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A TEMPORAL VIEW OF TERRANES AND STRUCTURES IN THE EASTERN NORTH CAROLINA PIEDMONT

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INTRODUCTION

This guidebook and field trip present some key aspects of the lithologic, metamorphic, and structural framework in the eastern North Carolina Piedmont, focusing specifically along the western flank of the Raleigh metamorphic belt. We will discuss the regional tectonic history in a broad time context rather than a detailed process context. The rocks now exposed in the eastern part of the southern Appalachian orogen are the products of at least three tectonic events which include: 1) Late Proterozoic to middle Paleozoic development of an Avalonian magmatic arc and its accretion to Laurentia; 2) late Paleozoic metamorphism, faulting, and magmatism during the Alleghanian orogeny; and 3) late Paleozoic to early Mesozoic development of faults and sedimentary basins during the continental rifting of Pangea.

This temporal view highlights field mapping acquired in part through support from the North Carolina Geological Survey (NCGS) STATEMAP and U.S. Geological Survey EDMAP programs. During the past two decades, a corridor of twenty 7.5-minute quadrangles has been studied within the Raleigh and Henderson 1:100,000-scale (100K) sheets (Figure 1). Investigations focus on the Late Proterozoic to Paleozoic crystalline western flank and the Late Triassic Durham basin.

Much of our regional understanding and subsequent interpretations on the lithologic and tectonic development of the western flank of the Raleigh metamorphic belt results from this detailed geologic mapping and using fundamental geologic principles to develop a relative chronology of overprinting relationships. Petrographic and geochemical analyses have allowed us to refine our interpretations of crystalline protoliths; establish regional lithologic correlations among a variety of igneous, metamorphic, and sedimentary rock types; and constrain the metamorphic character and kinematics of overprinting ductile and brittle faults.

An internally consistent Late Proterozoic to early Mesozoic tectonic history emerges from this work. However, many temporal relationships lack an absolute age reference. Limited absolute chronology helps constrain some key relative chronological relationships determined from mapping, but a lack of additional absolute data hinders making concrete lithologic and structural correlations. This lack also inhibits our ability to evaluate the role that episodic versus progressive orogenesis played in the tectonic history, especially as it pertains to Late Proterozoic to late Paleozoic plutonism, and late Paleozoic to early Mesozoic metamorphism and deformation. Thus, this temporal view also highlights problems in our hypotheses that absolute chronology would help resolve.

The field trip is divided into two parts in order to view the western flank in a time context (Figure 2). Stops 1-7 include an east-west transect across three crystalline terranes from the west edge of the Rolesville batholith to the Durham basin. Lithodemic relationships, and geochemical and geochronologic data, document the sequential development of Late Proterozoic to Paleozoic volcanogenic rocks, and Alleghanian metamorphism and intra- and inter-terrane faulting that overprint these rocks.

Stops 8-10 include a north-south transect of rocks and structures associated with the Mesozoic rifting of the western flank along the eastern boundary of the Durham basin. Lithologic and structural relationships, and preliminary $^{40}Ar/^{39}Ar$ dating document the sequential development of late Paleozoic to early Mesozoic ductile-brittle extension in crystalline rocks, and the formation of Triassic clastic sedimentary rocks and Jurassic diabase dikes, and their subsequent deformation.

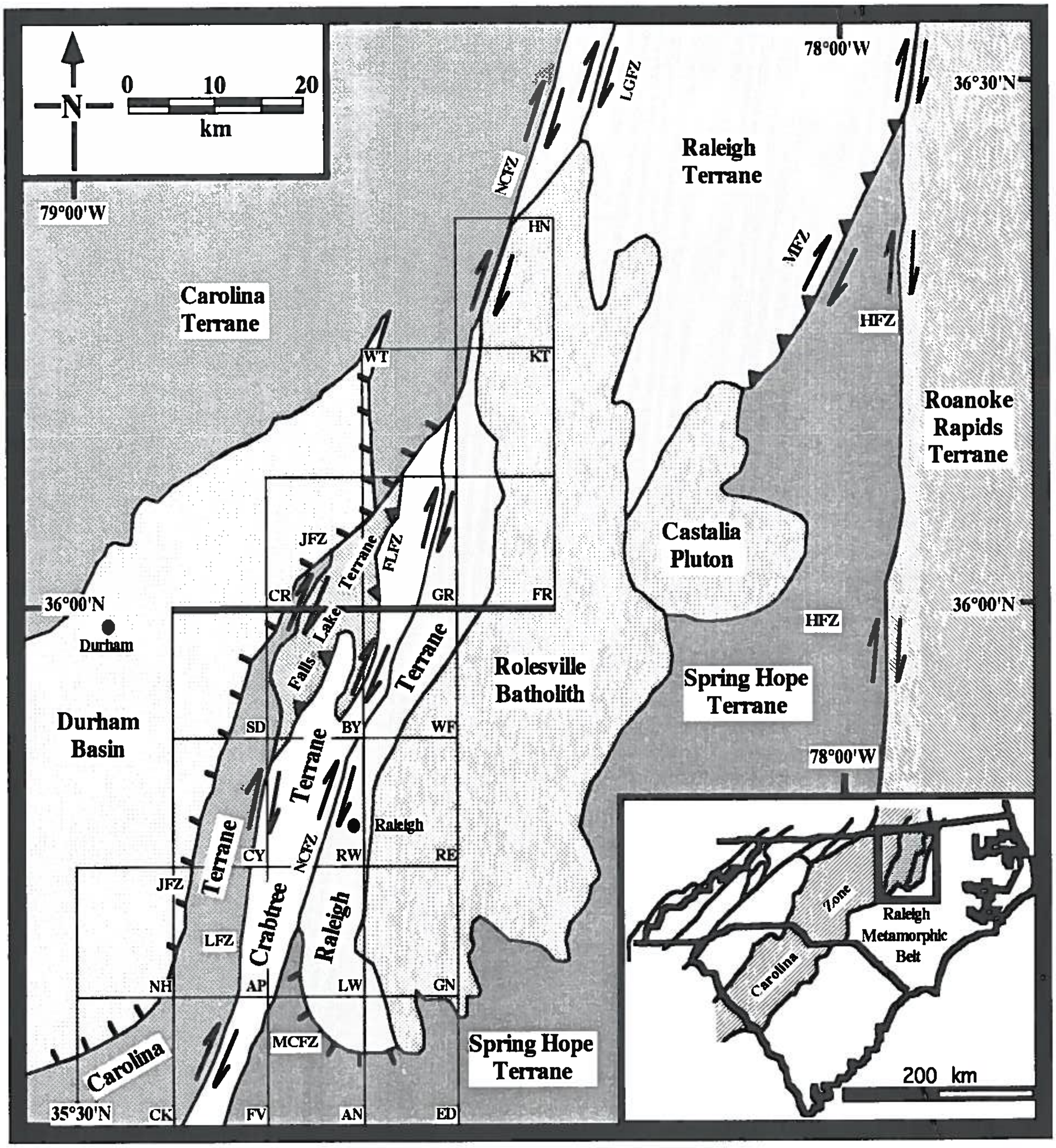

Figure 1. Tectonic map of the Raleigh metamorphic belt showing tectonostratigraphic terranes, Pennsylvanian plutons, late Paleozoic to Mesozoic faults, and the Late Triassic Durham basin in the eastern North Carolina Piedmont. Inset map depicts the Carolina zone and Raleigh metamorphic belt in the hinterland of the southern Appalachian orogen. Hachures indicate the Mesozoic Jonesboro normal fault (JFZ) and its northern, unnamed splay. Terrane discontinuities are the Leesville (LFZ), Falls Lake (FLFZ), Nutbush Creek (NCFZ), Lake Gordon (LGFZ), Middle Creek (MCFZ), Macon (MFZ), and Hollister (HFZ) fault zones. The corridor of twenty 7.5-minute quadrangles mapped for STATEMAP and EDMAP on the western flank include Cokesbury (CK), Fuquay-Varina (FV), Angier (AN), Edmondson (ED), New Hill (NH), Apex (AP), Lake Wheeler (LW); Garner (GN), Cary (CY), Raleigh West (RW), Raleigh East (RE), Southeast Durham (SD), Bayleaf (BY), Wake Forest (WF), Creedmoor (CR), Grissom (GR), Franklinton (FR), Wilton (WT), Kittrell (KT), and Henderson (HN). The thick, east-west-oriented line in the center of the corridor marks the Raleigh-Henderson 100K sheet boundary. Modified from Stoddard and others (1991), Horton and others (1994), Hibbard and Samson (1995), Grimes (2000), and Robitaille (2000).

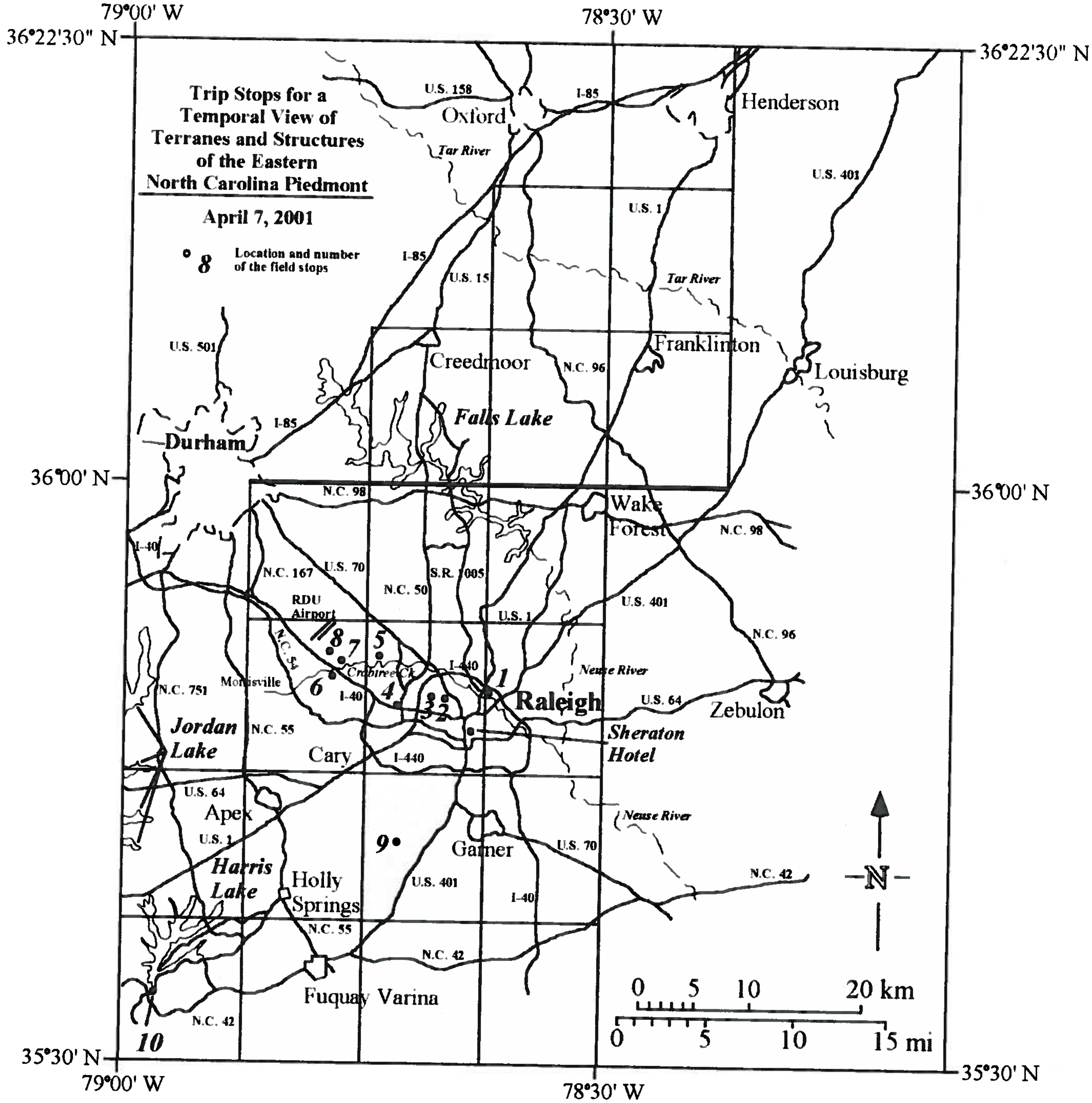

Figure 2. Geographic map showing the location and number of the 10 trip stops. Secondary roads are shown only in the vicinity of the stops. The corridor of twenty 7.5-minute quadrangles shown on Figure 1 is reproduced here to provide an anthropogenic reference to the STATEMAP and EDMAP mapping efforts.

PREVIOUS INVESTIGATIONS

Some of the initial geologic mapping of the Raleigh metamorphic belt began with Dr. John M. Parker and his students at North Carolina State University (NCSU; Fortson, 1959; Dickey, 1963; Cook, 1968; Carpenter, 1970). Parker and Broadhurst (1959) led the first Southeastern GSA field trip across the western flank in order to evaluate the metamorphic facies transition in west Raleigh. Parker (1979) then provided a systematic description of igneous, metamorphic, and sedimentary rocks of Wake County, as well as a discussion on structural and metamorphic events, geophysical surveys, geomorphology, and mineral and ground-water resources. His 1:100,000-scale mapping established the regional framework for subsequent work.

Farrar (1980) conducted regional-scale mapping across the eastern Piedmont of North Carolina. This work culminated in the first lithostratigraphic, lithodemic, and tectonic synthesis for the entire region including the western flank (Farrar, 1985a,b). Moye (1981), Hicks (1982), Druhan (1983), Wylie (1984), Blake (1986), and Stephens (1988) conducted geologic mapping, and geochemical and geophysical studies on crystalline rocks of the western flank. Several projects were combined with USGS work to produce a geologic map of the Falls Lake-Wake Forest area (Horton and others, 1992, 1994).

Since 1989, 1:24,000-scale mapping for the NCGS STATEMAP and USGS EDMAP programs, and MS theses from NCSU, Duke University, and UNC-Wilmington have focused upon crystalline and sedimentary rocks and structures (Hoffman and Gallagher, 1989; Heller, 1996; Stoddard and others, 1996; Phelps, 1998; Clark, 1998; Watson, 1998; Blake and others, 1999; Gaughan, 1999; Grimes, 2000; Robitaille, 2000; O Shaughnessy, in progress).

The product of this work is a lithostratigraphic, lithodemic, metamorphic, and structural framework that is used to decipher the tectonic history of Pangean amalgamation and dispersal in the eastern North Carolina Piedmont. Olsen and others (1991), Stoddard and others (1991), and Stoddard and Blake (1994) provide additional overviews and discussions on the regional geology and implications of lithostratigraphic and lithodemic units, geochronology, intrusive and deformational relationships, and water resources.

REGIONAL SETTING

This section provides a temporal outline for the Late Proterozoic to early Mesozoic geology of the western flank. The intent is to provide the field trip participant with a perspective on the tectonic evolution of the Raleigh area. The rocks now exposed in the eastern part of the southern Appalachian orogen are the products of at least three tectonic events which include: Stage 1) Late Proterozoic to middle Paleozoic development of an Avalonian magmatic arc and its accretion to Laurentia; Stage 2) late Paleozoic metamorphism, faulting, and magmatism during the Alleghanian orogeny; and Stage 3) late Paleozoic to early Mesozoic development of faults and sedimentary basins during the rifting of Pangea (Figure 3).

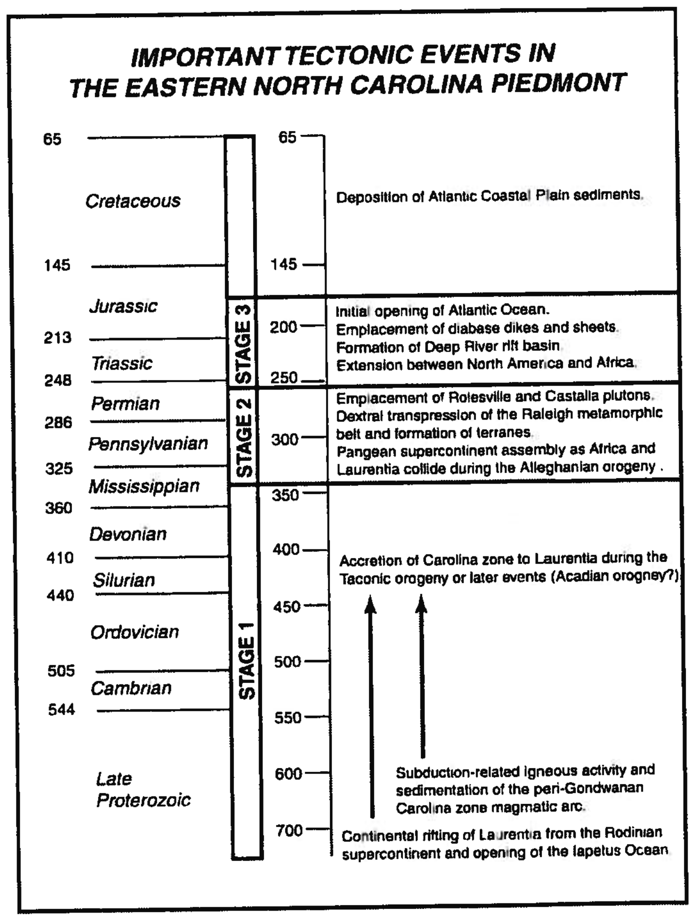

Figure 3. Schematic time line from the Late Proterozoic to Mesozoic showing the principle stages in the tectonic history of the Raleigh metamorphic belt and the Durham basin.

Stage 1: Late Proterozoic to Middle Paleozoic Development and Accretion of Magmatic Arc

The Carolina zone (see inset map, Figure 1) is a first-order tectonostratigraphic element in the southern Appalachian hinterland which links metamorphosed volcanogenic terranes having similar protoliths, ages, isotopic evolution, metamorphism, and deformation (Hibbard and Samson, 1995; Hibbard, 2000). The zone is, at least in part, of Avalonian affinity (Rankin and others, 1989; Nance and Thompson, 1996). The Carolina zone contains an infrastructure and suprastructure (Figure 4) documenting the complex development of Late Proterozoic to Early Cambrian ultramafic to felsic, deep-seated and hypabyssal plutons, pyroclastic deposits and subordinate flows, and their volcaniclastic equivalents. These rocks formed during subduction-related arc magmatism on a juvenile oceanic, or older orogenic volcanic, or sialic crustal substrate (Figure 4; Whitney and others, 1978; Feiss, 1982; Butler and Secor, 1991; Stoddard and others, 1991; Goldberg, 1994; Hibbard and Samson, 1995; Shervais and others, 1996).

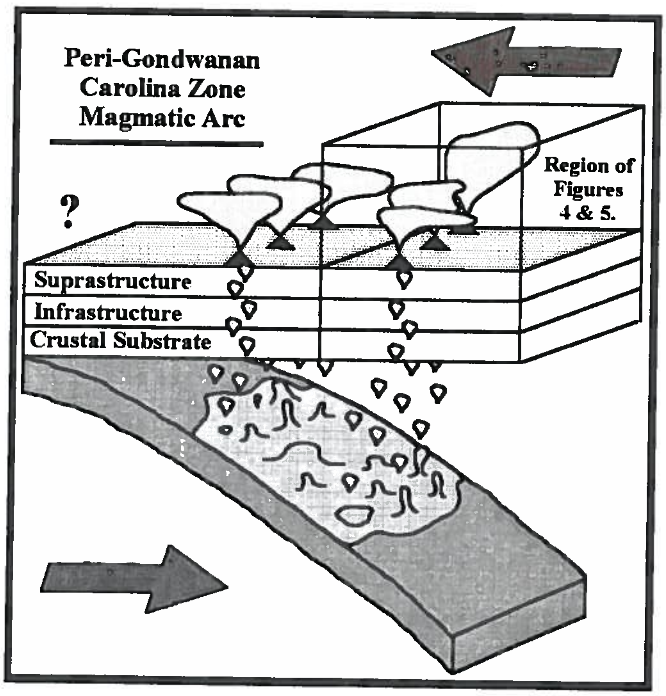

Figure 4. Schematic plate tectonic diagram illustrating the Late Proterozoic to early Paleozoic subduction-related evolution of the Carolina zone magmatic arc. The box marks the region of the Raleigh metamorphic belt depicted in Figures 5 and 6. Question mark indicates that the plate affinity of the subducting slab is uncertain.

The Carolina zone formed in a peri-Gondwanan setting (Nance and Thompson, 1996; Hibbard, 2000) at a time when the eastern Laurentian margin was experiencing continental rifting (Shervais and others, 1996). Based upon this constraint and the presence of early Paleozoic faunal assemblages exotic to Laurentia (Butler and Secor, 1991), the Carolina zone appears to be a far-traveled assemblage of magmatic arc rocks that was accreted to Laurentia during the Paleozoic era.

A lack of consensus exists concerning the exact timing and mechanism of arc accretion. Regional syntheses of paleomagnetic, stratigraphic, and structural data combined with thermochronologic studies in the Carolina zone indicate that the Ordovician to Silurian periods may have been a probable time for juxtaposition of these rocks against Laurentia, perhaps during the Taconic orogeny (Rankin and others, 1989; Butler and Secor, 1991; Hibbard, 2000).

Stage 2: Late Paleozoic Alleghanian Metamorphism, Magmatism, and Faulting

After accretion, the Carolina zone was caught between Laurentia and Gondwana during late Paleozoic assembly of the Pangean supercontinent. During this stage, dextral transpression overprinted the infrastructure and suprastructure of the arc (Gates and others, 1988), and faulted them into the current distribution of volcanogenic terranes.

The largest and most intact member of the Carolina zone is the Carolina terrane (formerly the Carolina slate belt, Charlotte belt, and a portion of the Kings Mountain belt), in the central Piedmont of North and South Carolina (Butler and Secor, 1991). In the eastern Piedmont of North Carolina, the Carolina zone is faulted into six smaller terranes. These include the easternmost portion of the Carolina, the Falls Lake, Crabtree, and Raleigh terranes (together, formerly the Raleigh belt), and the Spring Hope and Roanoke Rapids terranes (together, formerly the Eastern slate belt). These terranes combine to form the Raleigh metamorphic belt, an orogen-parallel structural culmination recording Alleghanian dynamo-thermal metamorphism, ductile faulting, and magmatism.

A macroscale, south-plunging foliation arch known as the Wake-Warren anticlinorium (Parker, 1979) exposes the six eastern Piedmont terranes (Figure 5). In the hinge zone of this late Paleozoic fold, Alleghanian middle to upper amphibolite metamorphism overprints the Raleigh terrane (Farrar, 1985a,b; Stoddard and others, 1991). The Pennsylvanian

Rolesville-Castalia granitoid plutons and a variety of smaller, similar-aged bodies were emplaced into this hinge zone and crosscut Raleigh terrane rocks. Together, these metamorphic and igneous rocks define the Raleigh metamorphic belt infrastructure.

Metamorphic effects decrease away from the hinge zone as a steep gradient from upper amphibolite to greenschist and hornfels facies conditions (Farrar, 1985a,b; Russell and others, 1985; Stoddard and others, 1991; Gaughan, 1998). This gradient affects the Carolina, Falls Lake, Crabtree, Spring Hope, and Roanoke Rapids terranes, which define the suprastructure of the belt on the flanks of the Wake-Warren anticlinorium. Lower greenschist facies assemblages are tentatively correlated with similar assemblages from the Carolina terrane suprastructure in the central North Carolina Piedmont where there are pre-Late Ordovician $^{40}Ar/^{39}Ar$ metamorphic cooling ages (Hibbard, 2000).

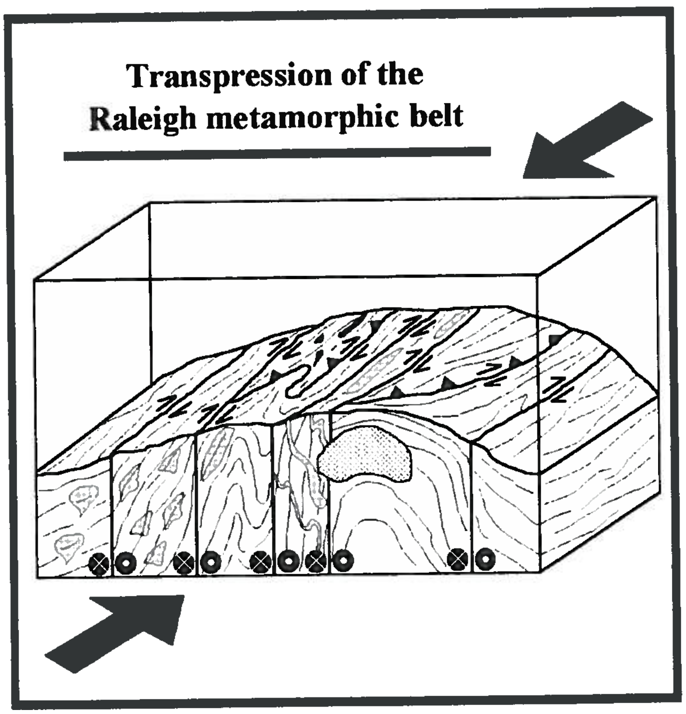

Figure 5. Schematic block diagram of the Raleigh metamorphic belt showing the effects of dextral transpression upon the easternmost Carolina zone. Terranes, faults, and plutons in this structural culmination correlate with Figure 1. Arrows and circles indicate strike-slip faults; teeth mark thrust faults.

Alleghanian ductile strike-slip faults define the bounding contacts of the Carolina zone terranes. Subvertical to steeply west-dipping high faults are strands of the dextral, eastern Piedmont fault system (Hatcher and others, 1977; Bobyarchick, 1981; Farrar, 1985b; Stoddard and others, 1991). The main strands on the eastern flank of the Raleigh metamorphic belt are the Macon and Hollister faults which separate the Raleigh, Spring Hope, and Roanoke Rapids terranes, respectively. The Macon fault has a component of east-directed thrusting (Sacks, 1999). The main western flank strands are the Leesville, Falls Lake, Nutbush Creek, and Lake Gordon faults separating the Carolina, Falls Lake, Crabtree, and Raleigh terranes, respectively (Stoddard and Blake, 1994). The Falls Lake fault is also proposed to have an early thrust history (Stoddard and others, 1994). The Middle Creek fault, separating the Raleigh and Spring Hope terranes, is of unclear origin.

These ductile faults have been traced for 200 km from southern Virginia into central North Carolina (Druhan and others, 1994; Sacks, 1999). Topographic lineaments and dynamically recrystallized rocks having a northeast-trending, subhorizontal stretch lineation and dextral kinematic indicators facilitate their mapping. Mineral assemblages in mylonite and phyllonite containing these indicators suggest that both intra- and inter-terrane faults formed under amphibolite to greenschist conditions. These faults also coincide with linear aeromagnetic anomalies used to extend the strands southward along the western and eastern flanks of the Kiokee metamorphic belt, an equivalent Alleghanian structural culmination in the eastern South Carolina Piedmont (Maher and others, 1991).

Stage 3: Late Paleozoic to early Mesozoic Continental Rifting of Pangea.

After Alleghanian dextral transpression, the western flank records very late Paleozoic to early Mesozoic extension during Pangean supercontinent breakup. Evidence for extension in crystalline western flank rocks includes ductile and brittle normal faults forming discrete to interconnected zones along the eastern boundary of the Durham basin (Figure 6). These faults are identified adjacent and up to 10 km east of the Jonesboro fault, a brittle normal fault which bounds the eastern margin of the Durham basin. Some ductile-brittle faults internally deform terranes and have similar trends to Alleghanian terrane-bounding faults. Others define or crosscut terrane boundaries.

Continuation of the Pangean breakup formed a series of irregularly-shaped half-grabens along the Atlantic margin of North America. The Deep River basin is one of the most southern exposed rift basins. The basin filled with a variety of Late Triassic clastic sediments, their depositional environments strongly controlled by local basin tectonics.

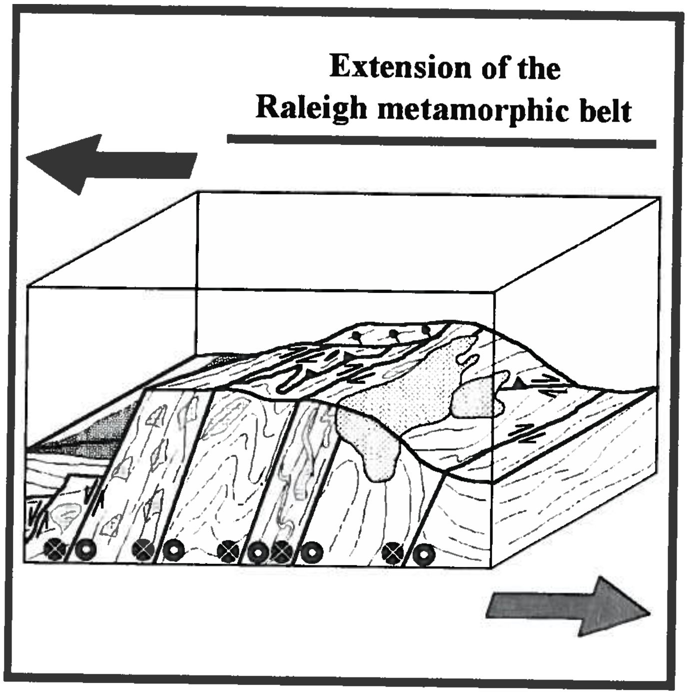

Figure 6. Schematic block diagram of the Raleigh metamorphic belt showing the effects of extension upon the easternmost Carolina zone. Terranes, rift basin, faults, and plutons in this structural culmination correlate with Figure 1. The fault scarp and ball and bar symbol mark the Jonesboro fault.

Alluvial fan complexes prograded westward into the basin from its topographically higher faulted margins. Sediment was transported north and south along the basin axis by meandering river systems and deposited in large alluvial plains. Fresh-water lakes formed in basin depocenters, accumulating deltaic (delta), lacustrine (lake), and paludal (swamp) deposits.

The basin sedimentary rocks are now recognized as the Chatham Group, part of the Newark Supergroup (Olsen, 1978; Luttrell, 1989). The Chatham Group contains varying amounts of conglomerate, sandstone, siltstone, claystone, shale, coal, and small amounts of limestone and chert. Bedding generally dips from west to east, but local variations are common, especially near faults and dikes. Thus, the lowermost (oldest) strata typically occur on the western side of the basin and the uppermost (youngest) strata occur on the east.

Continued crustal thinning and asthenospheric upwelling during the Early Jurassic allowed emplacement of extensive basaltic dikes, sills, and sheets. These dikes crosscut both the sedimentary rocks of the Durham basin and crystalline rocks of the Raleigh metamorphic belt, and are in turn, crosscut by the Jonesboro fault.

PROTEROZOIC TO PALEOZOIC ROCKS

In this section, we present an overview of crystalline terranes, sedimentary basins, and their structures, as well as correlations and hypotheses as to their origins. Late Proterozoic to late Paleozoic rocks in the eastern Piedmont of North Carolina consist of three types: 1) Late Proterozoic to early Paleozoic volcanogenic rocks overprinted by middle to late Paleozoic greenschist facies metamorphism and deformation; 2) Late Proterozoic to early Paleozoic volcanogenic rocks overprinted by late Paleozoic amphibolite facies metamorphism and deformation; and 3) late Paleozoic plutons that are unmetamorphosed and weakly foliated to unfoliated. On the western flank, these rocks occur in a steeply west- to southwest-dipping stack of Carolina zone terranes.

Raleigh Terrane

Within the hinge zone of the Wake-Warren anticlinorium, the Raleigh terrane exposes kyanite-sillimanite zone metamorphism overprinting a mixed assemblage of igneous and sedimentary protoliths, as well as the Rolesville batholith and Castalia pluton composite granitoids (Farrar, 1985a,b; Stoddard and others, 1991). Northeast of the Rolesville batholith between the Lake Gordon and Macon faults, the Raleigh terrane contains pelitic and mafic to felsic protoliths that are now paragneiss and orthogneiss (Sacks, 1999). Southwest of the batholith, the terrane contains the Raleigh Gneiss, a heterogeneous mix of metamorphosed mafic rocks and granitoid intrusions (Stoddard and others, 1991; Stoddard and Blake, 1994).

Internal character of the Raleigh Gneiss

Complex intrusive relationships between biotite ± hornblende, tonalitic to granitic orthogneiss and wall rocks of gabbroic to dioritic orthogneiss, amphibolite, and biotite schist produce a variably migmatitic aspect in the Raleigh Gneiss. This northeast-trending block of rock displays a penetrative gneissosity, mutilayer to single layer folds, mineral and stretch lineations, layer parallel boudinage, and porphyroclasts at a variety of scales.

Along its western contact with the Crabtree terrane, the Nutbush Creek fault produced subhorizontal mineral and stretching lineations, and transposed metaintrusive layering and mica gneissosity. Isoclinal to open folds have hinge zones oriented parallel to the lineations. A weak, subvertical mica foliation is locally axial planer.

The Falls Leucogneiss is a prominent pluton in the Raleigh Gneiss. This leucogranitic orthogneiss is a narrow, tabular body 75 km long and up to 2.2 km wide along the Crabtree and Raleigh terrane contact (N.C. Geological Survey, 1985; Farrar, 1985a,b; Horton and others, 1994). It records a penetrative subhorizontal lineation and magnetic anisotropy which are used to position the Nutbush Creek fault along its trace (Horton and others, 1994; Druhan and others, 1994). Mesozoic brittle faults truncate the orthogneiss at its southern termination in the Lake Wheeler quadrangle (Heller and others, 1998).

Because of its position along the terrane contact, the leucogneiss was originally thought to be a pluton that was intruded along the Nutbush Creek fault. In the Franklinton and Kittrell quadrangle, interlayered mafic to felsic orthogneiss and more minor metamorphosed ultramafic rocks including metapyroxenite are mapped as members of the Raleigh Gneiss (Robitaille, 2000). These rocks also record the Nutbush Creek fault strain. Based upon these relationships, Robitaille (2000) infers that the Falls Leucogneiss is a deformed, metaplutonic member of the Raleigh Gneiss.

The southwestern contact of the Raleigh Gneiss with the lower to middle greenschist facies Spring Hope terrane is the Middle Creek fault. Its effects are inferred, although it clearly indicates a metamorphic discontinuity that may be ductile or brittle in origin. A lack of outcrop in areas of crystalline exposure and the unconformable overlap of Coastal Plain sediments inhibits its investigation. Although this contact was originally mapped as a regional thrust fault placing greenschist over amphibolite facies rocks (Farrar, 1985b), its origin is still unclear. Recent hypotheses suggest that the fault may be: 1) an early Alleghanian ductile fault crosscut by the Nutbush Creek fault, or 2) a younger brittle fault related to Mesozoic rifting.

Regional Correlation

Farrar (1985a,b) correlates Raleigh terrane rocks and metamorphic mineral assemblages with the Grenville Goochland zone (Hibbard and Samson, 1995) in the Virginia Piedmont. However, the Lake Gordon and Hylas faults separate the Raleigh terrane from the Goochland zone (Sacks, 1999). A petrographic correlation of granulite facies assemblages of the Goochland zone with those in the Raleigh Gneiss does not appear to exist (Blake, 1986; Stoddard, 1989; Grimes, 2000; Robitaille, 2000). Instead, Raleigh Gneiss assemblages correlate with Alleghanian amphibolite facies metamorphism (Russell and others, 1985). In addition, the Raleigh Gneiss migmatitic aspect and mafic component southwest of the batholith appears different from lithologies north of the batholith.

Raleigh Gneiss samples yield 461-546 Ma $^{207}Pb/^{206}Pb$ zircon ages (Goldberg, 1994). The Falls Leucogneiss yields discordant $^{207}Pb/^{206}Pb$ zircon crystallization ages of 491 Ma (Horton and Stern, 1994) and 545-543 ± 20 Ma (Caslin and others, 2001). This similarity in dates supports mapping results that suggest that the Falls Leucogneiss and perhaps the bulk of the Raleigh Gneiss represents Late Proterozoic to early Paleozoic plutons metamorphosed during the late Paleozoic.

While the origin of the Raleigh Gneiss is still unclear, Farrar (1999) proposes that the Falls Leucogneiss, based upon its major and trace element characteristics, is a peralkaline granite associated with the rifting of Laurentia at the start of the Iapetan cycle. The leucogneiss intruded the western edge of the Goochland zone and was subsequently deformed along Alleghanian ductile faults.

Geochemical data also indicate that metamorphosed mafic rocks of the Raleigh Gneiss group with arc-related basalts on trace element tectonic discrimination diagrams, as do mafic rocks sampled locally in the Carolina and Spring Hope terranes (Stoddard and others, 1996). Field, geochemical, and U-Pb geochronologic studies suggest that the Raleigh Gneiss is more similar to Carolina zone terranes on the flanks of the Wake-Warren anticlinorium rather than being a fragment of the Goochland zone (Goldberg and others, 1995; Hibbard and Samson, 1995; Stoddard and others, 1996; Sacks, 1999; Caslin and others, 2001). The Raleigh Gneiss may represent multiply-intruded basement to a portion of the Carolina zone magmatic arc.

Crabtree and Spring Hope Terranes

The Crabtree and Spring Hope terranes lie structurally above and to the west and southwest of the Raleigh terrane, respectively, across the Nutbush Creek and Middle Creek faults. Although currently exposed at different metamorphic grades, similarities in lithology, protoliths, and geochemical signatures between the Crabtree and Spring Hope terranes exists (Stoddard and others, 1996). The Crabtree terrane displays the effects of staurolite-garnet-kyanite zone metamorphism superimposed upon pelitic and felsic rocks (Farrar, 1985a,b; Blake, 1986; Stoddard and others, 1991; Horton and others, 1994; Heller, 1996). The Spring Hope terrane contains chlorite-biotite zone felsic to mafic metavolcanic and metavolcaniclastic rocks (Farrar, 1985a,b; Carpenter and others, 1995a,b).

Internal Character of the Terranes

The Crabtree terrane is an elongate, northeast-trending block containing a suite of quartzitic white mica schist, felsic gneiss, pelitic schist, and graphitic schist, and localized biotite schist, biotite-hornblende gneiss, and amphibolite (Stoddard and others, 1991; Horton and others, 1994; Heller 1996; Blake, 2000). A lithodemic nomenclature is being developed for the suite.

White mica and biotite ± staurolite ± garnet ± kyanite index minerals identify the pelitic schists. Numerous small, discontinuous layers and at least four major horizons of graphite ± white mica ± garnet ± staurolite ± kyanite schist are traced for tens of km in the pelitic schist, attesting to the sedimentary origin for part of the terrane (Parker, 1979; Heller, 1996; Blake, 2000). One prominent graphite schist horizon supported mining operations. The carbon isotopic study of Lumpkin and others (1994) on the graphite supports a sedimentary origin for this schist.

Pelitic schist also interlayers with more felsic rocks. Locally, felsic gneiss with relict plagioclase phenocrysts are inferred to have dacitic to rhyolitic protoliths (Farrar, 1985a; Stoddard and others, 1991). Quartzitic and felsic to intermediate gneiss are penetratively deformed and may be volcanic or plutonic in origin. Biotite schist and amphibolite are recrystallized mafic dikes (Butler, personnel communication). The Crabtree Creek Gneiss crosscuts pelitic and graphite schist in the western part of the terrane. The pluton preserves relict phaneritic texture, and quartz porphyroclasts reflecting a relict porphyritic texture (Blake, 1994).

A steep west to subvertical dipping, penetrative schistosity to gneissosity and north-northeast-trending, subhorizontal mineral and stretch lineations dominate the entire terrane. Rocks are commonly proto- to ultramylonitic. The foliation is axial planar to mesoscale, recumbent tight to isoclinal, single layer and multilayer folds. This is especially true within intra-terrane faults and near the Falls Lake and Leesville faults defining the western boundary of the Crabtree terrane.

