CONCLUSIONS

The highest T-values were obtained from the pumping tests conducted in the diabase zones, suggesting the diabase and baked sedimentary rocks are the preferred area for well placement. Average T-values obtained from the diabase zones ranged from 110 to 800 ft<sup>2</sup>/d. The diabase and baked sedimentary rocks have higher K-values (average K of 180 ft/d) than the nonbaked, nonfractured sedimentary rocks (average K of 7.9 E-2 ft/d). Based on the correlation in K-values between the wells showing drawdown and those that did not at Site No. 1, and the conditions of the pumping tests at Site No. 2, it is felt that the reported values of T and S represent only the diabase zones and do not represent the unmetamorphosed sedimentary rocks.

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Table 2, Ground Water Quality Data for Triassic Rocks in Durham, Granville, and Wake Counties, North Carolina.

Constituent	Concentration in mg/L			
	Minimum	Maximum	Average	Number of Samples
Arsenic	<0.003	0.010	<.01	33
Barium	<0.10	0.64	0.20	35
Cadmium	<0.0001	0.005	<0.005	35
Calcium	2.3	154	49.4	24
Chloride	1.7	572	76.3	24
Chromium	<0.0001	<0.01	<0.001	34
Copper	<0.05	<0.05	<0.05	11
Fluoride	<0.10	1.50	0.20	46
Iron	<0.01	1.60	0.18	53
Lead	0.001	<0.03	0.027	35
Magnesium	3.0	37.0	13.2	24
Manganese	<0.01	0.98	0.19	55
Mercury	<0.0002	<0.001	<0.0002	35
Nitrate	<0.05	12	1.30	48
Selenium	<0.005	0.003	<0.005	36
Silver	0.0002	<0.05	<0.05	35
Sodium	1.6	310	40.6	36
Sulfate	1.0	25	7.2	13
Zinc	<0.05	0.09	0.06	11
pH	5.8	8.2	7.2	67
TDS	92	852	286	23
<p><b>Table References:</b>                      Bain, G. L. and Thomas, J. D., 1966, Geology and Ground Water in the Durham Area, North Carolina: N.C. Department of Water Resources, Ground-Water Bulletin No. 7, Raleigh, 147 p.                      May, V. and Thomas, J. D., 1968, Geology and Ground Water Resources in the Raleigh Area, North Carolina: North Carolina Department of Water and Air Resources, Ground-Water Bulletin No. 15, Raleigh, 135 p.                      N.C. Department of Human Resources, 1986, Unpublished Water Quality Records from Community Well Systems: Environmental Health Section, Division of Health Services, Water Supply Branch, Raleigh.</p>				

The reported values of T and S should be considered as the maximum values obtainable from wells installed in diabase zones. This condition occurs as a result of the common practice of installing the observation wells in the highly fractured, water bearing zones that are not necessarily representative of the entire formation. In fractured rock systems, a significant portion of the observation wells are installed in

the above average water bearing zones. This biases the test results because the less fractured areas are not necessarily represented on an equal basis. The diabase zones are not homogeneous with respect to the degree of fracturing. Therefore, the entire formation, which may extend hundreds of feet below ground surface, should not be considered as having the same T-value as that derived from an observation

## HYDROGEOLOGY OF THE DURHAM SUB-BASIN

well with a 12-foot long sandpack installed in an above average water bearing zone.

The range of T-values for the diabase zones convert into a range of 820 to 5,980 gal/day-ft. This implies a hypothetical well that penetrates 100 ft. of the saturated diabase zone could yield from 82,300 gal/day to 598,000 gal/day if 100 ft. of drawdown could be maintained in the pumping well. However, the T-values do not take into consideration the loss of flow associated with well efficiency, the heterogeneities in the diabase zone, and the sedimentary rock K-values limiting the long-term availability of ground water in the diabase zone as at site 1 after five years of pumping. Reducing proposed well yields derived from the reported T-values by an order of magnitude is suggested as a prudent design practice. This method brings the range of flow calculated for a hypothetical well using the reported T-values to within the range commonly observed, which is 5 to 50 gpm.

The diabase zones and the unmetamorphosed sedimentary rocks have been discussed in a manner that implies they react as separate aquifers. However, these two components are interrelated. The diabase zones provide ground water storage and a means of transmission. A well intersecting a diabase zone taps a large reservoir of available ground water. However, recharge of ground water to the diabase zone is controlled by the lower K of the surrounding unmetamorphosed sedimentary rocks. As the ground water is pumped from storage in the diabase and adjacent fractured sedimentary rocks, the yield to the pumping well decreases until an equilibrium is reached between the ground water being removed from the diabase zone and the recharge of ground water from the unmetamorphosed sedimentary rocks into the diabase zone.

Ground water is available in the Durham sub-basin on a limited basis. Ground water can be obtained with some degree of reliability from the diabase intrusions and resulting baked zones. Ground water is much more difficult to obtain from the unmetamorphosed sedimentary rocks.

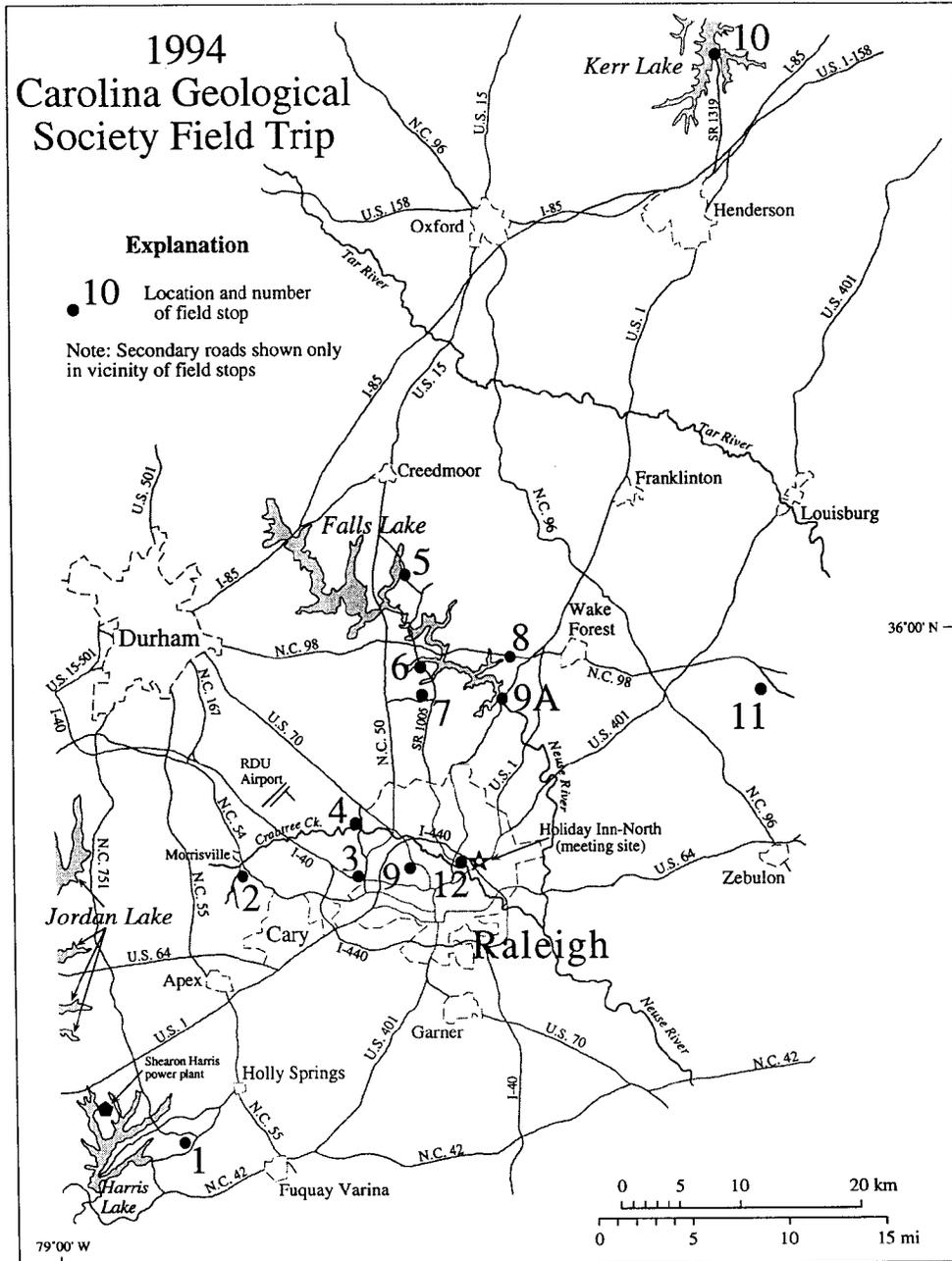
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## FIELD GUIDE TO THE GEOLOGY OF THE WESTERN FLANK OF THE RALEIGH METAMORPHIC BELT



### INTRODUCTION

This one and a half day field trip consists of 12 stops (plus one alternate). Eight stops are scheduled on Saturday and four on Sunday. The objectives of the field trip are to show key rock exposures and to provide a regional perspective in which to understand the evolution of the area. Saturday's trip focuses on the geology west of the Nutbush Creek fault zone, in the Carolina and Crabtree terranes, Crabtree

Creek pluton, Falls Lake melange, and the bounding Mesozoic basin. On Sunday, the focus will shift eastward to the geology of the Nutbush Creek fault zone, the Raleigh terrane, and the Rolesville granitoid batholith.

All stop locations are shown on the regional index map above. Individual stop locations are depicted, with no change in the 1:24,000 scale, in a reproduction of a portion of the pertinent 7.5' quadrangle that accompanies each stop description. North is toward the top of the figure in all loca-

## FIELD GUIDE TO THE WESTERN FLANK

tion maps.

The leaders acknowledge the advice and assistance of Dan Walker, Joe Smoot, and Rick Wooten (Stop 2), and Will Grimes (Stop 7). We appreciate the cooperation of representatives of Teer Aggregates, the U. S. Army Corps of Engineers (Falls Lake Project), Falls Lake State Park, Kerr Lake State Recreation Area and of the businesses and private land-owners who graciously permitted us on their property.

### DAY 1: SATURDAY, NOVEMBER 5

#### STOP 1A: FELSIC METAVOLCANIC ROCKS, CARY FORMATION

**LEADER: Bob Butler**

**Main pit, Holly Springs Quarry, Teer Aggregates, off Rex Road (SR-1127), 7.5 km southwest of Holly Springs, Cokesbury 7.5' Quadrangle**

The Holly Springs quarry (Figure 1-1) exposes schistose, felsic metavolcanic rocks, probably originally crystalline tuffs and lapillistones. These are typical rock types of a major map unit in the Cokesbury quadrangle (Figure 1-2) that can be traced northward to the vicinity of Cary, where they are the Cary sequence of Parker (1979) and the Cary formation (informal) of Farrar (1985a). The metavolcanic-metasedimentary rocks of the Cary formation are considered to be part of the Carolina terrane, separated from the main outcrop belt of the Carolina slate belt by the Triassic Deep River basin. The Cary formation is a major map unit occurring just southeast of the Jonesboro fault for a distance of about 60 km, from the Falls Lake area (Horton and others, 1992) to the Sanford area (J. R. Butler, unpublished mapping). Goldberg (this guidebook) obtained a zircon U-Pb age of  $575 \pm 12$  Ma for samples from the Cary formation just north of Cary.

The rocks in the quarry are medium light-gray, fine-grained, schistose volcaniclastic rocks, regionally metamorphosed in the upper greenschist facies. They are dacitic in composition and are composed mainly of quartz, plagioclase, white mica, biotite, and epidote, and have less than 2% garnet. The well-developed cleavage strikes NE and dips moderately NW, a characteristic orientation of foliated rocks in most of the Cokesbury quadrangle (Butler, 1994). Light-colored clasts of felsic metavolcanic rocks are strongly flattened in the plane of cleavage. Conformable mafic schist layers as much as 40 cm thick are probably altered and deformed mafic dikes.

#### STOP 1B: JONESBORO FAULT ZONE

**LEADER: Bob Butler**

**Diversion Channel, Holly Springs Quarry**

The Jonesboro fault zone is well exposed in the diver-

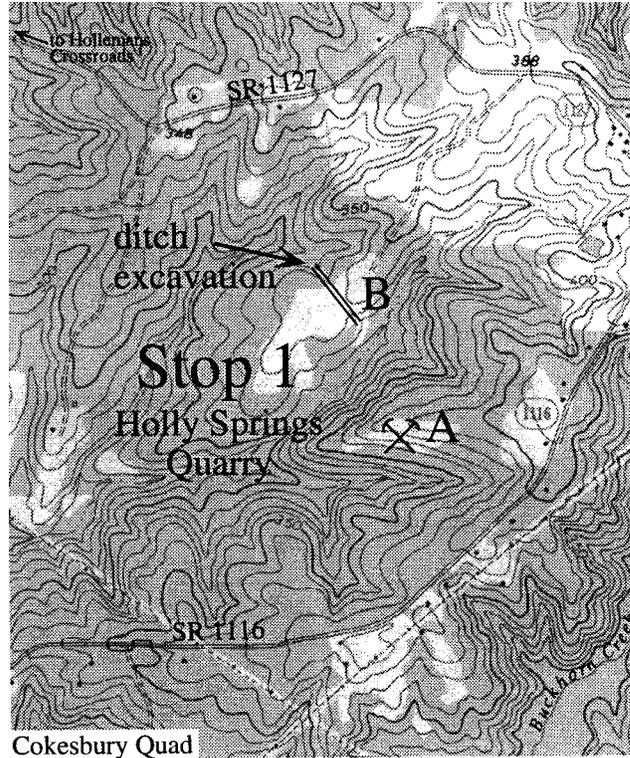


Figure 1-1. Location of Stop 1.

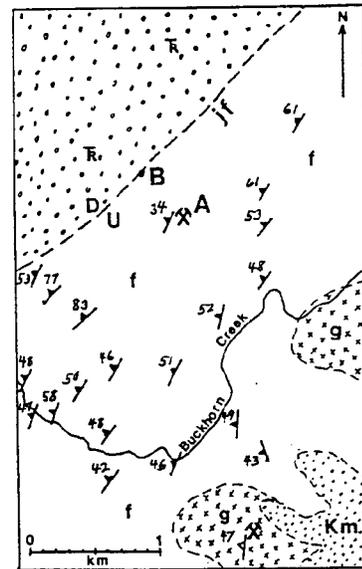


Figure 1-2. Geologic map of the area around the Holly Springs quarry. A and B are field trip stops described in the text. The Jonesboro fault is shown by the heavy dashed line (jf). Dip-and-strike symbols show the orientation of schistosity. Geology by J. R. Butler, 1993-94.