The foliation is structurally composite and reflects the progressive deformation overprinting the terrane. Two nearly parallel foliations define mesoscale to macroscale C-type shear bands and localized S-C domains that are intimately associated with an increase in stretch lineation intensity. Dextral kinematic indicators occur in some faults, especially mica fish in pelitic and coarse-grained metaplutonic units. The foliation and lithodemic contacts are refolded about a macroscale upright, shallow, doubly-plunging fold called the Raleigh antiform (Parker, 1979; Horton and others, 1994; Heller, 1996; Blake, 2000). The antiform also folds the Falls Lake fault at the Falls Lake-Crabtree terrane contact.

Dip parallel quartz shear vein fibers and fault slickenlines locally overprint the ductile faults. A complex network of brittle faults are mapped in the south-central part of the terrane and is attributed to dip-slip displacements during Mesozoic rifting (Heller, 1996; Heller and others, 1998). The foliation is highly oblique to fault orientation and the faults terminate several unit contacts. In addition, fault breccia clasts, some at greenschist facies, are not correlative with adjacent amphibolite facies fault wall rocks.

South of this brittle fault network, a less than 1 km-wide Nutbush Creek fault zone juxtaposes the Crabtree and Spring Hope terranes. Building from Farrar (1985a,b), a lithostratigraphic sequence of greenschist facies felsic to intermediate phyllite and greenstone having intercalated volcanic and clastic protoliths is proposed for the Spring Hope terrane (Carpenter and others, 1995a,b; unpublished NCGS STATEMAP mapping in the eastern Raleigh 100K sheet). This sequence is mapped and aeromagnetically traced westward from the eastern flank of the Raleigh metamorphic belt across the hinge zone of the Wake-Warren anticlinorium onto its western flank where the Nutbush Creek and Middle Creek faults truncate it.

The older portion of the sequence is the Stanhope Group of fine- to medium-grained, metamorphosed rhyodacitic flows and tuffs and interbedded greenstone. The Princeton and Webbs Mill Formations are units within the group. The younger portion is the Smithfield Formation of fine-grained meta-argillite overlain by massive metasiltstone. Carpenter and others (1995a,b) describe the genesis of the rock protoliths through: 1) building of the arc by subaerial deposition of felsic tuffs and more minor mafic flows; 2) collapse of the volcanic sequence, possibly related to rift-related subsidence; and 3) burial of the volcanic sequence by volcaniclastic sedimentary rocks which marks a change from subaerial to submarine deposition.

Alleghanian metamorphism and Rolesville batholith magmatism overprint Spring Hope terrane rocks, locally raising them from the greenschist to the amphibolite or hornfels facies across a steep gradient (Stoddard and others, 1991; Gaughan, 1999). Several greenschist to amphibolite facies cleavages and multilayer folds affect the terrane. Composite fabrics are locally developed adjacent to the Nutbush Creek fault.

Regional Correlation

In the Crabtree terrane, the Crabtree Creek Gneiss yields discordant $^{207}Pb/^{206}Pb$ zircon dates of 542 Ma (Horton and Stern, 1994) and 554 to 566 Ma (Goldberg, 1994). These dates are interpreted as minimum ages for crystallization (Horton and others, 1994), which suggests that its wall rocks are at least Late Proterozoic to Cambrian in age. In the Spring Hope terrane, biotite gneiss of Mill Creek yields an upper intercept date of 620 ± 9 Ma while a metamorphosed felsic tuff in the Webbs Mill Formation yields a discordant $^{207}Pb/^{206}Pb$ zircon crystallization date of 590 Ma (Goldberg, 1994). The Princeton Formation yields a 537 and 544 Ma age (unpublished results from the NCGS STATEMAP Raleigh 100K sheet). Based upon rock types and geochronology, grouping the Crabtree and Spring Hope terranes with the Carolina zone appears to be a compatible correlation. Lumpkin and others (1994) tentatively traced a graphite horizon eastward from the Crabtree terrane across the Nutbush Creek fault into the southwestern Spring Hope terrane, suggesting a physical link between the two terranes.

Falls Lake Terrane

The Falls Lake terrane lies structurally above and to the west of the Crabtree terrane across the Falls Lake fault. It lies east of the easternmost Carolina terrane across the Leesville fault. The Falls Lake terrane displays staurolite-garnet-kyanite zone metamorphism that overprints a mixed assemblage of ultramafic to felsic and pelitic rocks (Moye, 1981; Wylie, 1986; Blake, 1986; Horton and others, 1986; Stoddard and others, 1991; Horton and others, 1994).

Internal Character of the Terrane

The Falls Lake terrane is another elongate, northeast-trending block on the western flank. Mafic rocks including metagabbro, hornblende gneiss, and amphibolite and ultramafic rocks including hornblendite (metapyroxenite), actinolite-clinozoisite rock, serpentinite, talc, talc + actinolite ± staurolite, and talc + tremolite schist, and actinolite-chlorite schist are dispersed in an intermediate schist and gneiss matrix. The mafic and ultramafic rocks form numerous (over one hundred have been mapped) discontinuous blocks ranging in size from one cm to several km (Horton and others, 1986).

Locally, the mafic and ultramafic rocks preserve relict igneous minerals and phaneritic to cumulate textures. Combined with their geochemistry (Moye, 1981; Horton and others, 1986), their protoliths are inferred to be peridotite, principally dunite and harzburgite, gabbro, and possibly basalt that reflect dismembered oceanic crust. Relatively homogeneous quartz-oligoclase-biotite-white mica schist and gneiss forms the matrix and preserves both crystalloblastic and locally, relict phaneritic textures.

A penetrative west-dipping schistosity to gneissosity overprints both matrix and blocks. Many blocks are elongate, lenticular, or boudinaged parallel to the matrix foliation. This foliation is also axial planar to recumbent isoclinal, shallow north-northwest-plunging folds. Two additional generations of shallow north-plunging, upright open folds and variably northwest- and southeast-plunging chevron folds affect both blocks and matrix.

A penetrative, subhorizontal stretch lineation is well preserved along the contact with the Crabtree terrane at the Falls Lake fault. There, mm-scale biotite layered gneiss is inferred to be annealed mylonite (Wylie, 1984; Blake, 1986). Similar fabric relationships occur along the Leesville fault separating the Falls Lake rocks from the metavolcanic and metaplutonic rocks of the easternmost portion of the Carolina terrane (Horton and others, 1994; Phelps, 1998). The Raleigh antiform folds the Falls Lake fault, the Falls Lake terrane, and its regional foliation about a subhorizontally-plunging, northeast-trending hinge zone. The fold is upright and open.

The Jonesboro brittle normal fault truncates the northern extension of the Leesville and Falls Lake faults and the northwestern portion of the Falls Lake terrane. Resistant ridges of silicified breccia mark the brittle fault (Carpenter, 1970; Heller and others, 1998;

Robitaille, 2000). O Shaughnessy (mapping in progress) is currently evaluating the northeastern termination of the Falls Lake terrane and the Falls Lake fault.

Regional Correlation

Although other metamorphosed terranes along the western flank contain mafic and ultramafic rocks, distinct block-in-matrix structure at this metamorphic grade is confined to the Falls Lake terrane. This makes its direct correlation to adjacent rocks difficult. The abundance of overprinting relationships may indicate that the Falls Lake terrane records complex deformation including and perhaps prior to the late Alleghanian orogeny (Stoddard and others, 1994).

The schist and gneiss matrix is interpreted to be metamorphosed mudstone and graywacke into which the mafic and ultramafic rocks were incorporated by sedimentary and tectonic processes in an subduction-related, accretionary prism melange within the Carolina zone (Horton and others, 1986). This setting is unique as compared to the magmatic, volcanic, and volcaniclastic origin of rocks in adjacent terranes. One implication is that the Falls Lake terrane is exotic to this region and has been translated to its current position during thrusting or dextral faulting.

However, tentative $^{207}Pb/^{206}Pb$ crystallization ages from zircon (c. 590 Ma lower intercept date) in biotite schist from the northwestern portion of the terrane are consistent with a Late Proterozoic to early Paleozoic age for matrix development (Goldberg, 1994). This is also consistent with adjacent, Avalonian Carolina zone rocks. Goldberg (1994) inferred that the discordant date reflects the time of crystallization of the schist protolith, and that the matrix may contain fragments or intrusions of plutonic rocks that are similar in age to adjacent terranes.

Just north of the northern termination of the Falls Lake terrane and the Leesville fault at the Jonesboro fault, Robitaille (2000) mapped metamorphosed mafic and ultramafic enclaves in a biotite quartz metadiorite. These Carolina terrane rocks experienced greenschist facies metamorphism that may be late Paleozoic or earlier in age. The Jonesboro fault clearly marks a metamorphic discontinuity. It also uses an antecedent structure; greenschist facies mylonite and phyllite of unclear age are exposed along the western contact of the brittle fault.

Although the metamorphic grade and degree of recrystallization differ between the Carolina and Falls Lake terranes, the composition and style of block-in-matrix structure across the Jonesboro fault is quite similar. It is unclear whether the Falls Lake terrane represents a tectonic melange or a deformed and metamorphosed, enclave-rich pluton of the Carolina terrane at the amphibolite facies. The second hypothesis is compatible with the findings of Goldberg (1994). The mapping of O Shaughnessy (in progress) will evaluate this hypothesis.

Carolina Terrane

The easternmost portion of the Carolina terrane is the westernmost and structurally highest terrane along the western flank lying west of the Falls Lake and Crabtree terranes. It is a north-trending sliver of rock located to the west of the Leesville fault, and east of the Jonesboro fault, which forms the eastern boundary of the Durham basin. The terrane contains chlorite-biotite zone felsic to mafic and locally ultramafic metaplutonic rocks and felsic to mafic metavolcanic and metavolcaniclastic rocks (Farrar, 1985a,b; Stoddard and others, 1991; Horton and others, 1994; Blake and others, 1999).

Internal Character of the Terrane

Metavolcanic and metavolcaniclastic felsic phyllite to schist and greenstone to amphibolite define the Cary metamorphic suite. The suite designation is favored here instead of the Cary series of Parker (1979) or Cary Formation of Farrar (1985a) because there is a lack of data on younging criteria and absolute ages. The suite is divided into four main mappable units from east to west across the terrane (Blake and Butler, 1999; Stoddard, 2000; Blake, 2000; Blake and Clark, 2000).

Just west of the Leesville fault, the Turkey Creek Amphibolite contains fine- to medium-grained mafic hornblende gneiss to amphibolite representing metamorphosed basalt at the upper greenschist to lower amphibolite facies. The Big Lake-Raven Rock Schist contains lower to upper greenschist facies porphyritic plagioclase and quartz crystal dacitic to rhyolitic tuffs. Relict quartz phenocrysts are readily identified by their blue coloration. Locally, felsic lithic fragments are preserved in the metatuff and subordinate layers of metavolcaniclastic rocks are interlayered with the metatuff. The metatuff commonly contains thin layers of biotite schist inferred to be metamorphosed mafic dikes.

Thin interlayers of lower to upper greenschist facies Sycamore Lake Greenstone occur within the Big Lake-Raven Rock Schist and are inferred to be metabasaltic flows and perhaps mafic volcaniclastic sedimentary rocks derived from the erosion of adjacent mafic volcanic and plutonic rocks. The Coles Branch Phyllite is a lower to upper greenschist facies, fine-grained, felsic phyllite that locally preserves quartz and feldspar phenocrysts. It is unclear as to whether this unit is a pyroclastic or volcaniclastic in origin because of penetrative cleavage development and recrystallization adjacent to the Jonesboro fault.

Bodies of ultramafic to felsic rocks are intrusive units having the Cary metamorphic suite as their wall rocks. These bodies are thought to be, in part, subvolcanic feeders to the metamorphosed mafic to felsic volcanic rocks. The Umstead meta-intrusive suite is a complex, metamorphosed assemblage of subordinate pyroxenite associated with a swarm of gabbroic to granodioritic dikes and larger plutons in the Cary, Southeast Durham, and Bayleaf 7.5-minute quadrangles. The metamorphosed Reedy Creek Granodiorite and Beaverdam Diorite-Gabbro are two large plutonic complexes in the suite.

Southward in the Apex, Fuquay-Varina, and Cokesbury 7.5-minute quadrangles, individual satellite bodies include the metamorphosed Sunset Lake, Buckhorn Creek, Burt Creek, and Avents Creek plutons of granitoid compositions. The Buckhorn Dam meta-intrusive suite is another large metamorphosed ultramafic to felsic plutonic complex exposed north of the Cape Fear River and east of Shearon Harris Lake.

North of the Jonesboro fault in the Wilton 7.5-minute quadrangle, Carpenter (1970) and Robitaille (2000) mapped the metamorphosed Tar River Diorite whose wall rock appears to be lower greenschist facies mafic to felsic metavolcanic to metavolcaniclastic rocks of the main portion of the Carolina terrane.

A steep to moderate west-dipping penetrative cleavage overprints pluton-wall rock contacts throughout the terrane and mimics lithodemic orientation. Locally, open to tight, west-plunging folds deform the foliation and unit contacts. Near its eastern boundary with the Crabtree and Falls Lake terranes along the Leesville fault, phyllonitic to mylonitic rocks develop a moderate to shallow, north-northwest-plunging stretch lineation.

Fabrics and faults having normal displacements are commonly observed across this terrane and are especially well formed adjacent to the Jonesboro fault. These structures overprint the regional foliation. Three of the ductile normal faults are mapped in Umstead State Park. Ductile normal faults and localized high strain zones are identified on the basis of greenschist to subgreenschist composite fabric elements including C'-type shear bands, layer parallel boudinage, mineral and stretch lineations, and slickenlines that indicate oblique northwest-trending to down dip normal displacements. Slickenlines, silicified breccia and fracture sets, and hydrothermal alteration ornament the Jonesboro fault in crystalline rocks.

Regional Correlation

Field and petrographic relationships among the metamorphosed felsic and mafic tuffs, flows, volcaniclastic rocks, and their subvolcanic plutons reflect the exposure of multiple centers of dominantly explosive silicic volcanism that is Late Proterozoic to early Paleozoic in age (Blake and others, 1999). The metamorphosed volcanic and plutonic rocks share mineralogical and geochemical characteristics. A 575 ± 12 Ma zircon $^{207}Pb/^{206}Pb$ crystallization age was obtained from the Big Lake-Raven Rock Schist (Goldberg, 1994). This date is compatible with zircon ages obtained from adjacent western flank terranes.

Although these rocks are exposed at different metamorphic grades, similarities in lithology, protoliths, and geochemical signatures between the easternmost Carolina, Crabtree, Spring Hope, and Raleigh terranes exist (Stoddard and others, 1996). These rocks also appear to be correlative with Late Proterozoic to Cambrian calc-alkaline metavolcanic and metaplutonic rocks in the Carolina terrane west of the Durham basin that are subduction-related (Butler and Secor, 1991).

Low grade metamorphic assemblages from the easternmost Carolina terrane are tentatively correlated across the basin into central North Carolina where there are Late Ordovician dates for greenschist facies metamorphism (Butler and Secor, 1991; Hibbard, 2000). North of the Jonesboro fault in the Wilton 7.5-minute quadrangle, greenschist facies metaplutonic and metavolcanic rocks appear to be a part of the main portion of the Carolina terrane. These rocks are tentatively traced around the northern termination of the Durham basin into the central North Carolina Piedmont (N.C. Geological Survey, 1985).

The west to east increase in grade across the easternmost Carolina terrane marks the overprinting of Alleghanian metamorphism along the western flank. Clearly, dextral mylonite and phyllonite along the eastern terrane boundary at the Leesville fault are correlative with late Alleghanian dextral faulting.

The ductile to brittle normal faults suggest that the easternmost Carolina terrane experienced a ductile-to-brittle extensional history subsequent to ductile Alleghanian transpression. Based upon the proximity of dextral and normal faults on the western flank, an antecedent relationship between late Paleozoic structures and early Mesozoic rift basin development appears to exist. Similar relationships occur northward in the Virginia Piedmont along the Hylas fault (Bobyarchick and Glover, 1979).

Preliminary $^{40}Ar/^{39}Ar$ study results yield a date of 255 ± 2 Ma from rocks within one of the ductile normal faults that overprints the Coles Branch Phyllite adjacent to the Jonesboro fault (Blake and others, 2001; Hames and others, 2001). This date may indicate that Pangean rifting was initiated in the Late Permian, or it may represent ductile normal faulting in an event distinct from Mesozoic rifting.

EARLY MESOZOIC ROCKS

Early Mesozoic rocks in the eastern Piedmont of North Carolina consist of two types: 1) Late Triassic sedimentary rocks of the Deep River rift basin, and 2) Early Jurassic diabase dikes and sills intruding both Triassic sedimentary rocks and crystalline rocks of the western flank. These rocks were all formed in response to extension, crustal thinning, and asthenospheric upwelling during the breakup of the Pangean supercontinent.

Deep River Basin

The Deep River basin forms the western boundary of the western flank of the Raleigh metamorphic belt. The basin formed as a result of crustal extension during the breakup of Pangea and filled with a variety of Late Triassic clastic sediments. From north to south, the Deep River basin is subdivided into three smaller basins, the Durham, Sanford, and Wadesboro basins, respectively. The boundaries of these smaller, component basins are undefined.

Geometry and Structure of the Basin

The Deep River basin is a north- to northeast-trending half graben. The Jonesboro fault, a west-dipping high-angle, normal fault, borders the basin on its east side (Campbell and Kimball, 1923). This fault separates the Triassic sedimentary rocks from crystalline rocks of the western flank. The total amount of displacement along the fault is unknown, but a minimum estimate of 3.0 to 4.5 km of dip-slip displacement is proposed, depending on location (Campbell and Kimball, 1923; Reinemund, 1955; Bain and Harvey, 1977; Parker, 1979; Bain and Brown, 1980; Hoffman and Gallagher, 1989). Bain and Brown (1980) suggested the Jonesboro fault is actually a fault zone, characterized by "step-faulting" along numerous individual faults. Rider blocks are inferred to occur between these faults. Clark (1998) observed that the Jonesboro fault plane itself is extremely sharp, commonly with a 1-3 meter wide gouge zone of clay and foliated fault breccia in the footwall.

Stratigraphy of the Basin

Bain and Harvey (1977) proposed the first map units internal to the Durham basin based on reconnaissance-level mapping. The NCGS (1985) later consolidated these into four facies for the State Geologic Map. However, during detailed geologic mapping of the central Durham basin (Southeast and Southwest Durham 7.5-minute quadrangles), Hoffman and Gallagher (1989) found these facies, as defined, inadequate for describing the rocks in their map area. They found that several of these facies could be subdivided even further into more specific map units. They subsequently adopted the lithofacies system of nomenclature of Smoot and others (1988) for consistency with other geologic mapping throughout the Newark Supergroup.

As a result of their mapping, Hoffman and Gallagher (1989) identified seven distinct lithofacies in the central Durham basin. These lithofacies were grouped in three lithofacies associations, labeled Lithofacies Association I (LA I), Lithofacies Association II (LA II), and Lithofacies Association III (LA III), in ascending stratigraphic order. Olsen (1997) proposed an unconformity between LA I and LA II based on vertebrate fossil assemblages. An intertonguing relationship exists between LA II and LA III.

In general, LA I contains interbedded sandstone and siltstone and is interpreted as braided stream deposits. LA II also contains interbedded sandstone and siltstone, but is interpreted as a meandering fluvial system surrounded by a vegetated floodplain. LA III contains poorly sorted sandstone, pebbly sandstone, and conglomerate. LA III is interpreted as alluvial fan complexes characterized by broad, shallow channels having high sediment concentrations and locally, high-energy debris flows.

The lithofacies association system names individual lithofacies by combining its age, group, and lithology into one map unit abbreviation. The prefixes for age (Tr=Triassic) and group (c=Chatham Group) are common to all Triassic lithofacies in the Durham basin. The remainder of the unit name is reserved for the dominant lithology (i.e., si=siltstone, s=sandstone, sc=pebbly sandstone, c=conglomerate). Interbedded lithologies are separated by a slash, dominant lithology given first (i.e., s/c=interbedded sandstone and conglomerate). Similar lithofacies of different lithofacies associations are notated by subscript numerals (i.e., Trcs/si1 vs. Trcs/si2).

Watson (1998) extended some of the lithofacies of Hoffman and Gallagher (1989) into the central Durham basin in the Green Level 7.5-minute quadrangle. Clark (1998) also utilized the lithofacies system in the southern Durham basin in the Cary, New Hill, Apex and Cokesbury 7.5-minute quadrangles. Clark found two lithofacies of Hoffman and Gallagher (1989), Trcs (sandstone) and Trcsc (pebbly sandstone), were so intermixed in map pattern that he combined them into one mappable unit, Trcs/sc (interbedded sandstone and pebbly sandstone).

Early Jurassic Intrusive Rocks

Early Jurassic diabase dikes and sheets occur throughout North Carolina, but are most concentrated in the Deep River rift basin. These rocks belong to a large family of mafic rocks termed the eastern North America early Mesozoic mafic province (ENA province) and are interpreted to have resulted from the breakup of Pangea in the early Mesozoic (Ragland, 1991). The rocks typically occur as northwest trending, steeply dipping to vertical, gray to bluish-black, slightly to severely weathered, fine- to medium-grained diabase. A second set of north-south trending dikes exists in the central North Carolina Piedmont. More rare are a few sill-like or lopolithic sheets outcropping in the Deep River basin north of Durham.

All of the North Carolina dikes are mafic in composition, except for a few felsic dikes in the extreme northeastern Piedmont reported by Stoddard (1983), Stoddard and others (1986), and Sacks (1999). Ragland (1991) provides a thorough discussion of the dike petrology. Previous K-Ar and Ar-Ar isotopic studies result in a wide range of dates between 160-203 Ma; however, recent $^{40}Ar/^{39}Ar$ work by Hames (personnel communication) suggests an Early Jurassic age of 201± 5 Ma.

Ebasco Services, Inc. (1975) conducted a detailed investigation of diabase dikes during construction of the Shearon Harris nuclear power plant. Several of these dikes were observed to be laterally offset 30 cm to 4 m by the Harris fault, a south-dipping normal fault identified during power plant construction.

Ebasco Services, Inc. also conducted a magnetometer survey of a large (50 m wide) dike that crossed the Jonesboro fault. The resulting geologic map suggested 300 m of right-lateral offset of the dike by the Jonesboro fault (Bain and Harvey, 1977). These fault-dike observations are important in that they show Jurassic dikes offset by presumably Triassic faults. If the Early Jurassic age by Hames is correct, then tectonic activity (rifting) clearly continued past the Early Jurassic. The minimum age for this activity is unconstrained.

The only other rocks in the area are Late Cretaceous marine sediments of the Atlantic Coastal Plain that uncomformably overlie the Jonesboro fault. However, no attempts have been made to document fault offset at these locations. Snipes and others (1993) and Stieve and Stephenson (1995) studied a similar Triassic rift basin, the Dunbarton basin, along the South Carolina-Georgia border. The Dunbarton is buried by approximately 200 m of Late Cretaceous and Tertiary Atlantic Coastal Plain sediments. Seismic reflection and borehole data clearly show the basin-bounding normal fault, the Pen Branch fault, was reactivated during the Late Cretaceous and Tertiary as a reverse fault, offsetting the Coastal Plain sediments by as much as 30 m. It is therefore possible that studies could reveal similar late Mesozoic-early Cenozoic tectonic activity along the Jonesboro fault in North Carolina.

SUMMARY

Much of our understanding of the evolution of the eastern North Carolina Piedmont has been gained through the geologic mapping of the western flank of the Raleigh metamorphic belt. Recent geochronologic and geochemical studies provide data needed to test the validity of lithologic correlations established during mapping. In combination, these activities have allowed for the development of a detailed lithologic and structural framework for the region.

This framework is used to evaluate the tectonic history of the eastern Piedmont in a regional time context. In this context, three major stages define this tectonic history: 1) Late Proterozoic to middle Paleozoic development of an Avalonian magmatic arc and its accretion to Laurentia; 2) late Paleozoic metamorphism, faulting, and magmatism during the Alleghanian orogeny; and finally 3) late Paleozoic (?) to early Mesozoic faulting and sedimentary basin development during the continental rifting of Pangea.

The ductile-brittle transition that occurred between stage two and three may be a progressive event reflecting a plate motion change from the transpressional collision of Laurentia and the Carolina zone with Gondwana, to a Pangean transtensional breakup. It may also represent a distinct, very late Paleozoic to early Mesozoic extensional overprint upon a Paleozoic transpressional, structural culmination that was exhumed due to crustal thinning and uplift during rift basin development.

Additional studies are needed to test these hypotheses. Studies are also needed to constrain the absolute ages of terrane components and younger intrusive bodies and to determine the absolute timing of periods of metamorphism and structural deformation, including the development of ductile and brittle faults.

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FIELD STOPS

INTRODUCTION

Ten stops comprise this one-day temporal view of the Late Proterozoic to early Mesozoic tectonic history of the western flank. Stop locations are shown on the regional index map (Figure 2). Individual locations are depicted at the 1:24,000 scale in a reproduction of a portion of the 7.5-minute quadrangle that accompanies each stop description. North is at the top of each inset map.

Because the Raleigh and Henderson 100K sheets include the metropolis of Raleigh, several mapping strategies facilitate data acquisition. A range from rural to highly urbanized settings is traversed to maximize outcrop coverage. In the rural settings, traditional stream and roadside ditch traverses yield the best outcrops, while in urban settings, local and regional construction projects offer an additional window into bedrock geology. Thus, some key localities in urban settings are transient, or have excellent exposures that are out of place, or are in unique sites with respect to anthropogenic impact.

Rocks exposed within the Raleigh Greenways and Umstead State Park, on NCSU and RDU Airport property, and along the CPL Harris Spillway to Shearon Harris Lake will also be evaluated during the field trip. Due to the constraints on specimen collecting in North Carolina parks, no rocks may be removed from Umstead State Park.

Stop 1: Raleigh Gneiss in the Raleigh Terrane - empty lot behind Bojangles' Restaurant, northeast corner of Atlantic Avenue and Six Forks Road, Raleigh.
(Dave Blake and Matt Heller)

This stop lies on the north side of the Bojangles' parking area and consist of variably-sized boulders blasted from the excavation for the adjacent restaurant and convenience store (Figure 7). At the time of this writing, the future of these boulders is uncertain given the unknown plans for future urban development. This is one of the more transient stops on the field trip.
In the advent this stop disappears, proceed to Pigeon House Branch, which drains parallel to Capital Boulevard just north of downtown Raleigh. Particularly good exposures lie adjacent to the Raleigh Bonded Warehouse on the west side of Capital Boulevard and in the back lot of Harris Wholesale on the east side of Capital Boulevard. Both exposures are located between Fairview Road and Wake Forest Road offramps from Capital Boulevard 2 km southwest of Stop 1. Outcrops occur along the Raleigh Greenway to the north-south-oriented creek draining from Glenwood Road to Our Lady of Lourdes Church on Crabtree Creek, between Anderson Drive and Whitaker Mill Road. Both sites are in the Raleigh West quadrangle.

The rocks here are the Raleigh Gneiss, the dominant Raleigh terrane unit southwest of the Rolesville batholith. These fresh boulders characterize the

Figure 7. Location of Stop 1 in the Raleigh East 7.5-minute quadrangle.

lithologic, metamorphic, and structural variability of the unit (Figure 8). Typically, the Raleigh Gneiss contains medium- to coarse-grained, very well layered and locally migmatitic orthogneisses that experienced amphibolite facies metamorphism and variably partitioned strain.

The orthogneiss has gabbroic to granitic protoliths. They include melanocratic to mesocratic hornblende gneiss to hornblendite, amphibolite, and coarse-grained biotite schist, and more mesocratic to leucocratic biotite ± hornblende gneiss. The interlayers are typically discontinuous on the scale of meters and are cm to meters thick. Within the layers, hornblende and biotite are joined by variable amounts of granoblastic andesine, microcline, and quartz. Clinopyroxene, scapolite, calcite, apatite, titanite, garnet, white mica, and epidote occur locally. Thin layers of epidote lie along compositional contacts. Where hornblende and clinopyroxene share contacts, hornblende is partially or completely surrounded, implying that clinopyroxene crystallized late in the paragenetic sequence.

The Raleigh Gneiss documents a multiphase intrusive and deformational history. A significant attribute of the Bojangles' exposures is the range in metamorphosed intrusive relationships (Figure 8). Commonly, mafic gneiss and schist appear to have formed earlier than more intermediate to felsic gneiss. The mafic rocks form thick layers, or thin selvages along, or enclaves within, more differentiated compositional layers. In some blocks, mafic to felsic layers display semi-concordant, sill-like relationships. More felsic gneiss layers, unfoliated pegmatitic granite, and fine-grained granite to aplite form dikes and veins which truncate sill-like mafic to felsic interlayers. These dikes and veins are related to the Rolesville batholith exposed along the eastern portion of the Raleigh East quadrangle.

These interlayers also display a complex deformational history (Figure 8). Biotite and hornblende form a penetrative gneissosity to schistosity and locally, a nonpenetrative mineral lineation. In nearby outcrops, the foliation dips moderately to steeply west or east and strikes variably to the north-northeast. Felsic layers also develop symmetric to asymmetric boudinage and pinch-and-swell structures, and locally feldspar augen. A complex assemblage of single layer and multilayer folds and refolds are also preserved. Hinge zones have wavelengths and amplitudes from mm to tens of cm and fold style varies from open to isoclinal. Late-stage pegmatitic granite dikes at a high angle to gneissosity are buckled into ptygmatic folds. Others occupy brittle extension fractures. Some gneissic layers show mm to cm offsets along brittle faults.

Stop 2: Falls Leucogneiss, Nutbush Creek fault in the Raleigh terrane - service road behind Harris Teeter Supermarket, Glenwood Village Shopping Center, Glenwood Avenue at Oberlin Road, Raleigh.
(Dave Blake and Matt Heller)

Relatively fresh to variably weathered rock exemplifies this Falls Leucogneiss exposure along the service road behind the Harris Teeter supermarket in the Glenwood Village shopping center (Figure 9). Fresh boulders of leucogneiss also line the highway divide on Centennial Boulevard between Lake Wheeler and Avent Ferry Roads on the northeast side of the NCSU Centennial Campus. Because of the automobile and truck traffic, care must be taken when evaluating these stops.

The Harris Teeter outcrop is a fine- to medium-grained, light pinkish-gray, leucogranitic orthogneiss containing a penetrative stretch lineation of microcline, plagioclase, quartz, magnetite, and biotite. On surfaces perpendicular to the lineation, the orthogneiss has a recrystallized granitic structure; on surfaces parallel to the lineation, the orthogneiss is an L>S-tectonite (L=Linear>S=Planar). Pencil structure weathered parts, marking the lineation (Figure 10). Millimeter-scale layering of granoblastic magnetite and biotite versus felsic minerals highlights a weakly

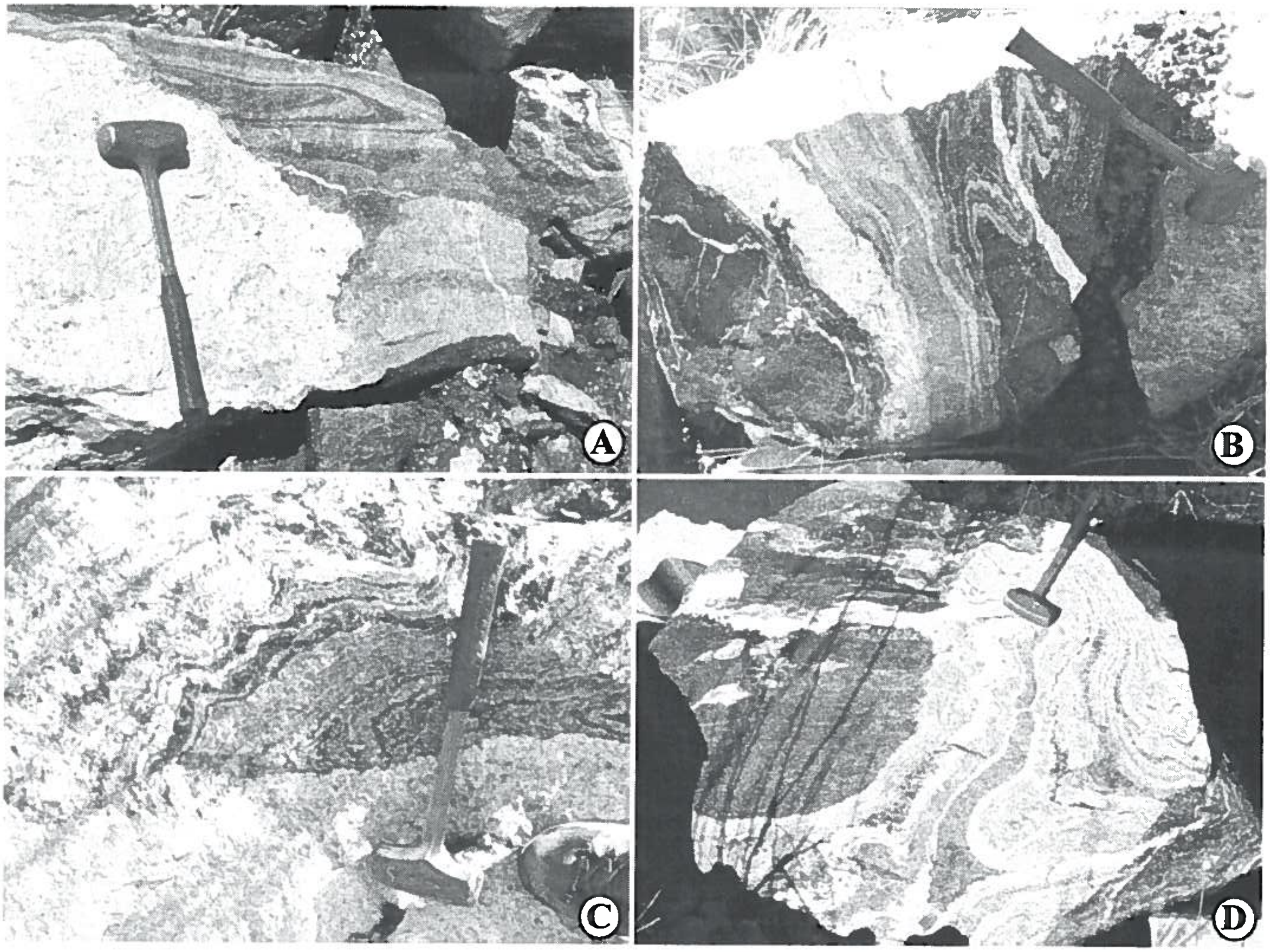

Figure 8. Examples of the variety of intrusive relationships, both metamorphosed and unmetamorphosed, and structural fabric development in the Raleigh Gneiss. (a) Isoclinal fold in mafic to intermediate orthogneiss crosscut by undeformed pegmatitic granite dike; (b) sequence of crosscutting relationships of mafic to felsic orthogneiss to granite; (c) multilayer folds of mafic/intermediate selvages and metagranitoid dikes crosscut by medium-grained granite; (d). Tight fold of orthogneiss layers. Biotite-hornblende gneiss locally develops a mineral lineation along gneissic layering. Hammer is approximately 41 cm long for scale in all views.

developed, subvertically-oriented gneissosity. Because of magnetite (identified by its attraction of a hand magnet), the Falls Leucogneiss produces a prominent positive magnetic anomaly on regional magnetic maps.

The stretch lineation trend in the leucogneiss averages between N15-20°E and plunges subhorizontally. The gneissosity typically strikes N15-20°E and dips subvertically to steeply east-southeast. Folding and ductile shear bands are not typically observed due to its granitic protolith texture and a lack of gneissosity. Late-stage, subvertically-oriented fractures striking perpendicular to the stretch lineation are another deformational element. Ductile strain in the leucogneiss is attributed to dextral strike-slip faulting along the Nutbush Creek fault. The Falls Leucogneiss is a marker unit when mapping this structure.

During the construction of Centennial Boulevard, Falls Leucogneiss boulders were placed in the highway divide. These large ornamental boulders are fresh to slightly weathered leucogneiss, lineated amphibolite, and layered mafic and felsic gneiss similar to the Raleigh Gneiss. Well lineated amphibolite bound several large boulders of leucogneiss. Other boulders display meter long and several cm wide, connected and

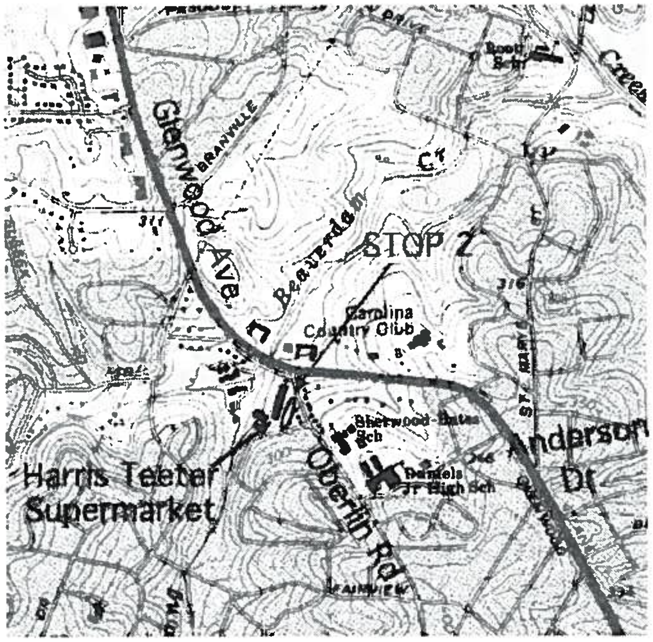

Figure 9. Location of Stop 2 in the Raleigh West 7.5-minute quadrangle.

Figure 10. Falls Leucogneiss behind the Harris Teeter showing the weathered pencil structure, and outcrop shape developed by the penetrative subhorizontal stretch lineation, L_s, and the thin sheeting produced by the subvertical gneissosity in this L>S tectonite. Hammer is approximately 41 cm long for scale. View to the southeast.

isolated apophyses, dikelets, and boudins of leucogneiss invading the amphibolite and layered gneiss (Figure 11). In pavement outcrops just to the south of the drive, lineated amphibolite occurs as enclaves within the leucogneiss. These relationships suggest that the leucogneiss is intrusive into the mafic rocks. They are compatible with the interpretations of Robitaille (2000) in the Tar River area where the Falls Leucogneiss appears to be a member of the Raleigh Gneiss.

Stop 3: Southwest Prong Gneiss, Nutbush Creek fault in the Crabtree terrane - Raleigh Greenway and bridge culvert, Brooks Avenue and Southwest Prong of Beaverdam Creek, Raleigh.

(Dave Blake and Matt Heller)

The next two stops display lithologic, protolith, and structural variations in the Crabtree terrane. This exposure is located at the Brooks Avenue bridge culvert beneath the private walkbridge across the Southwest Prong of Beaverdam Creek (Figure 12). Access to the outcrop is gained either by traversing the creek side slope from the adjacent Raleigh Greenway Park, or walking down the rock steps in the adjacent housing lot. At the time of this writing, this lawn lot is being sold. Communication with the new landowners will be required for future access by the rock steps.

The Southwest Prong Gneiss is an informal lithodemic name for fine-grained, white mica fesic gneiss that is characteristic mapping unit of the Crabtree ter rane (Wylie, 1984; Blake, 1986; Horton and others, a 1994; Heller, 1996). Abundant stream pavement and waterfall outcrops occur in the Lake Wheeler quadrangle northward to the Grissom quadrangle. Its outcrop pattern joins with white mica quartzitic schist, graphite schist, and biotite hornblende gneiss to delineate the Raleigh antiform.

Most outcrops including this stop on the eastern limb of the Raleigh antiform expose a very leucocratic, light gray to pinkish white to tan, fine-grained felsic gneiss containing white mica, quartz, microcline, plagioclase, biotite, opaque minerals, and locally sphene and apatite. Thin biotite layers can contain elongate, xenoblastic garnet porphyroblasts up to several mm. Locally, felsic gneiss on the western limb shows an increase in percent white mica and small porphyroclasts of plagioclase (Farrar, 1985a; Stoddard and others, 1991).