Kn: Middendorf Formation (Late Cretaceous); Tr: Triassic sedimentary rocks (Late Triassic); g: granite intrusions (Late Proterozoic or Early Paleozoic); f: felsic metavolcanic rocks (Late Proterozoic).

## RALEIGH METAMORPHIC BELT

sion channel of a relocated stream at the Holly Springs quarry, operated by Teer Aggregates. The channel cuts through a low ridge and creates an excellent exposure of the rocks on both sides of the fault. The Jonesboro fault is a major normal fault that is the southeastern border fault of the Triassic basin. To the southeast, there are felsic metavolcanic rocks of the Cary formation (Stop 1A) and to the northwest, there are Triassic conglomerates (Stop 2). Figure 1-2 depicts these relationships. The metavolcanic rocks are brecciated and strongly hydrothermally altered near the fault. The alteration defines a zone at least 20 meters thick. Thin sections show that the rock is brecciated, plagioclase is sericitized, biotite is partly chloritized, and there are numerous veinlets of quartz and calcite. Some samples have a network of calcite veinlets, and calcite has partly replaced the matrix of the breccia. The calcite typically has a deep red, but weak, fluorescence under short-wave ultraviolet light. Small exposures of brecciated rocks have been observed at two other localities on the Jonesboro fault along strike to the southwest of this exposure.

### STOP 2: TRIASSIC ALLUVIAL FAN DEPOSITS ADJACENT TO THE JONESBORO FAULT

**LEADERS: Kathleen Farrell and Bill Hoffman**  
Railroad cut, Norfolk and Southern Railway at Morrisville Parkway, Cary 7.5' Quadrangle

*The outcrop is located in a narrow cut along an active railroad right-of-way having limited sight distance for train operators as well as field trip participants. East-bound trains are typically moving rapidly as they travel down grade along this stretch. To ensure safety for field trip participants, it is imperative that the field trip party evacuate the right-of-way if a train is approaching. Trip leaders will be able to provide only very short notice in such a case. Thus, it is important to move quickly if an evacuation is requested.*

This outcrop, whose location is indicated on Figure 2-1, shows examples of architectural elements comprising the Trcs/c map unit (Lithofacies Association III) described by Hoffman and Gallagher (1989) and Hoffman (this guidebook). The Trcs/c map unit contains conglomerates and sandstones interpreted to be alluvial fan deposits adjacent to the southeastern border fault of the Durham basin. The outcrop, sketched in Figure 2-2 from a photomosaic, trends north-south, faces west, and exposes about 3.5 m of sedimentary section that is dipping northwestward at a shallow angle.

Two main lithofacies occur at this outcrop: (1) clast-supported, sandy conglomerate, and (2) sandstone, which is massive, graded or mixed with conglomerate to form matrix-supported conglomeratic units. Both lithofacies include a small percentage of silt- and possibly clay-sized sediment which may in part be attributed to the diagenetic alteration of

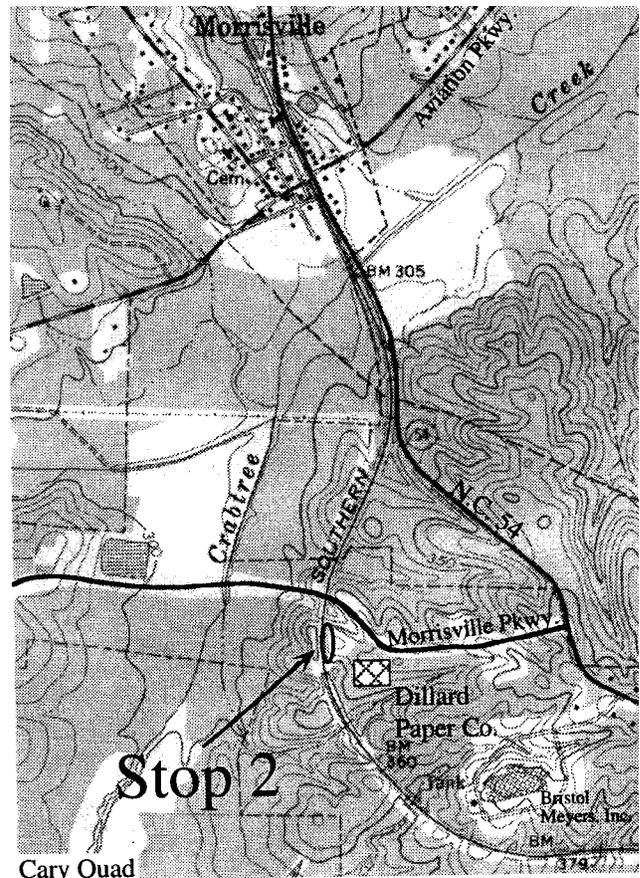


Figure 2-1. Location of Stop 2.

unstable minerals. The conglomerates and sandstones form a series of fining-upward sequences, each of which is up to one meter thick (Figure 2-3). Figure 2-2 shows several depositional sequences (delineated by heavy lines) and examples of features described and referenced below as “a” through “h”. Sandy siltstone, a minor lithofacies component at this outcrop, occurs locally at the tops of the fining upward cycles. Bioturbation was not observed, but this could simply be an artifact of preservation within the outcrop.

Clast-supported conglomerates form discontinuous, lens-shaped beds about 0.5 m thick that commonly have a basal cobble lag. Scour-and-fill surfaces or reactivation surfaces are common so that a single, laterally continuous lens-shaped bed may be composed of several smaller lens-shaped, internally cross-stratified, possibly imbricated or massive units. These clast-supported conglomerates range in shape and grain size from rounded, equant, cobble conglomerates that fill in trough-shaped depressions (a, Figure 2-2) to finer-grained, flat-pebble, sandy conglomerates with well-developed foresets (b, Figure 2-2). Locally, such as in the cobble conglomerates (a, Figure 2-2) stratification may be obscure. In addition to cross stratification, clast-supported conglomerates exhibit a component of marginal (?) accretion or infill as drapes in topographic lows, shown in outcrop as a

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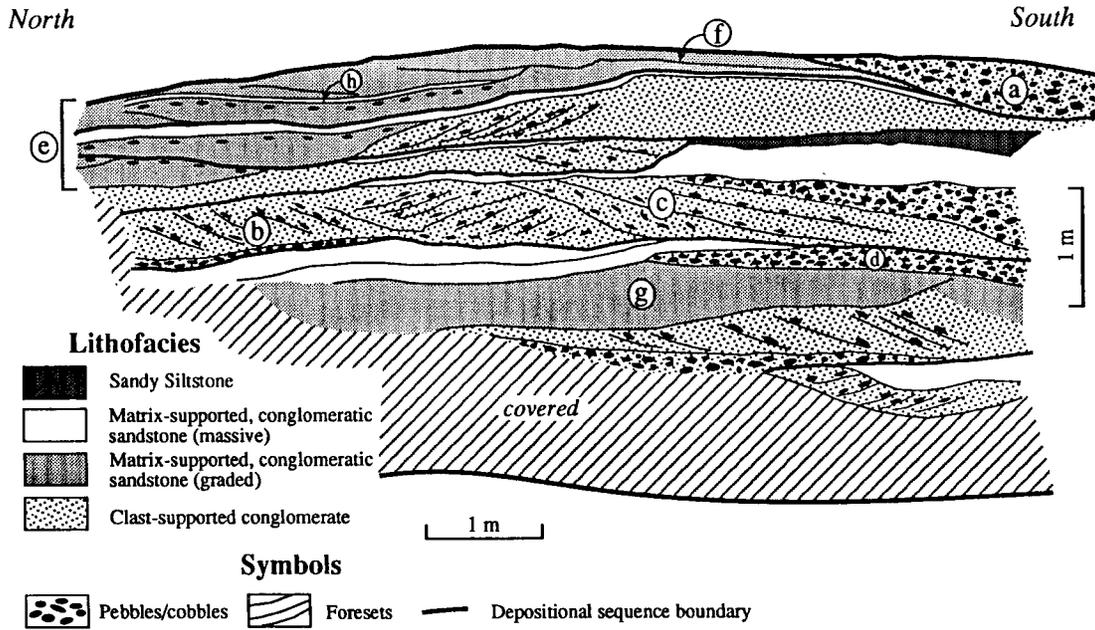


Figure 2-2. Diagram of outcrop exposed along the east side of Norfolk-Southern right-of-way just east of Morrisville Parkway. Circled letters indicate examples of features described and referred to in the text.

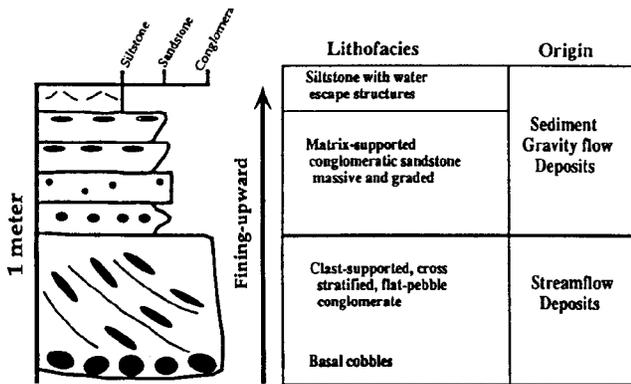


Figure 2-3. Representative fining-upward sequence shows the relationship between lithofacies and the depositing medium (streamflow versus sediment gravity flow). During a period of streamflow, clast-supported conglomerate having an erosional base was deposited as bedforms or bars in a braided stream associated with an alluvial channel. Subsequently, debris flow activity resulted in the deposition of several beds of massive and graded, matrix-supported, conglomeratic sandstone. The top of the sequence consists of siltstone having possible water escape structures, that are interpreted to indicate dewatering at the end of a depositional cycle.

series of subparallel, low-angle beds that dip southward (c, Figure 2-2). The grain size, internal stratification, lens-shaped beds, reactivation and scour surfaces, and clast-supported fabric suggest that this lithofacies was transported and deposited as bedload or traction load by locally erosive currents (streamflow segment in Figure 2-3). Some of the beds of conglomerate (d, Figure 2-2) may be analogous in fabric,

stacking arrangement, and origin with the sandstones described below.

The clast-supported conglomerates either grade upward into or are abruptly overlain along lithologically sharp contacts by poorly sorted, conglomeratic sandstones. These sandstones also form drapes that infill topographic lows (e, Figure 2-2) adjacent to clast-supported conglomerates as well as locally overtopping these conglomerate beds (f and g, Figure 2-2). These sandstones do not show cross stratification or bioturbation. Rather, the sandstones are: 1) normally and/or inversely graded within a single bed (e, Figure 2-2); or 2) massive with randomly dispersed granule-, pebble- and/or cobble-sized clasts (g, Figure 2-2). This lithofacies includes slightly silty, conglomeratic, medium to very coarse grained sandstones. Locally, however, poorly sorted, finer grained sandstones separate coarser beds (h, Figure 2-2). The massive beds are mottled with respect to grain size distribution. The sand fraction is clast-supported and acts as matrix for larger, gravel-sized particles that are either dispersed randomly, occur neatly at the tops of inversely graded beds, or occur in the middle of beds that are inversely to normally graded.

The inversely graded, normally graded, and dispersed conglomeratic sandstone beds resemble deposits interpreted by Schultz (1984) to represent deposition from pseudoplastic debris flows, considered to be slurries having a relatively low yield strength owing to a relatively high water content. Normal or inverse-to-normal grading is expected to develop from these flows because shear gradient, clast concentration, and dispersive pressure decrease away from the base of flow (Schultz, 1984). (Dispersive pressure is a grain support

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mechanism that is observable by shaking a box of flake cereal and noting that an inversely layered flake deposit is generated with the largest flakes maintained at the top of the pile by dispersive pressure set up by grain to grain (or flake to flake) collisions). In pseudoplastic debris flows, turbulence also helps suspend larger clasts during high velocity phases of flow. Immobilization of the slurries preserves the dispersion of the larger clasts in the matrix and produces massive (ungraded) beds. Normally graded (fining-upward) layers are interpreted as forming via settlement from suspension.

Locally, the conglomeratic sandstones fine upward into the sandy siltstone lithofacies. Siltstones are thin (cm-dm) and discontinuous where locally truncated by the overlying conglomerates that occur at the base of the next fining-upward sequence. The sandy siltstone lithofacies has an irregular fissility that is attributed to formation of secondary water escape structures. Dish and pillar structures, for example, form when water escapes from loosely packed sediment that was rapidly deposited from suspension (Lowe and LoPiccolo, 1974). These structures occur as faint, broken, concave-upward segments of lamination-like features.

Based on this limited, two-dimensional exposure, several inferences can be made regarding the origin of these deposits. Within each sequence, the stacking arrangement of lithofacies suggests that a period of bedload deposition (stream flow) was followed by a period of deposition from sediment gravity flows (Figure 2-3). This sequence of events is repeated several times in outcrop. The clast-supported conglomerates may have formed as a series of low-relief bedforms or bars in a braided channel associated with an alluvial fan, thus representing streamflow deposits. Topographically low areas between the bedforms or bars were infilled by a series of debris flows, which locally overtop and bury adjacent bars. The absence of bioturbation along the tops of beds suggests continuous, rapid deposition from a surging, but waning pseudoplastic debris flow. Sandy siltstones containing water escape structures locally mark the limit of suspension sedimentation and dewatering of the bed near the end of a depositional event. The question becomes, what is the relationship between the stream flow and pseudoplastic debris flow deposits within a single depositional cycle? Were channel networks with braid bars abandoned by stream flow and later infilled with debris flow deposits? Or are the traction deposits genetically related to the debris flow deposits in an evolving flow regime associated with a single major event? Also, what role, if any, did bioturbation have in producing the observed fabrics?

### STOP 3: GRAPHITE SCHIST OF THE CRABTREE TERRANE, WEST RALEIGH

**LEADERS: Barry Lumpkin, Dave Blake, and Skip Stoddard**

**District Drive extension, Raleigh West 7.5' Quadrangle**

*Be careful at this stop. There are particularly lush poison ivy and tangled briars adjacent to the creek, especially on the east side. Also, the creek banks are quite steep, the schist is slippery, and the creek has at least one fairly deep pool at the outcrop. So watch your step unless you want to go for a swim!*

In west Raleigh, the Crabtree terrane is represented predominantly by felsic gneiss and biotite-poor mica schist. These rocks are inferred to constitute a layered sequence of both metasedimentary and metavolcanic origin. Stop 3 (Figure 3-1) is an exposure of a very distinctive graphite-rich schist that is an important part of this layered sequence. It is located along a small creek on agricultural land belonging to North Carolina State University. The Raleigh graphite schist is noteworthy for several reasons. It was mined for its graphite through the early part of the 20th century. It is an unusual Piedmont rock type whose distinctiveness makes it a good marker for geologic mapping of structural relationships (e.g. Parker, 1979). In addition, its composition and inferred organic origin (Lumpkin and others, this guidebook) place constraints on permissible depositional settings for the protoliths of the rocks of the Crabtree terrane. The graphite schist is described in more detail, and its significance is addressed, in the separate article in this guidebook by B. L. Lumpkin and others.