White mica, biotite, and opaque minerals join with a felsic matrix to from a gneissic structure. A fine,

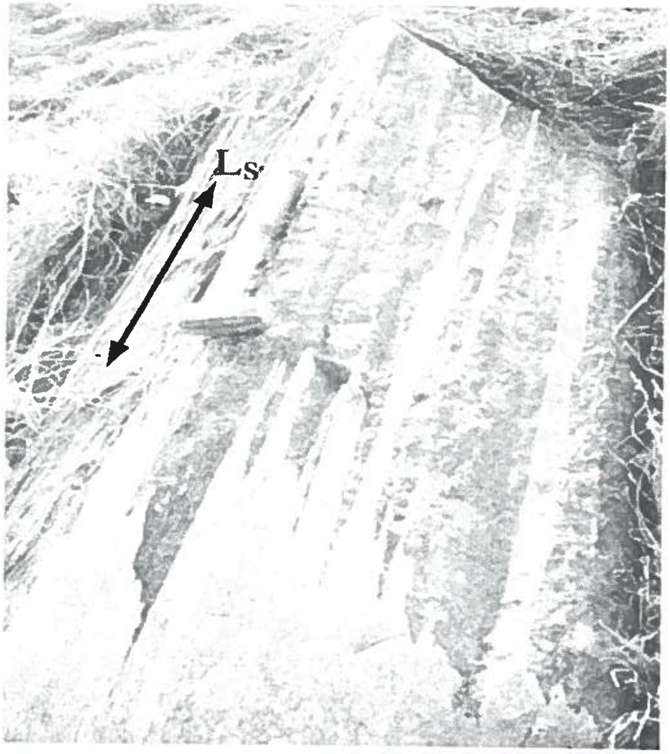

Figure 11. Falls Leucogneiss boulders in the highway divide of Centennial Drive. Dikes and apophyses of leucogneiss are oriented parallel to the penetrative lineation, L_s, and gneissosity in Raleigh Gneiss amphibolite. Hammer is approximately 41 cm long for scale. View to the west.

Figure 12. Location of Stop 3 in the Raleigh West 7.5-minute quadrangle.

granoblastic texture results from dynamic recrystallization, and locally quartz ribbons are preserved. The gneissosity is subvertical to steeply east-dipping at this stop. On the west limb of the antiform, it is more shallowly west dipping.

A subhorizontal stretch lineation of mica and felsic minerals is characteristic of the unit. It is especially well developed in outcrops adjacent to the Falls Leucogneiss (Figure 13). Free quartz forms larger boudinaged veins having maximum vein separation in the lineation direction. Some quartz veins are northwest-oriented tension gashes oblique to and in some sets, perpendicular to the lineation. Locally, these gashes crosscut upright, open to tight folds of the gneissosity.

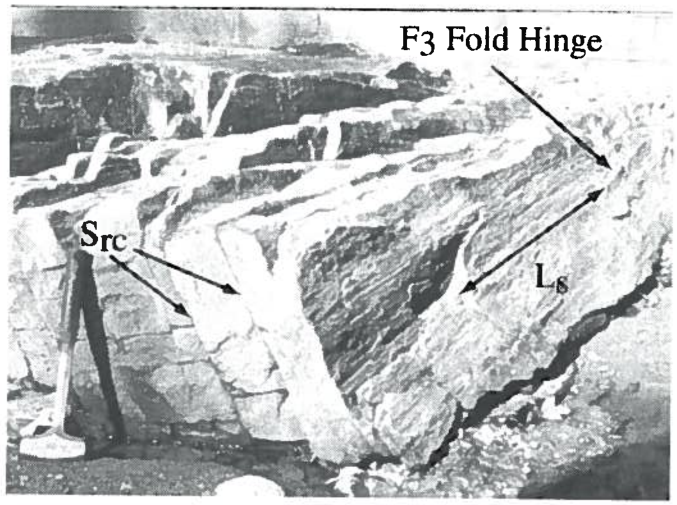

Figure 13. Southwest Prong Gneiss at Stop 3 displaying the penetrative subhorizontal stretch lineation, L_S, and mylonitic gneissosity, S_{rc}, preserved in felsic gneiss. A tension gash of free quartz crosscuts a subhorizontal hinge of a third generation upright, open fold. Hammer is approximately 41 cm long for scale. View to the north.

The Southwest Prong Gneiss appears to be a felsic mylonite to ultramylonite derived from mixed felsic volcanic and plutonic protoliths. The ability to preserve relict textures may indicate heterogeneous strain partitioning across this unit due to the Nutbush Creek fault. While commonly positioned at the Falls Leucogneiss, the penetrative subhorizontal stretch lineation and mylonitic foliation, in places composite, overprint the eastern and central portions of the Crabtree terrane. More discrete zones form in the western portion of the terrane. In west Raleigh, the Nutbush Creek fault appears to be wider than its typical 1 km thickness mapped to the north near the NC-VA line (Druhan and others, 1994).

Stop 4: Mine Creek and Richland Creek Schists in the Crabtree terrane - upper drainages of Richland Creek at the end of District Drive extension off Blue Ridge Road, Raleigh.

(Dave Blake and Matt Heller)

Be careful at this stop. This exposure is located at the end of the gravel drive leading west from the paved parking lots at the end of District Drive. It lies on agricultural land belonging to NCSU (Figure 14). The outcrop occurs on the north side of the culvert bridge across Richland Creek. The creek banks are quite steep on both sides of the outcrop due to stream incision caused by roadside runoff from Wade Avenue. The graphite and pelitic schist are very slippery and poison ivy is common. The best way to reach the stop is to traverse along the eastern side of the creek to a point where the bank slope shallows and then walk back up creek to the outcrop.

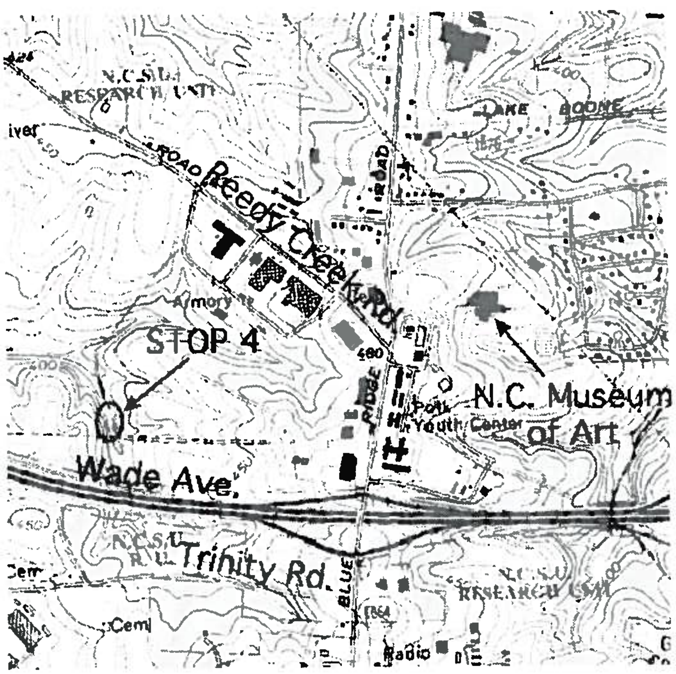

Figure 14. Location of Stop 4 in the Raleigh West 7.5-minute quadrangle.

Stop 4 displays metasedimentary rocks of the Crabtree terrane, which are primarily exposed in its central and western portions. The Mine Creek Schist is an informal name for this distinctive lithodeme composed primarily of graphite schist. Horizons of graphite schist are found within pelitic schist informally referred to as the Richland Creek Schist and within the white mica quartzitic schist to the east (no informal lithodemic name). All three rock types are mappable metasedimentary units of the Crabtree terrane.

The Mine Creek Schist is important because it was an economic resource for the area, being mined for its graphite content in the middle to late 19th and early 20th centuries (1840's to 1906, A. C. Barefoot, personal communication). Just west of Ridge Road between Ocotea Drive and Hampton Road, Mr. Barefoot excavated one of the adits to a graphite mine in 1991 (Figure 15).

Although a large tailings pile of graphite occurs in his backyard, Mr. Barefoot was not aware of any intact mine workings. After the construction of an adjacent new house, a large rainstorm opened a small sinkhole in Mr. Barefoot's yard at the horizontal opening to the mine. Mr. Barefoot excavated the opening, pumped ground water from the adit, and conducted a reconnaissance of the mine workings. Formerly a Professor of Forestry at NCSU, Mr. Barefoot obtained a wood sample from one of the timbers bracing the adit at a working face. The timber sample yields an 1867 ^{14}C date (A. C. Barefoot, personal communication). The adit has subsequently been sealed. Two other smaller pits occur within the same horizon approximately 0.5 and 7 km north of the mine.

The Mine Creek Schist is also important because it is a distinctive marker unit for mapping the Crabtree terrane and determining its metamorphic grade and structural history, and because its origin places constraints on the sedimentary depositional environment for its protoliths (Lumpkin and others, 1994).

Surrounding Stop 4, the Richland Creek Schist is the dominant rock. It is a homogeneous, medium- to coarse-grained, biotite and white mica schist bearing garnet and staurolite. Graphite schist interlayers with the pelitic schist. Twelve separate horizons are mapped and a number of other thin, unmappable horizons exist (Blake, 2000). The number of potential horizons is unknown and only the largest are mapped with confidence. Most exposures are transient, beingexposed during local construction. This interlayering and stratigraphic, petrographic, and carbon isotopic studies of Lumpkin and others (1994) suggest that the original carbonaceous material was biologically produced. This organic matter is likely algal in origin, perhaps derived in a back-arc basin environment.

At this stop, the Mine Creek Schist layers are small cm to meter thick horizons and several large, tens of meters thick horizons. White mica, biotite, quartz, staurolite, garnet, and graphite comprise the

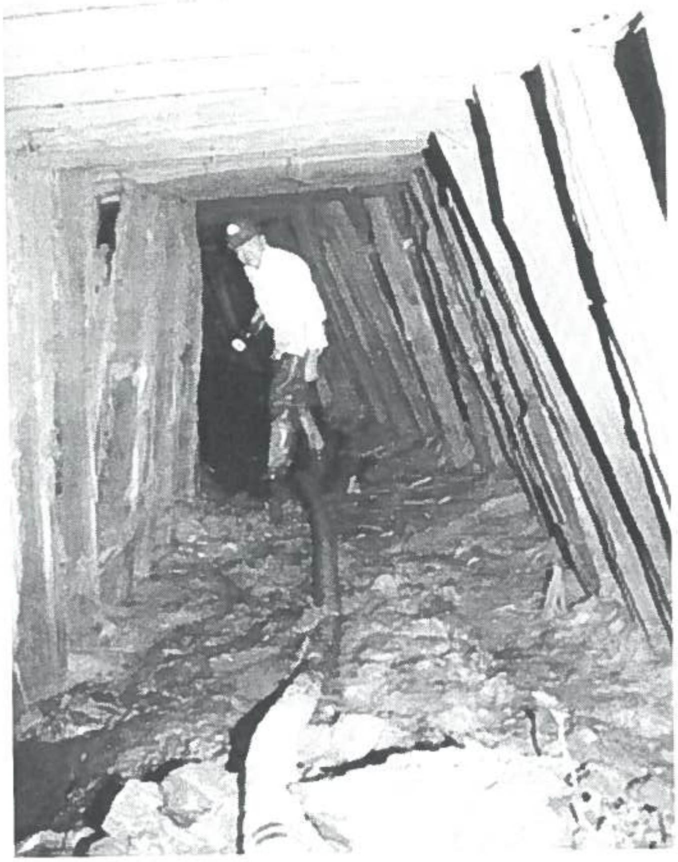

Figure 15. Northeast-oriented view of the graphite schist mine adit. Mr. A. C. Barefoot is working a hoseline during the withdrawal of ground water from the mine prior to reconnaissance of the support beams. Mr. Barefoot provided the photograph.

graphite schist. The graphite content varies among layers. In these layers, and those exposed along Ridge Road and House Creek in the quartzitic white mica schist, graphite is a dominant mineral, forming up to 40% by weight percent (which corresponds to a slightly higher modal percent because of the low specific gravity of graphite; Stoddard and Blake, 1994). Kyanite occurs locally in graphite schist farther to the east. Garnet forms 2-4 mm diameter lumps or rinds of iron oxide partially replacing or psuedomorphing relict porphyroblasts. Small honey brown staurolite prisms are less than 1 mm long.

Graphite and white mica form a schistosity to phyllitic structure, and mm-scale graphite-rich and -poor lenses define a weak compositional layering. An upright open fold of Mine Creek Schist defines the geometry here. Its hinge zone trends S20°W and plunges subhorizontally and is the same as a crenulation lineation of the schistosity (Figure 16). The mesoscale fold and crenulation mimics the geometry of open folds observed across the Crabtree terrane including the Raleigh antiform. The foliation and the fold overprint are Alleghanian fabric elements.

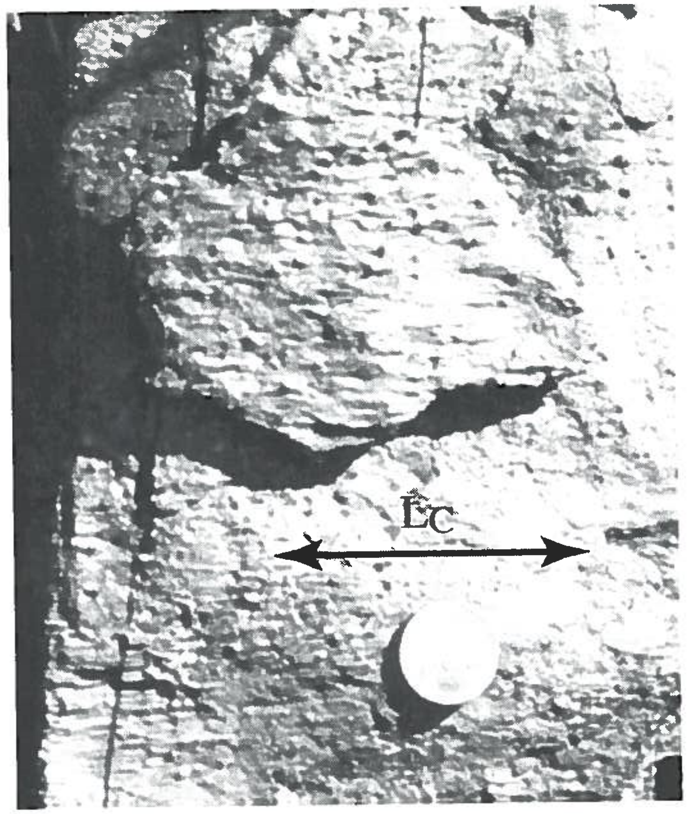

Figure 16. Hand sample of penetrative crenulation lineation overprinting the white mica and graphite schistosity at Stop 4. The subhorizontal crenulation mimics the orientation of the upright open fold of graphite schist at this stop. U.S. penny for scale.

Stop 5: Umstead Meta-Intrusive Suite in the Carolina terrane - hairpin bend of Crabtree Creek in Umstead State Park west of Ebenezer Church Road, Raleigh.

(Dave Blake)

Mesoscale contact relationships of the Umstead meta-intrusive suite and Turkey Creek Amphibolite wall rocks are well exposed at this stop. Steep hillside outcrops and exposures along an intermittent stream to Crabtree Creek lie approximately 0.75 km west of Ebenezer Church Road (Figure 17). Park for the stop on the east side of the road between Crabtree Creek and Turkey Creek at the beginning of an Umstead State Park horse trail.

Figure 17. Location of Stop 5 in the Cary 7.5-minute quadrangle.

Follow the horse trail to a small concrete bridge across Sycamore Creek and then uphill for approximately 0.5 km to a horse trail marker on the left side of the trail blazed with a red circle. Turn left or south from the trail and follow the deeply incised stream downhill for approximately 0.25 km until it joins with Crabtree Creek. Rock exposures are located just before the stream mouth and on the right or northwest side of this stream in the steep hillside to Crabtree Creek.

Melanocratic to leucocratic, fine- to medium-grained metagabbro and weakly foliated to unfoliated and weakly metamorphosed granitoids highlight the Umstead meta-intrusive suite. The metagranitoids crosscut the metagabbro in the stream and contain enclaves of the Turkey Creek Amphibolite wall rock in the hillside. Both outcrops display a complex mixture of veins, dikelets, and larger dikes or bodies on the order of mm to several meters of at least four facies of metagranitoids including diorite, trondhjemite, granodiorite, and granite (Figure 18). Many hillsides in eastern Umstead State Park expose mafic to felsic boulders or bear numerous small waterfall and pavement outcrops displaying these relationships.

Regionally, the Turkey Creek Amphibolite contains mesocratic to melanocratic, fine- to coarse-grained amphibolite and melanocratic biotite schist. As a whole, the mineral assemblage of the unit includes hornblende, andesine, biotite, chlorite, epidote or clinozoisite, sphene, quartz, and minor calcite, rutile, and opaque minerals having a crystalloblastic texture. Amphibole composition is dependent on bulk rock composition and metamorphic grade, with actinolite and blue-green hornblende indicating upper greenschist to lower amphibolite facies metamorphism.

Figure 18. Series of boulders on Crabtree Creek in which dikes and dikelets of the Umstead meta-intrusive suite crosscut and include the Turkey Creek Amphibolite as enclaves. At least four facies of metagranitoids are represented. Hammer is approximately 41 cm long for scale. View to the north.

Fine-grained amphibolite is inferred to be metabasalt. Biotite schist has a mesocratic color index and may be metamorphosed mafic dacite, recrystallized, fine-grained diorite, and/or metasedimentary layers derived from local source rocks. In both rock types, large saussuritized plagioclase porphyroclasts are relict phenocrysts in extrusive or intrusive protoliths. Most outcrops are moderately to strongly foliated. Locally, amphibolite is lineated along discrete zones, on its east side adjacent to the Leesville fault, and along its contact with the metamorphosed Reedy Creek Granodiorite. There, deformed amphibolite and metagranodiorite to mylonite are complexly interlayered and the contact is inferred to be a ductile normal fault based upon kinematic indicators.

Medium-grained amphibolite is transitional into recrystallized metagabbro or hornblende-biotite metadiorite of the Umstead suite. Relict phaneritic textures and crosscutting dikes indicate this relationship. Large metagabbro blocks are also enclaves within metagranitoid bodies. Metagabbro contains hornblende, andesine-oligoclase, epidote, and minor sphene, clinozoisite, biotite, apatite, quartz, and opaque minerals. Hornblende size variations are related to the development of hornblende gneissosity and mineral lineation. Hornblende, which shares relict igneous boundaries with plagioclase, is probably a primary phase in metadiorite. Epidote and clinozoisite partially replace plagioclase.

Locally, metagabbro increases in amphibole content to coarse-grained, chlorite-bearing actinolite rock, formerly pyroxenite. Actinolite is locally cored with fine-grained magnetite while smaller prisms form optically aligned decussate texture indicating pyroxene replacement. Minor minerals include calcic plagioclase, rutile, and clinozoisite. Some coarse-grained, optically continuous amphibole crystals surround plagioclase in a relict ophitic texture. Coarse-grained metapyroxenite has a more massive, relict xenomorphic (cumulate?) texture of hornblende after pyroxene than do finer grained rocks.

Metagranitoids are subdivided into general types based upon mineral assemblages and degree of metamorphism and foliation development. Their medium- to coarse-grained mineral assemblage of plagioclase, quartz, and K-feldspar delineate a facies transition from metamorphosed mesocratic tonalite and quartz diorite to leucocratic quartz monzonite, granodiorite, and granite plutons, dikes, and veins (Figure 19). Fine-grained quartz, and plagioclase or microcline rocks represent transposed trondhjemitic to granitic dikes. Minor minerals include white mica, biotite, hornblende, sphene, clinozoisite or epidote, chlorite, local garnet, and opaque minerals.

In weakly metamorphosed bodies, xenomorphic granular quartz, and variable plagioclase and microcline show grain boundary adjustments due to metamorphism. Plagioclase typically shows some degree of saussuritization and sericitization. Quartz has a crystalloblastic texture of smaller polygonal crystals and is locally porphyritic and blue in color. In strongly deformed and metamorphosed bodies, a finer grained granoblastic texture exists among the felsic minerals; white mica defines a non-penetrative to penetrative schistosity. Other rocks having composite-planar fabrics and sigma-type plagioclase and microcline porphyroclasts are augen protomylonites along faults. Micas also form an oblique northwest to down dip stretch lineation in the faults. These fabrics reflect either the transpressional or extensional deformation superimposed upon the easternmost Carolina terrane.

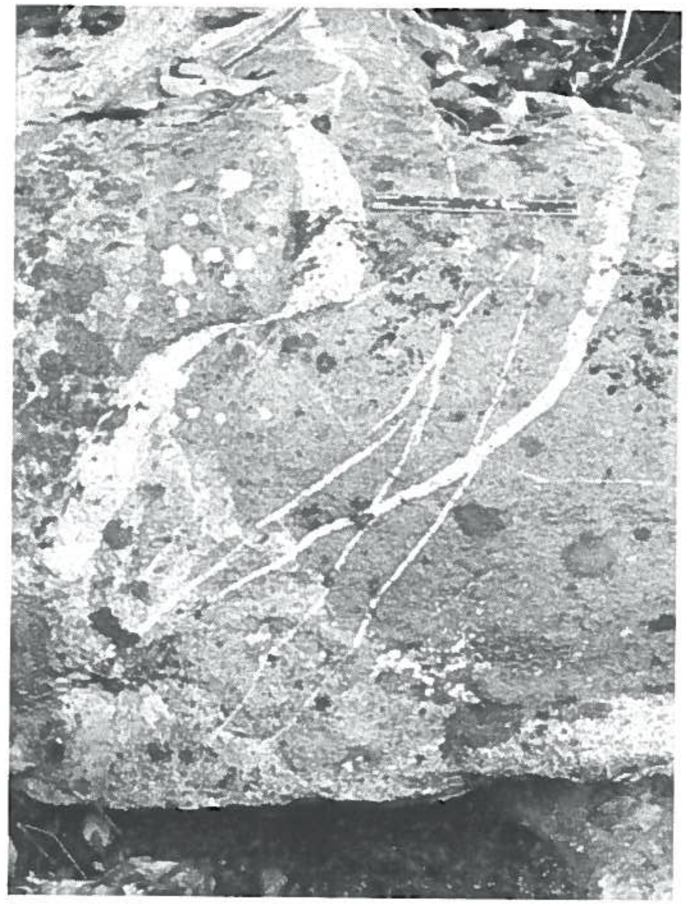

Figure 19. Close-up of the lower boulder of Figure 18 showing four leucocratic metagranitoid facies (lower left) crosscutting melanocratic Turkey Creek Amphibolite (upper right). Ruler is 15 cm long for scale. View to the northeast.

Stop 6: Sycamore Creek Greenstone in the Carolina terrane - path to Crabtree Lake Spillway, Crabtree Creek at Old Reedy Creek Road, Cary.
(Dave Blake)

Please be very careful at this stop! The outcrops are located along a small fishing trail heading south from the parking area on Old Reedy Creek Road along a large meander in Crabtree Creek. The trail traverses very steep banks and rocky ribs on the east side of the creek (Figure 20). A slow hiking pace is required. For those participants who do not wish to take the trail, large boulders line the entrance to and lie on the hill above the Cary Waterworks station across from the parking area.

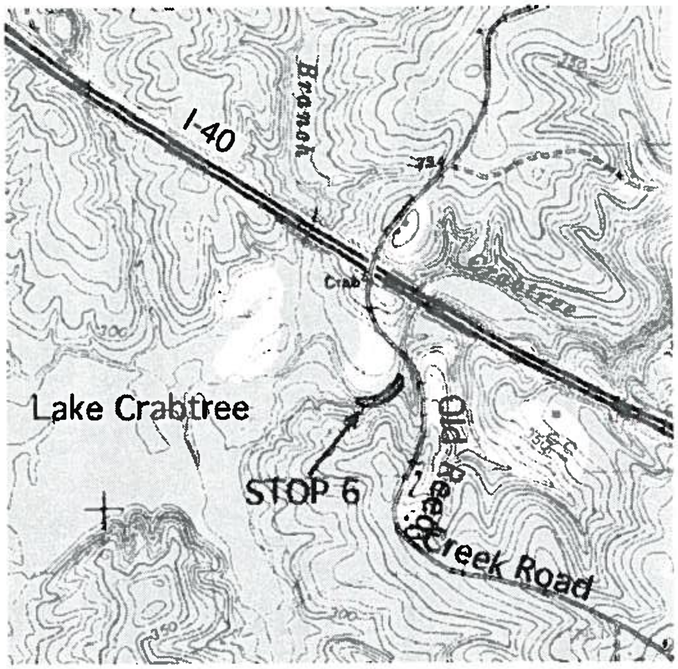

Figure 20. Location of Stop 6 in the Cary 7.5-minute quadrangle.

Throughout Umstead State Park, outcrops of greenstone having variable compositions are exposed as xenoliths in the metamorphosed Reedy Creek Granodiorite and as lithodemic horizons interlayered with either Big Lake-Raven Rock Schist or Coles Branch Phyllite. The unit is named for excellent exposures occurring along Sycamore Creek below the dam to and on the banks of Sycamore Lake.

Unfoliated to weakly foliated greenstone and epidosite contain biotite, chlorite, epidote, plagioclase, pale green actinolite, quartz, and opaque minerals including pyrite or magnetite. Locally, greenstone interlayers with biotite-chlorite to quartzitic phyllite to schist, epidote-rich greenstone, plagioclase-actinolite gneiss to actinolite rock and thinly banded quartz-epidote rock. Greenstone may coarsen to a fine-grained amphibolite.

Crystal size generally decreases westward and greenstone is more prevalent adjacent to the Jonesboro fault. Foliated mafic rock occurs along the contact and within the metamorphosed Reedy Creek Granodiorite. Foliation in greenstone xenoliths has the same orientation as the weak foliation in the metagranite. More biotite-chlorite rich-rocks develop a phyllosilicate cleavage and nonpenetrative mineral lineation of actinolite needles. Rod-like felsic domains can help to define a down dip lineation.

There is a variety of textural interlayering among the rocks lumped as the Sycamore Creek Greenstone. While the mineral assemblage indicates a mafic bulk composition for most outcrops in the unit, it is inferred from the relict textural relationships that both volcaniclastic and volcanic protoliths exist. The unit also preserves a variety of textures that are difficult to interpret and many are related to overprinting by greenschist facies metamorphism and transpressional to extensional deformation.

Relict sedimentary textures represent interlayered conglomeratic, graywacke, and mudstone horizons in a developing intra-arc basin. Crystal size differences are transposed compositional layers that may reflect original grain size distribution in sedimentary rocks. Elliptical mixtures of epidote, chlorite, actinolite, and small, subidioblastic garnet in a biotite-chlorite schist matrix may be relict clasts. In some localities, variably sized, rounded to angular lumps of epidosite in a finer-grained matrix that grades into biotite-chlorite greenstone are of uncertain origin.

Relict volcanic textures indicate the existence of interlayered basalt. White lumps of recrystallized plagioclase in fine-grained mafic matrix are inferred to reflect a relict phyric texture. Rounded domains in finer-grained mafic matrix may be recrystallized basaltic amygdules. Some epidote bleb clusters have straight boundaries and are inferred to be relict phenocrysts of either plagioclase or pyroxene.

Locally, coarse, angular domains of epidote suggestive of some form of relict phaneritic texture lie in a chlorite matrix. Relict phaneritic texture also includes saussauritized plagioclase having interstitial actinolite needles. Larger actinolite crystals have dustings of opaque minerals and partially preserve the shape of former pyroxene. They are surrounded by recrystallized plagioclase. These metagabbroic rocks are inferred to be transposed dikes that may be feeding flows. Tabular fine-grained biotite schist cross cutting felsic rocks of the Big Lake-Raven Rock Schist and Coles Branch Phyllite are metamorphosed basaltic dikes that may also be feeders for the flows. Rare actinolite rock is inferred to be metamorphosed pyroxenite. Its setting in the greenstone is unclear, but may reflect some form of relict magmatic differentiation in a larger volcanic-plutonic complex.

Greenschist facies metamorphism to the biotite zone overprints all protoliths. The timing of the epidozation is not clear. Large subidioblastic amphibole prisms that overgrow a finer-grained, foliated matrix may reflect two pulses of metamorphism. Locally, the blue-green hornblende may reflect growth during an increase in metamorphism to amphibolite facies. Local garnet may either reflect a grade increase or a compositional control on its stability. Although separated by the metamorphosed Reedy Creek Granodiorite and a ductile normal fault, the Sycamore Lake Greenstone may be the greenschist facies equivalent of the lower amphibolite facies Turkey Creek Amphibolite.

Stop 7: Big Lake-Raven Rock Schist in the Carolina terrane - Crabtree Creek in Umstead State Park east of Old Reedy Creek Road, Cary.
(Dave Blake)

Again, care must be taken at this stop due to the cliff-like outcrops. Park at the chain link fence on the east side of Old Reedy Creek Road approximately 0.3 km north of the I-40 overpass. Follow the dirt road east to a small lake and a foot trail across its earthen dam. Bear left along the dam and follow the trail up and over the hill strewn with quartz boulders. Cross over the incised intermittent stream. A large white arrow for aerial photography marks the trail location on the opposite side of this stream. Follow the foot trail north along the bluff and then walk downhill to the trail along Crabtree Creek. Two large cliff outcrops expose the Big Lake-Raven Rock Schist. The northern cliff marks Stop 7 (Figure 21).

In most of the eastern half of the Cary quadrangle, and the central to western portions of the Apex and Fuquay-Varina quadrangles, this felsic schist forms prominent, resistant outcrops in both streams and along hillside slopes. One of the type localities for the schist is located at the end of the spillway to Big Lake in Umstead State Park and in the hillsides and stream bottoms of two north-south tributaries to the spillway. The unit is also well exposed in the western end of the Wake Stone's Triangle quarry. It is traced south for approximately 60 km to its second type locality at Raven Rock State Park where it forms bluffs on the Cape Fear River.

Lumps of blue colored quartz and white to salmon colored plagioclase that range up to 6 mm in diameter typify this fine- to medium-grained, leucocratic schist. Both quartz and plagioclase have relict xenomorphic rounded shapes (Figure 22). Local horizons may

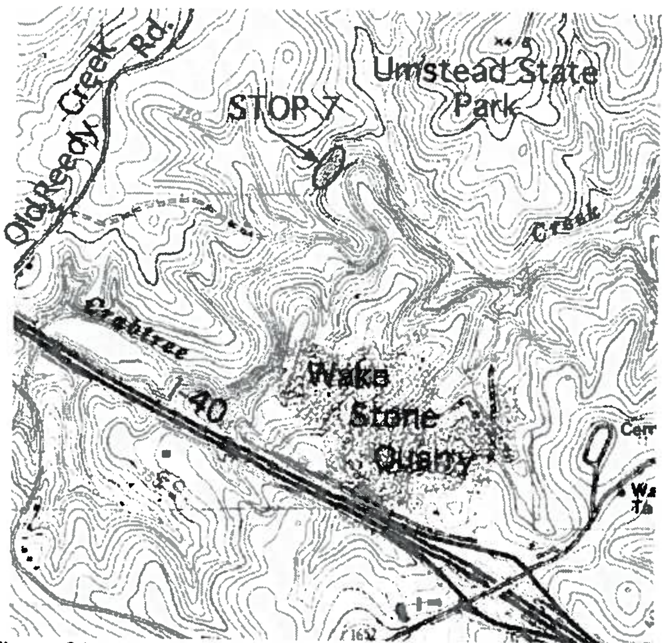

Figure 21. Location of Stop 7 in the Cary 7.5-minute quadrangle.

contain only relict plagioclase. Plagioclase crystals commonly are saussauritized. A white mica schistosity set in a granoblastic felsic matrix wraps around the larger relict phenocrysts. Some outcrops are more quartzitic. White mica, recrystallized felsic minerals, and locally chlorite or biotite also form a down dip-plunging mineral aggregate lineation. Sphere and pyrite occur locally. Magnetite, locally as octahedra and epidote are common accessory minerals.

At this stop and many others in the schist, small light- to dark-colored clasts are preserved. They have a finer felsic crystal size than the host matrix. Some

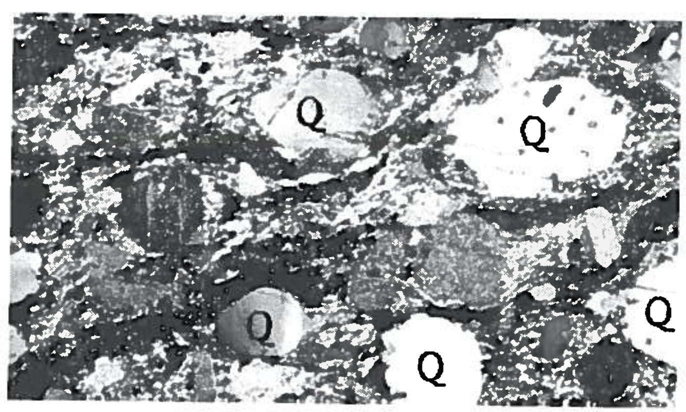

Figure 22. Photomicrograph of metamorphosed plagioclase- and quartz-rich dacitic crystal tuff of the Big Lake-Raven Rock Schist. Relict quartz phenocrysts are marked with the letter Q. White mica defines the schistosity. Plagioclase is unmarked. Field of view is 1 cm.

clasts are preserved as phyllitic films of white mica while others are recrystallized leucocratic gneiss. Clast horizons can include both chlorite and biotite. Clasts are flattened and elongate in the down dip direction and lie parallel to a stretch lineation. In the upper parts of the unit in contact with Coles Branch Phyllite, horizons of angular to rounded felsic gneiss and greenstone clasts are preserved. Some clasts range up to 30 cm in length, but most are less than 3 cm long (Figure 23).

Outcrops of fine-grained white mica gneiss are inferred to be metamorphosed dikes from the Reedy Creek Granodiorite. Fine-grained mafic biotite schist, which locally crosscuts the schist, are metamorphosed basaltic dikes. Horizons of Sycamore Lake Greenstone represent interlayered basaltic flows or volcaniclastic sedimentary rock derived from a local source. The fine-grain size and biotite zone assemblages place the schist and interlayered greenstone in the middle to upper greenschist facies of metamorphism.

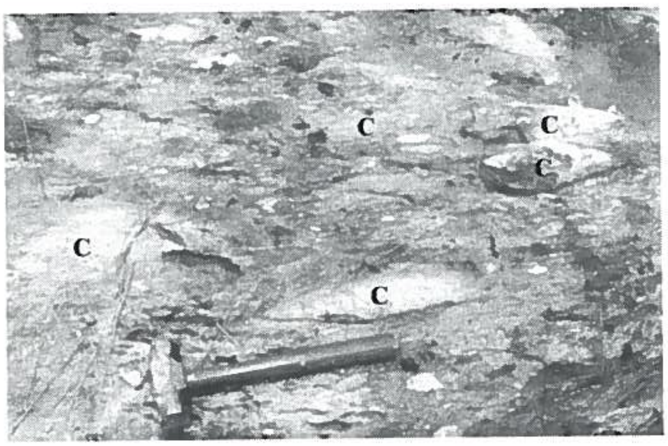

Figure 23. Metavolcaniclastic conglomerate horizon in the Big Lake-Raven Rock Schist. Flattened polymictic clasts include felsic schist and gneiss, and greenstone. The largest clasts labeled C are up to 30 cm long. Schistosity strikes left to right across this northwest-oriented view. Hammer is approximately 36 cm long for scale.

Based upon relict textures and its bulk composition, the Big Lake-Raven Rock Schist is inferred to be metamorphosed dacitic to rhyolitic ash fall or ash flow tuff. Variations within and alternating horizons of crystals-rich and clast-rich schist are probably a record of more than one pyroclastic event. Individual horizons are lithic tuff, lithic crystal tuff, crystal tuff, and vitric tuff. Local phyllite horizons may represent recrystallized ash tuff or reworked tuff deposited as volcaniclastic sedimentary rock. At the western end of the Triangle quarry, Goldberg (1994) obtained discordant $^{207}Pb/^{206}Pb$ ages of 573, 574 and 579 Ma and an upper intercept age of 575±12 Ma on zircon fractions from the schist which are interpreted as the time of meta-tuff crystallization. The dates are compatible with the Late Proterozoic to Early Cambrian age interpreted for the Carolina terrane in general.

Stop 8: Polymictic Conglomerate of the Durham basin - Haley's Branch west of Old Reedy Creek Road, Cary.

(Tyler Clark and Dave Blake)

From the parking area at Stop 7, return down Old Reedy Creek Road to Westin Parkway and Harrison Avenue, and turn west on I-40 (Figure 24). Exit I-40 at Aviation Parkway, turn right, and follow the signs to Park and Ride 3. Park just past the parking lot on the east side of the road. Follow the chain link fence east to Haleys Branch. The first cutbank outcrop is immediately behind Park and Ride 3 on the west side of the creek; the second cutbank outcrop is downstream on the east side of the creek.

This stop views some of the coarsest-grained boulder conglomerate in the Late Triassic Deep River rift basin. The basin developed into a half-graben, its eastern border marked by the Jonesboro fault, a west-dipping, high-angle brittle normal fault. Progressive movement along the Jonesboro fault created a significant topographic gradient, perhaps several thousand meters, between the basin and crystalline rocks of the western flank.

This gradient allowed for development of large alluvial fan complexes that prograded westward into deepening basin depocenters, rapidly burying fluvial and lacustrine sediments already deposited there. One such alluvial fan complex is centered near the present location of the Raleigh-Durham airport (Hoffman and Gallagher, 1989; Clark, 1998). This stop is mapped as part of the Trcc lithofacies of Lithofacies Association III (Clark, 1998). Detailed unit descriptions are provided in Clark and others, this guidebook, fieldtrip #2.

The units at this stop are mostly reddish-brown, massive and chaotically bedded, cobble to boulder conglomerate, having a very coarse-grained to gravelly sandstone matrix (Figure 25). The sandstone also occurs as small beds and lenses. Crude imbrication of clasts is locally preserved. Beds are typically several meters thick, and sandstone interbeds and lenses are between 10-50 cm thick. Bedding contacts are scour surfaces, making precise determination of strike and dip difficult. These units are interpreted as debris flow deposits originating from the topographically-higher western flank units to the east.

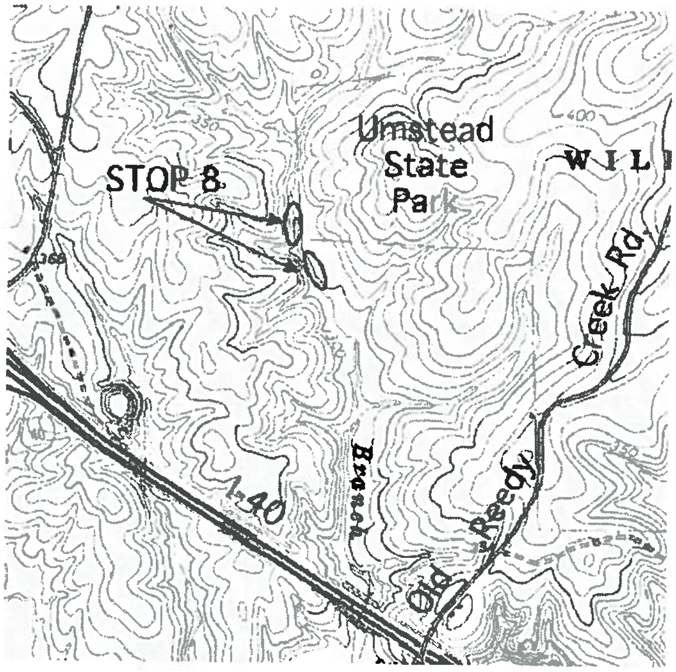

Figure 24. Location of Stop 8 in the Cary 7.5-minute quadrangle

The conglomerate clasts at this stop are the largest identified in the Deep River basin, with several clasts exceeding 2 meters in diameter. Clast size more commonly ranges from 1-30 cm in diameter. Preliminary provenance studies indicate that most of the clasts originated from the Carolina terranes immediately to the east. The majority of these clasts are derived from the Big Lake-Raven Rock Schist and metamorphosed Reedy Creek Granodiorite, with lessor amounts of greenstone and epidosite from the Sycamore Lake Greenstone. Schist and greenstone clasts are typically angular to lenticular, while metagranodiorite is rounded to subrounded. The large, angular clast size and nearby source area support the interpretation that these deposits were laid down in a high-energy, alluvial fan environment.

Stop 9: Silicified Fault Breccia in the Crabtree terrane - steep southwest slope of an unnamed, intermittent drainage to Lake Wheeler between Manor Ridge Drive and Jeffrey Drive, Lake Wheeler 7.5-minute Quadrangle

(Matt Heller and Tyler Clark)

Boulder-sized float blocks of vuggy quartz, cataclasite, and polylithic fault breccia are exposed in a 10-

Figure 25. Boulder-sized polymictic conglomerate along Haleys Branch. The dominant clast lithology is Big Lake-Raven Rock Schist. Imbricated clasts display a southwest dip (to the left) within a red-brown pebbly sandstone matrix. View to the west.

meter wide zone on the southwest slope of an unnamed intermittent drainage to Lake Wheeler. This location is accessed from either Manor Ridge Drive or Jeffrey Drive (Figure 26). Please note that this location is on private property. Permission to visit needs to be obtained in advance from the property owner.

The float blocks observed at this location are exposed along the trend of the Swift Creek fault, the largest of nine macroscale brittle fault and cataclastic zones identified in the Lake Wheeler 7.5-minute quadrangle (Heller, 1996). These brittle fault and cataclastic zones form a reticular network north and south of Swift Creek near Lake Wheeler. They overprint late Paleozoic structures and penetrative fabrics in Late Proterozoic to early Paleozoic crystalline rocks of the Crabtree, Raleigh, and Spring Hope terranes.

The Swift Creek fault is traced for 13 km and trends approximately N70°W. Where it is exposed, the fault has a nearly vertical dip. Inferred horizontal separations of variably dipping crystalline map units across the fault having as much as 410 m of offset were identified during 1:24,000-scale mapping (Heller, 1996). Similar separations are also identified across three nearby west-northwest-trending brittle faults. The pattern of these offsets is consistent with alternating dip-slip displacement, indicative of a graben and horst structure. Slickenline data are not available for these faults and therefore, no resolution of actual dip-slip, strike-slip, or oblique-slip motion is possible. Significant dip-slip displacement is indicated along the Swift Creek fault by the apparent truncation of the Falls Leucogneiss.

Figure 26. Location of Stop 9 in the Lake Wheeler 7.5-minute quadrangle.

In situ exposures along the Swift Creek fault are rare; the fault most commonly occurs as float of vug-rich quartz. Less commonly, float blocks consist of siliceous cataclasite or fault breccia. The western portion of the fault is expressed topographically by parallel steep, discontinuous bluffs having up to 25 m of relief. Topographic expression along the eastern portion of the fault is generally subtle to non-existent.

The polylithic breccia observed at this stop contains up to 40% rock fragments that range from <1 cm to >5 cm in diameter. The fragments are chemically weathered and angular, and they are cemented by massive to crystalline quartz. Locally, the fragments appear to be similar in composition and texture to the Falls Leucogneiss that forms the wall rock along this portion of the fault. Other clasts appear to be felsic metavolcanic rocks of low metamorphic grade. These clasts are not correlative with rocks currently exposed in the area and may represent material displaced along the fault, possibly derived from structurally higher levels of the Crabtree, Carolina, or Spring Hope terranes.

Repeated movement along the Swift Creek fault is suggested by rebrecciated textures in the polylithic breccia, including angular fragments of cemented quartz and fault breccia, and by euhedral quartz crystals within cemented matrix. The latter are interpreted as crystals that formed in vugs, were broken during later displacements, and then incorporated into a newly precipitated anhedral quartz matrix.

Stop 10: Ductile and Brittle Faulting in the Carolina Terrane - Harris Reservoir Spillway off of N.C. 42, Cokesbury 7.5-minute Quadrangle
(Tyler Clark and Dave Blake)

Use extreme caution at this outcrop! Permission should be obtained from Carolina Power and Light's Shearon Harris nuclear power plant prior to visiting this outcrop. Park along N.C. Highway 42 at a small dirt parking lot just south of its intersection with the railroad (Figure 27). A small dirt road marked by a cable barricade leads to the exposure. Walk along the road until it descends to the railroad grade at the spillway. Excellent exposures exist on both the east and west sides of the spillway, however the ledge on the western side is dangerously narrow, prohibiting thorough inspection. Cross the active railroad bridge to the east side of the spillway and descend down the steep slope. Traverse to the exposure along a narrow, 1-2 meter-wide concrete ledge.

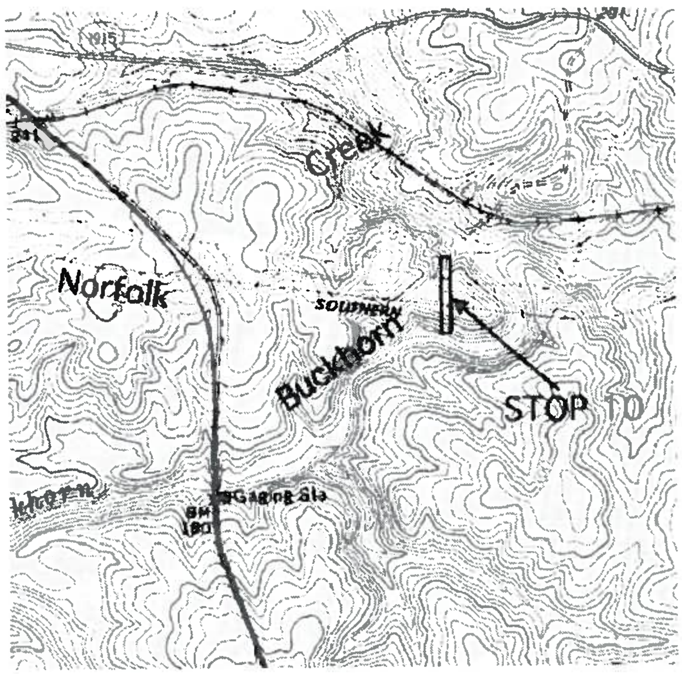

Figure 27. Location of Stop 10 in the Cokesbury 7.5-minute quadrangle.

Construction of the main spillway of Harris Reservoir required blasting through a ridge of metaigneous rocks approximately 1 km southeast of the Jonesboro fault. Butler (1994) grouped these rocks as part of the Buckhorn Dam complex, which contains a mixed assemblage of ultramafic to felsic metaplutonic and mafic and felsic metavolcanic rocks. The complex is one of several large plutonic-volcanic centers of calc- alkaline composition that line the easternmost Carolina terrane adjacent to the Durham basin.

North of the railroad bridge, rocks types range from metamorphosed, fine-grained, foliated, mesocratic, epidote-bearing diorite to foliated to unfoliated, coarse-grained, leucocratic granite. Locally, the granite contains several 2-10 cm diameter enclaves of metadiorite. South of the railroad bridge, at least three episodes of crosscutting intrusive events characterize the complex nature of the exposure.

Both ductile and brittle extensional deformation overprint these rocks. Several faults display a progressive transition from protomylonite to mylonite to ultramylonite along the length of the spillway. These faults range from 2 cm to several meters in thickness and exhibit composite fabric development including individual shear bands and domains of S-C fabric. The fabric indicates a tops-to-the-west or normal displacement sense. Most of these faults strike sub-parallel to the Jonesboro fault and have similar dips to the northwest. The granite typically contains a biotite aggregate stretch lineation and the diorite contains a hornblende mineral lineation, both plunging northwest along shear foliation.

A later brittle deformation overprints the ductile fabrics. Well-preserved slickensided fault surfaces, some with up to 1 cm thick vuggy quartz mineralization clearly offset ductile deformation. The best-developed slickensided fault surfaces occur along the C-surfaces of the ductile faults mentioned above. These faults also strike sub-parallel to the Jonesboro with similar northwest dips. This suggests that brittle faulting was concentrated on the preexisting ductile fault planes. Kinematic indicators such as step-faulting and lunate fractures suggest normal or "tops down" movement. Rare reverse faults are also present.

The main topic for discussion at this stop is the relative age of both the ductile and brittle deformation. While it is obvious that the brittle deformation postdates the ductile deformation, the age span between the two is unclear. Similar fault relationships have been observed at several locations in the western flank recently. At one such locality, preliminary $^{40}Ar/^{39}Ar$ dating of muscovite in the ductile faults indicated a 255±5 Ma (late Permian) age, suggesting continental rifting initiated in the late Paleozoic, rather than the early Mesozoic as is commonly thought.

END OF FIELD TRIP; RETURN TO SHERATON CAPITAL CENTER

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DEPOSITIONAL AND STRUCTURAL FRAMEWORK OF THE DEEP RIVER TRIASSIC BASIN, NORTH CAROLINA

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INTRODUCTION

The Deep River Triassic basin has one of the longest recorded histories of geologic research in North Carolina, starting with the work of Olmsted in 1820. Since that time, numerous investigations have attempted to unravel the complex nature of the basin's geology and mineral resources. As a result, varying methods of geologic mapping and stratigraphic nomenclature are found throughout the published literature. These differences typically manifest themselves by one particular map area using one particular system of stratigraphic nomenclature, with an adjacent map area using a different and incompatible system of nomenclature. Because of these incompatibilities, no basin-wide compilation of the entire Deep River basin has ever been produced using one standard system of map units and stratigraphic nomenclature.

This article highlights recent work to develop a standardized method of mapping that is flexible enough for the wide variety of lithologies and depositional environments encountered throughout the Deep River basin. Smoot and others (1988) proposed a system of uniform map symbols for all of the Mesozoic rift basins along the Atlantic margin of North America. The North Carolina Geological Survey (NCGS) adopted this system during recent geologic mapping in the Durham basin. This system uses map units called *lithofacies*, which can be composed of one to several different rock types (e.g., sandstone, siltstone, and mudstone). Similar *lithofacies* can be grouped together to form a *lithofacies association,* based on both lithology and interpreted depositional environment.

The lithofacies system of mapping differs slightly in organization and definition from the more traditional North American Stratigraphic Code units of *formation, member,* and *bed*. The Deep River basin lacks an abundance of good maker beds or horizons for assigning strata to a specific formation or member. This is primarily due to the gradational nature of lithologic contacts common in rift basin environments. Facies are laterally gradational and the same lithostratigraphic unit can vary from conglomerate to siltstone across the basin. Since the lithofacies system of stratigraphic nomenclature is unfamiliar to many geologists, this article compares and contrasts the various systems of geologic mapping currently used in the Deep River basin.

GENERAL GEOLOGIC SETTING

The Deep River basin, located in the east central Piedmont of North Carolina, resulted from early Mesozoic rifting of the supercontinent Pangea. This rifting created a series of irregularly-shaped half-graben along the Atlantic margin of North America. The Deep River basin is the southern-most exposed of these basins (Fig. 1). During rifting, the basin filled with a variety of Late Triassic clastic sediments, their depositional environments strongly controlled by local basin tectonics. Alluvial fans prograded into the basin from the topographically-higher, faulted margins. Sediment was transported along the basin axis by meandering river systems and deposited in large alluvial plains. Freshwater lakes formed in basin depocenters, accumulating deltaic (delta), lacustrine (lake), and paludal (swamp) deposits.

The deposits of the Deep River basin were buried and lithified, and are now recognized as the Chatham Group, part of the Newark Supergroup (Fig. 1) as defined by Olsen (1978) and Luttrell (1989). The Chatham Group in the Deep River basin consists of varying amounts of conglomerate, sandstone, siltstone, claystone, shale, coal, and small amounts of limestone and chert (and gypsum in cuttings from several wells).

Bedding generally dips east to southeast, but local variations are common, especially near faults and dikes. Thus, the lowermost (oldest) strata typically occur on the western side of the basin and the uppermost (youngest) strata occur on the east.

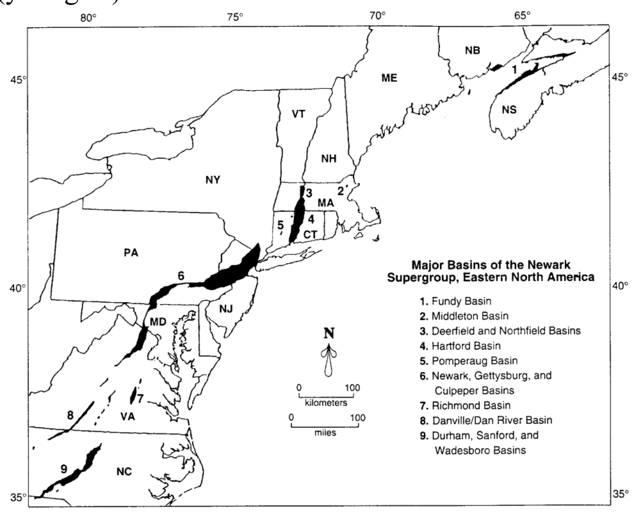


Figure 1. Exposed early Mesozoic basins of the Newark Supergroup. Note the Deep River basin (9) is listed by its three component basins (Durham, Sanford, and Wadesboro). Figure from McDonald (1996), after Unger (1988).

The Deep River basin is a north to northeast trending half graben. It is bordered on the east by the Jonesboro fault, a west-dipping high-angle, normal fault (Campbell and Kimball, 1923) that separates the Triassic sedimentary rocks from the Raleigh metamorphic belt and the Carolina zone metavolcanic and metasedimentary rocks (Fig. 2). The total amount of displacement along the fault is unknown but estimated to be a minimum of 3.0 to 4.5 kilometers of dip-slip displacement, depending on location (Campbell and Kimball, 1923; Reinemund, 1955; Bain and Harvey, 1977; Parker, 1979; Bain and Brown, 1980; Hoffman and Gallagher, 1989). Bain and Brown (1980) suggested that the Jonesboro is actually a fault zone, characterized by step faulting along numerous individual faults, with rider blocks occurring between these faults. Clark (1998) showed that the Jonesboro fault plane itself is extremely sharp, commonly with a 1-3 meter wide gouge zone of clay and foliated breccia in the footwall.

Several intra-basinal faults, both synthetic and antithetic to the Jonesboro, are also recognized throughout the basin (Fig. 2). Along the basin's western margin, sedimentary rocks of the basin unconformably overlie Late Proterozoic and Cambrian metavolcanic and metasedimentary rocks (NCGS, 1985). Minor (post-depositional?) faults also form the basin boundary locally along the western border.

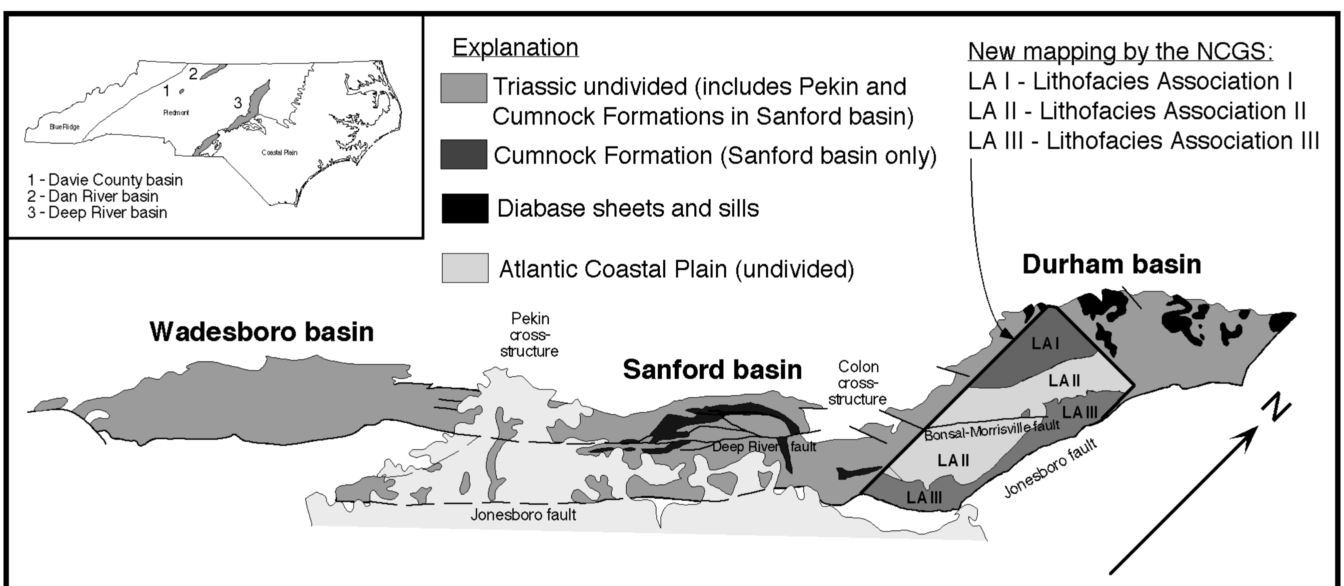


Figure 2. Generalized geologic map of the Deep River basin, NC. Modified from Reinemund (1955), Bain and Harvey (1977), NCGS (1985), Olsen and others (1989, 1991), Hoffman and Gallagher (1989), Clark (1998), and Watson (1998).

The Deep River basin is subdivided into three smaller basins, the Durham, Sanford, and Wadesboro basins, from north to south, respectively (Fig. 2). The boundaries of these smaller, component basins are undefined. The width of the Deep River basin dramatically narrows at the Colon cross-structure (Fig. 2), a basement high that separates the Durham basin from the Sanford basin (Campbell and Kimball, 1923).

The Colon cross-structure is well constrained by field mapping and seismic reflection data. Analyses of these data suggest that it formed by differential subsidence of the Durham and Sanford basins (Reinemund, 1955, Bain and Harvey, 1977, Dittmar, 1979). Slightly different lithologies occur on either side of the Colon cross-structure, suggesting that it may have acted as a barrier to sedimentation. A similar structure, the Pekin cross-structure, has been proposed between the Sanford and Wadesboro basins (Fig. 2). The existence of the Pekin cross-structure is speculative due to a thin veneer of Atlantic Coastal Plain sediments that blankets the area, as well as a lack of good subsurface data.

DEVELOPMENT OF MAP UNITS

A quick perusal of nineteenth and early twentieth century geologic literature in North Carolina reveals that the Deep River basin has received a tremendous amount of attention, second only, perhaps, to the gold deposits of the Carolina slate belt. This interest is attributed to the discovery of coal along the Deep River and the extensive efforts to determine its extent and recoverability. While these early researchers' primary interests were the coal deposits, many other important discoveries, observations, and hypotheses resulted from their investigations. The most noteworthy contributions are by Olmsted (1820, 1824), Emmons (1852,1856), and Wilkes (1858).

Emmons (1852) was the first to recognize and map lithologic units in the Sanford basin. He identified an upper and lower unit of red sandstone and conglomerate separated by a finer-grained unit of gray sandstone, black shale, and coal. Campbell and Kimball (1923) modified Emmons' work and formally named the three units the Pekin, Cumnock, and Sanford Formations, providing type localities for each of the formations (Fig. 3). Although Campbell and Kimball applied these names throughout the Deep River basin, their use today is applied only to the Sanford basin.

Campbell and Kimball (1923) also identified and described type localities of the Jonesboro, Deep River, and Carbonton faults. Although an inadequate understanding of rift basin development flawed many of their conclusions, the work of Campbell and Kimball should be regarded as the first modern foundation in our understanding of the Sanford basin.

Reinemund (1955) built on Campbell and Kimball's stratigraphic framework with the addition of detailed surface mapping and subsurface data from coalmines and exploratory coreholes. The U.S. Bureau of Mines drilled 8 coreholes totaling 11,890 feet into the Cumnock Formation between 1944 and 1948. In addition, Walter Bledsoe and Company drilled 11 coreholes in 1945-1946. This data, combined with observations from the numerous coal mines in the area, greatly increased the understanding of the basin's subsurface.

Reinemund's compilation of this information (1955) includes a thorough mining history of the area as well as technical data on coal quality and mine conditions. In addition to the three-sheet color geologic map of the region, the report presents detailed geologic surface mapping and subsurface mine mapping of the Carolina mine, concentrating on the extent and thickness of coal, faulting, and diabase intrusions. Reinemund also provides detailed discussions of the Pekin, Cumnock, and Sanford Formations and their depositional environments. This all-encompassing compilation still stands today as the most comprehensive report about the Sanford basin. At the time of this writing, copies were still available from both the U.S. Geological Survey and the North Carolina Geological Survey.

Later researchers learned that the three-layer system of formations in the Sanford basin was not present in the Durham or Wadesboro basins. Randazzo and others (1970) did recognize a "coarse-fine-coarse" sequence similar to that of the Sanford basin (Fig. 3), but did not produce any detailed geologic maps depicting the extent of the deposits. No other investigations of the Wadesboro basin have occurred since that time.

In the Durham basin, Bain and Harvey (1977) identified seven mappable "facies" (Fig. 3). These facies were later consolidated into four facies during compilation of the 1985 State Geologic Map (NCGS, 1985). These facies were subsequently replaced entirely during NCGS geologic mapping of the southern and central Durham basin using the Smoot and others (1988) lithofacies system of nomenclature.

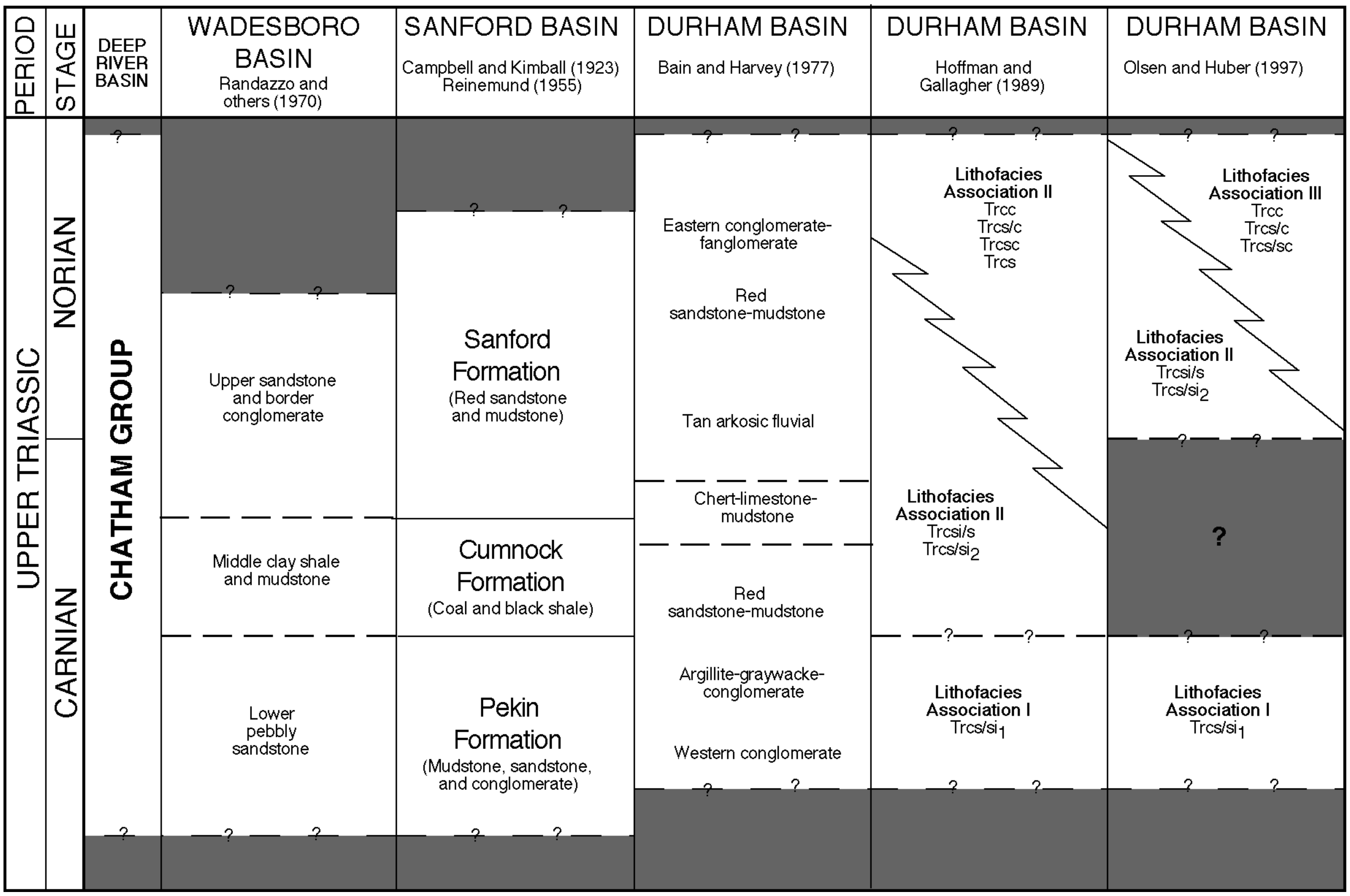


Figure 3. Stratigraphy of the Chatham Group in the Deep River basin of North Carolina and South Carolina. Modified after Olsen and others (1991), Huber and others (1993), Olsen and Huber (1997), and Clark (1998).

In the 1980's, multiple investigators conducted abundant sedimentological and paleontological work in the in the Sanford and Durham basin. Gore (1986) provides a good compilation of these researchers' work along with site-specific details at several locations throughout both basins. Their work refined the depositional framework of the Sanford and Durham basins within the context of the two different systems of stratigraphic nomenclature currently in place. Since none of these investigations included detailed geologic mapping, no new map units were produced.

Hoffman and Gallagher (1989) conducted detailed geologic mapping in the central Durham basin utilizing the lithofacies system of Smoot and others (1988). Further mapping by Clark (1998) and Watson (1998) extended Hoffman and Gallaghers's lithofacies map units from the central Durham basin south to the Colon cross-structure. Here, the lithofacies mapping of Clark (1998) abuts the formation mapping of Reinemund (1955), resulting in an incompatible match of map units. The mapping of Bain and Harvey (1977) is still used in the northern Durham basin since detailed geologic mapping there is not yet underway. Detailed geologic mapping is completely absent from the Wadesboro basin and stratigraphic units are only generally defined (Randazzo and others, 1970).

As a result of these different styles and types of mapping, no basin-wide system of stratigraphic nomenclature exists for the Deep River basin. This work is an attempt to link these systems of stratigraphic nomenclature in the Sanford and Durham basins together through the use of lithologic descriptions, correlation diagrams, and map patterns, all derived from detailed geologic mapping. The stratigraphic units of the Sanford and Durham basin are presented first, followed by a brief summary discussion of the stratigraphic correlation between the two basins.

STRATIGRAPHY OF THE SANFORD BASIN

The three formations currently recognized in the Sanford basin are the Pekin, Cumnock, and Sanford Formations, in ascending stratigraphic order (Fig. 4). The Pekin and Sanford Formations are dominated by fluvial and alluvial fan deposits and the Cumnock Formation is dominated by lacustrine (lake) and paludal (swamp) deposits. These formations grade into one another, and are in part lateral facies equivalents (Gore, 1986). The best descriptions of Pekin, Cumnock, and Sanford Formations are provided by Gore (1986) and are summarized below.

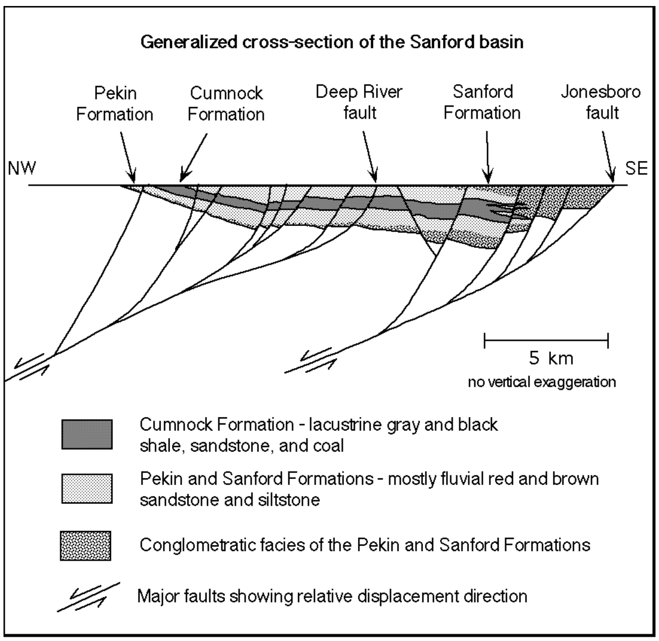


Figure 4. Generalized cross section of the Sanford basin showing the Pekin, Cumnock, and Sanford Formations and the approximate locations of the Jonesboro and Deep River faults. Based largely on seismic profiles and deep drill hole data. Modified from Olsen (1991).

The formations can be traced northeastward towards the Colon cross-structure but the Cumnock grades into coarser-grained sediments very similar to the Pekin and Sanford Formations, and cannot be traced into the Durham basin (Fig. 2). The Cumnock is absent throughout most of the Colon cross-structure, and the contact between the Pekin and Sanford Formations is difficult to position because of their lithologic similarity.

Herein lies one of the failings of the traditional system of formational, stratigraphic nomenclature. The Pekin and Sanford Formations are so lithologically similar, that they cannot be discerned from one another except when the Cumnock Formation is present between them.

Pekin Formation

The Pekin Formation is present along the western border of the Sanford basin and is dominated by red terrigenous clastics. The formation is between 542 to 1240 meters thick, depending on location in the basin. The base of the Pekin contains a distinctive gray, quartz-rich conglomerate, up to 10 m thick, known as the “millstone grit” (Reinemund, 1955). Stagg (1984) determined the “millstone grit” was derived from the Carolina zone to the west. The “millstone grit” is interpreted as an alluvial fan deposit that formed under humid conditions (Textoris and others, 1986). The remainder of the Pekin Formation is dominated by red, brown, and maroon cross-stratified sandstone, siltstone, and mudstone with minor conglomerate and shale, interpreted as fluvial and floodplain deposits (Reinemund, 1955). Wells near the center of the basin (Butler #1 well, V. R. Groce #1 well) show nodular and bedded gypsum associated with light brown to red shales and conglomerates in the lower Pekin Formation, interpreted as playa lake deposits. Near the center of the Pekin Formation in the northern part of the basin near Gulf, gray sandstone, siltstone, and shale are present indicating deposition in a reducing environment, probably in a shallow floodplain lake.

Spectacular plant fossils occur in gray siltstone beds of the Pekin Formation at the Boren Clay Company pit (STOP 1) near Gulf (Hope and Patterson, 1969a; Delevoryas, 1970; Hope, 1970; Hope and Patterson, 1970; Delevoryas and Hope, 1971, 1973; Schultz and Hope, 1973; Hope, 1975, 1977; Gensel, 1986). Several vertebrate fauna, footprints, and trackways have also been described in the area (Baird and Patterson, 1967; Patterson, 1969; Olsen and Galton, 1977; Olsen and others, 1989; Olsen and others, 1991). A reconsideration of these flora and fauna assemblages by Olsen and Huber (1997) suggests an early Tuvalian (early Late Carnian) age for the middle Pekin Formation. They also hypothesized that a syn-rift unconformity exists between the middle Pekin and the upper Pekin, largely based on vertebrate biostratigraphy. A similar syn-rift unconformity is recognized in the Newark, Richmond, Taylorsville, and Fundy basins of the Newark Supergroup and the Argana basin of Morocco (Olsen, 1997).

Cumnock Formation

The Cumnock Formation overlies the Pekin Formation in the middle and northeastern portions of the Sanford basin. The Cumnock is a distinctive unit approximately 230 to 250 m thick, dominated by black and dark gray shale, with associated gray sandstone and coal (Reinemund, 1955). The lower part of the Cumnock is dominated by gray siltstone and fine sandstone with minor shale and claystone. These beds are in part laterally equivalent to the upper Pekin Formation and probably represent a deltaic complex (Gore, 1986; Olsen and Huber, 1997).

Approximately 60 to 80 m above the base of the Cumnock, two major coal seams (and several thinner seams) are present (STOP 2). The lower Gulf coal seam consists of one bed ranging from a few centimeters to nearly 1 m thick. The upper Cumnock coal seam consists of three beds ranging from 1 to 3 m thick. The coal beds are thickest in the northwestern part of the Sanford basin, approximately 5 km northeast and southwest of Gulf (Reinemund, 1955). The coal-bearing interval is overlain by 150 to 155 m of locally calcareous and carbonaceous gray and black shale with minor claystone, siltstone, and sandstone (Reinemund, 1955). The middle Cumnock Formation was deposited in a large, hydrologically-open, quiet-water lacustrine environment (Gore, 1986; Gore 1989). The thick sequence of black lacustrine shale overlying the coal appears to represent a profundal (deep-water) lacustrine environment, apparently uninterrupted by major transgressions and regressions, subaerial exposure, paleosol development, or fluvial deposition (Gore, 1989). The open-basin model is also based on the absence of evaporites in the Cumnock, and the presence of siderite concretions, which form in low-sulfate, freshwater lakes (Gore, 1989).

The upper part of the Cumnock is dominated by gray shale, siltstone and fine sandstone, grading upward into red and brown fluvial deposits of the Sanford Formation. This probably represents a delta or shoreline prograding into the lake from the southeast.

Hu and Textoris (1994) found evidence of sedimentary cycles in wells through the Cumnock Formation, using gamma-ray logs. They interpreted these cycles to be related to astronomically-controlled climate change, corresponding to the Van Houten cycles noted in other Newark Supergroup basins (Olsen, 1996). Astronomically-induced climate changes led to changes in precipitation, which caused the expansion and contraction of a hydrologically-open lake. The climate did not become dry enough, however, to produce red evaporitic subaerial cycles that are found in some of the northern Newark Supergroup basins (Hu and Textoris, 1994). Hu and Textoris (1994) also identified five lithofacies within the Cumnock, interpreted as lacustrine deposits, turbidites, deltaic deposits, paludal or swamp deposits, and basin-margin sands.

Abundant non-marine invertebrate and vertebrate fossils are documented in the Cumnock (Emmons, 1852, 1856, 1860; Baird and Patterson, 1967; Patterson, 1969; Swain and Brown, 1972; Olsen and others, 1982; Gore, 1985a, 1985b). The invertebrates include conchostracans or clam shrimp, ostracodes, and insects. Vertebrates include fish, amphibians, reptiles, dinosaurs, and mammal-like reptiles. Vertebrae, ribs, teeth, and portions of a cranium of the phytosaur *Rutiodon* have been collected from coaly shale in the lower Cumnock Formation. Traverse (1986) and Robbins and Textoris (1986) reported a late Julian (middle Carnian) age based on pollen and spores, but Olsen and Huber (1997) reassigned the Cumnock (and uppermost Pekin) as late Tuvalian (middle to late Carnian).

Sanford Formation

The Sanford Formation conformably overlies the Cumnock Formation and is exposed in the central and southeastern part of the Sanford basin. The Sanford Formation is a 930 to 1240 m thick sequence dominated by lenticular beds of red to brown terrigenous clastics, including claystone, mudstone, siltstone, fine-grained sandstone, and conglomerate (Reinemund, 1955). There are few distinctive beds, and no consistently mappable subdivisions within the formation (Reinemund, 1955). Lenticular beds of gray, coarse-grained to conglomeratic, arkosic sandstone are present in the lower 425 to 490 m of the formation, decreasing towards the southwest. Red to brown, coarse-grained, arkosic sandstone and conglomerate, with associated claystone, siltstone, and fine-grained sandstone dominate the upper 300 meters of the Sanford Formation. Grain size coarsens to the southeast, and conglomerate units, interpreted as alluvial fan deposits, are present along the southeastern edge of the basin adjacent to the Jonesboro fault. Fossils are scarce in the Sanford Formation. Gore (1986) documented one the few known fossil localities.

STRATIGRAPHY OF THE DURHAM BASIN

The map units recognized in the Durham basin differ greatly from those of the Sanford basin. Unlike the Sanford basin, no formal formations are identified in the Durham basin, largely due to the absence of good marker beds equivalent to the Cumnock Formation.

Bain and Harvey (1977) proposed the first map units internal to the Durham basin, based on reconnaissance-level mapping. The NCGS (1985) later consolidated these into four facies for the State Geologic Map. These four facies are 1) Tan arkosic sandstone facies, 2) Red sandstone-mudstone facies, 3) Chert-limestone-mudstone facies, and 4) Border conglomerate facies. However, during detailed geologic mapping of the central Durham basin (Southeast and Southwest Durham 7.5-minute quadrangles), Hoffman and Gallagher (1989) found these facies, as defined, inadequate for describing the rocks in their map area. They found that several of these facies could be subdivided even further into more specific map units. They subsequently adopted Smoot and others' (1988) lithofacies system of nomenclature for consistency with other geologic mapping throughout the Newark Supergroup.

As a result of their mapping, Hoffman and Gallagher (1989) identified seven distinct lithofacies in the central Durham basin. These lithofacies were grouped in three lithofacies associations, labeled Lithofacies Association I (LA I), Lithofacies Association II (LA II), and Lithofacies Association III (LA III), roughly in ascending stratigraphic order (Fig. 5). Olsen and Huber (1997) proposed an unconformity might exist between LA I and LA II based on vertebrate fossil assemblages (see figure 3). An intertonguing relationship likely exists between LA II and LA III.

In general, LA I contains interbedded sandstone and siltstone and is interpreted as braided stream deposits (Fig. 5). LA II also contains interbedded sandstone and siltstone, but it is interpreted as a meandering fluvial system surrounded by a vegetated floodplain (Fig. 5). LA III contains poorly sorted sandstone, pebbly sandstone, and conglomerate. LA III is interpreted as alluvial fan complexes characterized by broad, shallow channels with high sediment concentrations, and locally, high-energy debris flows (Fig. 5).

The lithofacies terminology of Smoot and others (1988) used by Hoffman and Gallagher (1989) names individual lithofacies by combining the unit's age,

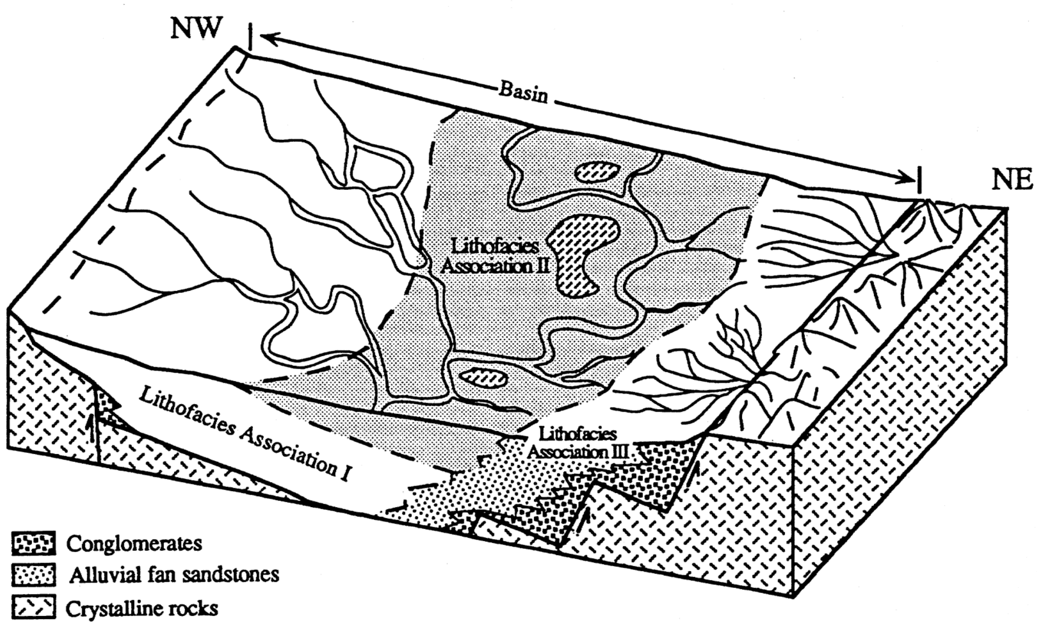


Figure 5. Schematic block diagram illustrating a conceptual model for the distribution of lithofacies associations in the central Durham basin. Lithofacies Association I represents braided stream deposits, Lithofacies Association II represents a meandering river system in a vegetated floodplain, and Lithofacies Association III represents alluvial fan deposits (from Hoffman, 1994).

group, and lithology into one map unit abbreviation. The prefixes for age (Tr = Triassic) and group (c = Chatham Group) are common to all Triassic lithofacies in the Durham basin. The remainder of the unit name is reserved for the dominant lithology (i.e., si = siltstone, s = sandstone, sc = pebbly sandstone, c = conglomerate). Interbedded lithologies are separated by a slash, dominant lithology given first (i.e., s/c = interbedded sandstone and conglomerate). Similar lithofacies of different lithofacies associations are notated by subscript numerals (i.e., $Trcs/si_1$ vs. $Trcs/si_2$).