The exposure at Stop 3 is compositionally layered, with the apparent proportions of graphite varying from layer to layer. As elsewhere in the west Raleigh area, the graphite schist is composed mainly of white mica, quartz, and graphite, in varying proportions. In some rocks graphite is the most abundant mineral, ranging up to 40% by weight (corresponding to a slightly higher modal percentage, considering

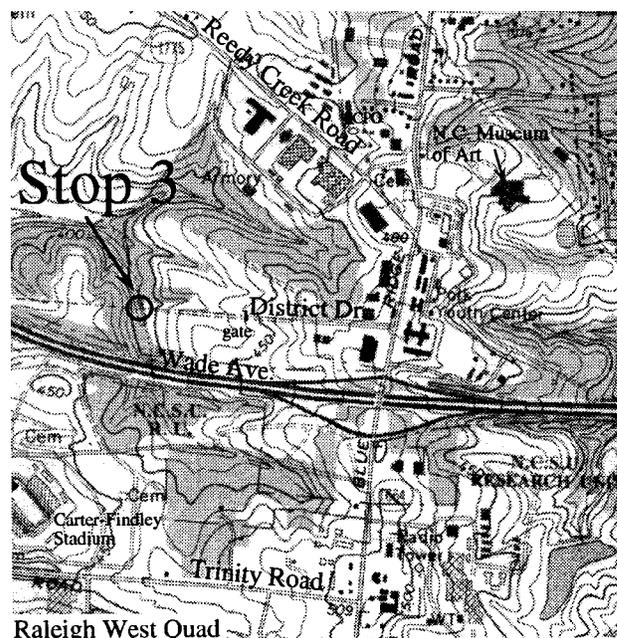


Figure 3-1. Location of Stop 3.

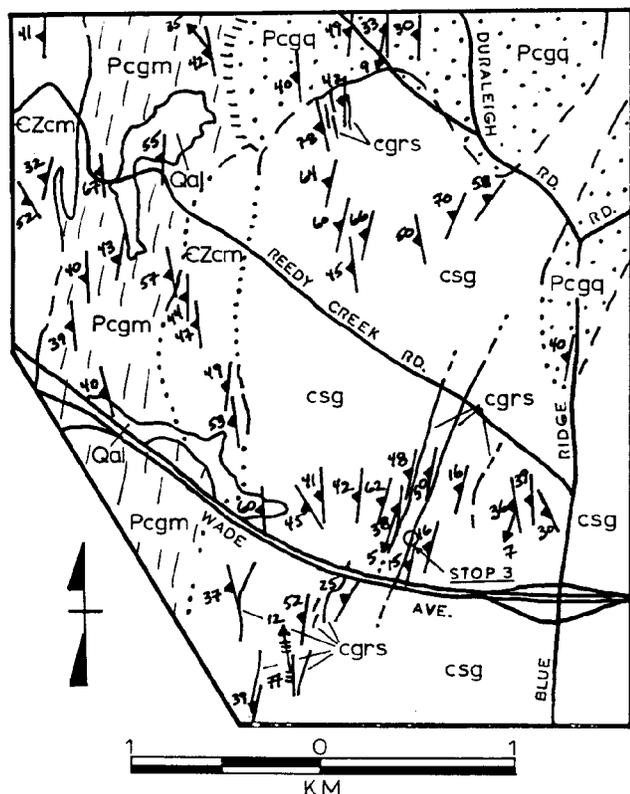


Figure 3-2. Geologic map of a portion of the northern Raleigh West 7.5' Quadrangle (modified after Blake, 1994) showing the distribution and contact relationships of mapped graphite schist units in the Crabtree terrane. In the north-central part of the map, graphite schist is truncated by the Crabtree Creek pluton.

Pcgq, Pcgm: facies of the Crabtree Creek pluton; csg: schist and gneiss of the Crabtree terrane; cgrs: graphite schist; CZcm: Turkey Creek amphibolite of the Carolina terrane. Foliations, lineations, and folds are  $S_2$ ,  $L_2$ , and  $F_3$ , respectively, of Blake (this guidebook).

the low specific gravity of graphite). Thin sections from Stop 3 contain the following approximate modal mineralogy: graphite (20%), white mica (60%), quartz (10%), garnet (5%), with lesser amounts of staurolite and biotite. The foliation is defined by flakes of white mica and graphite, and by discontinuous lenses of graphite. The graphite schist is interlayered with graphite-poor white mica schist, locally containing garnet and staurolite. Saprolite of the mica schist can be seen in an eroded ditch along the dirt access road to Stop 3, at the edge of the pasture just east of the creek and north of the dirt road, and in the creek for nearly 300 m downstream from Stop 3.

The schistosity strikes from  $N14^\circ W$  to  $N15^\circ E$  and dips toward the west at low to moderate angles ( $10^\circ$  to  $45^\circ$ ). Dips in Crabtree terrane schists in the vicinity are generally somewhat steeper, around  $50^\circ$  to  $60^\circ$  (Figure 3-2), but upright, open folds affecting the rocks at Stop 3 produced a series of

NNE-SSW trending folds and crenulations. A strong crenulation lineation has a subhorizontal, NNE-SSW attitude in graphite schist. Pods and veins of quartz are present at this outcrop, but this is not a common feature of other graphite schist exposures.

The number of individual layers of graphite schist within mica schist of the Crabtree terrane is unknown; only the thickest of them can be mapped with confidence. The occurrence of thin (as thin as 2-4 cm) and discontinuous graphitic zones is known from short-lived construction excavations in the area. An example of such relatively fine interlayering is depicted by Parker (1979, his Figure 2); other examples were observed recently in excavations north and west of Carter-Finley stadium, located 0.75 km SSW of Stop 3 along strike (Figure 3-2). The thickest mapped zones of graphite schist range up to 30 m or more in width (e.g. Stoddard and others, 1991).

Recent mapping in the Raleigh West Quadrangle (Blake, 1994) indicates that a zone west of Ebenezer Church Road, located about 2 km NNW of Stop 3, and containing several thin horizons of graphite schist, is transected at a high angle by the Crabtree Creek pluton (Figure 3-2). The tentative late Proterozoic age of the pluton (Goldberg, this guidebook; Horton and Stern, 1994) provides a minimum depositional age for the protoliths of the Crabtree terrane, including the graphite schist.

#### STOP 4: ORTHOGNEISSES OF THE CRABTREE CREEK PLUTON

**LEADER: Dave Blake, assisted by James Izzell and Jim Sprinkle**

**Teer Aggregates' Crabtree Quarry, Duraleigh Road at Crabtree Creek, northwestern Raleigh West 7.5' Quadrangle**

*Buses will park at the processing plant at the southern end of the quarry. Please be alert for potential hazards. For safety reasons, only view the quarry rocks along the haul road that leads north from the processing plant and lies adjacent to the eastern and northern walls of the mine pit. Do not climb on the quarry walls or benches and maintain a proper distance from steep embankments. Be careful of water-saturated, overhanging rock ledges as they are susceptible to failure. Hard hats are required.*

Orthogneisses of the Crabtree Creek pluton are well exposed in the eastern and northern walls of the mine pit at Crabtree Quarry, located just west of Duraleigh Road (SR 1664) on the north side of Crabtree Creek (Figure 4-1). The quarry is currently owned and operated by Teer Aggregates which mines the metaplutonic rocks for construction aggregate, landscape stone, and culvert rip-rap in west Raleigh. The quarry is reported to have been opened in the early to mid 1940's by the N. C. State Highway and Public Works

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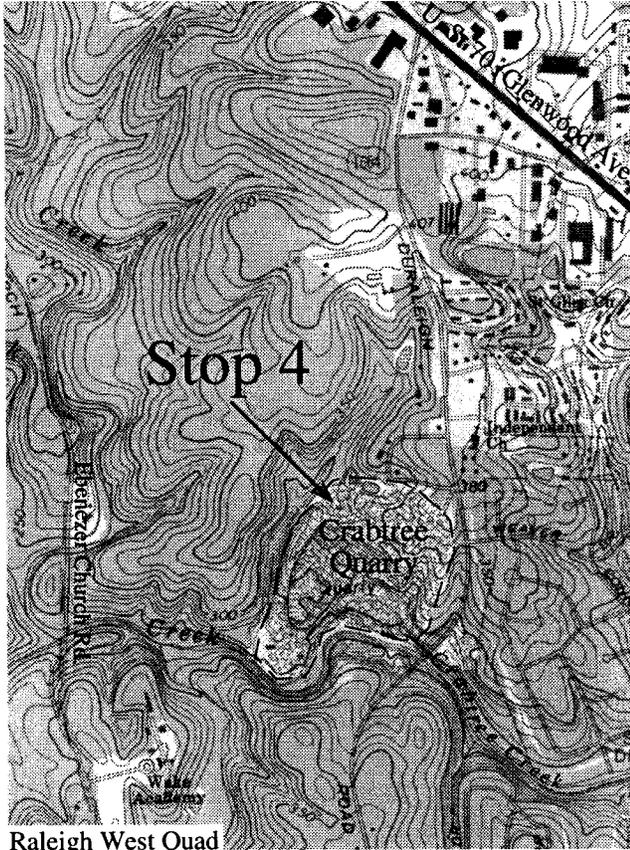


Figure 4-1. Location of Stop 4.

Commission, and has been continuously active since 1954 (Parker, 1979). Removal of quarry rocks has resulted in a mine pit that is approximately 0.5 km in diameter and 0.1 km deep.

The Crabtree Creek pluton, originally named by Kish and Campbell (1986) for rocks at this locality, separates mafic rocks of the Turkey Creek amphibolite body of the Carolina terrane from felsic gneiss and pelitic and graphite schists of the Crabtree terrane (Figure 4-2). At the quarry, both the western and eastern facies of the Crabtree Creek pluton can be observed (Figure 4-3; Blake, this guidebook). The western facies consists of a foliated, medium-grained, leucogranitic orthogneiss. It is in gradational contact with the eastern facies, a moderately to well foliated to lineated, leucocratic, medium- to coarse-grained granitic orthogneiss containing abundant porphyroclastic disks or rods of quartz. A more detailed discussion of the petrography, structure, and field relations of the Crabtree Creek pluton is provided in the article in this guidebook by D. E. Blake.

As one descends into the quarry on the haul road along the eastern and northeastern pit walls, greenish-gray to pink, coarse- to medium-grained, porphyroclastic orthogneiss (eastern facies of the pluton) is visible. The rocks are composed chiefly of K-feldspar, plagioclase, quartz, and white

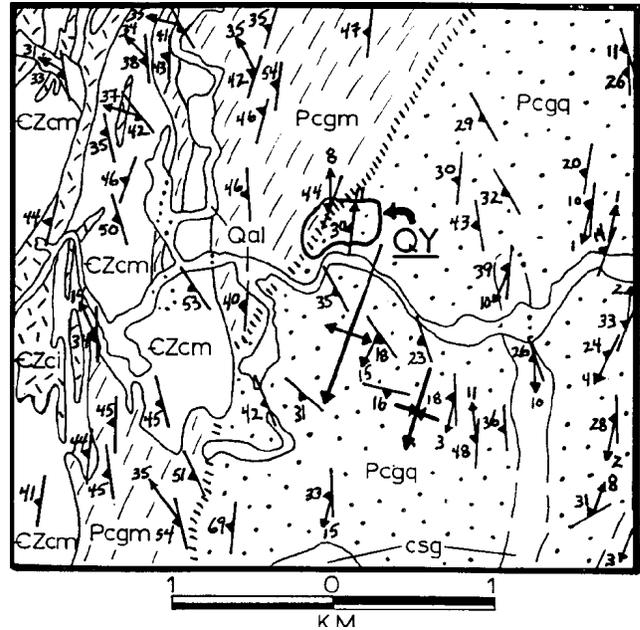


Figure 4-2. Geologic map of a portion of the northern Raleigh West 7.5' Quadrangle (modified from Blake, 1994) showing contact relationships between the Crabtree Creek pluton and rocks of the Crabtree and Carolina terranes. Location of Teer Aggregates' Crabtree Quarry is outlined by the heavy line and labelled "qy."

PCGq: porphyroclastic granitic orthogneiss of the Crabtree Creek pluton; PCgm: leucocratic orthogneiss of the Crabtree Creek pluton; EZcm: Turkey Creek amphibolite of the Carolina terrane; EZci: granitoid sills and dikes of Reedy Creek (Parker, 1979); csg: schist and gneiss of the Crabtree terrane. Foliations, lineations, and folds are S<sub>2</sub>, L<sub>2</sub>, and F<sub>3</sub>, respectively, of Blake (this guidebook).

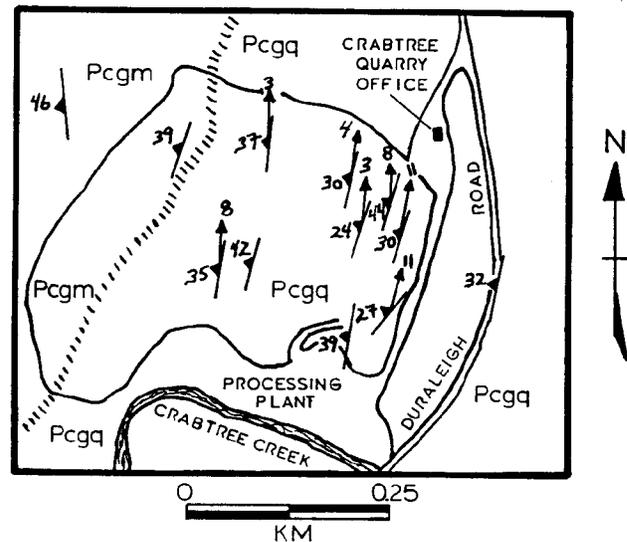


Figure 4-3. Detail of Figure 4-2 showing geologic relationships in Crabtree Quarry.