Mapping by Watson (1998) extended some of Hoffman and Gallagher's lithofacies into the central Durham basin (Green Level 7.5-minute quadrangle). Clark (1998) also utilized the lithofacies system in the southern Durham basin (Cary, New Hill, Cokesbury, Apex, and Fuquay-Varina 7.5-minute quadrangles). Clark (1998) found that two lithofacies of Hoffman and Gallagher (1989), Trcs (sandstone) and Trcsc (pebbly sandstone), were so intermixed in map pattern that he combined them into one mappable unit, Trcs (interbedded sandstone and pebbly sandstone). All other map units are consistent with Hoffman and Gallagher (1989) and Watson (1998).

A discussion of each of the map units in the central and southern Durham basin, along with their interpreted depositional environments, follows.

Lithofacies Association I

Lithofacies Association I is interpreted as sandy, braided channel belts intercalated within thick sequences of heavily bioturbated siltstones, mudstones, and fine-grained sandstone lenses representing vegetated, flood basin facies (Hoffman and Gallagher, 1989; Watson, 1998). They further interpret LA I as representing deposition by anastomosing streams on a muddy floodplain (Fig. 5). LA I consists of a single, mappable lithofacies: sandstone with interbedded siltstone ($Trcs/si_1$).

$Trcs/si_1$ - Sandstone with Interbedded Siltstone

This lithofacies consists of 1) pinkish-gray to light-gray, fine- to medium-grained, micaceous arkoses and lithic arkoses; 2) pale red, muddy, fine-grained sandstones; and 3) reddish-brown, bioturbated siltstones and mudstones. Fine-grained biotite and very fine-grained heavy minerals are distinctive accessories. Fine- to coarse-grained muscovite is also common, though not diagnostic to this facies.

Sequences of sandstone, one- to more than five-meters thick, contain fining-upward cosets of trough crossbeds (Fig. 6). Individual cosets decrease in thickness from the base of a sequence to the upper portions. The base of these sequences is sharp or scoured. Sandstone overlying the erosional base is pebbly, granular, or very coarse-grained, and contains abundant mudstone intraclasts scattered along scour surfaces. Locally, along the shoreline of Jordan Lake, the tough crossbedded sandstone fines upward into ripple-laminated, very fine-grained sandstone and siltstone (STOP 4).

Bioturbation is extensive in the finer-grained siltstones and mudstones and within the thinner, sandy beds of this facies. Light greenish-gray, threadlike bifurcating horizontal mottles and/or vertical to oblique mottles (elliptical in diameter and interpreted as root marks) are common to ubiquitous. Meniscate *Scoyenia* burrows and other sand or mud in-filled burrows are common, extending downward from the upper surfaces of beds. Locally, thin zones of carbonate nodules (interpreted as caliche and indicating an arid to semi-arid climate), ferric concretions, and platy to curved fractures occur within the sequences of finer-grained strata (interpreted as paleosols?).

Lithofacies Association II

Lithofacies Association II is interpreted as deposits of a meandering fluvial system flowing into a deltaic and lacustrine depositional environment (Fig. 5). LA II is dominated by 1 to 4 meter-thick, fining-upward, trough cross-bedded channel sequences scoured into underlying fine-grained siltstone (Fig. 6). Grain size of the deposits gradually increases from west to east in the area west of the town of Apex until the siltstone component can no longer be found. Conglomeratic basal lags in these channel complexes can have clasts in excess of 20 cm in diameter.

Lithofacies Association II consists of two similar lithofacies: 1) sandstone with interbedded siltstone ($Trcs/si_2$) and 2) siltstone with interbedded sandstone (Trcsi/s). The subscript numeral 2 differentiates the $Trcs/si_2$ lithofacies from the similar sandstone and interbedded siltstone ($Trcs/si_1$) of Lithofacies Association I. An arbitrary break of 50% sandstone verses siltstone separates LA II into its two component lithofacies.

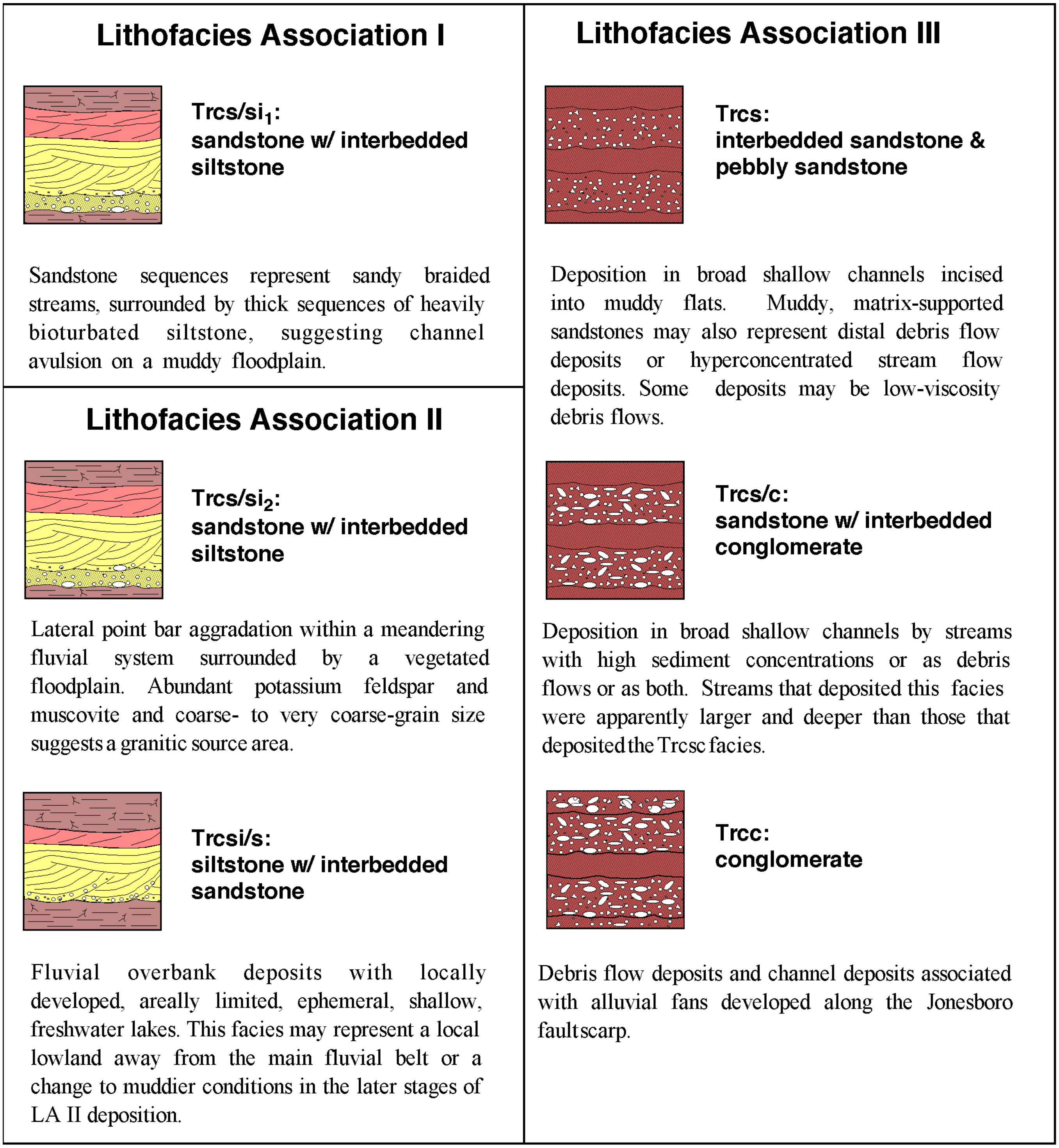


Figure 6. Lithofacies found in the Durham basin. Lithofacies Association I is interpreted as braided stream deposits. Lithofacies Association II is interpreted as a meandering fluvial system. Lithofacies Association III is interpreted as alluvial fan and related deposits. Based on interpretations of Hoffman and Gallagher (1989).

Trcs/si$_2$ - Sandstone with Interbedded Siltstone

This unit consists of cyclical depositional sequences composed of whitish-yellow to grayish-pink to pale red, coarse- to very coarse-grained, trough cross-bedded lithic arkose that fines upward through yellow to reddish-brown, medium- to fine-grained sandstone, to reddish-brown, burrowed and rooted siltstone (Fig. 6). Bioturbation is usually surrounded by greenish-blue to gray reduction halos. Coarse-grained portions contain abundant muscovite, and basal gravel lags consist of clasts of quartz, bluish-gray quartz crystal tuff, and mudstone rip-ups.

Exposures of the Trcs/si$_2$ lithofacies are deeply weathered owing to the unit's high feldspar and muscovite content. The high feldspar content suggests that the lithofacies was derived from a different source area than LA III. Exposures are usually limited to man-made outcrops, creating large data gaps in areas of little human disturbance. Topography in the Trcs/si$_2$ map unit generally consists of low, rounded ridges with few surface streams. This unit is one of the few in the entire Deep River basin suitable for farming. The boundaries of this map unit can be crudely determined by tracing on a U. S. Geological Survey topographic map the extent of the "white areas", which indicate open areas (usually farms).

Trcsi/s - Siltstone with Interbedded Sandstone

This unit consists of reddish-brown, extensively bioturbated, muscovite-bearing, siltstone interbedded with tan to brown, fine- to medium-grained, muscovite-bearing, arkosic sandstone, usually less than one meter thick (Fig. 6). Siltstones can contain abundant, bedded, calcareous concretions (interpreted as caliche) and iron nodules. Bioturbation is usually surrounded by greenish-blue to gray reduction halos.

The Trcsi/s lithofacies, due to its fine grain size, is not very resistant to erosion. Topography in this map unit usually consists of broad, flat areas, with little to no surface streams. The unit is poorly exposed except for excavations in brick pits.

The Triangle Brick pit in the Trcsi/s lithofacies is a world-class locality for both continental invertebrates and vertebrates, particularly reptiles (Olsen, 1977; Renwick, 1988; Gore and Renwick, 1987; Olsen and others, 1989; Good and Huber, 1995, Olsen and Huber, 1997). Recovered specimens include fragmentary plants, clams, crayfish, fish, reptile (phytosaur) teeth, and abundant coprolites.

Olsen (1977), Olsen and others (1982), and Olsen and others (1989) argued that the presence of the fish *Turseodus* in the Triangle Brick quarry indicated a late Carnian age, similar to that of the Cumnock Formation in the Sanford basin. However, Huber and others (1993) pointed out that *Turseodus* ranges throughout the Carnian and Norian, and therefore was of limited time-stratigraphic value. Huber and others (1993) instead suggested that the presence of *Stegomus* in the Triangle Brick quarry indicated an early to middle (?) Norian age (Olsen and Huber, 1997). If the Triangle Brick quarry deposits are indeed Norian in age, they are significantly younger than Cumnock Formation of late Carnian age.

Lithofacies Association III

Lithofacies Association III, as defined by Hoffman and Gallagher (1989), consists of four lithofacies: 1) sandstone (Trcs); 2) pebbly sandstone (Trcsc); 3) sandstone with interbedded conglomerate (Trcs/c); and 4) conglomerate (Trcc). Clark (1998) found the sandstone and pebbly sandstone lithofacies so intermixed in the southern Durham basin, he combined them into one map unit. This lithofacies is termed Trcs - interbedded sandstone and pebbly sandstone.

LA III is interpreted as an alluvial fan complex (Fig. 5). Outcrops contain good examples of chaotically-bedded, broad, shallow channels, with numerous scour surfaces, characteristic of high-energy fan environments.

Surface widths of LA III map units vary greatly. LA III obtains a maximum surface width of several kilometers around the Harris Reservoir (Cokesbury quadrangle) and near the Raleigh Durham (RDU) airport (Cary quadrangle). Conglomerate clast size increases eastward at these locations as well, with clasts locally in excess of 1 meter in diameter.

LA III is almost non-existent in the southern Durham basin (near the town of Apex), Small "jogs" in the surface trace of the Jonesboro fault suggest this area may contain several non-overlapping faults segments. These "jogs" could be small relay ramps where fault displacement was minimal. This condition would result in a topographic low along the border fault, which would be an ideal location for sediment-carrying rivers and streams to enter the basin. The coarse-grained fluvial nature of LA II rocks in close proximity to the Jonesboro fault at this location supports this hypothesis.

The variability of the surface widths of LA III map units can be explained in several ways. First, variability in shape can occur as a result of the lobe-shaped depositional nature of alluvial fans. Interfingering of multiple fans can produce complicated map patterns. Second, Clark (1998) reported several broad, open anticlines and synclines, which are most likely superimposed on the lobe-shaped alluvial fans. A third factor may lie in the definition of the map units themselves. All the contacts between lithofacies internal to LA III are gradational in nature, and components of one lithofacies can occur within another map unit, only not in great abundance. Owing to the high amount of vegetation and the lack of numerous surface streams, poor data density can strongly influence the location of geologic contacts.

Topography in LA III is generally steep and rugged in the Trcs/c and Trcc lithofacies. Erosion-resistant bedding holds up both ridges and waterfalls. In some cases, strikes of parallel ridges and first-order drainages can be used to predict bedding strike in areas of sparse outcrop data. Topography usually decreases in elevation and gradient as one moves away from the Jonesboro fault. The rocky nature of the deposits and the steep terrain limit the agricultural potential, and as such, the area is sparsely populated and few roads exist in this isolated region of the basin.

Trcs - Interbedded Sandstone/Pebbly Sandstone

This unit consists of reddish-brown to dark brown, irregularly bedded to massive, poorly to moderately sorted, medium- to coarse-grained, muddy lithic arkoses, with occasional, matrix-supported granules and pebbles or as 1-5 cm thick basal layers (Fig. 6). Muscovite is common to absent. Occasional bioturbation is usually surrounded by greenish-blue to gray reduction halos. Beds are tabular, 1-3 meters thick, with good lateral continuity. This unit grades eastward into Trcs/c.

Trcs/c - Sandstone w/ Interbedded Conglomerate

This unit consists of reddish-brown to dark brown, irregularly bedded, poorly sorted, coarse-grained to pebbly, muddy lithic sandstones with interbedded pebble to cobble conglomerate (Fig. 6). Muscovite is rare to absent in the matrix. Well-defined conglomerate beds distinguish this unit from conglomerate basal lags of Trcs. An arbitrary cut-off of less than 50 percent conglomerate distinguishes this unit from the Trcc conglomerate facies. Clasts are chiefly miscellaneous felsic and intermediate metavolcanic rocks, quartz, epidote, bluish-gray quartz crystal tuff, muscovite schist, and meta-granitic material, with rare banded gneiss (Raleigh gneiss?) near the town of Apex. Conglomerate beds are channel-shaped and scour into the underlying sandstone beds. This unit grades eastward into Trcc.

Trcc – Conglomerate

This unit consists of reddish-brown to dark brown, irregularly bedded, poorly sorted, cobble to boulder conglomerate (Fig. 6). Muscovite is rare to absent in the very coarse-grained to gravelly matrix. An arbitrary cut-off of greater than 50 percent conglomerate distinguishes this unit from the Trcs/c facies.

Clasts are chiefly miscellaneous felsic and intermediate metavolcanic rocks, quartz, epidote, bluish-gray quartz crystal tuff, muscovite schist, and rare meta-granitic material. Maximum clast diameters are in excess of 1 meter along the shore of Harris Reservoir and in excess of 2 m along Haleys Branch east of the RDU airport. These large clast sizes suggest paleo-relief along the Jonesboro fault scarp was great enough to produce high stream gradients capable of transporting boulders-sized clasts.

CORRELATION OF MAP UNITS

A thorough attempt to correlate between the Sanford and Durham basins cannot be performed until additional geologic mapping is conducted. This article merely attempts to document the current state of mapping and interpretations in the Deep River basin. However, several general observations can be made at this time regarding correlation between the Sanford and Durham basins.

There is not a one-to-one match between the three formations in the Sanford basin and the three lithofacies associations in the Durham basin. For example, the top and bottom of the Cumnock Formation is defined by the first occurrence of gray shale. This definition excludes any of the reddish-brown siltstone or purple mudstone above or below the first gray shale, but all of these units have a similar depositional environment. In the lithofacies mapping system, the gray shale would be combined with the reddish-brown siltstone and purple mudstone as part of one map unit, namely the Trcsi/s lithofacies.

Another example of this incompatibility exists in the coarser-grained sections. By definition, the Sanford

Formation includes everything stratigraphically higher than the last gray shale of the Cumnock, including both fluvial sediments and alluvial fan conglomerates. In the lithofacies system of mapping, fluvial and alluvial fan sediments are separated into two completely different lithofacies associations, namely LA II and LA III.

This incompatibility between map units is further complicated by the apparent temporal differences between the basins. As stated previously, Olsen (1977), Olsen and others (1982), and Olsen and others (1989) argued that the Trcsi/s sediments at Triangle Brick (central Durham basin) indicated a late Carnian age, similar to that of the Cumnock Formation in the Sanford basin. However, Huber and others (1993) suggested an early to middle (?) Norian age (Olsen and Huber, 1997). If the Triangle Brick quarry deposits are indeed Norian in age, they are significantly younger than Cumnock Formation of late Carnian age. In contrast, Clark (1998) mapped Trcsi/s sediments nearly identical to the Triangle sediments in the extreme southern Durham basin that preliminarily appear to be Cumnock equivalents (P.E. Olsen, personal commun.). Therefore, lithology certainly cannot be used alone in assigning stratigraphic order, let alone age.

If indeed there is missing section between LA I and LA II in the Durham basin, and between the middle and uppermost Pekin in the Sanford basin, as Olsen suggests, then where is the unconformity? Does it manifest itself as a period of non-deposition between conformably map units? Is it an angular unconformably not yet recognized? Has basin-longitudinal faulting played a role? These are questions without easy answers. Unfortunately, the LA I/LA II contact is either concealed by Jordan Lake or occurs in an area of poor exposure. Additional mapping is needed along the basin's western border to clarify the nature of the contact. Even then, the issue probably won't be resolved without subsurface data or new fossil finds.

The opportunities are limited for new fossil finds in the Durham basin for comparison with the Sanford basin. The Durham basin sediments are coarser-grained than the Sanford basin and there is no evidence for a large paleolake like the one responsible for the fossil-rich Cumnock Formation.

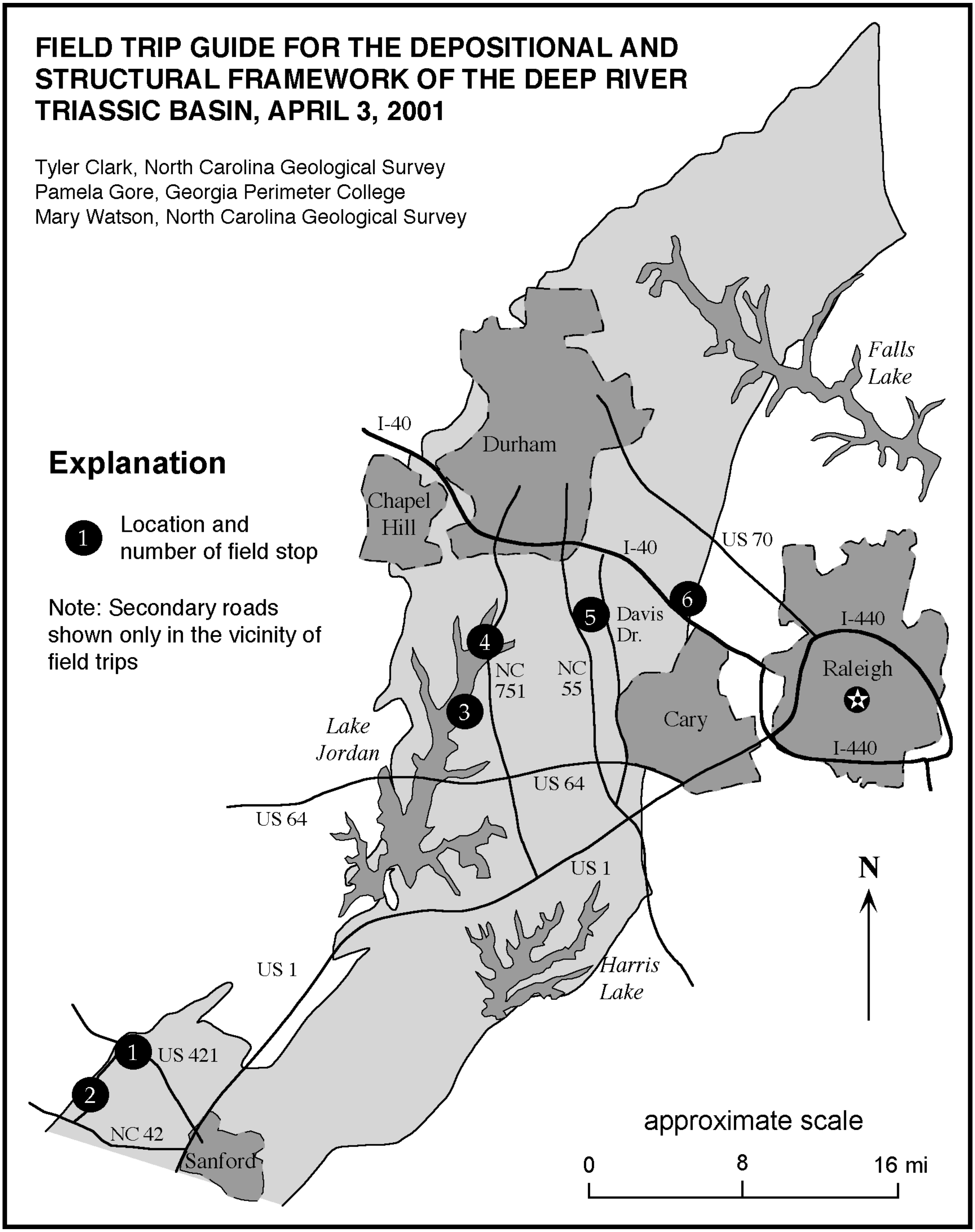
The next step in correlating between the two basins is to revisit many of the outcrops along the "mismatch" between Reinemund (1955) and Clark (1998). Special care should be given to the Cumnock Formation and its fine-grained equivalents in the northern Colon cross-structure.

In conclusion, it is premature to attempt any stratigraphic correlation between the Sanford and Durham basin at this time. Additional geological mapping is needed, coupled with any supporting data that might present itself in areas of poor exposure. A thorough link between the formation mapping of the Sanford basin and the lithofacies mapping in the Durham basin will require a multidisciplinary approach of field mapping and supporting data such as fossils, pollen, subsurface coring, and geophysics.

ACKNOWLEDGMENTS

We would like to dedicate this fieldtrip and guidebook to John A. Reinemund on the 50th anniversary of his mapping of the Sanford basin for USGS Professional paper 246: Geology of the Deep River Coal Field, North Carolina. This all-encompassing compilation still stands today as the most comprehensive report about the Sanford basin.

We wish to acknowledge the U.S. Geological Survey's STATEMAP and EDMAP programs that provided the resources to conduct parts of this study. We are indebted to many individuals for their earlier work in the Triassic rocks of North Carolina, their inspiration, or their advice and assistance, including Paul Olsen, George Bain, Dan Textoris, Walt Wheeler, Skip Stoddard, Rick Wooten, Kathleen Farrell, Bill Hoffman, Jeff Karson, Peter Malin, Mike Medina, Rich Hayes, Steve Driese, Joe Smoot. TWC especially would like to thank his wife Karen and family for the sacrifices made during field mapping.


FIELD TRIP GUIDE FOR THE DEPOSITIONAL AND STRUCTURAL FRAMEWORK OF THE DEEP RIVER TRIASSIC BASIN, APRIL 3, 2001
Tyler Clark, North Carolina Geological Survey
Pamela Gore, Georgia Perimeter College
Mary Watson, North Carolina Geological Survey
Explanation
Location and number of field stop
Note: Secondary roads shown only in the vicinity of field trips
Falls Lake
I-40
Durham
Chapel Hill
US 70
I-40
Davis Dr.
I-440
Raleigh
NC 751
NC 55
Lake Jordan
Cary
I-440
US 64
US 64
US 1
N
US 1
Harris Lake
US 421
NC 42
Sanford
approximate scale
0
8
16 mi

FIELD STOPS

INTRODUCTION

This one-day field trip consists of six stops: two in the Sanford basin and four in the Durham basin. The objectives of this field trip are to show a variety of rock sequences throughout the Deep River basin and compare the different styles of map units currently used. All stop locations are shown on the regional index map (previous page). Individual stop locations are shown on reproductions of 7.5-minute quadrangle maps. North is toward the top in all figures. The field trip leaders appreciate the cooperation of representatives of Boren Clay Products and all of the private landowners who graciously permitted us on their property.

STOP 1: Pekin Formation
Boren Clay Products, Gulf, NC
(Pamela Gore and Tyler Clark)

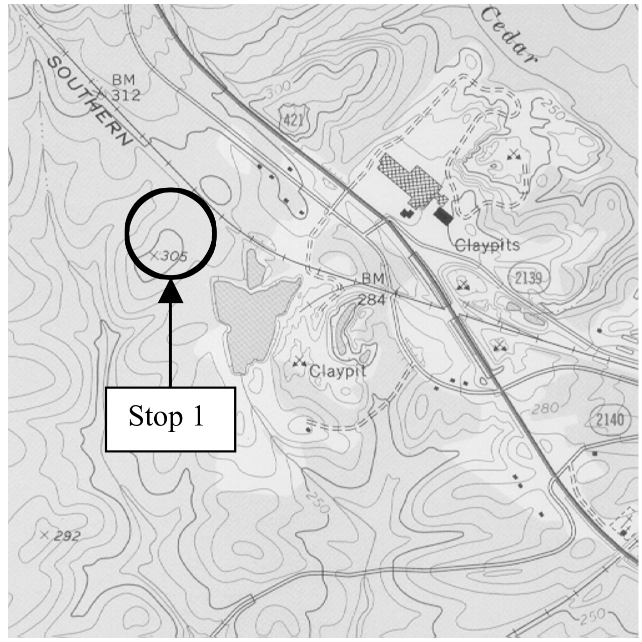


Figure 7. Boren Clay Products brick pits. Goldston 7.5-minute topographic map.

The Boren Clay Products pits are located about 1.5 miles east of the western border of the Sanford basin on both sides of US 421. Written permission must be gained from Boren Clay Products before entering the property. The pits expose strata of the middle Pekin Formation that are being mined to produce bricks and drainpipes (Gore, 1986). The Boren operations consist of several old pits northeast of US 421, as well as the old Pomona Pipe Works on the southwestern side of US 421 (now occupied by the lake in Figure 7). At present, quarrying is concentrated on the southwestern side of US 421, (Fig. 7).

The rocks in the Boren pits are dominantly reddish-brown, siltstone and sandstone. Tan to white, arkosic channel sands and purple mudstones are also present in lesser amounts. Plant fragments are present in some of the finer-grained units. Most units are overprinted by *Scoyenia* bioturbation, including large backfilled burrows (up to 1.0 cm wide and 50 cm long), probably attributable to a decapod such as a crayfish (Gore, 1986). Vertebrate tracks are also present. Invertebrate fossils are scarce, but present locally, including conchostracans or clam shrimp and small freshwater bivalves.

Thin diabase dikes are present in the pits on both sides of US 421. A diabase dike along the northeastern wall of the new pit has thermally metamorphosed the sediments, accentuating the bioturbation. The diabase weathers to a yellowish-orange color, contrasting with the surrounding grayish red and reddish-brown strata. Drag folding, faulting, and intense fracturing are common near the dike.

Field trips led by Gore (1986) and Olsen and others (1989) visited the quarry on the northeastern side of US 421, which was active at the time, but which is now abandoned. This pit is one of the premier sites for Triassic plant fossils in the eastern US. The plant fossils are found in gray siltstone and shale units and yellow-tan siltstones, which are not exposed in the new pits on the southwestern side of US 421. The old pits contain abundant stems, roots, cones, and leaves of a variety of seed and non-seed plants (Fig. 8).

Gensel (1986) provided a thorough description of these fossil plants, which include ferns, horsetail rushes, cycads, cycadeoids, and conifers. One of the most unusual plant fossil finds is the only known intact specimen of *Leptocycas gracilis*, one of the oldest known cycads, a gymnosperm sometimes called the sago palm (News release, NC State University, 2000). The plant fossils suggest a tropical to subtropical climate (Gensel, 1986). Fern spores and conifer pollen are present in the gray shales and siltstones. These palynomorphs were interpreted by Traverse (1986) as Julian (middle Carnian) in age.

The Pomona Pipe quarry on the southwestern side, of US 421 (now filled with water) has yielded vertebrate fossils from reddish-brown clayshales. The most abundant vertebrate is a crocodile-like phytosaur,

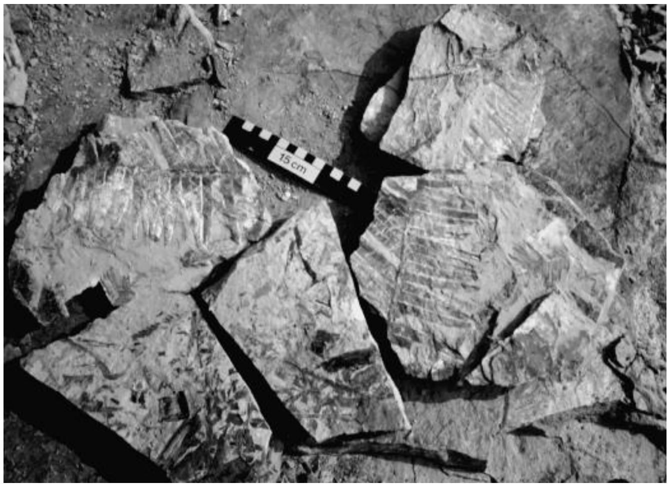


Figure 8. Examples of plant fossils from the Boren Clay pits.

Rutiodon, known from teeth and bones. Also present are: *Typothorax*, a 2.5 meter-long armored pseudosuchian similar to a horned toad and previously unknown east of Texas; teeth of a large carnivorous theropod dinosaurand; and several specimens of *Placerias*, a herbivorous, dicynodont, mammal-like reptile (Baird and Patterson, 1967; Patterson, 1969). Fish remains, including undetermined redfieldiid scales and bones also occur (Olsen and others, 1989).

The Pomona Pipe quarry has also yielded the oldest vertebrate track assemblage in the Late Triassic of eastern North America (Olsen and Huber, 1997. Tracks include both three- and five- toed forms, ranging in size from 10 to 30 cm (Olsen and Huber, 1997). The tracks are apparently dinosaurian, making them among the oldest known dinosaurian tracks in the world (Olsen and Huber, 1997).

The vertebrate assemblage indicates an early Tuvalian (early Late Carnian) age, and correlates with the Vinita Formation of the Richmond basin and the Falling Creek Member of the Taylorsville basin (Huber and others, 1993).

STOP 2: Cumnock Formation
Black Diamond Coal Mine
Indian Creek, near Carbonton, NC

(Pamela Gore and Tyler Clark)

The Black Diamond coal mine and exposures of the Cumnock Formation occur in a heavily forested area on the top and side of a large bluff on the south side of Indian Creek (Fig. 9), approximately 300 meters east of the intersection of Indian Creek and SR 2306 (Goldston-Carbonton Rd.), and about 2 km NE of Carbonton, NC. Approximately 25 m of nearly continuous section, consisting of black and gray shales, coal beds, and a diabase intrusion, are exposed along the base of the bluff at the edge of the stream. Both the Gulf and the Cumnock coal beds are exposed. This is the largest natural exposure of the Cumnock Formation in the Deep River basin (O. F. Patterson, personal communication, 1988). The beds are steeply dipping, compared with most exposures in the basin, with a 42-degree southeastern dip. Evidence of extensive mine operations are present along the top of the bluff.

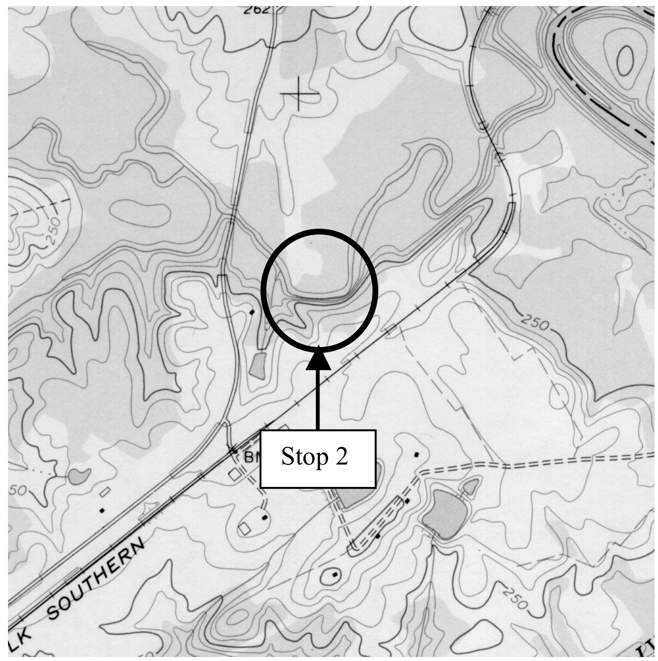


Figure 9. Black Diamond coal mine. Goldston 7.5-minute topographic map.

The coal exposed in this outcrop can be traced over 25 km across the northwestern part of the Sanford basin, along and near the Deep River. In total, seven beds of coal are present in the lower to middle Cumnock Formation. There are two main seams, the lower Gulf coal seam and the upper Cumnock coal seam, separated by 8.5 to 12 m of black to gray shale and siltstone (Robbins and Textoris, 1986). The Gulf coal seam typically consists of one bed ranging from a few centimeters to nearly 1 m thick, and in places it is underlain by a rooted underclay (Hope, 1975) or by sandstone. The upper Cumnock coal seam consists of three beds, together ranging from 1 to 3 m thick.

At the Indian Creek stream-cut near the Black Diamond Mine, a diabase intrusion (nearly 1 m thick) is present near the base of the section. The Gulf coal seam is exposed roughly 3 m above the diabase (measured section in Reinemund, 1955, plate 8). At this locality, the lower Gulf coal seam consists of approximately 40 cm of coal to bony or shaley coal, overlain and underlain by blackband (ferruginous black shale with siderite nodules). The blackband is overlain by shale and carbonaceous shale. About 2 m above the Gulf coal seam there are several thin beds of coal ranging from about 5 to 15 cm thick (Fig. 10).

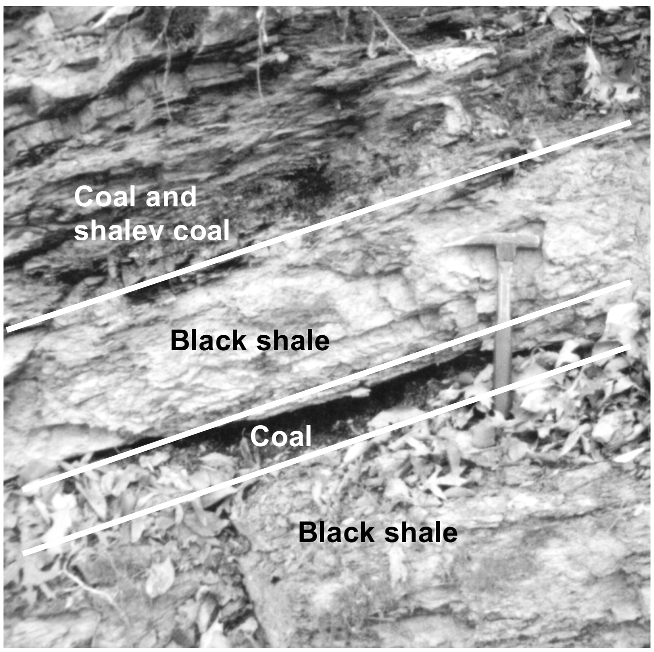


Figure 10. Outcrop of coal, shaley coal, and black shale along Indian Creek. Rock hammer for scale.

About a meter above these thin beds (as measured within the mine nearby) is a west-dipping high-angle normal fault with associated drag folding. Approximately 4 m above the fault, the Cumnock coal crops out in three main seams (measured by John McIvor in 1933, as reported by Reinemund, 1955, plate 8). The lower of the three coal seams is 50 cm thick, overlain by about 10 cm of black shale. This is overlain by about 30 cm of coal, topped by 50 cm of blackband. The upper bed of the three (main bench of the Cumnock coal) overlies the blackband and is about 50 cm thick. The main bench of the Cumnock coal seam is overlain by several meters of shale, which contains two thin (less than 10 cm) coal beds associated with blackband and carbonaceous shale (section description based on measured section from Black Diamond Mine, in Reinemund, 1955, plate 8).

Coal in the Cumnock Formation is interpreted as evidence for a tropical paleoclimate with high precipitation and/or humidity in a lake-fringing swamp environment with low rates of clastic sedimentation (Hope, 1975; Gensel, 1986; Textoris and others, 1989). The blackband siderite deposits associated with the coal indicate anoxic, low sulfate waters (Berner, 1981). The black shales are interpreted as offshore lacustrine deposits in a large, hydrologically-open, perennially-stratified lake (Gore, 1986, 1989).

This section has not been adequately studied, but elsewhere in the Cumnock Formation, fossils are extremely common, including plants, conchostracans or clam shrimp (*Cyzicus*), ostracodes (*Darwinula*), insects, freshwater unionid bivalves, fish (*Sinorichthys*, *Cionichthys*, and cf. *Pariostegus* or *Diplurus* - a coelacanth), labyrinthodont amphibians (*Dictyocephalus*), reptiles, dinosaurs, and mammal-like reptiles (*Dromatherium* and *Microconodon*) (Olsen and others, 1989; Olsen and others, 1991). The coals and adjacent blackband layers produce abundant vertebrate fossils (Olsen and others, 1991).

Many of the mines in this area operated intermittently and unsuccessfully due to a complex system of faults which have displaced the coal, and related diabase intrusives, which have metamorphosed it from bituminous coal to anthracite or semianthracite, locally associated with natural coke (Reinemund, 1955, p. 101-104). Anthracite and coke are most extensive near Carbonton (approximately 2 km SW of the Black Diamond mine) where the diabase intrusives are largest and nearest the coal (Reinemund, 1955, p. 104).

Reinemund (1955) summarized the history of coal mining in the Sanford basin. The coal has been used locally since Revolutionary War times. By 1850, many prospects and small mines had opened along the coal outcrop. The first commercial shaft mines were opened in the 1850's. The Cumnock (or Egypt) Mine (located approximately 10 km to the northeast) penetrated the coal at a depth of 430 feet (Campbell and Kimball, 1923). The plan was to haul the coal to the Deep River and ship it downstream on barges, however the Civil War broke out just as the construction of locks and dams along the Deep River was completed. During the Civil War, the Confederate Army took over some of the mines, and the Black Diamond mine (among others) supplied coal for ships of blockade runners in Wilmington, NC. Some of the mines were sealed near the end of the Civil War to prevent the Union armies from exploiting the coal.

Reinemund (1955, p. 91) stated that the Black Diamond mine was referred to by Chance (1885, p. 43) as the 'slope at the Evans place'. It has also been called the Carbonton mine. Chance (1885) stated that all of the workings of the Black Diamond mine were confined to the lower two benches of the Cumnock coal bed. The mine was worked during the Civil War, but was not used much afterward. The mine was opened several times during the 1930's, but it has been closed since then. The combined production of the Black Diamond mine and some other pits in the area probably did not exceed 15,000 or 20,000 tons, according to estimates (Reinemund, 1955, p. 94). Reinemund (1955, p. 93) apparently visited the site in 1949 and issued the following assessment of the mine. “The workings consist of an old slope (now caved), a shaft, and an airway; all of these are connected by a gangway that joins the slope at a slant depth of about 93 feet. The airway was open in 1949, but it was flooded to within 10 feet of the portal. There are a great many surface prospect pits in the vicinity” (Reinemund, 1955, p. 93). Today all that visibly remains is the sloped entrance to the mine, a spoil pile, a caved shaft, and several small trenches and pits. Care should be used around any old mine workings!

The coal mines in the Cumnock Formation are associated with large amounts of methane gas. A gas explosion in the Carolina mine, about 13 km to the east of this site, killed 53 men in the mine in 1929 (Reinemund, 1955). Over the years, gas explosions in the basin killed more than 200 miners. The coal beds were tested as a possible commercial source of methane for use by the local brick-making industry in the early 1980's (Hoffman and Beutel, 1991). Data suggested that as much as 40,000 cubic feet of methane could be produced per day (Hoffman and Beutel, 1991).

Renewed interest in the Deep River basin coals occurred around the end of World War II with the growth of industry in central North Carolina. The US Bureau of Mines and a private company drilled several holes in the coal field during the 1940's to test the coal. The Carolina mine was reopened in 1947, and by 1950 was producing more than 100 tons of coal per day, most of which was sold to the Carolina Power Company (Reinemund, 1955). The last major mine was flooded and closed in 1953 (Textoris, 1985).

In all, more than 2 million tons of coal were produced from the Deep River coal field (Robbins and Textoris, 1986). Textoris (1985) calculated the remaining coal resources to be about 140,000,000 short tons. A test pit (approximately 30 m by 70 m) was opened in late 1987 by the Chatham Coal Company near Gulf, NC as part of a short-lived investigation into strip-mining the coal (Olsen and others, 1989, p. 27).

STOP 3: Lithofacies Association II Trcs/si$_2$: Sandstone w/ Interbedded Siltstone Martha’s Chapel outcrops, Jordan Lake, NC Intersection of SR 1752 and SR 1008

(Mary Watson and Tyler Clark)

This outcrop exposes a 100-meter continuous section of the Trcs/si$_2$ lithofacies. Wave action has sculpted the shoreline into a continuous cliff exposure of fresh-surfaced rock, allowing an excellent view into the architecture of the rocks (Fig. 11).

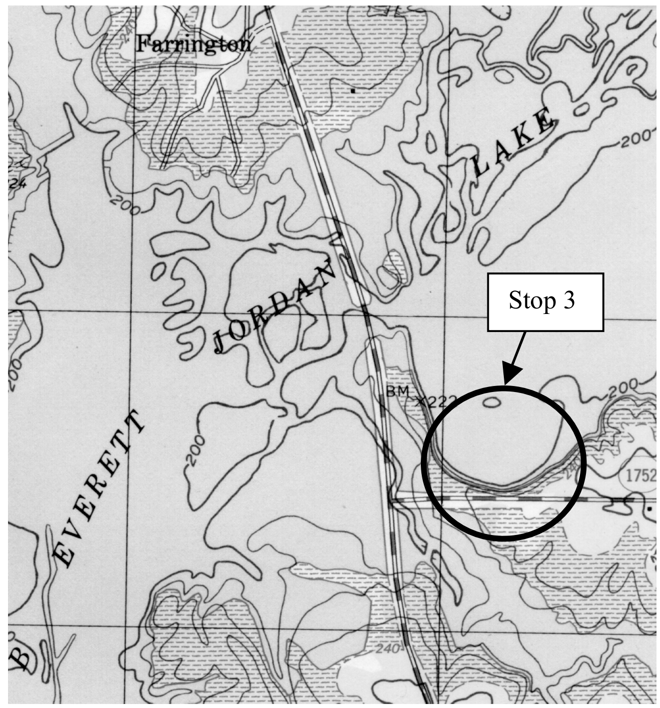


Figure 11. Martha’s Chapel outcrops. Farrington 7.5-minute topographic map.

This site is typified by consistent, rhythmic fining upward sequences in which coarse to very coarse-grained pebbly sandstones overlie scoured surfaces (Fig. 12). Bed thickness at this location ranges from less than one meter to more than six meters. Beds strike north northeast to northeast with an average dip of 15 degrees. A striking color contrast exists between the light colored sandstones and the darker hued finer grained mudstones and siltstones. The sandstones are commonly cross-bedded and contain rip-up clasts. The sandstones grade upward into mottled siltstones and mudstones.

The arkoses and lithic arkoses contain abundant coarse-grained muscovite and pink feldspar, which are identifying characteristics of this facies. The

Figure 12. Martha's Chapel outcrops showing scoured contact between sandstone (light color) and siltstone (dark color).

sandstones are dominantly light in color, variously yellow, white, pink, or pinkish gray. Low angle, high amplitude cross bedding is characteristic of the sandstones at this outcrop. Both trough and tabular cross bedding occurs. Sharp, scoured contacts are found at the base of the sandstones beds. Rip-up clasts and lithic pebbles can be observed scattered throughout the sandstone beds but are concentrated at the base above the scoured contact. Trains of imbricated pebbles can be observed in several sandstone beds. Preliminary examinations of paleocurrent indicate transport directions conformable with axial basin trends. Many sandstones are bioturbated, a phenomena that intensifies at the overlying contact with the fine-grained sediments. Macerated plant fragments were noted in one sandstone bed at this location.

The siltstones and mudstones are varicolored ranging in hue from dark red, purplish red, light red and are invariably drably mottled light greenish gray. The mottles are elliptical, mainly vertical and generally extend from four to ten centimeters in length. The degree of mottling varies from about 10 to 100%. Mottled fabric is interpreted to arise from rooting of plants and the burrowing of organisms. The finer grained sediments are very poorly sorted and in many cases original fabric has been obliterated by bioturbation.

Preliminary observation suggests that this section is faulted at several places (possibly three) along the section. The fault planes trend northeast and are marked by a zone of very fine silty green clay. The section is interpreted to represent lateral point bar aggradation and crevasse splays within an axial fluvial system surrounded by a vegetated floodplain (Fig. 5).

STOP 4: Lithofacies Association I Trcs/si$_1$: Sandstone w/ Interbedded Siltstone and Post-Chatham (TKu) Unit, Jordan Lake, NC

(Mary Watson and Tyler Clark)

Stop 4 occurs on the point of a peninsula along the shoreline of B. Everrett Jordan Lake (Fig. 13). Park along the side of NC 751 just north of the lake and walk west along a dirt road until it ends in a field. Walk through the woods to the shoreline and the outcrop.

Geologic mapping of Watson (1998) identified rocks of Late Triassic age overlain uncomformably by deposits younger than the Chatham Group (Fig. 14). These deposits are provisionally designated as the TKu map unit: post-Chatham Group undifferentiated sediments. The age, Cretaceous (?) to Tertiary (?), of the deposit is uncertain.

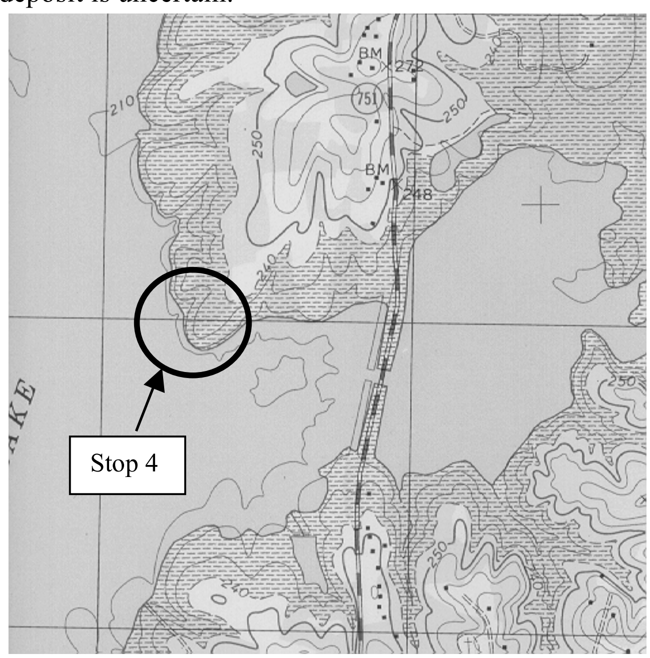


Figure 13. Location of Stop 4 on the Green Level 7.5-minute topographic map.

The deposits are dark-yellowish-orange, or brownish-yellow to yellow-gray; friable to moderately indurated; granular, pebbly, or cobbly; clayey, medium- to very coarse-grained, subarkosic sandstone.

Figure 14. Rick Wooten points his finger to the Triassic/post-Triassic unconformity at STOP 4. The unconformity is nearly horizontal, while the Triassic beds dip 15 degrees to the east-southeast (left to right).

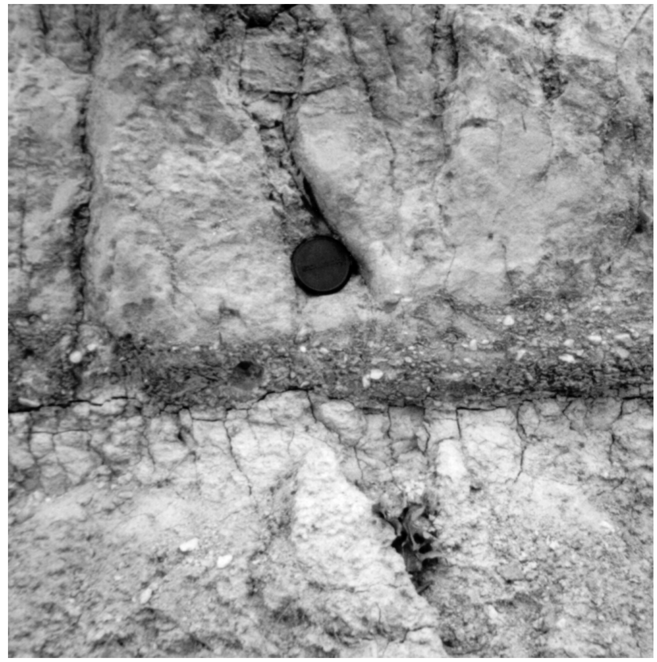


Figure 15. Close-up view of the Triassic/post-Triassic unconformity at STOP 4. Above the unconformity lies a 10-30 cm zone of small pebbles and granules. Camera lens cover for scale.

The base of the unit is an angular unconformity overlying the Triassic rocks (Fig. 15). Above this contact typically lies a 10-30 cm zone of small pebbles and granules. Thin, scattered zones of quartz and/or lithic pebbles or cobbles, locally imbricated, are widespread.

Cosets, 5-10 cm thick, of graded or cross-stratified strata are common. The deposit is speckled with feldspar grains that are generally bright white and altered to kaolin (Fig. 15). Other distinctive constituents include rose quartz; very fine-grained heavy minerals (ilmenite and euhedral garnets); cobbles of white, foliated, kaolinitic, siliceous metamorphic rocks; and petrified wood.

On drainage divides, irregular, linear or patchy, outliers of tan to reddish-orange; very fine to very coarse grained; subrounded to rounded quartz sandy soil or clayey, quartz sandy soil occurs. This soil ranges in thickness from less than one meter up to greater than three meters. Subrounded to rounded quartz pebbles ranging from 0.5 to 6.0 cm are common, found either as surface float or above a nonconformable base of the sandy soil. In places, the sediment rests on older rocks in indistinct contact. Rose quartz pebbles and very fine-grained heavy mineral are common to abundant. The provisional limits of the undifferentiated sediments are indefinite. Road cuts and eroded hill slopes have revealed a few scattered outcrops.

STOP 5: Bonsal-Morrisville Fault Zone and LA II Sediments, Cary/Morrisville, NC

(Tyler Clark)

This excellent exposure of faulted Triassic sandstone occurs along a small tributary of Kit Creek, approximately 1000 feet north of SR 1632 (Fig. 16). The faulting is interpreted as part of the Bonsal-Morrisville fault zone, a west-dipping, intra-basinal normal fault (Bain and Harvey, 1977)

The two main rock units at this location include: 1) medium-grained, moderately sorted, lithic arkoses containing 10-15% lithic grains and pebbles which consist of schists, gneisses, slates, phyllites, and metavolcanics (in order of abundance) with index minerals such as garnet, magnetite, myrmekitic feldspar, and epidote; and 2) reddish-brown, poorly to moderately sorted, matrix-supported, muddy sandstone. These rocks are provisionally correlated with Trcs map unit of Lithofacies Association III, interpreted as distal alluvial fan deposits in which sandstone units were deposited in broad shallow channels incised into muddy flats (Hoffman and Gallagher, 1989; Hoffman, 1994). The

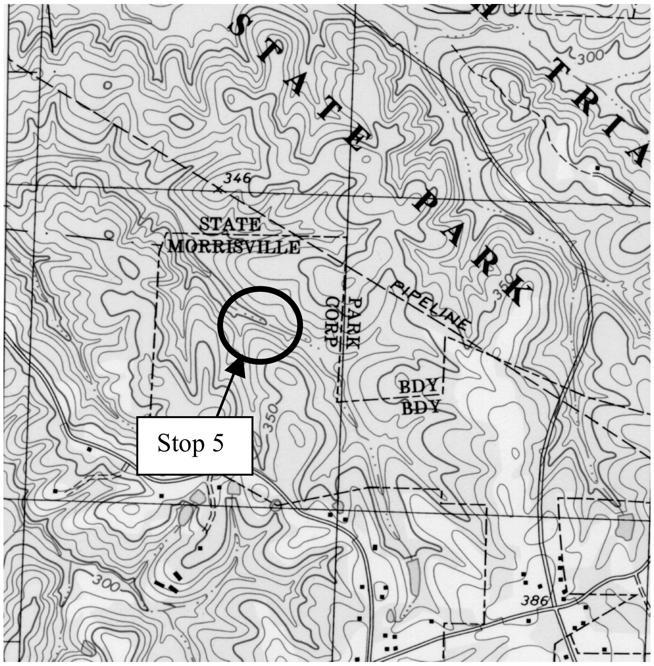


Figure 16. Location of the Bonsal-Morrisville fault. Cary 7.5-minute topographic map.

average strike and dip of these units is N.30°W. 10-15°NE.

The small creek has undercut the steep hillside, creating a 5-m high by 20-m wide outcrop. Blocks of rock have recently fallen from the hillside, exposing a left-lateral, oblique-slip (?) main fault and numerous small-scale, strike-slip faults in both the footwall and hanging wall of the main fault (Fig. 17).

The main fault is oriented N.48°E. 76°W. and is defined by a 5 cm wide foliated breccia. Foliated clayey components of the breccia wrap around more resistant, rounded sandstone clasts.

The numerous small-scale, strike-slip faults have very undulatory and slickensided surfaces. Kinematic indicators along these surfaces include lunate fractures and "step faulting." Slickenlines plunge to the northeast with 15-24° rakes. These faults exhibit both left- and right-lateral sense of movement. Most of the faults strike N.02°E. to N.30°E. and dip 75-90° to both the northwest and southeast.

Compositional layering (clay drapes and gravel layers) in the sandstones serve as excellent marker horizons for measuring small offsets along the faults. Most of the faults have little to no dip-slip component of offset, but a few show dip-slip offset of as much as 0.5 m. In relationship to the main fault, the orientations of these small-scale faults suggest they might be synthetic Riedel shears in a left-lateral shear zone.

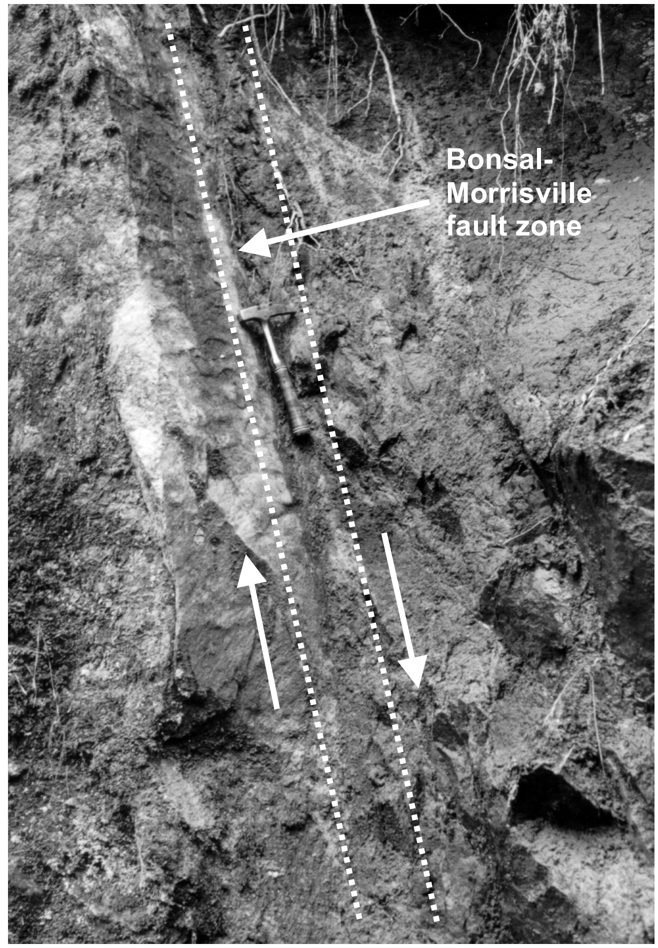


Figure 17. Close-up photograph of the Bonsal-Morrisville fault. Arrows show sense of slip. Rock hammer for scale.

The location of the outcrop is directly along the projected N.40°E. strike of the Bonsal-Morrisville fault (see figure 2) of Bain and Harvey (1977). They interpreted the Bonsal-Morrisville fault as a basin-longitudinal normal fault with approximately 600-1200 m of vertical offset. Large variations in the strike and dip of closely spaced bedding measurements occur in the fault projection area (Clark, 1998). In addition, strong anomalies exist in the fault projection area on aeromagnetic surveys (U.S. Geological Survey, 1974), gravity surveys (Mann and Zablocki, 1961), and electrical resistivity surveys (Ackerman, Bain, and Zohdy, 1976). Finally, a large anomaly exists on an east-west seismic line (Texaco line 85SD11) in the area of the fault. It is certainly not unreasonable to suggest that the fault here is probably a related structure.

STOP 6: Lithofacies Association III
Trcc: Conglomerate, Haleys Branch, Cary, NC
(Tyler Clark)

Exit I-40 at Aviation Parkway, turn right, and follow the signs to Park and Ride 3. Park just past the parking lot on the east side of the road. Follow the chain link fence east to Haleys Branch. The first outcrop is immediately behind Park and Ride 3 on the west side of the creek; the second outcrop is downstream on the east side of the creek (Fig. 18).

This stop views some of the coarsest-grained boulder conglomerate in the Deep River rift basin. Progressive movement along the Jonesboro fault created a significant topographic gradient, perhaps several thousand meters, between the basin and crystalline rocks to the east. This gradient allowed for development of large alluvial fan complexes that prograded into deepening basin depocenters. One such alluvial fan complex is centered near the present location of the Raleigh-Durham airport (Hoffman and Gallagher, 1989; Clark, 1998). This stop is mapped as part of the Trcc lithofacies of Lithofacies Association III (Clark, 1998).

The units at this stop are mostly reddish-brown, massive and chaotically bedded, cobble to boulder conglomerate, having a very coarse-grained to gravelly sandstone matrix (Fig. 19).

Figure 18. Haleys Branch boulder conglomerate. Cary 7.5-minute topographic map.

Figure 19. Boulder-sized polymictic conglomerate along Haleys Branch. The dominant clast lithology is Big Lake-Raven Rock Schist. Imbricated clasts display a southwest dip (to the left) within a red-brown pebbly sandstone matrix. View to the west.

The sandstone also occurs as small beds and lenses. Crude imbrication of clasts is locally preserved. Beds are typically several meters thick, and sandstone interbeds and lenses are between 10-50 cm thick. Bedding contacts are scour surfaces, making precise determination of strike and dip difficult. These units are interpreted as debris flow deposits originating from the topographically-higher rocks to the east.

The conglomerate clasts at this stop are the largest identified in the Deep River basin, with several clasts exceeding 2 meters in diameter. Clast size more commonly ranges from 1-30 cm in diameter. Preliminary provenance studies indicate that most of the clasts originated from the Carolina terranes immediately to the east. The majority of these clasts are derived from the Big Lake-Raven Rock Schist and metamorphosed Reedy Creek Granodiorite, with lesser amounts of greenstone and epidosite from the Sycamore Lake Greenstone. Schist and greenstone clasts are typically angular to lenticular, while metagranodiorite is rounded to subrounded. The large, angular clast size and nearby source area support the interpretation that these deposits were laid down in a high-energy, alluvial fan environment.

END OF FIELD TRIP - RETURN TO SHERATON IMPERIAL CENTER

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A NORTH-SOUTH TRANSECT OF THE GOOCHLAND TERRANE AND ASSOCIATED A-TYPE GRANITES, VIRGINIA-NORTH CAROLINA

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INTRODUCTION

The Goochland terrane is the southeastern- most and most interior massif of Grenville-age basement rocks of the southern Appalachians. It was named by Farrar (1982), and Glover et al. (1982), and was defined by Farrar (1984) as the areal extent of granulite-facies and retrogressed granulite-facies rocks of the eastern Virginia Piedmont, with possible extension southward into the northern North Carolina Piedmont (Fig. 1). The granulite facies metamorphic event is recognized by the occurrence of orthopyroxene-bearing assemblages in intermediate to mafic orthogneisses and sillimanite+ Kfeldspar in rocks of pelitic composition (Farrar, 1984). The definition of terrane boundaries is difficult in that granulite assemblages were overprinted by at least one later greenschist to amphibolite facies metamorphic event, with accompanying rehydration and ductile deformation of much of this granulite terrane, and with formation of numerous mylonite zones. These mylonite zones, of at least two generations, both bound the Goochland terrane and slice it into numerous fragments.

This belt of high grade gneisses and schists has long been known, and appears, among other places, on the 1932 Geologic Map of the United States. With the application of plate tectonic models to the southern Appalachians in the 1970's, it became apparent that much of the Piedmont comprised accreted terranes that developed elsewhere and were amalgamated in the Paleozoic to form the Appalachian belt (e.g. Hatcher, 1972; 1989). Any models that included Virginia showed at least one suture west of what is here called the Goochland terrane. What to do about this high-grade terrane? A number of possibilities have been proposed: (1) Many models assigned it to a higher-grade portion of one of the accreted arc-volcanic

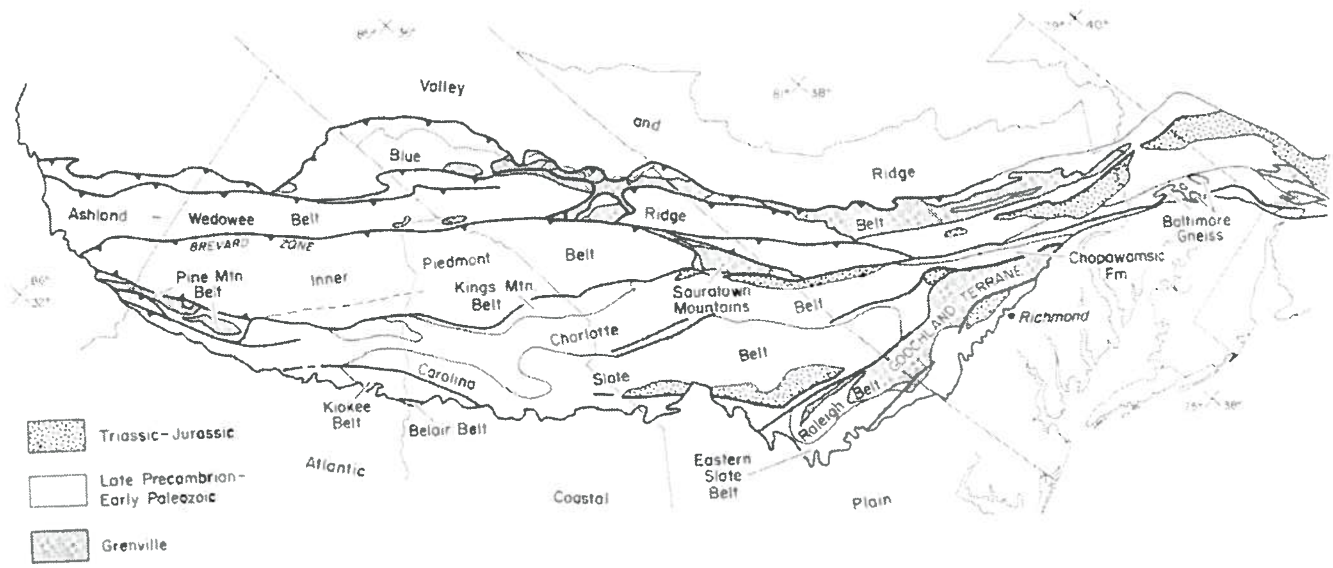


Figure 1. Distribution of Grenville terranes in the southern Appalachians

terranes of probable late Precambrian age. (2) Others (see Rankin, 1975; 1976) recognized that this terrane differed significantly from surrounding terranes and suggested it may have originated as part of another continent - perhaps Africa. (3) It could be a Grenville fragment of North America that was rifted away, had arc volcanics deposited on it, and was reemplaced onto North America. (4) It could be a thinned edge of North American Grenville, with, or without, nonconformable cover, exposed as a window through accreted terranes:

The nonconformity hypotheses certainly had a familiar ring. All previously described Grenville terranes of the southern Appalachians (Fig. 1), including those of the Blue Ridge, Pine Mountain belt, Sauratown Mountains, Baltimore Gneiss domes, West Chester prong, and Honey Brook upland, comprise deep crustal Grenville basement rocks, exposed by erosion and nonconformably overlain by upper Precambrian to lower Paleozoic units of sedimentary and/or volcanic origin. These overlying sequences all have stratigraphic ties, or probable ties, to North America, which help to confirm the North American (Laurentian) origins of these terranes. The more internal (southeastern) of these terranes are then exposed through allochthonous cover. When mapping of the Goochland terrane defined domes of gneiss (State Farm) surrounded by amphibolite and metapelitic rocks, it was natural to assume that this would be another case of Grenville gneiss domes nonconformably overlain by a volcanic/sedimentary sequence. When the first radiometric age control became available, giving a Grenville age for the State Farm (Glover et al., 1978; 1982), this was combined with the rarity of pelitic rocks elsewhere in the Grenville of the southern Appalachians to further support the nonconformity hypothesis. Farrar (1984) argued against the nonconformity hypothesis for the Goochland Terrane, saying the entire terrane was metamorphosed to granulite facies, and that this granulite metamorphism was, in all probability a Grenville event.

Glover, in a series of articles based largely on geophysical data, culminating in Glover et al. (1997), has discussed the tectonic role of the northern (James River traverse) portion of the Goochland terrane as one of several basement thrust sheets clipped off the eastern (present orientation) thinned, rifted, margin of Laurentia during amalgamation of the terranes which comprise the southern Appalachians. Other such slices include the Blue Ridge thrust sheets themselves, and additional Grenville slices buried under the Coastal Plain sediments of Virginia and Maryland to the east. Rather complex thrust, strike-slip, and late normal faulting combined to expose the Goochland Terrane in a huge window through overlying accreted terranes. These faults now comprise the boundaries of the Goochland Terrane. This Glover et al. (1997) model interprets the existence of Laurentian crust in the subsurface approximately to the present continental margin.

Following the model of Glover et al. (1997), the Goochland terrane was part of Laurentia through Grenvillian mountain building and late Precambrian rifting events, only becoming allochthonous during Paleozoic accretionary thrusting which emplaced it farther onto the continent. According to this model the Goochland Terrane rocks were subjected to most of the same tectonic events as the Blue Ridge Grenville. These would include Grenvillian intrusive, metamorphic and deformational events and late Precambrian rifting with its deformational and intrusive events. Paleozoic records could be expected to differ in that these slices ended up in different positions within the Appalachian Orogen.

GOOCHLAND TERRANE

This field guide will start with the northern, more extensively described James River traverse (Fig. 2.), and then progress southward into the proposed continuation of this terrane, the Meherrin River traverse, which some authors (see Sacks, 1999) prefer to discuss as the Raleigh terrane. The terrane is bounded on the west by the Spottsylvania lineament, the Lakeside mylonite zone, then an indefinite boundary the authors haven't examined, then the Nutbush Creek mylonite zone, and at the southern end the D2 decollement of Farrar (1985b) and the Rolesville granite. On the east it is bounded by the Hylas mylonite zone, then a complex interfingering of mylonites (Fig. 2) that eventually becomes the Hollister mylonite zone, then to the D2 decollement that is cut by the Castalia and Rolesville granites on the south. A convenient subdivision between the two portions of the terrane would be the Lake Gordon to Hylas mylonite zone, which others speculate, separates Goochland terrane from speculative extensions to the south.

James River Traverse

Where first defined along the James River traverse (Fig. 3), the Goochland Terrane comprises, in structural succession, the State Farm Gneiss, Sabot

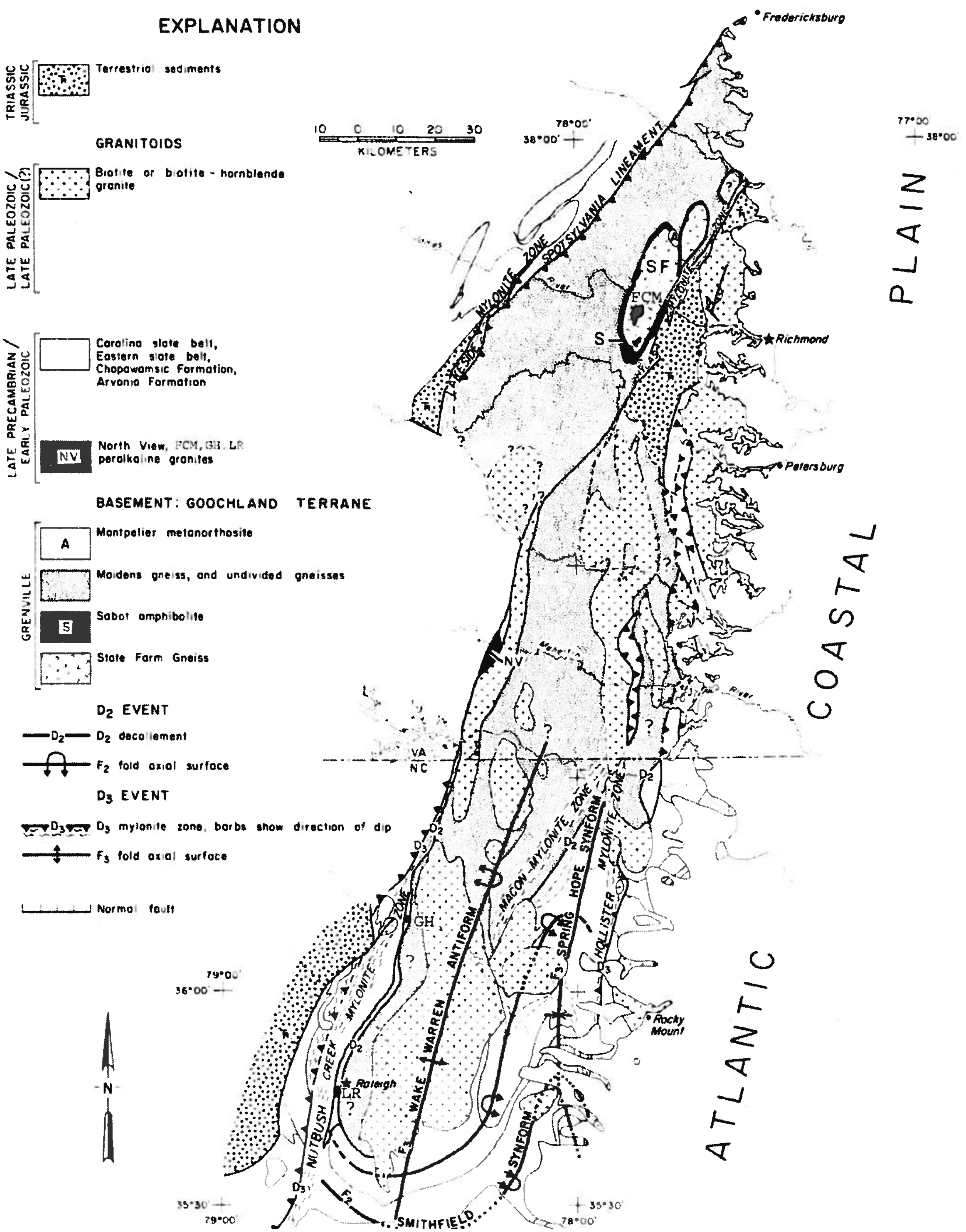
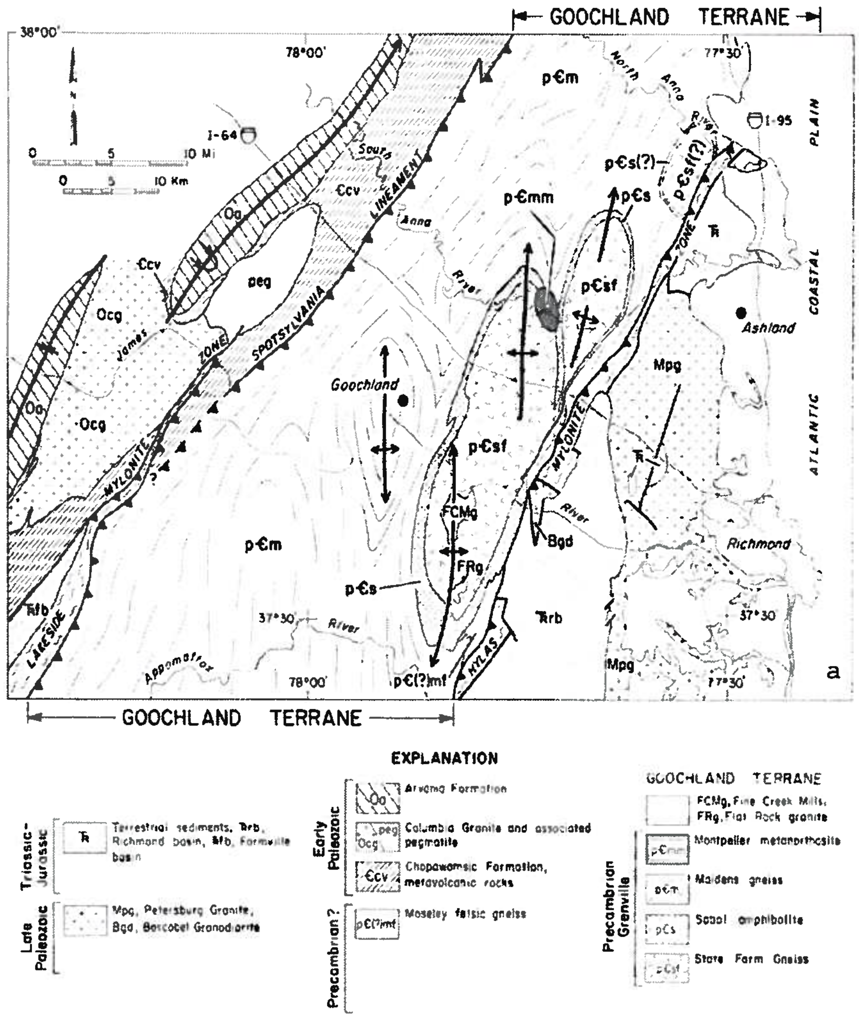


Figure 2. Geologic map of the Goochland terrane, modified from Farrar (1984; 1985b).



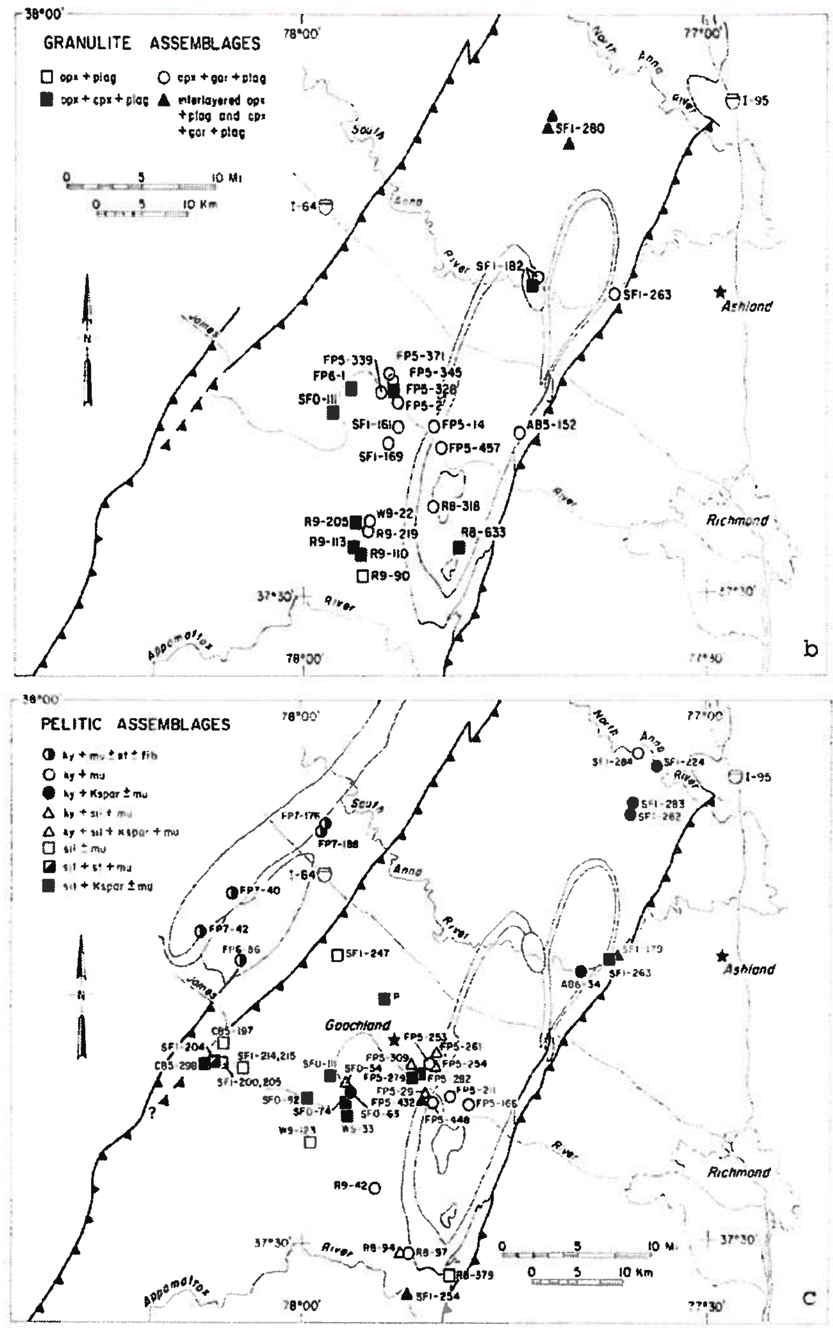


Figure 3. (a) Geologic map of the James River traverse; (b) distribution of granulite assemblages; and (c) distribution of pelitic assemblages used to define the areal extent of the Goochland terrane in the area of the James River traverse. Modified from Farrar (1984).