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mica. Accessory minerals are tourmaline, biotite, epidote, calcite, garnet, zircon, apatite, and magnetite. White mica is the dominant phyllosilicate in the orthogneiss. However, biotite can be locally concentrated, defining mesoscopic biotite schist compositional layers. Garnet tends to be located in the biotite schist layers. In addition, subhedral to euhedral books of biotite associated with quartz crystals are found locally.

Along this wall, the porphyroclastic granitic orthogneiss is moderately to well foliated and lineated. Both the white mica and the biotite define the dominant NNE-striking and moderately west-dipping foliation (Figure 4-3). In some domains, the foliation is less well developed and discontinuous. Changes in orientation of the discontinuous foliation and faint banding define nonpenetrative tight folds in some exposures. In other domains, the foliation is closely spaced and penetrative at the mesoscopic scale (Blake, this guidebook, Figure 6a). In these domains, phyllosilicate minerals, tourmaline, aggregates of felsic minerals, and long axes of quartz disks and rods define a shallowly north-plunging lineation (Figure 4-3) that is interpreted to be a stretching lineation. Grain size reduction of the feldspars and formation of microstructures (*e.g.* undulatory extinction, deformation bands, subgrains, grain boundary migration, grain size reduction; De Paor and Simpson, 1993) are common in these domains, with quartz remaining as more competent porphyroclasts (Blake, this guidebook, Figure 7). The fine-grained feldspars combined with white mica define the matrix surrounding quartz porphyroclasts. The asymmetry of minor K-feldspar and more abundant quartz porphyroclasts and shear bands define a tops-to-the north shear sense in the west-dipping foliation. Rocks in these domains are classified as protomylonites. The existence of these higher strain zones in the eastern and northeastern pit walls is interpreted to represent the effects of ductile strain partitioning and westward propagation of deformation resulting from oblique to right-lateral shearing contemporaneous with the formation of the D<sub>3</sub> Nutbush Creek fault zone.

Along the north pit wall of the quarry, porphyroclastic granitic orthogneiss is less penetratively foliated. Porphyroclastic quartz disks are quite conspicuous as 0.5-1.5 cm quartz “eyes” in a pink, medium- to coarse-grained felsic matrix. These rocks are more typical of the “quartz disk” gneiss of Parker (1979). These rocks were sampled by S. A. Goldberg for geochronologic study (article in this guidebook). In some localities, K-feldspar-rich granitoid dikes cut across the porphyroclastic granitic orthogneiss along this wall. This crosscutting relationship has also been observed in outcrops outside the boundaries of the quarry. These dikes appear to have a syenitic mineralogy. Their origin and significance are not clear. Along this wall, several enclaves up to several meters in diameter of fine- to medium-grained biotite schist are exposed. These enclaves are interpreted to represent xenoliths of wallrock schists of the Crabtree terrane

similar to rocks that crop out south of Crabtree Creek near the intersection of Duraleigh Road (SR 1664) and Ebenezer Church Road (SR 1649). A large enclave of biotite schist can also be observed in the lower pit wall of the eastern part of the quarry. This schist body has been previously interpreted to represent a metamorphosed and chemically altered mafic dike (Parker, 1979).

Along the northwestern pit wall, porphyroclastic granitic orthogneiss is in gradational contact with leucogranitic orthogneiss (western facies of the pluton). This gradational contact is marked by a decrease in abundance and size of the quartz disks. The pinkish to gray-white leucogranitic orthogneiss consists chiefly of medium- to fine-grained K-feldspar, plagioclase, quartz, and white mica. Biotite and tourmaline occur locally. The moderately developed foliation is marked by an abundance of white mica.

Geochronologic results (S. A. Goldberg, this guidebook) on zircon fractions obtained from porphyroclastic granitic orthogneiss collected at the quarry suggest that crystallization of the leucogranitic to porphyroclastic granitic pluton occurred in the Neoproterozoic (discordant <sup>207</sup>Pb/<sup>206</sup>Pb ages of 554, 564, and 566 Ma). Because lobes and dikes of the pluton locally display intrusive contacts with metavolcanic and metasedimentary rocks of the Carolina terrane and Crabtree terrane, the Crabtree Creek pluton appears to be an intrusion that stitched the two terranes together during a Neoproterozoic to early Paleozoic magmatic event (Blake and Stoddard, 1993). Consequently, the Crabtree Creek pluton provides constraints on the timing of amalgamation of tectonostratigraphic terranes along this segment of the western flank of the Raleigh metamorphic belt.

## LUNCH

### STOP 5: METAMORPHOSED QUARTZ DIORITE OF THE BEAVERDAM DIORITE-GABBRO COMPLEX (OPTIONAL)

**LEADERS: Wright Horton and Skip Stoddard**  
**Hilltop roadcut on both sides of SR-1901 near Falls Lake, 350 meters north of Little Beaverdam Creek, Creedmoor 7.5' quadrangle**

The Beaverdam diorite-gabbro complex (informal name of Parker 1979), consists of metamorphosed plutonic rocks that range in composition from quartz diorite and tonalite to gabbro and, locally, pyroxenite (Parker, 1979; Horton and others, 1992, and this guidebook). These rocks intrude metamorphosed volcanogenic rocks of the Cary formation (informal name of Farrar, 1985a) just east of the Triassic Deep River basin. At this locality, metamorphosed quartz diorite of the Beaverdam diorite-gabbro complex is well exposed in roadcuts through the hilltop on both sides of SR 1901 (Figure 5-1).

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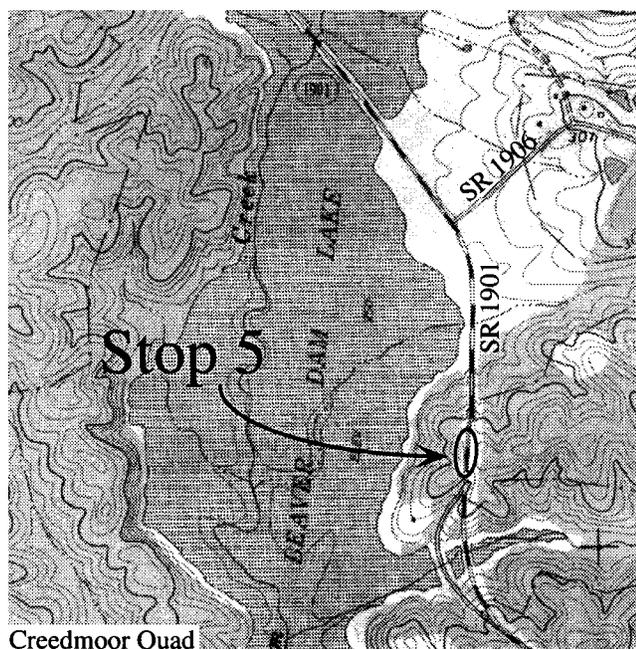


Figure 5-1. Location of Stop 5.

The quartz diorite at this outcrop is massive to weakly foliated, predominantly medium-grained, and equigranular. A representative chemical analysis is provided in Table 5-1. The rock has a hypidiomorphic granular texture and appears speckled due to the contrast between patches of dark-greenish-gray to greenish-black minerals (about 15-30%) and very light gray saussuritized plagioclase (about 55-66%) and quartz (about 10-18%). The larger grains of quartz are distinctly bluish in color, and probably represent relict phenocrysts. The dark patches comprise mostly chlorite+epidote/clinozoisite pseudomorphs after primary prismatic phenocrysts believed to have been calcic amphibole. The highly saussuritized plagioclase is sodic andesine ( $An_{32}$ - $An_{34}$  by Michel-Levy method). Metamorphic veinlets, one mm or less in width, composed of epidote/clinozoisite and carbonate minerals, are common. The metamorphic minerals define a lower to middle greenschist facies assemblage, in the chlorite or biotite zone.

Xenoliths of chlorite phyllite up to 20 cm in width having distinct discordant contacts with quartz diorite were visible in this cut in the late 1970's. The phyllite exhibited kink or chevron folds having wavelengths on the order of 5 cm. The phyllite xenoliths bore a strong resemblance to rocks of the Cary formation. Smaller inclusions of fine-grained, dark colored material, still visible, may be partly digested xenoliths, or alternatively, may be schlieren of magmatic origin.

Gabbroic dikes cutting the quartz diorite, although not observed in this roadcut, are found in nearby exposures along the shore of Falls Lake (J. W. Horton, Jr., unpublished data). Metagabbro occurs mainly near the northern end of the complex, where it contains possible cumulate layers and

Table 5-1. Chemical and normative composition of a sample of quartz diorite of the Beaverdam diorite-gabbro complex from Stop 5 (J. W. Horton, Jr., unpublished U.S. Geological Survey rapid rock analysis; H. Brown, analyst, 1985).

Weight % Oxides		CIPW Norm	
SiO <sub>2</sub>	61.3	Q	16.2
TiO <sub>2</sub>	0.48	or	8.3
Al <sub>2</sub> O <sub>3</sub>	17.5	ab	35.5
Fe <sub>2</sub> O <sub>3</sub>	2.1	an	24.8
FeO	2.3	di	1.2
MnO	0.09	hy	7.0
MgO	2.3	mt	3.0
CaO	5.5	il	0.9
Na <sub>2</sub> O	4.2	ap	0.4
K <sub>2</sub> O	1.4	cc	1.5
P <sub>2</sub> O <sub>5</sub>	0.15		
H <sub>2</sub> O <sup>+</sup>	1.7	D.I.	60.0
H <sub>2</sub> O <sup>-</sup>	0.18	An%	41.1
CO <sub>2</sub>	0.59		
Total	99.79		

lenses of hornblendite that were probably originally pyroxenite (Parker, 1979; Moye, 1981; Horton and others, 1992).

The Beaverdam diorite-gabbro complex is in contact to the east with the Falls Lake melange along an inferred thrust fault (Horton and others, 1992); Parker (1979) interpreted the same contact as intrusive in nature. Internal contacts are rarely visible so the relationships among lithologic types within the complex remain obscure. Based on one detailed petrographic and chemical traverse near the northern end of the complex, Moye (1981 and references therein) inferred that at least part of the body represents a layered gabbroic intrusion. Further study of the Beaverdam diorite-gabbro complex is currently underway (Haydee Phelps, NCSU M.S. Candidate).

Although not yet dated isotopically, these rocks should be no older than the Cary formation, which has a preliminary U-Pb zircon age of about  $575 \pm 12$  Ma (S. A. Goldberg, this guidebook). The age of the Beaverdam diorite-gabbro complex is inferred to be late Proterozoic or Cambrian based on similarity to dated plutons in other parts of the Carolina terrane as summarized by McSween and others (1991, Table 7-1 and references therein). Samples of quartz diorite from this roadcut have very low Rb/Sr ratios (about 0.1) and permit an estimated  $^{87}\text{Sr}/^{86}\text{Sr}$  initial ratio of about 0.7030-0.7035 (P. D. Fullagar, written communication, 1990), which is within the range characteristic of Carolina slate belt metavolcanic rocks (McSween and others, 1991 and references therein).

The metamorphic foliation in the Beaverdam diorite-

gabbro complex generally strikes northeast and dips moderately to steeply northwest. The unusual N30°E, 62°SE attitude of foliation in part of this roadcut may (or may not) reflect rotation associated with nearby strands of the Triassic Jonesboro fault and related cross faults. This exposure (location 5 in Figure 2 of Horton and others, this guidebook) lies in a diorite-gabbro promontory that juts westward into the Triassic Deep River basin. The indentation of the basin margin is similar, but larger than that described by Bartholomew and others (this guidebook) near U.S. Highway 70, about 18 km to the south. Perhaps the relatively massive diorite-gabbro formed a structural buttress, locally deflecting the Jonesboro fault. Metamorphosed quartz diorite is a substantial contributor of rounded boulders and cobbles in alluvial-fan border conglomerates up to 10 km from where the unit presently intersects the eastern edge of the Triassic basin.

**STOP 6: ULTRAMAFIC ROCKS OF THE FALLS LAKE MELANGE**

**LEADERS: Skip Stoddard, Wright Horton, and Dave Blake**  
**Six Forks Road (SR 1005) at Falls Lake, Bayleaf 7.5' Quadrangle**

This site description is reproduced with modifications from an earlier version in the Geological Society of America Centennial Field Guide (Stoddard and others, 1986, Stop B). The stop is located on a low ridge just south of the Lower Barton Creek arm of Falls Lake (Figure 6-1). The ridge was cleared in 1979 during excavation associated with the reservoir and is on public land. A parking area, intended for fishing access, is available on the west side of SR 1005.

This stop is a good (though deteriorating) exposure of a portion of one of the largest mappable ultramafic pods in the Falls Lake melange. As mapped by Horton and others (1992), the exposed pod is about 4 km in length, and up to 1 km in width, extending south to Adam Mountain (shown on Figure 7-1, just south of Stop 6) and north beyond N. C. Highway 98. It was depicted as two or more separate pods in earlier maps (Parker, 1979; Wylie, 1984).

At Stop 6, examples can be found of most of the ultramafic rock types within the Falls Lake melange. The four predominant ultramafic rock types present are serpentinite, soapstone and talc schist, chlorite-actinolite ± talc schist, and hornblendite. The serpentinite is a pale green to white, massive, relatively dense rock containing small porphyroblasts and very thin streaks of magnetite. Some asbestiform serpentine has been found here, but most of the serpentine is a fine-grained massive type, possibly antigorite (Stoddard and others, 1986). Asbestiform tremolite has been identified in nearby pods. Olivine has been reported from serpentinite in another ultramafic body (Parker, 1979; Moye, 1981). Chromite occurs on Adam Mountain and was encountered as

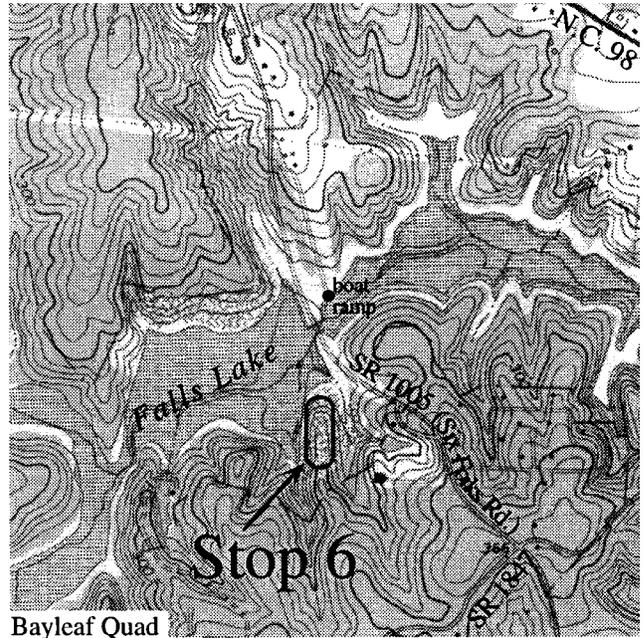


Figure 6-1. Location of Stop 6. The southern edge of this map is 750 m north of the northern edge of Figure 7-1.

disseminated grains in serpentinite from an exploratory drill hole on the south end of Adam Mountain (Parker, 1979). Small pods of metamorphosed chromitite are present elsewhere in the melange (Stoddard and others, 1989). Either chlorite or actinolite may predominate in the chlorite-actinolite schist; minor talc, and magnetite octahedra are locally present. Soapstone contains some chlorite and actinolite, as well as a carbonate mineral (perhaps magnesite) whose former presence is indicated by rhombohedral crystal molds. Both pure talc schist and soapstone occur at Stop 6; clinopyroxene, possibly of primary igneous origin, has been observed in thin sections of soapstone from this site, but it is exceedingly rare. A thin section of black hornblendite, present near the north end of the ridge, showed that it consists mainly of blue-green amphibole, about 10% epidote, and minor garnet (Stoddard and others, 1986).

Chemical analyses of serpentinite, chloritite, and soapstone from eight sites along Lower Barton Creek, including a small abandoned soapstone quarry, are presented by Moye (1981, Table 3). On the basis of these analyses as well as petrography, Moye inferred that the protoliths of the “Adam Mountain ultramafic body” were dunite and harzburgite with low Al<sub>2</sub>O<sub>3</sub>, TiO<sub>2</sub>, CaO, Na<sub>2</sub>O, and K<sub>2</sub>O. The hornblendite at Stop 6 clearly had a different protolith, perhaps a plagioclase-bearing pyroxenite. The field relationships among the different ultramafic rock types at this stop suggest that the pod was originally a compositionally layered body (Stoddard and others, 1986). Layering, possibly of cumulate origin, is also suggested by relict textures in some serpentinite and soapstone, where possible pseudomorphs (after original pyroxene or olivine?) seem to occur in bands on the order of

## RALEIGH METAMORPHIC BELT

1-5 cm thick.

The crest of Adam Mountain (Figure 7-1) is underlain by resistant quartz rock that is composed of fine-grained polycrystalline quartz crisscrossed by numerous veinlets of banded chalcedony and containing cavities lined with drusy quartz crystals (Stoddard and others, 1986). In serpentinite at Stop 6, late brittle fractures 4 mm or less wide have surfaces that are covered with similar drusy quartz crystals. The same rock types occur nearby in other ultramafic bodies. The origin of the quartz rocks and significance of their association with serpentinite are undetermined.

The western contact of the ultramafic body is constrained by a small outcrop of biotite-muscovite schist at the water line about 200 m west of the ridge crest. A reentrant of biotite-muscovite schist also appears to be present at the north end of the ridge. Contacts between the different rock types at Stop 6 are generally parallel to the undulatory schistosity, which varies considerably in orientation (Stoddard and others, 1986). Tight folds of schistose layers in phyllosilicate-rich ultramafic rocks have been observed locally.

### STOP 7: FALLS LAKE MELANGE

**LEADERS: Wright Horton, Dave Blake, and Skip Stoddard**

**Tributary of Lower Barton Creek, 0.25 km north of Norwood Road (SR 1834) near Bayleaf community, Bayleaf 7.5' Quadrangle**

*This exposure is located on private property and permission of the owner should be acquired before entering the property.*

Stop 7 will involve a short traverse downstream along a small creek (Figure 7-1) located on the west limb of the Raleigh antiform as shown in Figure 2 of Horton and others (this guidebook). The traverse begins in fine-grained, poorly banded, white mica-bearing felsic gneiss of the Crabtree terrane, and continues westward downhill across the contact with the structurally overlying Falls Lake melange. This contact, the Falls Lake thrust, is quite sharp at Stop 7, and the biotite ribbon gneiss, which occurs sporadically elsewhere along the thrust, is missing here, although it is found nearby (within 1.5 km) along the thrust to both the north and south of Stop 7. A detailed discussion of the Falls Lake thrust is provided in the paper in this guidebook by Stoddard and others.

Along the creek east of the mapped Falls Lake thrust, quartzofeldspathic gneiss strikes N15°W to N7°E, and dips 50°-60° toward the west. A very fine-grained felsic gneiss having ultra thin (<0.5 mm), spaced, discontinuous layers of polygonal quartz occurs near the thrust contact. This rock may be a recrystallized mylonite. The absence of obvious biotite ribbon gneiss along the thrust at this location may be attributed to the biotite-poor composition of the rock.

In the Falls Lake melange, the mica schistosity of the matrix schist is the dominant planar fabric. Near the thrust and west of it in the Falls Lake melange, strikes are more variable (N4°W to N40°E), and the westward dips are shallower (about 15°-30°) near the thrust. Within 100 m downstream to the west, dips in the schist steepen to 40°-50°.

The Falls Lake melange at Stop 7 is predominantly represented by saprolitized muscovite-biotite schist and gneiss, which contain disseminated pods, lenses, and boudins of ultramafic rock. The geology and geologic setting of the Falls Lake melange are discussed briefly in the paper by Horton and others in this guidebook; further discussion and details may be found in Horton and others (1986) and Blake (1986).

The melange matrix is a heterogeneous unit in which muscovite-biotite schist and gneiss are interlayered and intergradational as micas vary in abundance. In most exposures at this locality, the matrix rock is more gneissic than usual, but otherwise is typical. Biotite is more abundant than muscovite, and chlorite is present in lesser amounts. Sodic plagioclase and quartz vary in abundance. Metamorphism was in the staurolite + kyanite zone of the amphibolite facies (Parker, 1979; Wylie, 1984). Though neither of these index minerals has been observed at Stop 7, both may be found in more pelitic rocks in the vicinity.

The ultramafic pods here consist of olive-green actinolite rock, dark greenish-gray chlorite-actinolite schist, and white to cream-colored talc-actinolite schist. Talc has also been observed in pressure shadows between boudins of actinolite rock. All of the fragment-in-matrix structures at this site can be explained by tectonic processes. Small ultramafic

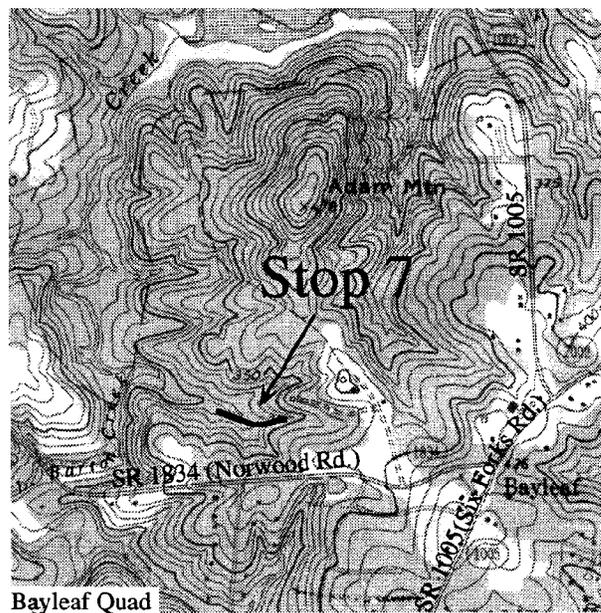


Figure 7-1. Location of Stop 7. The northern edge of this map is 750 m south of the southern edge of Figure 6-1.



Figure 7-2. Saprolite exposure of the Falls Lake melange at Stop 7 showing rectangular block of ultramafic chlorite-actinolite rock in muscovite-biotite schist matrix. View looking south; dominant foliation and parallel metamorphic layering dip west (toward right; orientation N12°W, 48°SW). Gently-dipping secondary cleavage (orientation N16°E, 26°NW) appears to transect earlier structures.

fragments are most abundant near larger fragments of similar material, and the ultramafic boudins and lenses appear to be parts of larger masses that have been tectonically sliced or pulled apart. Ultramafic fragments as small as a few centimeters across have been observed along the creek, although most of the fragments are larger. Figure 2 of Horton and others (this guidebook) shows map-scale bodies of ultramafic rock nearby.

Mesoscopic textures and structures are well preserved in the saprolite, and exposures at this locality are more typical of those routinely used for geologic mapping in this region than are the large road-cut and quarry exposures of fresh rock selected for some of the other field trip stops.

Locally, two mica foliations can be observed in some of these saprolite exposures (Figure 7-2). The earlier foliation and parallel metamorphic layering vary in orientation, but generally have the northerly strikes (N20°W to N20°E) and moderate westerly dips characteristic of this position on the west limb of the north-plunging Raleigh antiform. Lenses and boudins of ultramafic rock and intrafolial isoclinal folds are generally concordant with this layering and foliation, although similar layering and foliation within the boudins may be discordant with the external foliation. A secondary mica schistosity locally crosscuts the earlier gneissic layering as well as the margins of ultramafic pods. This later schistosity also has northerly strikes and westerly dips at this locality, but the dip angles are gentle to moderate and characteristically less than dip angles for the earlier layering. In

some places, the foliation and layering are contorted and irregular.

## STOP 8: PELITIC SCHIST OF THE CRABTREE TERRANE

**LEADERS: Alex Speer, Skip Stoddard, and Dave Blake**

**N.C. Highway 98 about 1.8 km west of U.S. Route 1, Wake Forest 7.5' Quadrangle**

*Stop 8 is located along a very busy two-lane highway with little room between the outcrop and the road. The traffic is fast and noisy. Stay together, follow the leaders' instructions, and be wary of the traffic. The group will be split in half to examine the outcrop.*

The outcrop at Stop 8 (Figure 8-1) is locally renowned as a collecting spot for kyanite and garnet; it is the continual collecting activity that accounts for the fresh exposure. The rock was the subject of a recent metamorphic petrology class project at North Carolina State University and this stop description reports some of the data and conclusions.

This distinctive pelitic schist belongs to the Late Precambrian to Early Paleozoic mica and hornblende gneiss and schist of Parker (1979), garnet-kyanite schist of Wylie (1984), Smithfield Formation of Farrar (1985a), and garnet-kyanite schist of Horse Creek of Horton and others (1992). Horton and others (1992 and this guidebook) consider it to

## RALEIGH METAMORPHIC BELT

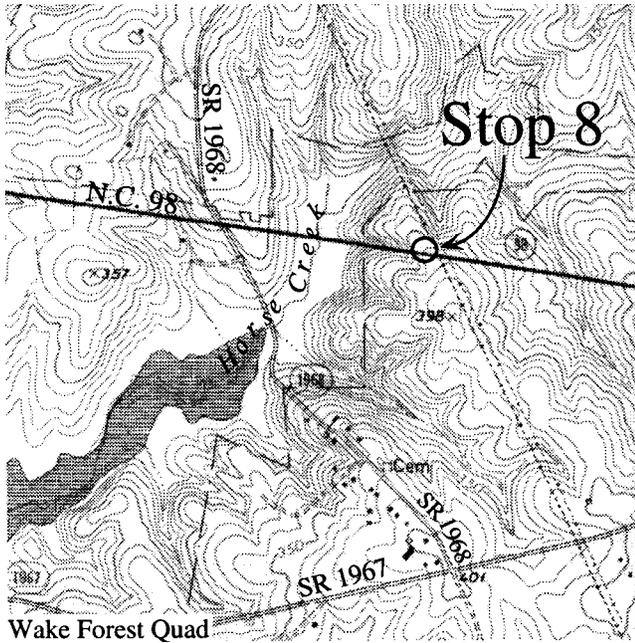


Figure 8-1. Location of Stop 8.

be a unit of the Crabtree terrane, along with felsic gneisses and muscovite and graphite-rich schists. Articles in this guidebook by Blake, Lumpkin and others, and Stoddard and others provide further discussion of the Crabtree terrane. The schist may be traced from Stop 8 about 4.5 km south to a point west of the Falls Lake dam where it is truncated against

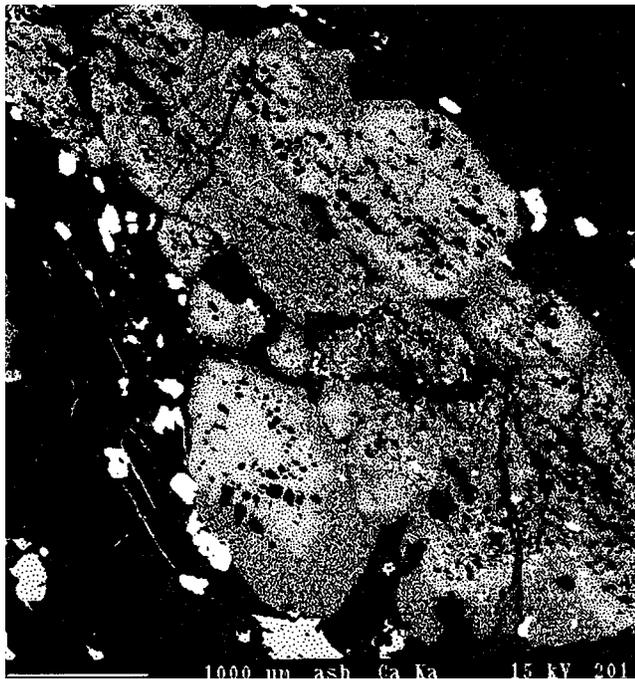


Figure 8-2. Ca X-ray compositional map of garnet from Stop 8. Lighter regions correspond to regions of higher Ca content. White scale bar at lower left represents 1 mm.

Table 8-1. Whole rock chemical analysis of pelitic schist from Stop 8. Analysis by Chemex Labs

Wt. %		ppm	
SiO <sub>2</sub>	61.83	Li	32
TiO <sub>2</sub>	1.26	B	15
Al <sub>2</sub> O <sub>3</sub>	18.78	Cl	<100
Fe <sub>2</sub> O <sub>3</sub>	3.68	Co	19
FeO	5.26	Ni	33
MnO	0.17	Cu	31
MgO	1.79	Zn	42
CaO	2.04	Rb	88
BaO	0.05	Sr	170
Na <sub>2</sub> O	1.62	Y	40
K <sub>2</sub> O	1.94	Nb	10
H <sub>2</sub> O+	1.24	Mo	<1
H <sub>2</sub> O-	0.19	Ba	470
P <sub>2</sub> O <sub>5</sub>	0.26	Zr	260
C	0.24		
F	0.03		
S	0.02		
O=F,Cl,S	-0.02		
Total	100.38		

the Nutbush Creek Fault zone (Wylie, 1984; Horton and others, 1992). To the north, Horton and others (1992) have mapped it for an additional 2 km. In the core of the Raleigh antiform, pelitic schist of the Crabtree terrane in north and west Raleigh may be equivalent (Horton and others, 1992; Blake, unpublished mapping).