Amphibolite, and Maidens Gneiss (Glover and Tucker, dominantly granodiortic to granitic composition, with small gabbroic bodies and minor included lenses of pelitic gneiss. Where least deformed it has relict coarse intrusive textures. The Sabot is dominantly a sheet-like body of hornblende-plagioclase amphibolite with varying amounts of augite and garnet. Similar, less extensive sheets of amphibolite occur in the structurally overlying Maidens. The Maidens Gneiss is an extensive and variable map unit that should eventually be further subdivided. It comprises pelitic gneiss, biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, orthopyroxene-bearing intermediate-to-mafic gneisses, hornblende-plagioclase amphibolite, biotite granitic gneiss, clinopyroxene-plagioclase calcsilicate rock, minor marble, and minor quartzite.

State Farm Gneiss

The state Farm Gneiss (Brown, 1937; Poland, 1976; Reilly, 1980) (Figs. 2; 3) is medium- to coarse-grained, massive to moderately layered, and variably foliated. Much of it is a biotite-garnet-hornblende-quartz-Kfeldspar-plagioclase gneiss. Modal analyses by Reilly (1980) give ganodiorite to tonalite compositions and small gabbroic bodies have been found. It would appear that the map unit comprises several intrusive bodies with a range of compositions, with narrow screens of pelitic gneiss and schist caught between the plutons. Where least deformed, the gneiss is massive and coarse-grained with some granulite facies assemblages preserved. Elsewhere, the granulite pyroxene is pseudomorphically replaced by hornblende+quartz+/-garnet+/-biotite.

The Grenvillian whole-rock Rb/Sr age of 1031+/-94 Ma (Glover et al., 1982) has recently been confirmed by U-Pb zircon geochronology. Three samples from the main State Farm Gneiss dome, which span a range from 57 to 75 wt. % SiO_2, yield upper intercept ages of ~1039 Ma, ~1046 Ma, and ~1022 Ma, respectively (Owens and Tucker, 1999, and unpublished results). These ages are interpreted as the time of crystallization of the igneous protoliths, which were broadly granitic in composition.

Sabot Amphibolite

The Sabot amphibolite (Poland, 1976; Reilly, 1980) structurally overlies the State Farm Gneiss complex. The Sabot is dominantly a medium- to coarse-1979). The State Farm is a meta-intrusive complex of grained hornblende-plagioclase amphibolite which in places has plentiful coarse-grained augite, partially replaced by hornblende. It has minor interlayers of quartz-biotite-plagioclase gneiss, quartz-feldspar leucogneiss, and thin pelitic gneiss layers. The main Sabot is in the form of a sheet 0.7-1.0 km thick, exposed around the periphery of the State Farm antiform and the subsidiary State Farm domes to the northeast (Figs. 2; 3). Thinner, less continuous amphibolite units in the structurally overlying Maidens Gneiss may be related in origin to the Sabot.

Maidens Gneiss

The heterogeneous Maidens Gneiss (Poland, 1976) structurally overlies the Sabot amphibolite. Lithologic variability, combined with structural complexity and lack of exposure combine to make subdivision difficult. However, eventually it will be subdivided into at least three units. (1) Immediately overlying the Sabot is a dominantly pelitic unit with subordinate amphibolite, dirty quartzite, and minor marble with associated calcsilicate layers. Minor peraluminous granite dikes are sillimanite-bearing. This unit surrounds each of the Sabot-ringed domes. Here this unit is called the Hewlett metapelite. (2) To the west of (above?) the pelitic unit lies a thick sequence dominated by biotite-hornblende-plagioclase gneiss and containing the most continuous preserved granulite assemblages of orthopyroxene-clinopyroxene granulite gneiss and clinopyroxene-garnet granulite gneisses. The type location Maidens cave exposure is dominantly biotite–hornblende–quartz-plagioclase gneiss. The best granulite exposures are referred to as the Old Bandana granulite. Although these gneisses dominate this part of the Maidens, there are pelitic interlayers. Some of these exposed along the James River have granulites and pelitic gneisses interlayered on a scale of 10's of centimeters. Coarse augen granitic gneisses and small marble pods surrounded by calcsilicate layers also occur in this unit. (3) The westernmost unit is dominated by a variety of biotite granitic gneisses, some relatively fine-grained, some with coarse augen. Interlayered with the granitic gneisses are subordinate layers of biotite-hornblende gneiss and pelitic gneiss.

There is no age control on the Maidens along the James River, but Horton et al.(1995) report an igneous zircon age of 1035+/5 Ma on a hornblende-biotite granitoid gneiss in the Maidens 20 km southwest of the State Farm dome, near Amelia Court House.

Montpelier Anorthosite

The Montpelier anorthosite is a small massif of alkalic anorthosite, dominated in its igneous assemblage by antiperthite in very large, blocky crystals up to at least 40 cm in length (referred to by collectors as moonstone) with accompanying concentrations of coarse quartz with smokey rims. In much of the body ilmenite, and its metamorphic byproducts rutile and titanite, are the only mafic minerals. Elsewhere, there are mafic clots of very large augite, hypersthene, ilmenite, biotite, and apatite, with their accompanying metamorphic biotite, hornblende, garnet, rutile, and titanite.

Most of the Montpelier anorthosite body was strongly deformed and recrystallized under granulite facies conditions and again, later, under amphibolite facies conditions. There was major grain-size reduction with the creation of a strongly layered anorthositic gneiss from the originally massive body. This layering was isoclinally folded and refolded into complex fold interference patterns. With recrystallization, the feldspar formed separate oligoclase and microcline grains, the quartz was flattened into lenses, and the mafic minerals recrystallized to smaller biotite, hornblende, garnet, rutile and titanite.

Aleinikoff et al. (1996) describe this anorthosite and the dating of one very large zircon and smaller zircons collected from crushing of this anorthosite, giving a crystallization age of 1045 +/- 10 Ma for the anorthosite. Age of Grenville metamorphism, and age of late Paleozoic cooling are discussed below.

Despite its small size, the Montpelier anorthosite is significant in that it appears to have one of the most evolved compositions of any anorthosite on earth (or any other planet!). Specifically, whole-rock analyses show that Montpelier feldspars are unusually alkalic (~$An_{26}Or_{21}$), and it is the most potassic anorthosite yet recognized (Fig. 4a). Figure 4a also shows that Montpelier is more evolved than the Roseland, Virginia anorthosite (located in the Blue Ridge), but that both are enriched in alkalis relative to other anorthosites in the Grenville Province of Quebec. In addition, Figure 4b shows that Montpelier is probably the most Ba-rich of all anorthosites, consistent with its high K. The Roseland body also contains high Ba, but levels of Sr in Roseland and Montpelier are more like those at St. Urbain rather than the unusually Sr-rich Labrieville massif. Collectively, the atypical compositional similarities shared by Montpelier and Roseland suggest some common source characteristics or petrogenetic process in their origin. Furthermore, Montpelier and Roseland are essentially the same age (~1045 Ma). Thus, these anorthosites seem to provide a link, albeit poorly understood, between the Goochland terrane and Laurentia (as represented by the Blue Ridge Grenville).

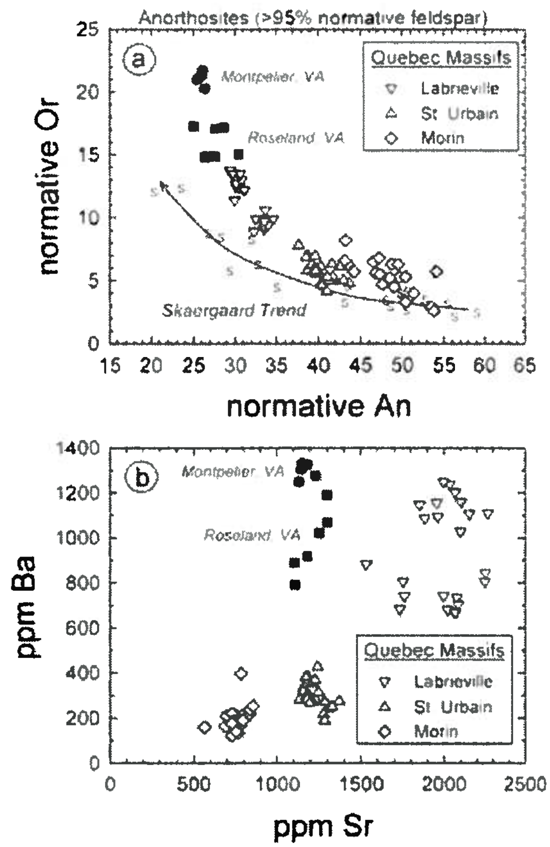


Figure 4. (a) A plot of whole-rock normative An vs. Or for anorthositic rocks of the Montpelier (filled circles) and Roseland (filled squares) anorthosites compared with data for the Labrieville, St. Urbain, and Morin massifs of Quebec [sources of data: Owens and Dymek (1999); Owens and Dymek (2001); and Owens and/or Dymek, unpublished results]. Also shown for reference are whole-rock compositions and a generalized trend arrow for the Skaergaard Intrusion, Greenland (data from McBirney, 1989). The two most evolved samples in the Skaergaard are from the sandwich horizon. (b) A plot of ppm Sr vs. ppm Ba in the same samples as in (a).

Late Proterozoic Granites

Several late Proterozoic granites have been found to intrude the State Farm Gneiss: the Fine Creek Mills, Flat Rock (Fig. 2, 3), and several smaller granitic plutons. The Fine Creek Mills and Flat Rock granites (Reilly, 1980) are medium- to coarse-grained, Kfeldspar rich, biotite or hornblende granites with accessory allanite, garnet, and fluorite. All of these granites are metaluminous, but they display the distinctive chemical signatures of A-type granites, including high Fe/Mg and Ga/Al, and high concentrations of Nb, Y, Zn, etc (see Discussion below). They are clearly intrusive into the State Farm Gneiss, and have a strong lineation to foliation imprinted on them in later tectonic events. New U-Pb zircon results for the Fine Creek Mills pluton indicate an age of ~629 Ma (Owens and Tucker, 2000). Similar results for the Flat Rock pluton and several other unnamed small bodies within the main State Farm Gneiss dome suggest widespread granitic magmatism in this area during the late Proterozoic (Owens and Tucker, unpublished results).

Meherrin River Traverse (Southern Goochland Terrane)

Farrar (1985a, 1985b) suggested that the interior of the Raleigh metamorphic belt comprises a southern continuation of the Goochland terrane. The rocks of this part of the Goochland terrane are characterized by an early, high grade event, evidence for which is lacking in the surrounding Carolina terrane and Spring Hope terrane (Eastern slate belt and outer Raleigh belt) rocks. Other workers (see Sacks, 1999, and references therein) prefer to refer to this as the Raleigh terrane. Farrar (1985a) subdivided this region into the Macon formation and the Raleigh gneiss. A third unit, Farrar's (1985a) Littleton gneiss lies along the eastern edge of the terrane and will not be visited or discussed further here. This terminology will be used in this guide, in that there appear to be no significant boundaries separating these rocks in southern Virginia from those described in North Carolina by Farrar (1985a).

Raleigh Gneiss

The Raleigh gneiss (Farrar, 1985a), described by Parker (1979) as Injected Gneisses and Schists, comprises layered biotite gneiss, biotite-hornblende gneiss, hornblende-clinopyroxene-quartz-plagioclase gneiss, amphibolite, minor pelitic gneiss and schist, and quartzite. Coarse-grained, gneissic, biotite granite dikes commonly parallel or cut gneissic layering at a low angle. In the Raleigh area, the unit is clearly dominated by the biotite gneiss and biotite hornblende gneiss with subsidiary hornblende-plagioclase amphibolite. In southern Virginia, the biotite gneiss and biotite-hornblende gneiss are more commonly accompanied by hornblende-clinopyroxene-quartz-plagioclase gneiss.

The contact between the Raleigh gneiss and adjacent Macon Formation is quite sharp but commonly interfingers as a result of large-scale isoclinal folds with axial planes approximately parallel to the NNE trend of the contact.

Macon Formation

The Macon formation (Farrar, 1985a) in North Carolina comprises pelitic schist and muscovite-biotite granitic gneisses. The schist consistently has textural and mineralogical evidence of an early sillimanite or sillimanite-Kfeldspar high-grade assemblage, but has been very much rehydrated to assemblages that range from greenschist to lower amphibolite facies. The granitic gneisses probably represent granitic intrusions into a pelitic pile, but the entire package has been very strongly deformed. The granitic rocks texturally range from protomylonites to ultramylonites and interlayered pelitic rocks are, in many cases, phyllonites. These textures are found in part because there are at least two generations of mylonites in this area: (1) the mylonites, later recrystallized, that are associated with the D2 decollement (Fig. 2); and (2) mylonite of the very wide Macon mylonite zone, and smaller zones which also cut the Macon formation.

Deformation is somewhat less intense in some of the Virginia portion of the Macon formation, and some of the early mineral assemblages are better preserved here.

Late Proterozoic(?) Granites

Along the western border of the Goochland terrane with the Carolina terrane, there are at least three peralkaline granite plutons, from north to south, the North View, Green Hill, and Lake Raleigh.

The North View pluton, in southern Virginia, lies along the border between the Goochland terrane, to the east, and the Carolina terrane to the west (Fig. 2). It is separated from the Goochland terrane proper by the late Paleozoic Buggs Island granite. The North View is roughly lenticular in plan view and is texturally and, to some extent, mineralogically zoned. Mylonite zones bound it on all sides, and thus its intrusive relationships are not clear. The North View has been overprinted by a greenschist or amphibolite facies metamorphic event that resulted in substantial recrystallization of the granite with the formation of a foliation of variable strength. Exposures of medium-grained North View granite cut by mylonite zones indicate that most of the western and eastern edges of the pluton have been cut off. The northern and northeastern boundaries of granite are porphyritic with a fine-grained or granophyric groundmass. Although also cut by mylonites, these exposures must be very close to the pluton's intrusive contact. The least deformed texture of the pluton interior is a medium-grained, light gray, hypersolvus, peralkaline granite, texturally characterized by blocky mesoperthitic feldspar with a slightly finer-grained groundmass of quartz, aegirine (Fig. 5a), riebeckite (Fig. 5b), and magnetite (Bentley, 1992). Accessory minerals include fluorite, Y-bearing garnet, and a Y-carbonate. The hypersolvus nature of this granite, combined with its fine-grained to granophyric border facies indicate that it was a very shallow intrusion. Horton et al. (1999) determined a U/Pb zircon age of 571±5 Ma for the North View granite.

Two peralkaline granite masses have been found in what has been described (Farrar, 1985a) as the Falls leucogneiss, which borders most of the North Carolina portion of the Raleigh gneiss on the west. Over most of its length, the Falls has been described as a leucocratic biotite or magnetite granite with a strong foliation or lineation. Two bodies within the Falls are mineralogically peralkaline granites (Fig. 5). The Green Hill granite is fine-grained, and strongly foliated or lineated. Quite thorough recrystallization has resulted in most of the perthite recrystallizing to separate microcline and albite, but relict mesoperthite is preserved. Mafic minerals include aegirine-augite (Fig.5a), riebeckite (Fig. 5b), magnetite, and Y-bearing garnet. The Lake Raleigh granite has very similar feldspars, and mafic minerals include aegirine (Fig. 5a) and magnetite. The development of the strong foliation and lineation of these bodies has destroyed evidence of their igneous textures.

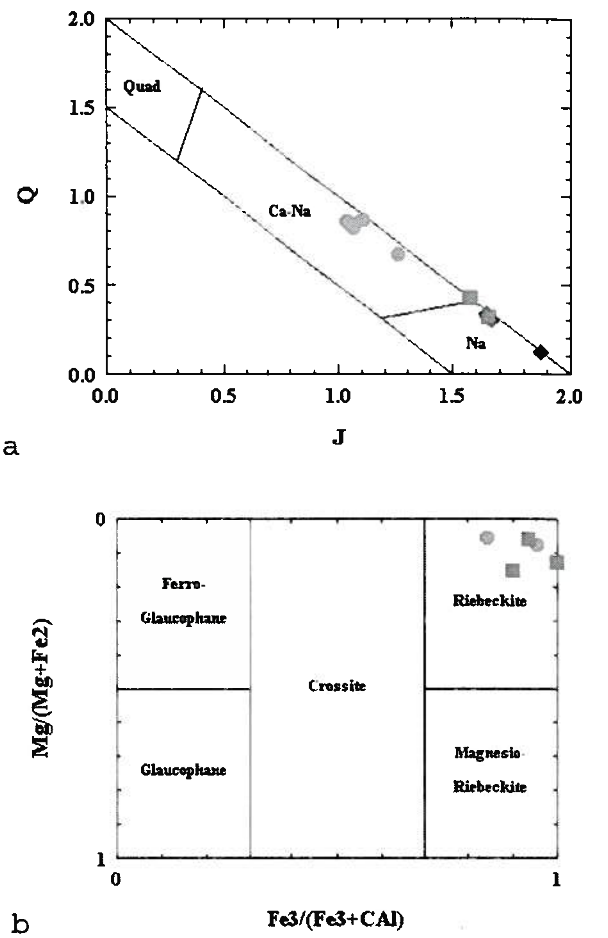


Figure 5. (a) Q-J plot for sodic pyroxenes. Na are aegirine and Ca-Na are aegirine-augite. Squares are North View; circles are Green Hill; diamonds are Lake Raleigh. (b) Classification of sodic amphiboles. Squares are North View; circles are Green Hill.

METAMORPHISM

Metamorphic Event I

The James River traverse rocks were metamorphosed to granulite facies (Fig. 3b), as described by Farrar (1984). There are granulite assemblages preserved within the State Farm Gneiss, Sabot Amphibolite, Maidens Gneiss, and Montpelier Anorthosite that document this event. Distribution of orthopyroxene and clinopyroxene+garnet assemblages are shown in Figure 3 and pyroxene compositions are shown in Figure 6. As described above, the most plentiful granulite assemblages are found in the central unit of the Maidens Gneiss, which is described here as the Old Bandana granulite. In pelitic compositions this granulite event is represented by coexisting Kfeldspar and sillimanite (Fig. 3c). The only inconclusive area in the northern Goochland Terrane is the northeastern-most pelitic unit (the Hewlett metapelite of the Maidens), where no preserved sillimanite has been found.

The Meherrin River traverse rocks were metamorphosed to high metamorphic grade (probably granulite facies). In the Union Mill area of the Raleigh gneiss (Stops 9, 10), assemblages of hornblende-augite-quartz-plagioclase probably represent this metamorphic event. In the Macon metapelite surviving assemblages of garnet-sillimanite-Kfeldspar represent this

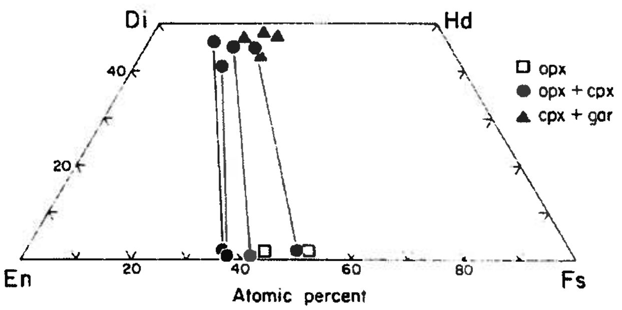


Figure 6. James River traverse pyroxenes; tie lines connect coexisting pyroxenes. Modified from Farrar (1984).

event. Although the sillimanite and Kfeldspar are not commonly preserved in contact, they are preserved in the same rock, separated by retrograde minerals. Examples of the relict pyroxene gneisses and sillimanite-bearing pelitic rocks are shown in Farrar (1985a; 1985b) and Stoddard et al.. (1987).

Metamorphic Event II

The James River traverse rocks have been overprinted by a second, amphibolite facies metamorphic event. Orthopyroxene and clinopyroxene have, in large part, been replaced by hornblende and biotite (Farrar, 1984). Pelitic gneisses with sillimanite+Kfeldspar have commonly been recrystallized to muscovite+kyanite+/-staurolite. In many individual samples the sillimanite and Kfeldspar have been completely removed, but, as seen in Figure 3, sillimanite survives in some samples across the entire traverse except the northeastern corner, near Hewlett (see Stop 1), where kyanite+Kfeldspar±muscovite is found. Probably the kyanite has replaced sillimanite in this assemblage, but no relict sillimanite survives. If the kyanite+Kfeldspar were a stable assemblage, it would represent much higher temperature and pressure than is found in the rest of the region for the second metamorphic event.

The Meherrin River traverse shows a greenschist to lowermost amphibolite facies second event. Pyroxene-bearing assemblages show major replacement by epidote+chlorite+actinolite at greenschist facies and hornblende at amphibolite facies. Pelitic gneiss shows major replacement by muscovite+chlorite+/- chloritoid at greenschist facies and staurolite at lower amphibolite facies. These replacements are essentially the same as found in the North Carolina part of the terrane (Farrar, 1985a; 1985b).

DISCUSSION-CONCLUSIONS

The Goochland Terrane was defined (Farrar, 1984) by the presence of the granulite, and assumed granulite, assemblages of metamorphic event I described above. This terrane is separated from adjacent terranes by a combination of Mesozoic normal faults, Alleghanian mylonite zones (Hylas zone, Lakeside zone, Nutbush Creek zone, Hollister zone) and recrystallized pre-Alleghanian mylonite zones (Spottsylvania lineament, D2 decollement) (Fig. 2). At its southern terminus in North Carolina the Alleghanian Rolesville and Castalia granites cut the D2 decollement. In Virginia the Burkville granite may also cut the boundary.

Evidence of Grenvillian Intrusions into and Metamorphism of the Goochland Terrane

The Goochland terrane was interpreted to be Grenville in age based on the Grenvillian whole-rock Rb/Sr age of 1031+/- 94 Ma (Glover et al., 1982) for the State Farm Gneiss, the similarity of the Montpelier Anorthosite to the Grenville Roseland Anorthosite of the Virginia Blue Ridge, and the fact that these rocks, and none of the surrounding terranes had been metamorphosed to granulite facies. The Grenville age of the State Farm Gneiss has recently been confirmed by U-Pb zircon geochronology. Specifically, three samples from the main State Farm gneiss dome, which span a range from 57 to 75 wt. % SiO_2, yield upper intercept ages of ~1039 Ma, ~1046 Ma, and ~1022 Ma, respectively (Owens and Tucker, 1999, and unpublished results). These ages are interpreted as the time of crystallization of the igneous protoliths, which were broadly granitic in composition. In addition, these ages indicate that the State Farm protoliths were approximately coeval with the ~1045 Ma crystallization age of the Montpelier anorthosite, as dated by Aleinikoff et al. (1996). The Grenvillian age of this terrane is further supported by the report of an igneous zircon age of 1035±5 Ma (Horton et al., 1995) on a hornblende-biotite granitoid gneiss in the Maidens Gneiss southwest of the State Farm dome.

Also, Aleinikoff et al. (1996) determined a metamorphic zircon age of 1011±2 Ma for the Montpelier Anorthosite. We interpret this metamorphic age to also apply to the rest of the contiguous Goochland terrane, in that a younger granulite event would have resulted in a younger metamorphic age.

The atypical compositional similarities shared by

Montpelier and Roseland anorthosites (described above) suggest some common source characteristics or petrogenetic process in their origin. These chemical characteristics, plus the fact that the Montpelier and Roseland are essentially the same age (~1045 Ma), combine to suggest that these anorthosites provide a link, albeit poorly understood, between the Goochland terrane and not just Laurentia in general, but specifically that part exposed in the Virginia Blue Ridge.

Late Proterozoic A-type Granites and Rifting

An interesting feature of the State Farm Gneiss zircon results (Owens and Tucker, 1999) is that all samples define discordia with lower intercepts of ~600 Ma, reflecting Pb loss or new metamorphic zircon growth in the late Proterozoic. This late Proterozoic "event" in the Goochland terrane can now be correlated with emplacement of several granitic plutons, including the Fine Creek Mills and Flat Rock granites. New U-Pb zircon results for the Fine Creek Mills pluton indicate an age of ~629 Ma (Owens and Tucker, 2000). Similar results for the Flat Rock pluton and several other unnamed small bodies within the main State Farm gneiss dome suggest widespread granitic magmatism in this area during the late Proterozoic (Owens and Tucker, unpublished results). However, the zircon systematics for all samples are complex in that most fractions plot near the lower end of discordia, and show variable amounts of Grenvillian (~1 Ga) inheritance. These results probably indicate that the late Proterozoic granites were derived from Grenvillian crust, either the State Farm gneiss or an equivalent Grenville-age source.

Some insights into the tectonic setting of this late Proterozoic magmatism can be gained from the chemical characteristics of the granites. All are metaluminous, but they display the distinctive chemical signatures of A-type granites, including high Fe/Mg and Ga/Al, and high concentrations of Nb, Y, Zn, etc. (Fig. 7). Thus, these granites share somecompositional features with the late Proterozoic Robertson River igneous suite in the Blue Ridge, interpreted to represent a failed episode of Laurentian rifting at ~735-702 Ma (Tollo and Aleinikoff, 1996).

The North View, Green Hill, and Lake Raleigh peralkaline granites, which border the southern Goochland terrane on the west, share petrographic similarities to the peralkaline members of the Robertson River suite as well. The only age control for this group is the U/Pb zircon age of 571±5 Ma for the North View

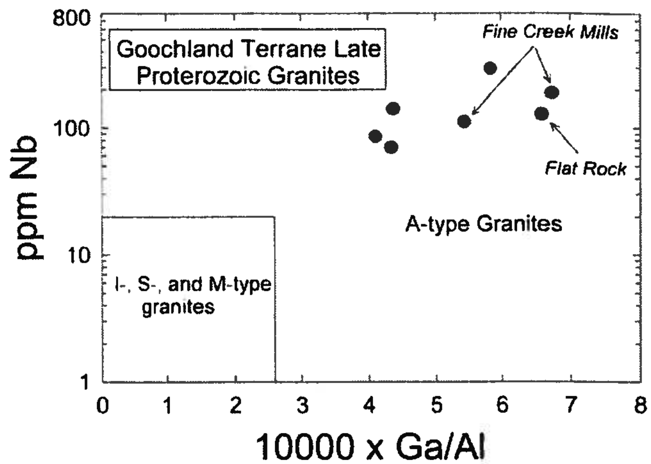


Figure 7. A plot of 10000 x Ga/Al vs. ppm Nb for Late Proterozoic granites in the Goochland Terrane. Unlabelled points represent analyses from small unnamed bodies. Diagram modified from Whalen et al. (1987).

granite (Horton et al., 1999).

A plausible interpretation for all of these A-type to peralkaline granites of the Goochland Terrane is that they also reflect late Proterozoic rifting. Although their ages are ~100 Ma younger than the Robertson River and Crossnore suite of granites of the Blue Ridge, interestingly, the ~600±30 Ma ages for the Goochland A-type granites are just slightly older than reported ages (~570 Ma) for the Catoctin metabasalts and metarhyolites in the Blue Ridge, which are thought to represent successful Iapetan rifting of Laurentia (Badger and Sinha, 1988; Aleinikoff et al., 1995). As for the alignment of the North View, Green Hill and Lake Raleigh plutons along the edge of the exposed Goochland terrane, it is quite reasonable to expect that they would intrude along extensional fractures in the thinned edge of the Laurentian craton, and that this fracture could be reactivated by later faulting.

Alleghanian Age of Metamorphic Event II

How many metamorphic events occurred during the Paleozoic in this terrane is not known. It is known that there were a number of Alleghanian granitic intrusions into the southern part of this terrane, and along its eastern boundary, and that these were emplaced at moderate depth. It has been shown that late Alleghanian cooling marked the end of metamorphism in the Raleigh belt of the North Carolina portion of the terrane (Russell et al., 1985) and that cooling was of a similar age (late Alleghanian) in the James River traverse (Gates and Glover, 1989; Aleinikoff et al., 1996).

Conclusion

Petrographic, geochemical and geochronologic evidence gathered in the last few years support the tectonic model of the Goochland Terrane as part of the tectonically thinned, rifted margin of Laurentia, intruded by A-type granites at about the time of successful rifting (~ 600 Ma). It probably remained part of Laurentia and was clipped off the margin and thrust up onto the continent with accreted terranes during Paleozoic compressional mountain building. Evidence available at this time suggests, but does not prove, that the southern Goochland terrane had the same tectonic history.

FIELD TRIP STOPS

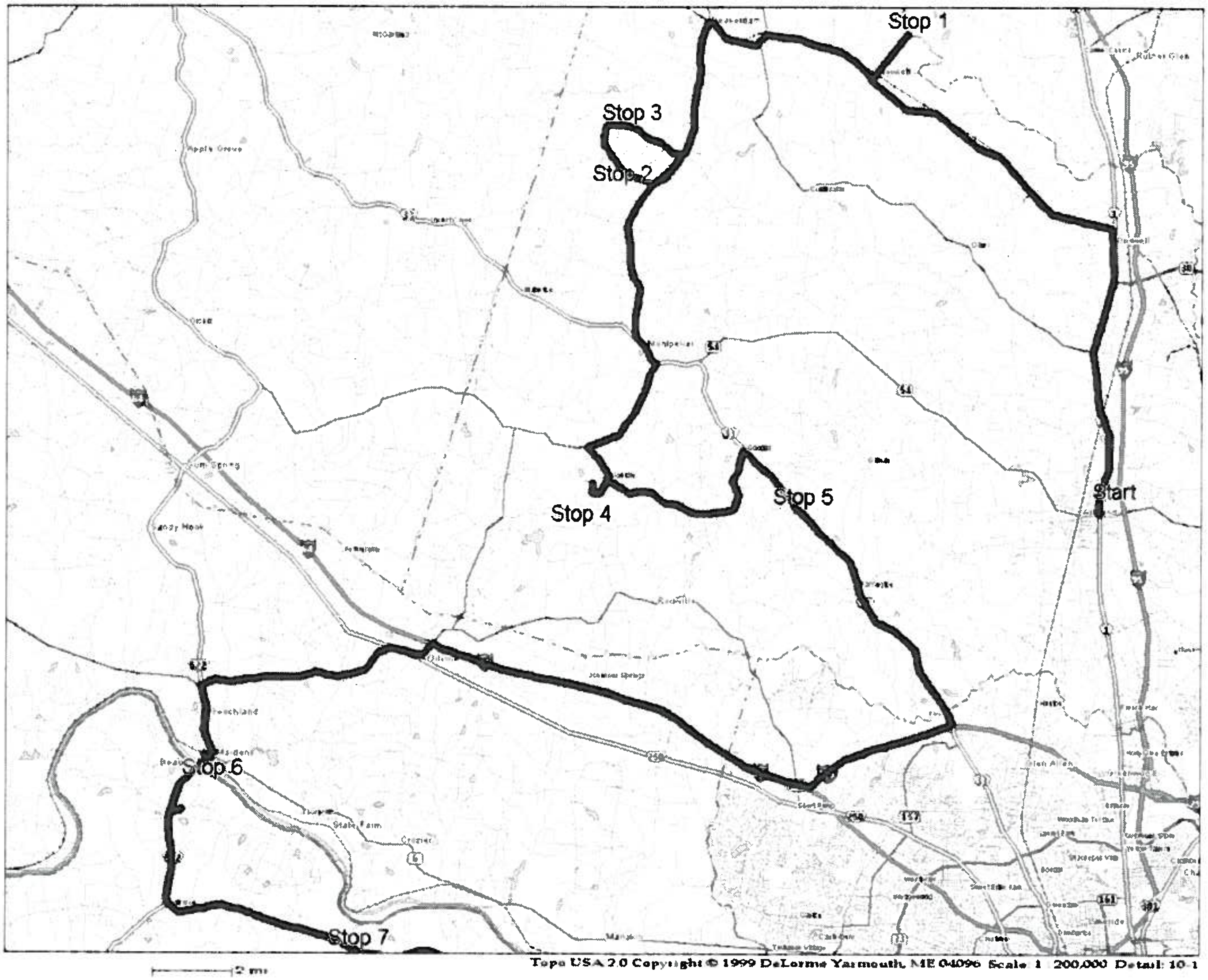


Figure 8. Field trip stops for Day 1.

DAY 1: TUESDAY APRIL 3

Stop 1. Hewlett metapelite of the Maidens Formation. Extensive exposures in the North Anna River at Butlers Bridge on CR 601 in the Hewlett quadrangle

Ledges in and adjacent to the river expose gently dipping, strongly layered, coarse-grained, pelitic gneiss. The assemblage biotite-plagioclase-garnet-kyanite-quartz-Kfeldspar is clearly identifiable in outcrop and thin section. Careful examination of thin sections has shown minor late-forming muscovite, which can also be seen concentrated along fractures in outcrop.

In this northeastern part of the Goochland terrane the pelitic gneiss consistently shows coexisting kyanite-Kfeldspar with no direct evidence of the preexisting sillimanite that is found in the pelitic gneisses to the west and south in the terrane. One of the challenges in working with these rocks is to eventually determine whether kyanite and Kfeldspar were a stable association in these rocks, and if so, whether this was in the Grenville event or the later Paleozoic metamorphism (Compare to Stop 5).

Stop 2. Old Bandana granulite. The outcrop is in a small meadow and streambed north of CR 733 at Tanyard Creek in the Beaverdam quadrangle. Get homeowner's permission to go on property.

The granulite gneiss is tan-weathering, fine-grained, thin-layered, with isoclinally refolded small-scale folds with axial planar foliation dipping steeply. The dominant gray, tan-weathering, gneiss shows biotite, quartz, and plagioclase, with minor garnet and a few grains of hypersthene large enough to be visible in outcrop. Subordinate green-gray layers comprise hornblende, garnet, augite, quartz, and plagioclase. Minor coarse-grained biotite granite dikes cut the gneiss at a low angle to foliation.

Stop 3. Old Bandana granulite. The small outcrops are along Roan Horse Creek north of CR 608 in the Beaverdam quadrangle.

Thin sections of this granulite (SF1-280; SF1-280-2) are described in Farrar (1984). SF1-280-2 is fine-grained bio-opx-qtz-plag gneiss with accessory apatite. SF1-280 is bio-hbd-cpx-gar-qtz-plag gneiss with accessory scapolite, titanite, opaque, and apatite. Both samples retain their granulite assemblages with little evidence of retrogression. The rock here and at Stop 1 is representative of the best preserved granulite assemblages in the Goochland terrane. Several samples of this have been almost completely anhydrous. In fresh exposures, the thin layered, hard, slabby gneiss rings like a bell on sampling.

Stop 4. Montpelier Anorthosite. Active quarry operated by U.S. Silica, at Gouldin in the Montpelier quadrangle. Visit only with prior permission. Hard hat required

The Montpelier anorthosite is a small massif of alkalic anorthosite, dominated in its igneous assemblage by an antiperthite in very large, blocky crystals that are up to at least 40 cm in length (referred to by collectors as moonstone) with accompanying concentrations of coarse quartz with smokey rims. In much of the body ilmenite, and its metamorphic byproducts rutile and titanite, are the only mafic minerals. Elsewhere, there are mafic clots of very large augite, hypersthene, ilmenite, biotite, and apatite, with their accompanying metamorphic biotite, hornblende, garnet, rutile, and titanite. There are also rare, apparently rounded enclaves of pyroxenite, where the pyroxenes show multiple generations of complex exsolution.

Most of the Montpelier anorthosite body was strongly deformed and recrystallized under granulite facies conditions, with further deformation later under amphibolite facies conditions. Recrystallization resulted in major grain-size reduction with the creation of a strongly layered anorthositic gneiss from the originally massive body. This layering was isoclinally folded and refolded into complex fold interference patterns that can be seen in some of the large quarry blocks. The transition from coarse to recrystallized was exposed over a distance of about a meter in a quarry wall, but can now apparently only be seen in loose blocks. With recrystallization, the feldspar forms separate oligoclase and microcline grains, there is flattening of the quartz into lenses and the mafic minerals are now mostly stringers of biotite, hornblende, garnet, rutile and titanite.

Large xenoliths of various weathered country rock gneisses and amphibolite are also exposed around the quarry. There is ongoing debate about whether these gneisses represent State Farm, Sabot, Maidens, or a combination of these units. Quarry walls also show two generations of basaltic dikes cutting the anorthosite. One generation is metamorphosed (apparently post-granulite) and now has an amphibolite assemblage. The second is post-metamorphic diabase, and may be related to other nearby Mesozoic dikes.

The recrystallized anorthosite, which is referred to locally as "aplite" is the preferred material for quarrying, and most of the active quarrying is of this unit. The large feldspars are difficult to crush, so the coarse unit is being avoided, and much of the coarse anorthosite is now buried under the conveyor belt system. Because this is an active quarry, the rock actually exposed varies from visit to visit.

Aleinikoff et al. (1996) describe this anorthosite and the dating of one very large zircon and smaller zircons collected from crushing of this anorthosite. Their interpretation of age of intrusion, age of Grenville metamorphism, and age of late Paleozoic cooling are discussed above.

Stop 5. Maidens metapelite. Outcrops on South Anna River at U.S. 33 bridge, Hanover Academy quadrangle. Metapelite outcrops on both sides of bridge.

This is typical of the metapelites of the Maidens that show evidence of two metamorphic events. Event 1 (granulite event) produced an assemblage of biotite-plagioclase-quartz-garnet-sillimanite-perthitic Kfeldspar. Event 2 converted some of the sillimanite+ Kfeldspar to muscovite + kyanite. All of these minerals are now present in this rock.

To the west, within 1 km along a fishing trail which follows the river, there are exposures of several other rock types of the Maidens, including: fine grained peraluminous granite layers which contain sillimanite; dirty quartzite with pelitic interlayers; garnet-diopside-plagioclase-scapolite calcsilicate; diopside-rich marble; and clinopyroxene-bearing amphibolite.

This metapelite, overlying the Sabot amphibolite, appears to be a major map unit and is continuous with the Hewlett metapelite of Stop 1. This unit, with granulite gneiss interlayers, also overlies the Sabot amphibolite along the James River to the west of the State Farm dome, and is interpreted to be the structurally lowest member of the Maidens Gneiss.

Stop 6. Maidens Formation granulite gneiss, biotite gneiss and biotite-hornblende gneiss. Maidens cave above railroad tracks east of Maidens, Goochland quadrangle.

This is the type locality of the Maidens Formation (Poland, 1976). This little rock overhang exposes thin layered, tan weathering, gar-biotite-hornblende-quartz-plagioclase gneiss, the dominate rock unit of the central part of the Maidens formation. This outcrop exposes a refolded isoclinal fold, illustrating the complex structures of this unit. Thin sections show that thin, green-gray layers have the same garnet-clinopyroxene-hornblende-quartz-plagioclase assemblage found in the Old Bandana granulite. It is interpreted that this is a retrograde amphibolite facies gneiss formed from an Old Bandana-type granulite gneiss.

Stop 7. Fine Creek Mills granite. At Fine Creek Mills in the Fine creek Mills quadrangle. Get permission at house before visiting exposure that is in yard on both sides of Fine Creek.

Coarse-grained, foliated, hornblende - quartz-plagioclase - Kfeldspar granite is well exposed in pavements along Fine Creek. This ~629 Ma A-type granite is one of several which intrude the Grenvillian State Farm Gneiss (see Discussion above).