The north-trending subhorizontal linear fabric of the outcrop at Stop 8, exemplified by a preferred orientation of kyanite blades, records the influence of deformation associated with the Nutbush Creek fault zone. Foliation strikes nearly north-south and dips steeply to the west.

The rock is a pelitic schist having a composition (Table 8-1) between an average greywacke and shale (Wedepohl, 1969), although it is more aluminous than either. The silicate minerals are quartz, plagioclase, muscovite, biotite, kyanite, garnet, and staurolite. Quartz and the micas are the abundant minerals, followed by kyanite, plagioclase, and two populations of garnet, large and small. Staurolite is uncommon. These minerals are concluded to comprise the peak metamorphic assemblage. Small amounts of chlorite are believed to be either part of a retrograde assemblage or an isolated two-phase inclusion assemblage. Accessory minerals include graphite, rutile, apatite, ilmenite containing intergrown rutile, chalcopyrite, pyrite and possibly monazite or xenotime.

Representative mineral compositions are provided in



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garnet cores grew, the garnet zoning preserves a drop in both temperature and pressure. Mica compositions indicate that water was the dominant fluid species. The apparent absence of melting indicates that  $P_{H_2O} < 0.5 P_{total}$ .

### END OF DAY 1. RETURN TO HOLIDAY INN-NORTH, RALEIGH

**DAY 2: SUNDAY, NOVEMBER 6, 1994**

### STOP 9: LINEATED GNEISS (FALLS LEUCOGNEISS)

**LEADERS: Bob Butler, Dave Blake, and Bob Druhan**  
Service road behind Harris Teeter Supermarket, Glenwood Village Shopping Center, Glenwood Avenue at Oberlin Road, Raleigh West 7.5' Quadrangle

Linedated leucogranite gneiss (Falls leucogneiss of Farrar, 1985a, and Horton and others, 1992) is well exposed in fresh and variably weathered outcrops along the service road behind the Harris Teeter supermarket in Glenwood Village shopping center (Figure 9-1). This linedated gneiss, together with schists and gneisses of the eastern Crabtree terrane, are the main rock types in the Nutbush Creek fault zone in the west Raleigh area (Figure 9-2). The linedated gneiss is described in more detail, and its significance is discussed further, in the description of (optional) Stop 9A in this guidebook.

The rock here is a light pinkish-gray, fine-grained leucogranitic orthogneiss. On surfaces broken perpendicular to the prominent lineation, the texture appears to be that of an undeformed granite. However, on surfaces parallel to the

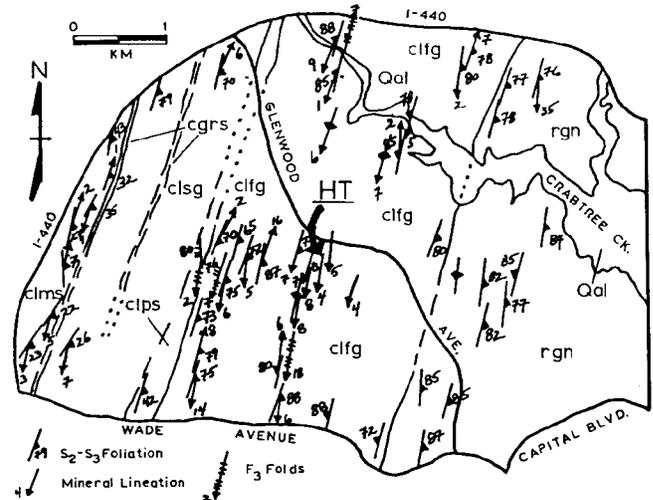


Figure 9-2. Geologic map of a portion of the northern Raleigh West 7.5' Quadrangle (modified from Blake, 1994) showing relationships of lithologic units in the vicinity of Stop 9 ("HT"), located within the Nutbush Creek fault zone.

rgn: Raleigh gneiss of the Raleigh terrane; clfg: linedated Falls leucogneiss of Farrar (1985a); clps: linedated pelitic schist of the Crabtree terrane; cls: linedated schist and gneiss of the Crabtree terrane; cgrs: graphite schist of the Crabtree terrane; clms: linedated two-mica gneiss of the Crabtree terrane.

lineation, the rock is obviously an L-tectonite, having a well-developed lineation defined by elongate aggregates of microcline, quartz, plagioclase, magnetite, and biotite. In the saprolite, the linear aggregates weather into a pencil structure (e.g. Ramsay and Huber, 1983). Photographs of fresh and weathered rocks illustrating these features are shown on the cover of this guidebook. The average trend of lineations in this outcrop is  $S18^{\circ}W$ , with a plunge of  $4^{\circ}$ . Locally, the rock has a weak foliation defined by planar aggregates of magnetite and biotite. The foliation in these and nearby outcrops typically strikes  $N10^{\circ}-20^{\circ}E$  and dips steeply to the ESE. Thin section analysis shows that the rock has a granoblastic texture, and is composed mainly of microcline and quartz, with lesser amounts of sodic plagioclase, magnetite, and biotite. A discordant  $^{207}Pb/^{206}Pb$  zircon age of 491 Ma for the leucogneiss was reported by Horton and Stern (1994), and a younger Rb/Sr whole-rock age of  $463 \pm 20$  Ma was determined by Kish and Campbell (1986). Perhaps the most plausible interpretation is that the linedated leucogneiss represents an early Paleozoic granitic pluton that was deformed by right-lateral strike-slip movement in the late Paleozoic (Druhan and others, this guidebook). The linear fabric is interpreted to be a stretching lineation.

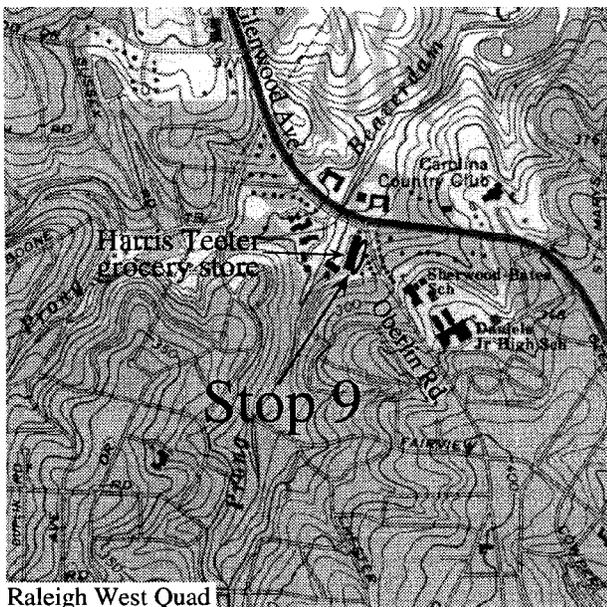


Figure 9-1. Location of Stop 9.

**STOP 9A: LINEATED GNEISS, NUTBUSH CREEK FAULT ZONE**

**LEADERS: Bob Butler and Bob Druhan**

**Emergency spillway at Falls Dam, Wake Forest 7.5' Quadrangle. Directions: From Raleigh, travel northward on Falls of the Neuse Road (SR 2000). About 1 km south of the village of Falls, turn left on the road to Falls Dam, then bear right on road across dam to parking area at end of road. Walk downhill just behind dam to enter the emergency spillway from the lower end.**

*Permission to visit the spillway must be obtained from the Falls Lake Project, U.S. Army Corps of Engineers. Do not climb on the spillway walls!*

The lineated gneiss in the emergency spillway at Falls Dam on the Neuse River (Figure 9A-1) is a spectacular LS tectonite, having a strong lineation formed by strings of magnetite grains and by elongate aggregates of microcline or quartz. The rock commonly has a faint to distinct gneissic foliation defined by aligned biotite flakes. The Falls lineated gneiss (Mims and others, 1990) or Falls leucogneiss (Farrar, 1985a, b; Horton and others, 1992) forms a narrow body 75 km long and a maximum of 2.2 km wide (N. C. Geological Survey, 1985). The lineated gneiss is one of the main rocks occurring in the Nutbush Creek fault zone (Druhan and others, this guidebook). In the Falls Dam area, the lineated gneiss defining the Nutbush Creek fault zone is about 2 km wide, and is bounded on the east by the Raleigh terrane and on the west by the Crabtree terrane and Falls Lake melange (Figure 9A-2). The Falls Lake thrust is truncated by the Nutbush Creek fault zone about 1.2 km southwest of Falls Dam (Figure 9A-2).

The lineated gneiss is a fine-grained, moderate orange pink to pinkish gray, metamorphosed leucogranite, composed mainly of quartz, microcline, plagioclase, biotite, and magnetite. The lineation trends NNE and is subhorizontal; the foliation generally dips moderately SE (Figure 9A-3). The lineation is interpreted to be a stretching lineation caused by strike-slip movement on the Nutbush Creek fault zone. The lineated gneiss probably formed by high-temperature, ductile deformation of a granitic rock, but the mechanisms of such deformation are poorly understood.

Kish and Campbell (1986) obtained a Rb-Sr whole-rock age for the lineated gneiss from this locality of  $463 \pm 20$  Ma, with an initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of  $0.7081 \pm 0.0020$ . They interpreted the lineated gneiss to be part of a deformed leucocratic granitic pluton. Horton and Stern (1994) obtained a preliminary zircon  $^{207}\text{Pb}/^{206}\text{Pb}$  age of 491 Ma for the gneiss. Russell and others (1985) analyzed Rb-Sr isotopes in two biotite-whole rock pairs from lineated gneiss collected at a quarry 2.8 km south of Falls Dam. The pairs gave dates of 238 and 242 Ma, interpreted to represent the time of cooling below about 300°C (Russell and others, 1985). These dates agree with others in the Raleigh metamorphic belt in indicat-

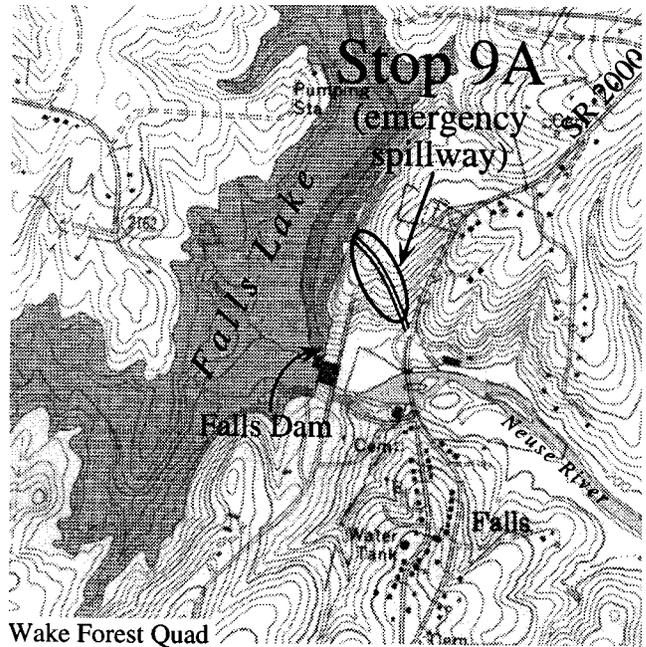


Figure 9A-1. Location of Stop 9A.

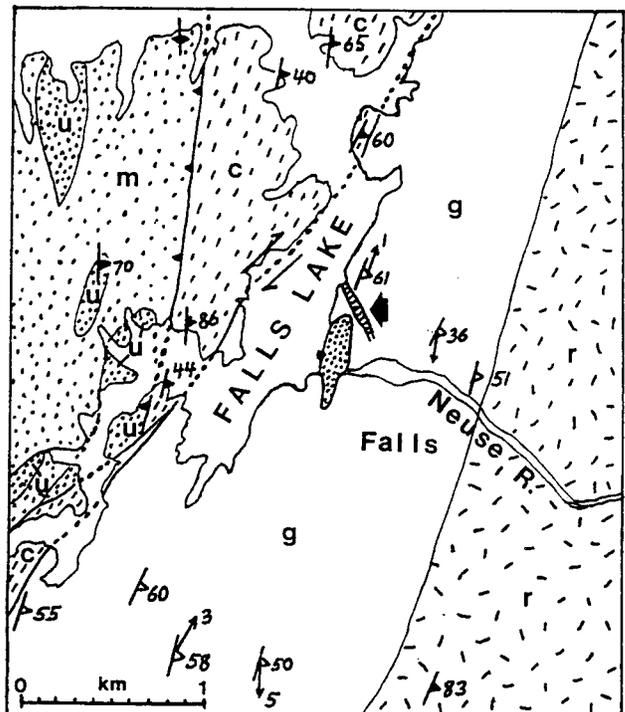


Figure 9A-2. Geologic map of Falls Dam area, Wake County. Falls Dam emergency spillway is indicated by the arrow. (The dam is indicated by the stippled area just south of the spillway.) The Nutbush Creek fault zone coincides with the lineated gneiss (g). Geology modified after Horton and others (1992). Map units are described by Horton and others (this guidebook).

r: Raleigh gneiss; c: rocks of the Crabtree terrane; m: Falls Lake melange; U: pods of ultramafic rocks in the Falls Lake melange.

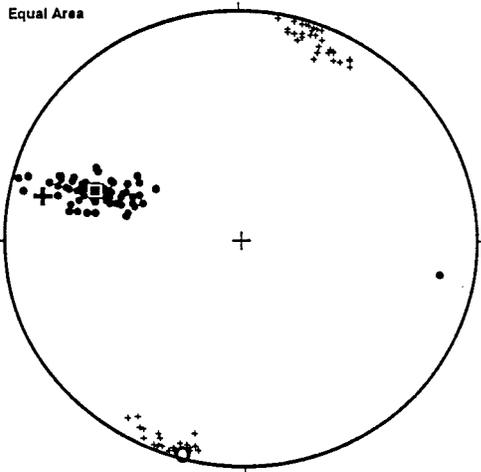


Figure 9A-3. Stereographic projection of structural and magnetic susceptibility data from Falls Dam emergency spillway. Data from Mims and others (1990). Lower hemisphere, equal-area net. dots: mylonitic foliation, n = 75; square: best-fit vector, mylonitic foliation; + signs: mineral lineation, n = 63; small circle: best-fit vector, maximum-susceptibility axes ( $k_1$ ); dark +: best-fit vector, minimum-susceptibility axes ( $k_3$ ).

ing late Paleozoic cooling after an Alleghanian thermal peak at about 300 Ma (Russell and others, 1985). The thermal peak was at least partly contemporaneous with emplacement of the huge volume of granitic magma represented by the Rolesville batholith (see the paper by J. A. Speer in this guidebook).

The lineated gneiss is probably derived from an early Paleozoic (or late Proterozoic) intrusive granite that was deformed by right-lateral strike-slip movement in the late Paleozoic (Druhan and others, this guidebook). The protolith of the lineated gneiss is potassium rich, unlike the typical sodium-rich granitoids of the Carolina terrane, and probably has affinities to the Crabtree terrane.

The lineated gneiss is anomalously magnetic for a granitic rock (most samples even attract a hand magnet) and causes a prominent positive magnetic anomaly that marks the position of the Nutbush Creek fault zone through much of North Carolina. Mims and others (1990) studied the magnetic susceptibility of lineated gneiss from this locality. The numbered drillholes in the spillway are the localities of samples collected by Mims. Mims and others (1990) found a close correspondence between the mesoscopic fabric elements and the magnetic susceptibility axes. The magnetic susceptibility ellipsoid is strongly prolate: the average maximum susceptibility axis is oriented parallel to the mineral lineation; the average minimum susceptibility axis is nearly parallel to the average pole to foliation (Figure 9A-3).

**STOP 10: NUTBUSH CREEK FAULT ZONE**

**LEADERS: Bob Butler and Bob Druhan**

**Satterwhite Point, Kerr Reservoir, 10.8 km North of Henderson, N.C., Middleburg 7.5' Quadrangle. Directions: From Raleigh, take I-85 north to Henderson. Take Exit 217, turn left on Satterwhite Point Road (SR 1319), and continue 10.7 km to Satterwhite Point. Turn left on Glass House Road (SR-1372) and proceed 0.6 km to the parking area at Picnic Shelter #1, Kerr Reservoir State Recreation Area.**

Stop 10 is a traverse across the western boundary of the Nutbush Creek fault zone, from mildly deformed granitoid rocks of the Vance County pluton eastward into mylonites and phyllonites within the fault zone. Satterwhite Point is at the end of a peninsula extending northward into Kerr Reservoir (Figure 10-1). The peninsula is bounded on the west by the Nutbush Creek arm of the reservoir. Tom Casadevall (1977; Casadevall and Rye, 1980), who recognized and named the Nutbush Creek fault zone, considered Satterwhite Point to be the best place to see the nature of the zone (personal communication, 1977). Thus, it is the “type locality” of the Nutbush Creek fault zone. The exposures are mainly in saprolite and saprock on this traverse and in most places around the lake. Because nearly all of the exposures are located along the shore, their accessibility depends on the lake level. “Normal” pool elevation is 300 feet, but the lake level fluctuates according to a seasonal schedule and variations in runoff. If the lake level is higher than about 301 feet, few of the exposures are accessible. The lake level can be

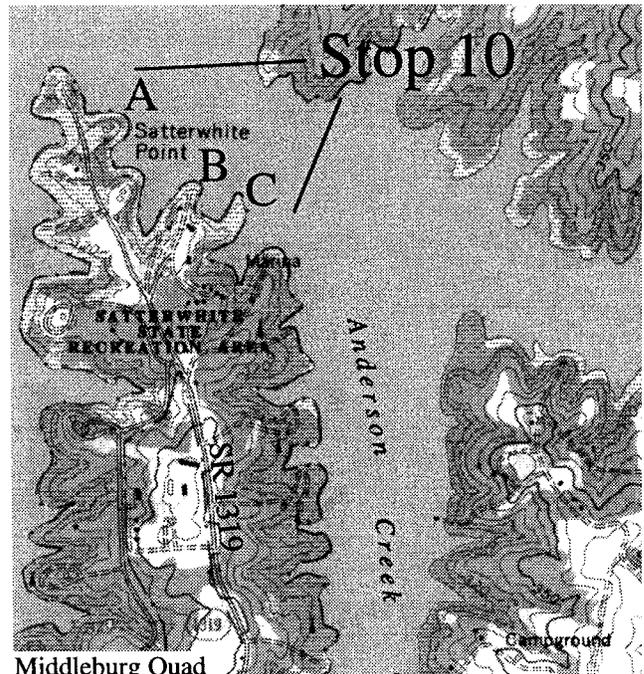


Figure 10-1. Location of Stop 10.

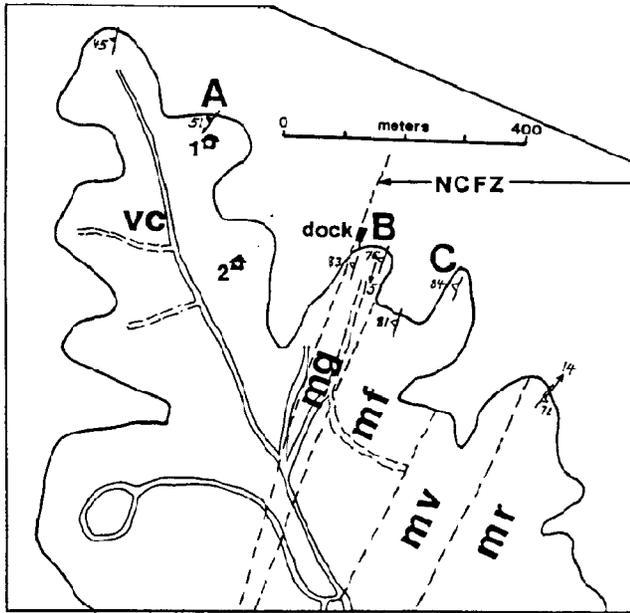


Figure 10-2. Geologic map of Satterwhite Point. A, B, and C are localities described in the text. Picnic shelters 1 and 2 are shown. Western border of Nutbush Creek fault zone (NCFZ) is indicated. Geology by R.M. Druhan and J.R. Butler.

vc: granitoid rocks of the Vance County pluton; mg, mf, mv, and mr are mylonites and phyllonites of the NCFZ, as follows: mg-mylonitized granitoid rocks of the Vance County pluton; mf-mylonitized felsic to intermediate metavolcanic rocks; mv-mylonitized mafic to intermediate metavolcanic rocks; mr-mylonitized gneiss of the Raleigh belt.

obtained by calling (804) 738-6371 for a recorded message available 24 hours a day. The exposures have deteriorated over the years because of construction of recreation facilities and attempted stabilization of the shoreface by riprap.

The traverse at Satterwhite Point begins in relatively undeformed granitic rocks of the Vance County pluton, traverses the western boundary of the zone, and crosses several phyllonitic and mylonitic lithologic units to about the middle of the zone (Figure 10-2). The eastern part of the Nutbush Creek fault zone and the contact with Raleigh terrane gneisses are not well exposed near Satterwhite Point, although there are good outcrops of non-mylonitized gneiss at several places along the lakeshore to the east.

The Vance County pluton is a batholith that intrudes rocks of the Carolina slate belt (Casadevall and Rye, 1980). It forms the western flank of the Nutbush Creek fault zone for about 40 km in North Carolina and adjacent Virginia. The main rocks in the batholith are albite granodiorite according to Parker (1963) and trondhjemite according to Farrar (1985a). LeHuray (1989) obtained a discordant U-Pb age of 571 Ma on zircons from the Vance County pluton at the State Line quarry, about 18 km northwest of Satterwhite Point. The pluton and adjacent country rocks were regionally metamorphosed under conditions of the middle greenschist facies

(biotite grade).

**Stop 10A: Features of the Vance County pluton just west of the Nutbush Creek fault zone**

Saprolite and saprock derived from relatively undeformed rocks of the Vance County pluton are exposed in low cliffs along the lakeshore just north of Picnic Shelter #1. Schistosity is sporadically developed, forming most readily in the mica-rich rocks. The main rock units, in sequence from oldest to youngest, are: (1) Mafic, fine-grained, spindle-shaped to angular inclusions in the granitoids; (2) Dark-colored, medium- to coarse-grained, biotite-hornblende metatonalite or metagranodiorite having a color index of about 45, the rock type that makes up most of the Vance County pluton; (3) Metamorphosed mafic dikes, generally less than 2 m thick, and greenstones and mafic schists; and (4) Metamorphosed dikes of leucogranite, aplite, and pegmatite.

**Stop 10B: Western margin of the NCFZ at Satterwhite Point Marina**

The traverse from the Vance County pluton into the Nutbush Creek fault zone begins at the boat-launching ramp just east of the marina and continues eastward along the shore north of the marina. Some of the shoreline exposures are obscured by riprap and marina facilities. Intensity of deformation increases rapidly as one crosses the western boundary of the Nutbush Creek fault zone. Slightly deformed rocks of the Vance County pluton grade into mylonites having well-developed fluxion structure over a distance of about 30 m. The mylonitic foliation and compositional layering consistently strike NNE and dip steeply WNW. Highly deformed rocks of the Vance County pluton are recognizable within the western part of the fault zone. Laminated mylonites are derived from various granitoid rocks of the pluton. Thin layers of mafic phyllonites are probably derived from mafic dikes and inclusions. Because of the high strain, formerly cross-cutting dikes were rotated into parallelism with the mylonitic foliation and the contacts of the shear zone.

**Stop 10C: Mylonites and phyllonites of the Nutbush Creek fault zone, cove northeast of the marina**

At the head of the cove just east of the marina office and shops, the outcrops are white mylonites having strongly developed mylonitic foliation (fluxion structure), probably developed from strongly sheared aplite or leucogranite. The foliation strikes NNE and dips nearly vertically WNW.

On the east side of the cove, dark green phyllonites and schists are not like rocks of the Vance County pluton; they are probably sheared mafic volcanic rocks or a mafic dike. The rocks show a variety of kinematic indicators, including S-C composite fabrics, normal-slip crenulations, and large-scale shear bands. Small folds have vertical hinges and dextral sense of rotation. The fabrics consistently indicate right-lateral sense of shear. See the article in this guidebook by R. M. Druhan and others for a more detailed discussion and for illustration of some of these features.

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In the next cove to the east, pieces of massive black rock occurred along the shoreline and were formerly exposed as veins in saprolite at the head of the cove. The rock looks like pseudotachylite in both hand specimen and thin section, but X-ray diffraction indicates that it is composed mainly of very fine-grained tourmaline and quartz. Pseudotachylite should reflect the composition of the rocks from which it was derived, but this rock may be metasomatically altered pseudotachylite; if so, it might indicate seismic faulting along the Nutbush Creek fault zone.

### STOP 11: PAVEMENT EXPOSURE OF GRANITOID ROCKS OF THE ROLESVILLE BATHOLITH

**LEADER:** Alex Speer

Along Norris Creek south of N.C. Highway 98 and east of SR 1715, Bunn West 7.5' Quadrangle

*This exposure is located on private property and permission of the owner should be acquired before entering the property.*

This outcrop (Figure 11-1) is among the larger pavements in the Rolesville batholith. It has many features in common with other pavements throughout the southeastern United States. It has plant and animal life that differ from those of the immediate surroundings. It was quarried privately for local building stone, and it is used as a recreational and dumping site. Additionally, it is a good place to examine the more subtle features of the batholith. The rock here is Rolesville main granitoid, the rock type that dominates the batholith. For further discussion of the batholith, and brief descriptions of a number of its component facies, see the article in this guidebook by J. A. Speer.

As elsewhere in the Rolesville batholith, the rock here varies in appearance as a result of the range in color index and grain size, the degree of development of a foliation and, where present, the nature of the foliation. The rock also varies due to the presence or absence of subhedral alkali feldspar megacrysts. However, regardless of texture, all varieties can be described as leucocratic, medium- to coarse-grained monzogranites.

The igneous varietal minerals are biotite and very minor muscovite. These varietal minerals reflect the fact that the granitoid is slightly peraluminous, with the molecular A/CNK = 1.07 (Table 11-1). The alkali feldspar is microcline microperthite. Plagioclase shows normal oscillatory zoning, having cores of An<sub>30</sub> and rims about An<sub>20</sub>. Accessory minerals are apatite, allanite, chalcopyrite as inclusions in the rhombohedral oxide minerals, ilmenite-hematite intergrowths exsolved from an originally intermediate composition rhombohedral oxide mineral, magnetite, and zircon. Biotite is locally altered to chlorite, rutile, and fluorite.

Mineral compositions from two different granitoids of

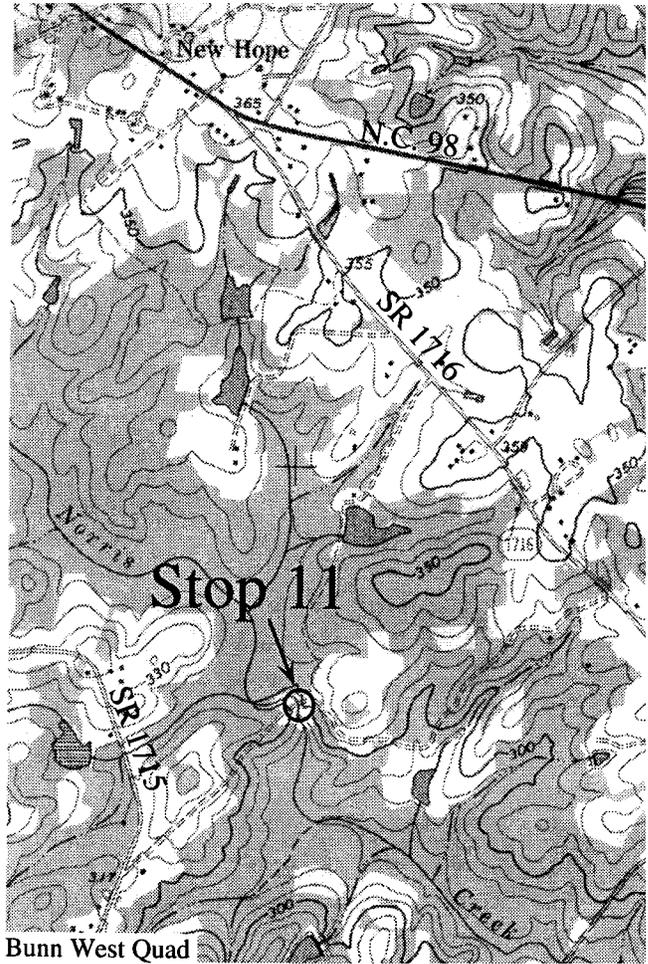


Figure 11-1. Location of Stop 11.

Table 11-1. Average of 19 rock analyses from the RL4 drillcore (Sinha and Mertz, 1977), Stop 11.

SiO <sub>2</sub>	70.95
TiO <sub>2</sub>	0.28
Al <sub>2</sub> O <sub>3</sub>	16.26
Fe <sub>2</sub> O <sub>3</sub>	1.78
MnO	0.03
MgO	0.76
CaO	1.83
BaO	0.05
Na <sub>2</sub> O	3.98
K <sub>2</sub> O	4.91
P <sub>2</sub> O <sub>5</sub>	0.09
total	100.92
Th, ppm	16.4
U	5.4
cation F/(FM)	0.542
mol.A/CNK	1.07

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Table 11-2. Typical mineral compositions, granitoid rock of Stop 11: 12a, b: samples RVBW-12a and 12b. Probe analyses by JAS at VPI.

	biotite 12a	biotite 12b	musc 12a	musc 12b	kfs 12a	kfs 12b	pl rim 12a	pl core 12a	pl rim 12b
SiO <sub>2</sub>	36.69	36.75	46.30	46.54	64.78	65.01	63.45	62.08	63.39
TiO <sub>2</sub>	3.16	3.05	0.85	1.00	0.00	0.00	0.03	0.08	0.04
Al <sub>2</sub> O <sub>3</sub>	16.15	16.13	28.89	29.36	18.33	18.35	22.39	24.17	22.58
FeO	19.95	21.08	5.67	5.65	0.02	0.11	0.00	0.00	0.06
MnO	0.26	0.40	0.11	0.05	0.00	0.00	0.00	0.00	0.03
MgO	8.65	8.64	1.25	1.22	0.03	0.00	0.00	0.00	0.00
BaO	0.61	0.07	0.08	0.16	0.60	0.29	0.07	0.03	0.03
CaO	0.05	0.04	0.00	0.00	0.02	0.05	4.14	6.05	4.24
Na <sub>2</sub> O	0.06	0.06	0.34	0.28	1.38	1.31	9.34	8.33	9.47
K <sub>2</sub> O	9.43	9.57	10.88	10.86	14.55	14.58	0.31	0.18	0.28
F	0.57	0.64	0.18	0.16					
Cl	0.03	0.02	0.00	0.02					
H <sub>2</sub> O	3.61	3.61	4.24	4.28					
O=F,Cl	0.25	0.27	0.08	0.07					
Total	99.47	100.33	98.87	99.65	99.71	99.70	99.73	100.92	100.12

this outcrop are given in Table 11-2. The two samples differ in color index; RVBW-12b is more leucocratic than RVBW-12a and occurs as an enclave in the dominant granitoid. Mineral compositions in the two rocks are not significantly different. This similarity among granitoid facies in the Rolesville batholith is a feature not found in other composite plutons in the southern Appalachians (Speer and others, 1980). It indicates that the minerals crystallized under comparable compositional and physical conditions regardless of facies.

There are several features found throughout the batholith, including this outcrop, that constitute evidence for the multiphase nature of the batholith:

[1] Enclaves of granite in granite are located along the southwest edge of the pavement adjacent to the access road. The enclaves are angular and up to 3 m across. The contrast between them is a result of slightly differing textures and modal abundances. Enclaves are also evident as a result of the crosscutting pegmatite dikes contained within them that terminate at the enclave edges. While the differences among the granitoids are readily apparent here where the various rock types are in contact, it is difficult to carry these observations to other outcrops. One could imagine the difficulty of mapping many of these differing granitoid types if the rocks

were geographically separated, had differing weathering and viewing conditions, and were viewed several hours, days, weeks or years apart.

[2] Planar biotite schlieren only a few mm thick, but up to several meters long, occur on the southwest side of the stream where it is crossed by the road tracks. They are locally folded. The orientation of the schlieren parallels the regional foliation in the batholith. Where the schlieren are abundant the granite has a banded appearance.

[3] Biotite schlieren are cut by ductile faults and displaced up to a meter.

[4] Fractures showing apparent displacement (faults?) occur in the granite, and are locally filled by pegmatite or aplitic granitoid dikes up to 10 cm wide.

This pavement is the location of the RL4 drillhole used by the Virginia Polytechnic Institute Geothermal Program. The drillhole is located on the downstream (southern) end of the pavement. It is the rusted pipe embedded into the pavement. The drillhole is 196.3 m (644 ft) deep. A fracture with flowing groundwater was encountered at 93.59 m (307 ft). This is the source of the artesian flow from the well. Such upward flow disturbs the temperature gradient in the upper half of the drillhole. Below this depth the temperature gradient is undisturbed and determined to be 16.9°/km (Costain

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and others, 1986). Average thermal conductivity of granitoid samples from the drillcore is  $2.96 \pm 0.27$  W/m<sup>2</sup>C. Together these two measurements yield a heatflow of  $50.0 \pm 4.5$  mW/m<sup>2</sup> (milliWatts per square meter). This is greater than the regional Piedmont heat flow of 40 mW/m<sup>2</sup> in rocks with low contents of radiogenic heat-producing elements (<2 ppm U and <10 ppm Th). The higher heat flow of the Rolesville batholith shows the effectiveness of its greater radioactive element contents (Table 11-2) in producing heat in the shallow crust. An U-rich granitoid such as the Cuffytown Creek pluton, South Carolina (average U about 10 ppm) has a heat flow of 67.7 mW/m<sup>2</sup>. The log of the drillcore shows as much petrographic variation as seen in the pavement (Farrar, 1977).

### STOP 12: RALEIGH GNEISS (OPTIONAL)

**LEADERS: Skip Stoddard and Dave Blake**  
**Atlantic Avenue between Highwoods Boulevard and Crabtree Creek, Raleigh East 7.5' Quadrangle**

In the event that there is insufficient time to visit Stop 12 during the 1994 CGS Field Trip, the exposure is conveniently located for a quick visit by interested persons upon their departure from the meeting headquarters at the Holiday Inn. Proceed south on Capital Boulevard from the hotel parking lot and turn right on Highwoods Boulevard (just after Don Murray's Restaurant and before the Days Inn). At the stoplight at the end of Highwoods, turn left onto Atlantic Avenue. Proceed under the I-440 overpass and continue about 0.7 km south (Figure 12-1). Turn right into the driveway of Electronic Office Systems and park in the back lot.

The exposures here consist of blasted cuts at the back of the parking lot, deeply eroded gullies exposing saprolite along the east side of the CSX railroad grade, and numerous loose blocks of material blasted from the excavations here. At the time of this writing, the future quality and accessibility of these exposures are uncertain due to plans for further construction. Other good exposures of Raleigh gneiss can be viewed in and around Pigeon House Branch, which runs along Capital Boulevard just north of downtown Raleigh. Particularly good outcrops are in Pigeon House Branch at Raleigh Bonded Warehouse and in the same creek at the west end of the parking lot of Harris Wholesale (distributor for Anheuser-Busch; outcrop shown in Figure 12-2). Both of these outcrops are between the Fairview Road and Wake Forest Road offramps from Capital Blvd., and about 2 km southwest of Stop 12, at the eastern edge of the Raleigh West quadrangle.

The Raleigh gneiss (informal name of Farrar, 1985a) is the dominant lithologic unit of the Raleigh terrane in this area. It consists of interlayered, medium- to coarse-grained, well banded and locally migmatitic gneisses, ranging from granitic to gabbroic in bulk composition, and containing biotite, hornblende, or both (Horton and others, this guidebook). These rocks are the "injected gneiss and schist" of

Parker (1979). At Stop 12, and at other exposures in and around downtown Raleigh, the gneiss is strongly layered. Typically it shows discontinuous, melanocratic to mesocratic hornblende gneiss, amphibolite, and coarse-grained biotite schist layers from about 10 cm to more than several meters in thickness. These mafic layers alternate with layers of similar thickness comprising mesocratic to leucocratic biotite ± hornblende granitoid gneiss.

The mafic rocks are most commonly represented by hornblende + andesine, with or without epidote. In some exposures, epidote forms thin layers parallel to compositional layering. Clinopyroxene, scapolite, calcite, and titanite occur locally. Textures are generally granoblastic. Where hornblende occurs in contact with clinopyroxene, the hornblende is commonly partially or completely surrounded by the clinopyroxene, implying that the pyroxene grew late in the petrogenetic sequence. The granitoid gneisses, ranging from trondhjemites to granites, are dominated by plagioclase and quartz with K-feldspar occurring locally and in lesser abundance. These rocks commonly display semi-concordant intrusive relationships with hornblende- and biotite-rich rocks. Locally, granitoid gneiss contacts complexly crosscut more mafic rocks and other granitoid gneiss, demonstrating that the intrusive history of the Raleigh gneisses was multiphase. In addition, both mafic and felsic rocks are crosscut by granitic pegmatite and aplite dikes.

The western contact of the Raleigh gneiss with the Falls leucogneiss (Farrar, 1985a) is strongly overprinted by the Nutbush Creek fault zone. Strain effects of this right-lateral shear zone include formation of a subhorizontally-plunging mineral stretching and mineral elongation lineation and sub-

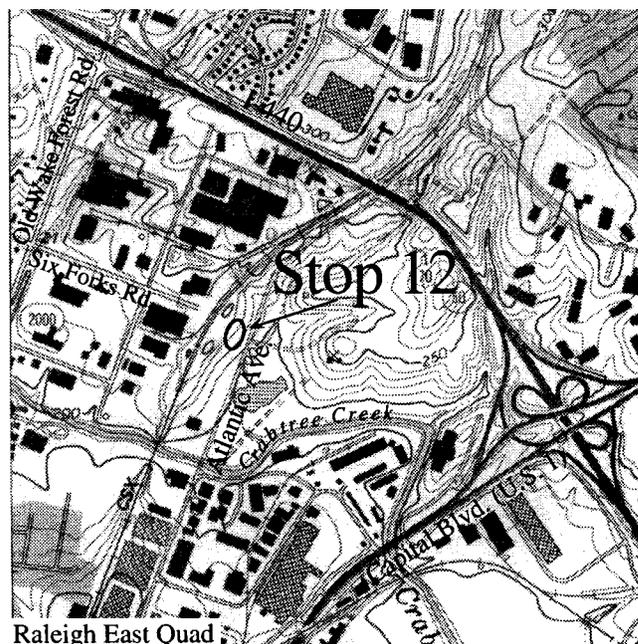


Figure 12-1. Location of Stop 12.

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Figure 12-2. Pavement outcrop of Raleigh gneiss located in Pigeon House Branch adjacent to the southwestern end of the parking lot of Harris Wholesale, Capital Boulevard, eastern edge of the Raleigh West 7.5' Quadrangle. NNE-striking planar fabrics (consisting of biotite foliation and gneissic banding) are visible. Complex cross-cutting relationships are apparent among leucocratic to mesocratic orthogneisses and younger granitic pegmatite and aplite dikes. View is toward the north; standard 32.5-cm geologic hammer for scale.

parallel, subvertically dipping lithologic layering and mica foliation in the Falls leucogneiss and Raleigh gneiss (see papers by Blake; Druhan and others; and Horton and others in this guidebook). Banding in these rocks generally ranges up to no more than several centimeters in thickness. Both rock units exhibit upright, open folds of the foliation and banding; the fold axes are oriented subparallel to the mineral lineations. A weak, subvertical axial planar foliation is locally developed associated with these folds.

In contrast, schists and gneisses east of the fault zone exhibit a banding ranging up to several meters in width, and a schistosity defined by parallel alignment of biotite. Locally, the biotite foliation cuts across mafic/felsic lithologic contacts. Some of the felsic layers show symmetric boudinage and pinch-and-swell texture, with two-dimensional stretching parallel to strike. The foliation is difficult to discern in some amphibolite outcrops. At Stop 12, the gneissic foliation ranges in strike from  $N4^{\circ}$ - $16^{\circ}E$ , with moderate to steep ( $48^{\circ}$ - $80^{\circ}$ ) easterly dips.

Locally, folds of several styles are present in the gneiss. Hinges of early isoclinal, intrafolial folds up to 10 cm in wavelength may be visible. Late, upright, tight to open folds are also common. North of downtown Raleigh, multilayer and single layer open to tight folds show consistent southerly trends and plunges ranging between  $30^{\circ}$  and  $40^{\circ}$ . At least

some of the late-stage granitic pegmatite dikes that intrude at a high angle to the gneissosity are locally buckled into ptygmatic, single layer folds; others occupy brittle extension fractures in the gneiss. A recumbent fold, refolded by a late upright open fold, is present in the weathered and overgrown cut behind the Sears Service building across the railroad tracks from Stop 12, toward the west. In the saprolite exposed in the gullies at Stop 12, a series of late reverse faults are visible. Two fault surfaces measured strike N to NE and dip moderately toward the E and SE, so the apparent sense of motion is tops-to-the W or NW. Visible displacement is up to 20 cm, and obvious drag may be seen in both hanging and footwall blocks along the fault.

It has been suggested that the Raleigh gneiss represents continental basement (Stoddard and others, 1991), possibly correlative with granulite-grade Grenville basement in the Virginia Piedmont (Farrar, 1984). However, a search for petrographic evidence of an early granulite-facies metamorphic event in the Raleigh gneiss in Wake and Franklin Counties, North Carolina, was unsuccessful (Stoddard, 1989), and the highest grade minerals, such as clinopyroxene, were concluded, on textural grounds, to be the result of the last (late Paleozoic) metamorphism to affect the rocks (*e.g.* Russell and others, 1985).

New isotopic and chronologic evidence suggests a different origin for the rocks of the Raleigh gneiss. They may belong to a volcanogenic slate belt sequence that was intruded by abundant granitoid dikes and plutons, and highly deformed, thus developing a strong gneissic banding due to transposition of intrusive contacts. This evidence includes: (1) Recent mapping in the Raleigh West and Raleigh East quadrangles shows the presence of more abundant mafic material in the gneiss than heretofore suspected (Blake, 1994); (2) Pb, Sr, and Nd isotopic analyses on Alleghanian granites in the area, including the Rolesville batholith, indicate that little or no Grenville basement was likely to have constituted the source regions of the granitic magmas (Coler and others, 1994); and (3) Preliminary discordant  $^{207}Pb/^{206}Pb$  zircon ages for the Raleigh gneiss (Horton and Stern, 1994; Goldberg, this guidebook), independently determined by two laboratories, range from 546 to 461 Ma and are similar to ages determined for rocks farther to the west in the Crabtree terrane and Carolina terrane (Goldberg, this guidebook). The Raleigh gneisses may represent higher metamorphic equivalents of Carolina terrane rocks farther to the west, or perhaps the underpinnings of the adjacent slate belts arc(s) exposed by folding in the Wake-Warren anticlinorium. The Raleigh gneisses and Raleigh terrane may constitute an infrastructure analogous to the Charlotte belt.

### END OF FIELD TRIP. RETURN TO HOLIDAY INN-NORTH, RALEIGH

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