END OF DAY 1; DRIVE TO SOUTH HILL, VA FOR OVERNIGHT STAY

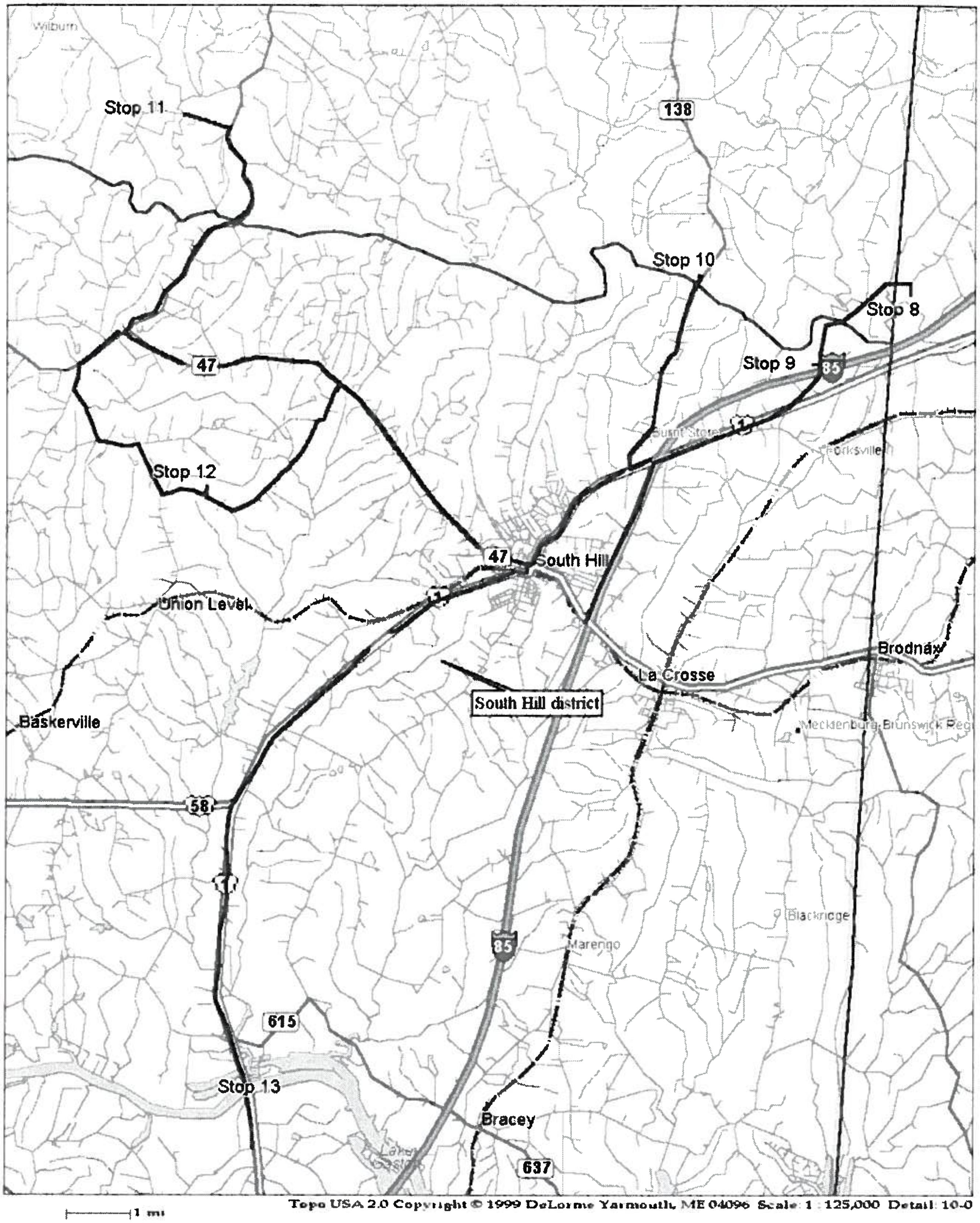


Figure 9. Field trip stops, Day 2 in the South Hill Virginia area., Goochland terrane.

DAY 2: WEDNESDAY APRIL 4

Stop 8. Macon metapelitic gneiss-schist. Forksville quadrangle, VA. Park beside CR 621, 0 .5 km east of Aaron Creek. Walk south to steep bank of Meherrin river (Fig. 9).

Steep bank has outcrop and large slabs of complexly folded coarse-grained pelitic gneiss which retains large porphroblasts of garnet, Kfeldspar, and sillimanite, including sillimanite crystals 1-2 cm in length, most of which have been pseudomorphically replaced by muscovite, but commonly retain sillimanite cores. Quartz-muscovite-feldspar pods appear to be the result of retrogression of assemblages produced by partial melting at the high grade of the sillimanite-producing event. The chlorite-muscovite-quartz retrograde assemblage in this area suggests greenschist facies for the second event, although approximately two km to the north the occurrence of staurolite indicates borderline amphibolite facies for this late event. This major pelitic map unit extends southward into North Carolina where it was described by Farrar (1985b) as the Macon formation. It potentially correlates to the north with the pelitic Maidens Gneiss, which we saw yesterday.

None of the plentiful Raleigh belt pelitic schists surrounding the Goochland terrane to the west, south, or east have this metamorphic sequence of early high-grade sillimanite-Kfeldspar gneiss followed by greenschist to amphibolite facies retrogression.

Stop 9. Union Mill Gneiss, within the larger unit mapped as Raleigh gneiss. Forksville quadrangle, VA. Small stream valley west of CR 621 immediately north of Interstate 85.

Thin-layered, tan, slabby, biotite - quartz-plagioclase gneiss and biotite – hornblende – quartz - plagioclase gneiss, with thin layers of green-gray hornblende – clinopyroxene – quartz - plagioclase gneiss. Coarse-grained, foliated, muscovite-biotite granite layers are later dikes, which can be found to cut isoclinally folded gneiss layers.

Stop 10. Union Mill gneiss. Forksville quadrangle, VA, west of CR 138, 200 m north of Union Mill bridge over the Meherrin River.

The Union Mill gneiss, very similar to Stop 9, comprises interlayered biotite-quartz-plagioclase gneiss, biotite-hornblende-quartz-plagioclase gneiss, and hornblende – clinopyroxene – quartz - plagioclase gneiss. These medium to fine-grained, thin-layered, and isoclinally folded gneisses are cut at low to high angles by later, coarse-grained biotite granite dikes which are generally a few cm to tens of cm thick. These granitic dikes are, themselves, commonly foliated and folded.

The gneisses are cut by a post-metamorphic porphyritic dike that is also exposed along this little creek. Similar dikes are plentiful in this area.

Stop 11. North View peralkaline granite. Roadcut on CR 655 at Mason Creek in the North View quadrangle.

The North View pluton lies along the border between the Goochland terrane, to the east, and the Carolina terrane to the west (Fig. 2). It is separated from the Goochland terrane proper by the late Paleozoic Buggs Island granite. The North View is roughly lenticular in plan view and is texturally and, to some extent, mineralogically zoned. Mylonite zones bound it on all sides, and thus its intrusive relationships are not clear. The North View has been overprinted by a greenschist or amphibolite facies metamorphic event that resulted in substantial recrystallization of the granite with the formation of a foliation that is variably developed in this exposure, which is in the pluton interior. The least deformed rock here is a medium-grained, light gray, hypersolvus, peralkaline granite, texturally characterized by blocky mesoperthitic feldspar with a slightly finer-grained groundmass of quartz, aegirine, riebeckite, and magnetite. To the north, closer to the pluton border, the grain-size becomes finer, the feldspar more clearly porphyritic, and the groundmass in some areas is a granophyric intergrowth of feldspar and quartz.

Aleinikoff et al. (1999) determined a U/Pb zircon age of 571 ± 5 Ma for the North View granite, using samples from this location.

Stop 12. Buggs Island Granite. Quarry north of CR 655, South Hill quadrangle, VA.

Brief stop at gate of quarry in the Buggs Island granite to observe mineralogy and texture of this Alleghanian, foliated, two-feldspar, subsolvus, biotite granite to contrast it texturally and mineralogically with the North View granite.

Stop 13. Raleigh Gneiss. Under the south end of U.S. Route 1 bridge over the Roanoke River, Bracey quadrangle, Virginia.

Thin-layered, biotite gneiss, biotite-muscovite gneiss, and biotite-hornblende gneiss of the Raleigh gneiss of Farrar (1985a). The layered gneiss here is typical of a range of compositions that can be found within the Raleigh gneiss. Exposures to the east, along the shores of Lake Gaston, show varieties very similar to the Union Mill gneiss of Stops 9 and 10.

Stop 14. Macon formation pelitic schist. Business U.S. 158, 2 km east of Warrenton, Warrenton quadrangle, NC (Fig. 10).

Retrograde pelitic schist of the Macon formation of Farrar (1985a). Relict sillimanite is preserved in a foliation cut by the retrograde assemblage chlorite-muscovite-chloritoid. The condition of this exposure is poor, but small slabs of the schist with very visible chloritoid porphyroblasts are plentiful.

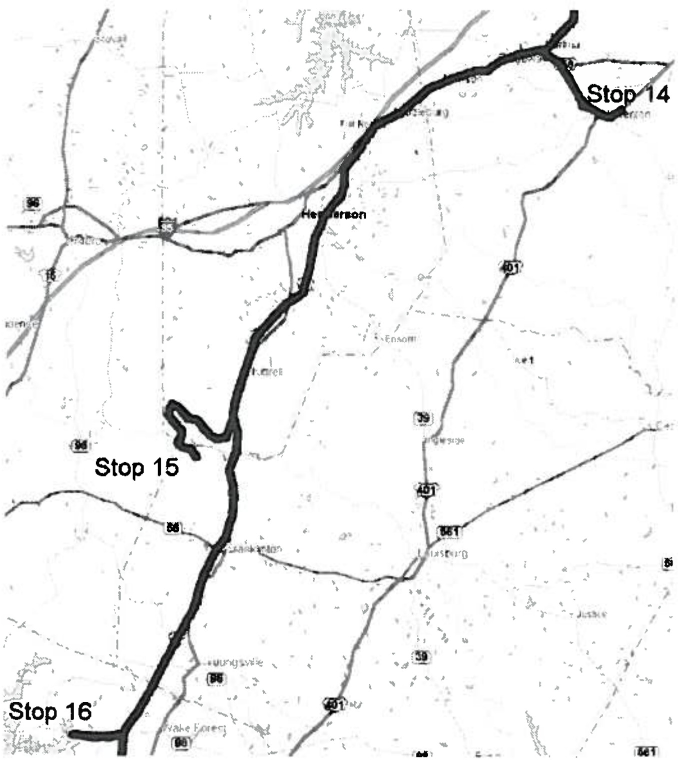


Figure 10. Field trip stops, Day 2 in the northern North Carolina Goochland terrane.

Stop 15. Green Hill peralkaline granite. Low roadcuts on both sides of Green Hill Road (CR 1203), 1 km south of the Tar River, Kittrell quadrangle, NC.

The Green Hill granite is a fine-grained, foliated and lineated magnetite+ riebeckite+ aegirine-augite+quartz+albite+microcline peralkaline granite with accessory Y-garnet and fluorite. The mafic minerals are generally too small to identify in outcrop, but the texture of the rock looks quite similar to the more strongly deformed parts of the North View. This exposure lies within the northern end of the Falls leucogneiss (Farrar, 1985a) and is very similar in mineralogy and texture to the Lake Raleigh granite near the southern end of the Falls leucogneiss - which we will not visit on this trip.

Stop 16 (Optional). If there is time, a brief stop will be made at a spectacular roadcut of Raleigh belt pelitic gneiss-schist on NC 98 west of Wake Forest.

This muscovite–biotite–staurolite–kyanite-quartz-plagioclase gneiss-schist, which lies outside the Goochland terrane, shows all indications of being a prograde mineral assemblage with no evidence, textural or mineralogical of an earlier sillimanite-bearing assemblage.

END OF FIELD TRIP: TRAVEL TO RALEIGH FOR WELCOMING PARTY OF THE 50th ANNUAL SE GSA MEETING.

ACKNOWLEDGMENTS

We appreciate the many property owners who are allowing us on their land. I (SF) thank Lynn Glover for the support, both monetary and geological, that he gave me in the several years that I worked on Piedmont geology in Lynn's Orogenic Studies Laboratory at Virginia Tech. Farrar also thanks J. W. Horton, Jr., for support for mapping through the USGS. Farrar's mapping was also supported by KY/NSF EPSCoR Grants in 1987 and 1992, and EKU Research funds.

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STRUCTURAL FEATURES EXPOSED IN TRIASSIC SEDIMENTARY ROCKS NEAR THE PROPOSED LOW-LEVEL RADIOACTIVE WASTE DISPOSAL SITE, SOUTHWESTERN WAKE COUNTY, NORTH CAROLINA

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INTRODUCTION

A primary purpose of the geological framework studies, which were undertaken at this site in the Deep River Triassic basin (Figs. 1 and 2), was to determine the geologic controls on the local ground-water flow. Geologic mapping (1:12 to 1:3,750 scale), structural analysis, and seismic reflection profiling revealed that extensional and transtensional faulting accompanied by folding and joint development occurred during deposition of these Triassic sedimentary strata. Triassic beds are well exposed in excavations made in the late-1970's for material to construct the auxiliary dam for the nearby Shearon Harris nuclear power plant (Ebasco Services, Inc., 1975). These outcrop areas, which are informally referred to as the north and south borrow pits, expose a heterogeneous sequence of siliciclastic, rift-basin deposits, that are characteristic of the Deep River Triassic basin and include conglomerate, sandstone, siltstone, and mudstone. The general lack of distinctive and laterally continuous marker horizons complicates surface and subsurface mapping. Geologic mapping, trenching, coring and seismic reflection profiling did, however, reveal some stratigraphic marker units, some map and outcrop-scale folds, and six faults not previously reported. In some cases stratigraphic and seismic marker units can be traced along strike for several hundred feet (or meters).

Initial geological characterization of the site showed that most of the sedimentary rocks here had little primary porosity; hence, groundwater flow was likely to be affected by fracture porosity. As a result, detailed study of the structure in and around the site (Figs. 1 and 2) began in 1992 with examination of fractures at exposures of both Triassic sedimentary rocks and crystalline rocks of the Piedmont Province within about 10 miles (16 km) of the site (Bartholomew and Fleischmann, 1993). Analysis of these fractures related the principal joint sets to fault sets that reflected Triassic movement along the basin-bounding Jonesboro fault (Fleischmann and others, 1997). Subsequent work included examination of the Jonesboro fault between Durham and Raleigh (Bartholomew and others, 1994), delineation of the south borrow pit fault (SBPF) (Wooten and others, 1996; 1997a), trenching of the W-8, W-82, and south borrow pit faults at the site (Bartholomew and others, 1997), examination of Mesozoic or younger faults in the crystalline rocks near the Jonesboro fault (Fig. 2) (Heller and others, 1997, 1998; Stoddard and Heller, 1998), interpretation of seismic data from both across the site (Clark and Weil, 1997; Wooten and others, 1997b) and adjacent parts of the Deep River basin (Davis, 1997). This field trip focuses on some of the structural features that can be observed in the borrow pits along the northeast side of the site area.

REGIONAL TRIASSIC FRACTURE SETS

During the Triassic, the Jonesboro fault was probably seismogenically similar to modern-day analogues of segmented, active basin-bounding normal faults in extensional terranes such as those found along the East African rift (e.g., Burgess and others, 1992) or in the Basin and Range Province (e.g., Crone and others, 1987; Machette and others, 1989; Scott and others, 1985; Stickney and Bartholomew, 1987; Wheeler and Krystinik, 1988). Along active faults, principal faults

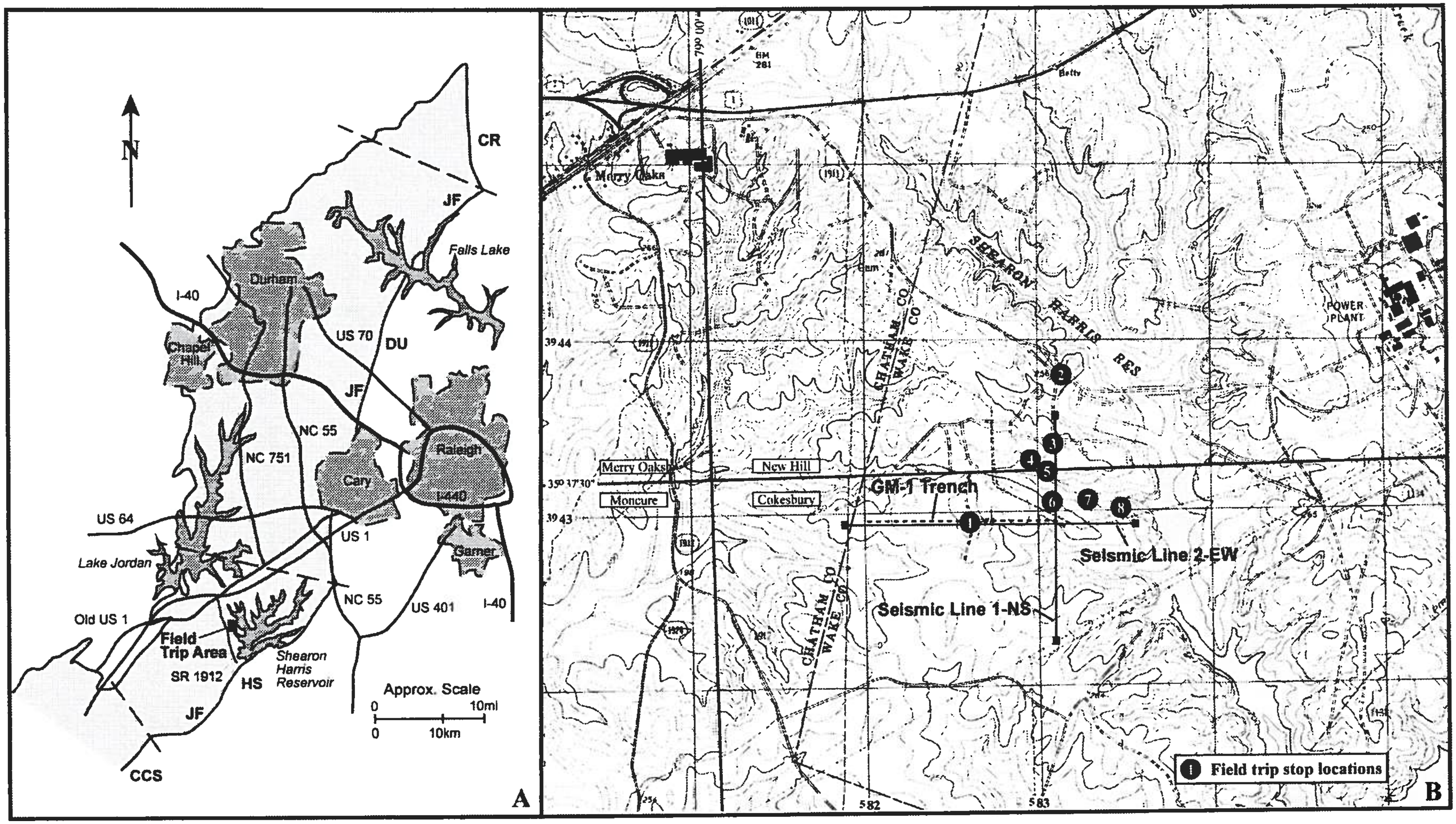
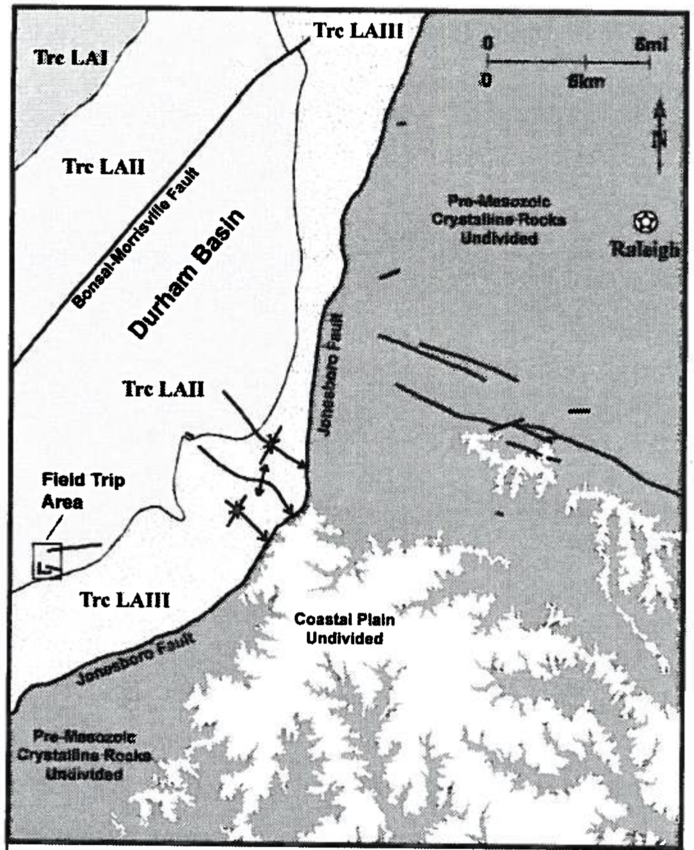


Figure 1. A) Regional map of the Durham basin showing the field trip area relative to segments of the Jonesboro fault (JF) proposed by Bartholomew and others (1994). Segments of the Jonesboro fault: CR=Creedmoor segment; DU=Durham segment; HS=Holly Springs segment; CCS=Colon cross structure. B) Location of field trip stops, seismic lines and GM-1 trench (closed) shown on U.S.G.S topographic map base (from Merry Oaks, New Hill, Cokesbury and Moncure 7.5-minute quadrangles).



Late Triassic Chatham Group Lithofacies Associations - Durham Basin

Trc LAI	Interbedded sandstone and siltstone; braided stream system.
Trc LAII	Interbedded sandstone and siltstone: meandering fluvial system.
Trc LAIII	Interbedded poorly sorted sandstone, pebbly sandstone and conglomerate; alluvial fan complexes.

Figure 2. Map showing faults and related folds in the Durham basin, and brittle faults in crystalline basement rocks in the vicinity of the field trip. Sources of information: Clark and others (2001, this volume); Clark (1998); Stoddard and Heller (1998); Watson (1998), Blake and Clark (in prep.); and North Carolina Geological Survey (unpublished mapping).

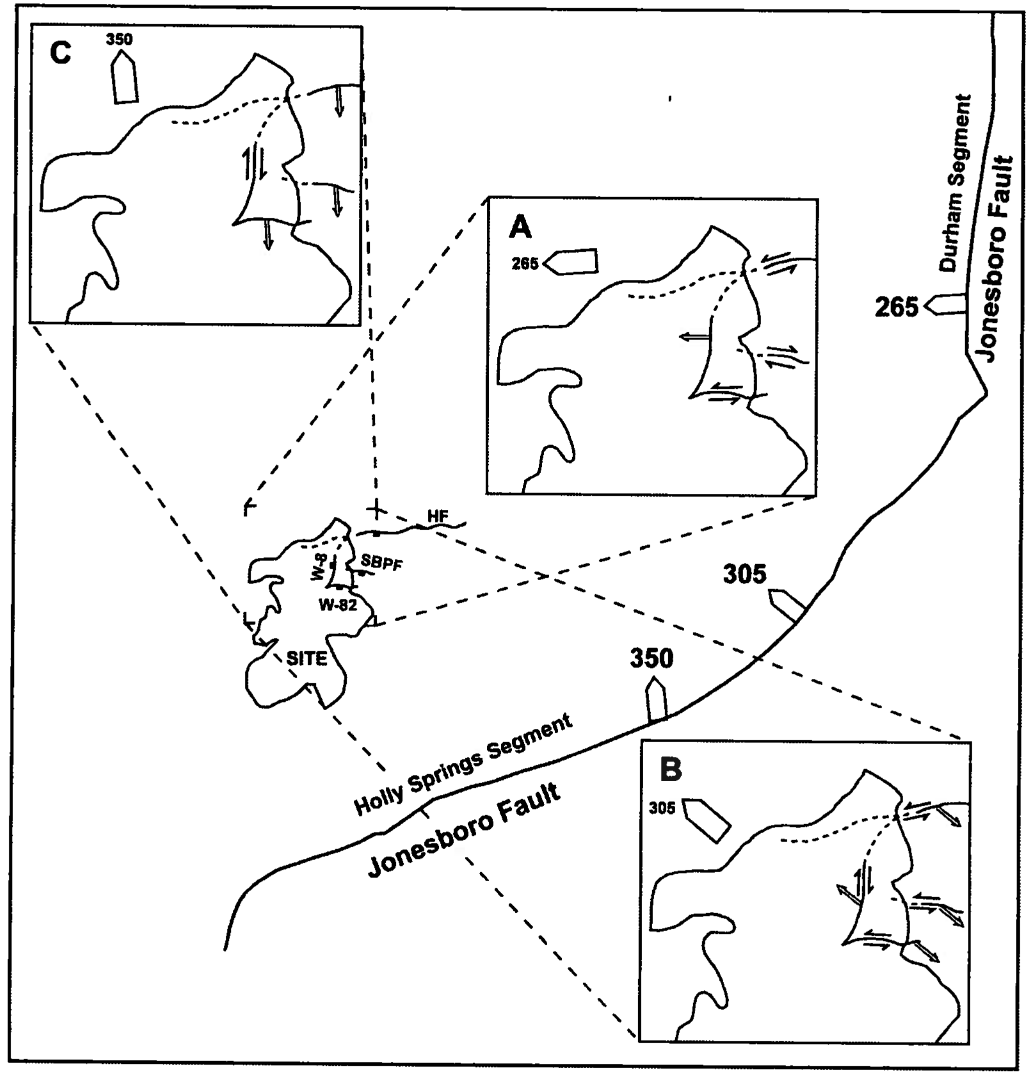


Figure 3. Map showing types of displacement expected along the Harris fault (HF), south borrow pit fault (SBPF), W-8 and W-82 faults relative to the three principal displacement directions along the Durham and Holly Springs segments of the Jonesboro fault during development of the Deep River basin (modified after Bartholomew and Fleishmann, 1993; Fleischmann and others, 1997). A) E-W displacement on the Durham segment. B) NW-SE displacement on the Holly Springs segment. C) N-S displacement on the Holly Springs segment.

segments may slip relatively independently of adjacent segments during major earthquakes. Over time, such independent slip can result in different sedimentological attributes such as thickness and lithology (e.g., Crone and others, 1987; Hannemann and Wideman, 1991) in adjacent parts of a basin, which are separated by a segment-boundary zone that accommodates differential displacement on adjacent fault segments. Such segment-boundary zones may be marked by minor faults and folds and will extend across the basin from a sharp bend that typically marks the segment boundary along the basin-bounding fault. Earthquakes, such as the M 7.3, 1983 Borah Peak, Idaho earthquake (Doser and Smith, 1985), commonly nucleate at depth at segment boundaries and the fault-rupture propagates from there along one segment to the next boundary. In the case of the Borah Peak earthquake, the surface rupture was continuous on the 12-mile (19 km) long, Thousand Springs segment of the Lost River fault and essentially stopped at the Willow Creek boundary zone (Crone and others, 1987). Minor faults and fractures were noted within the boundary zone and discontinuous surface rupture occurred for 8 miles (13 km) north of the zone (Crone and others, 1987).

Based on such modern analogues, the northern part of the Jonesboro fault has been divided into four fault segments (Figs. 1 and 3) (Bartholomew and Flesichmann, 1993; Bartholomew and others, 1994). Recurring displacement on two of these, the Durham segment and the Holly Springs segment, during the Triassic can account for the development of most of the structural features observed around the site which is located near the boundary zone between them (Fig. 3). Some of the joints are filled with either sandstone dikes or claystone dikes (Bartholomew and Fleischmann, 1993). This indicates that these joints developed before the enveloping sediments were buried very deeply and allows the inference that the older joint sets, which the dikes filled, are syndepositional features. Fleischmann (1993) calculated the shallow fluid pressure transients associated with emplacement of these clay dikes. Orientations, lengths, and relative ages of the older joint sets combined with the rapid, fluidized injection of clay and sand into some joints, is consistent with their development during recurring large paleo-earthquakes associated with displacement on the adjacent Durham and Holly Springs segments of the Jonesboro fault (Bartholomew and Fleischmann, 1993; Fleischmann and others, 1997).

STOP 1: OVERVIEW AT INTERSECTION OF GM 1 TRENCH AND N-S ACCESS ROAD

At this stop we will provide an overview of the basin scale features as expressed on regional geological maps and the local seismic reflection data. We have selected two local seismic profiles to summarize the fault structure and reflection stratigraphy of the site (Figs. 1B, 5 and 16).

During site characterization activities in 1993, an aquifer pump test was conducted at this location adjacent the W-8 fault (Figs. 4A, B and C). The elongate drawdown pattern shown by the contours of maximum drawdown in monitoring wells (Fig. 4A) indicated that the W-8 fault had an influence on the local groundwater flow. The results of this aquifer test and borehole packer tests provided the impetus to further characterize the faults and related fractures at the site through trenching and seismic reflection profiling.

The first profile (Figs. 1B and 5) is an E-W-trending line that begins at Harris Lake and extends westward for approximately 1.5 miles (2.4 km) across the site. N-S-trending extensional faults are apparent on this line. Regional relations, seismic reflection data, and examination of strata adjacent to the W-8 fault, collectively suggest that displacement along these normal faults, which parallel the basin-bounding Jonesboro fault, occurred during the Triassic but did not result in surface ruptures. In the GM1 trench, the S-striking fault (W-8 fault) with the largest displacement dips 55°W. (NOTE– Orientations of structural features, such as faults or joints, follows the right-hand convention: strike is from 1 to 360 degrees with the dip direction to the right; dip is from 1 to 90 degrees; and pitch is from 1 to 180 degrees measured from the strike direction.)

The second profile (Figs. 1B, 16), which will be discussed later, is an approximately 1 mile- (1.6 km-) long, N-S-trending line, which is centered on the E-W-trending profile. Several steeply S-dipping faults, which are apparent on this line, are transverse to the long axis of the basin. Fault related folding associated with these transverse faults shows a component of N-S extension, which is in agreement with the structural analysis. Combined, the N-S- and E-W-trending faults break the local geology up in to fault-bounded blocks.

The seismic profiles image less than a kilometer-thickness of the basin's stratigraphy. Thus major sequence boundaries, time horizons, or lithologic markers

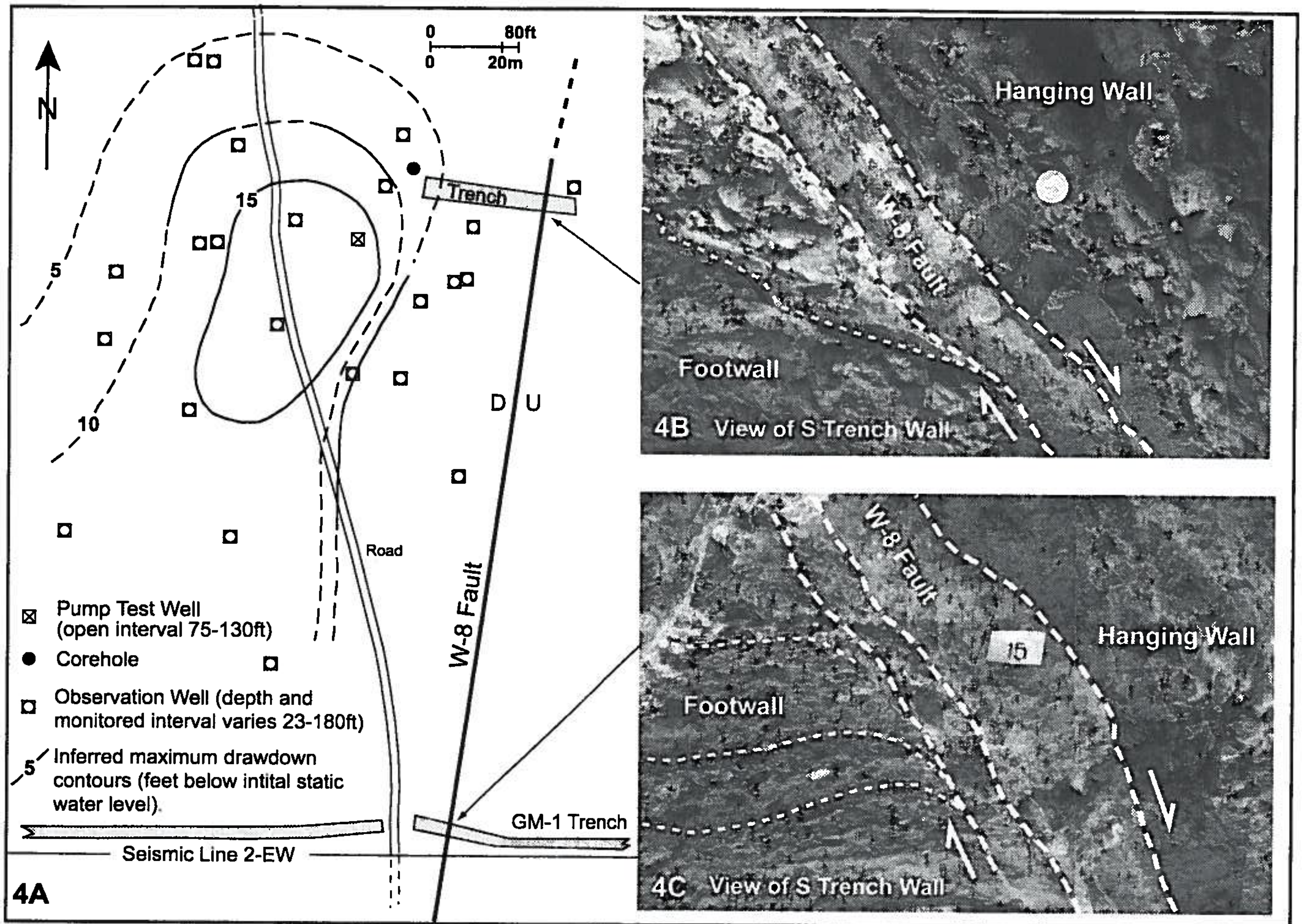


Figure 4. A) Generalized map showing the maximum drawdown in observation wells at aquifer test 4 along the W-8 fault at STOP1 (adapted from Chem-Nuclear Systems, Inc., 1993) B) Close-up photograph of the W-8 fault exposed in a trench near aquifer test 4 showing intense fracturing (quarter for scale). C) Photograph of the W-8 fault exposed in the GM-1 trench (3in x 5in station marker for scale). Heavy dashed lines highlight faults; light-weight dashed lines highlight bedding contacts and show drag folding in conglomerate beds in the footwall in 4C. NOTE: Photographs 4B and 4C show S-facing views of the W-dipping W-8 fault.

are not readily distinguishable because of the shallow depth. Core and geophysical logs in several wells along the E-W profile suggest that many observed reflective horizons represent transitions from mudstone to sandstone, which are, perhaps, the result of a series of upward-fining sequences. Ties between profiles suggest that these reflective horizons may extent laterally from a few to several hundred yards (meters), which is in agreement with the lateral continuity of beds mapped in the borrow pits. These horizons are commonly truncated by the faults. We interpret the reflection data as intrabasinal expressions of basin-scale, half-graben sedimentation and concomitant faulting in the Mesozoic Deep River rift basin. The intrabasinal longitudinal and transverse faults, which accommodated differential displacement histories on adjacent segments of the Jonesboro fault, resulted in a complex system of fault-bounded blocks a few hundred yards (meters) on a side. The transverse faults coupled with the fracture sequence, suggest that episodes of predominantly E-W extension, which characterized Triassic rifting on the Durham segment of the Jonesboro fault, was followed by subordinate episodes of more NW-SE and N-S extension. The combination of fault orientations and displacement directions results in conflicting kinematic indicators along individual faults (Fig. 3).

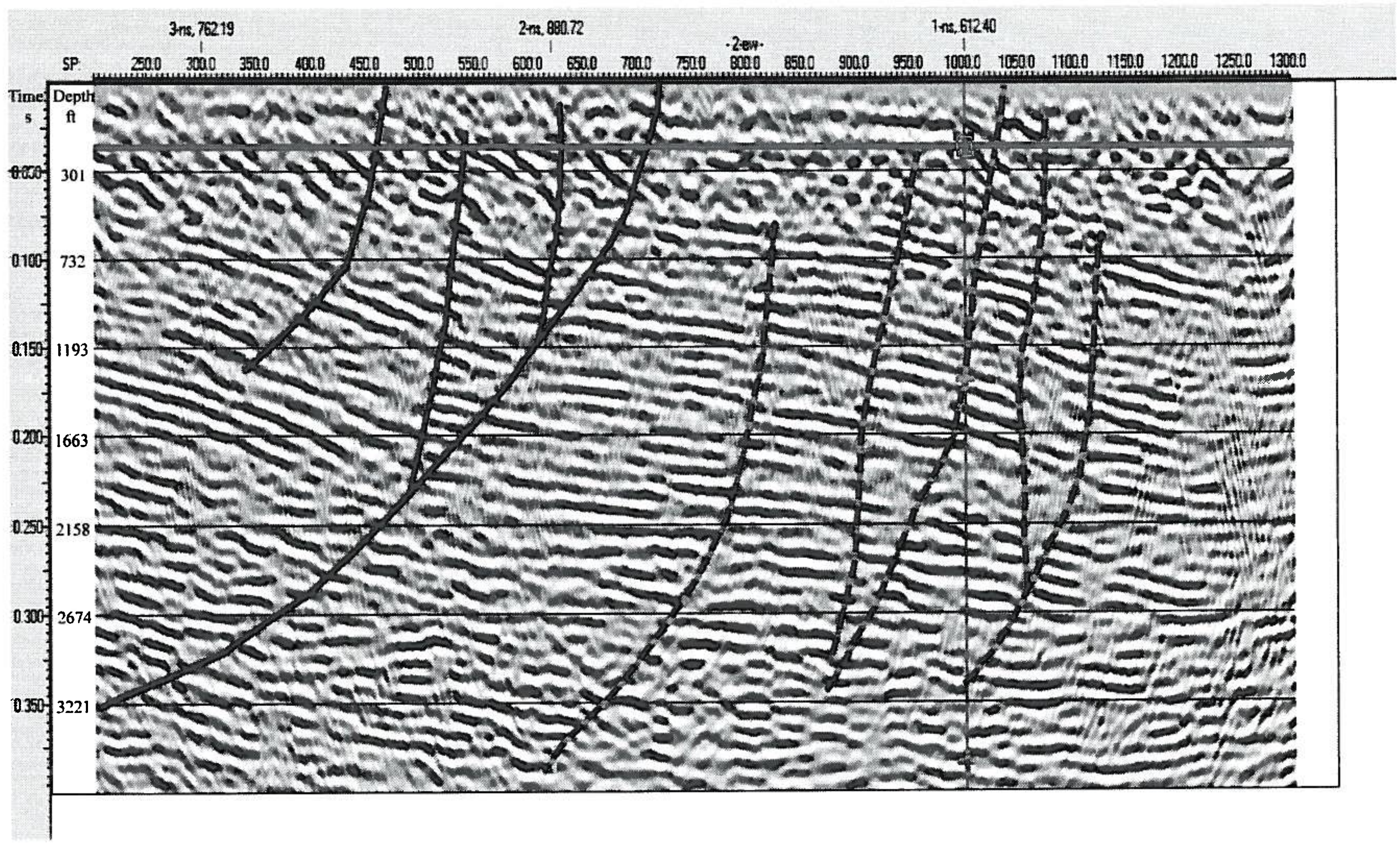


Figure 5. Seismic reflection profile 2-EW. This E-W-oriented dip-profile was gathered with 10-ft shot and station spacings. The source array of 5 caps with silver-nugget boosters at 2.5-ft intervals was centered between stations. The receiver array of 6 high-frequency 40 Hz geophones at 4-ft intervals was centered one station beyond the cable-connection station. The common midpoint (CMP) section shown is a final time stacked time section with lateral and vertical varying velocities. Depths shown to the right of the time scale are based on average stacking velocities for the survey area. Signals above 40 ms are processing artifacts. The vertical line at Shot Point 1001 shows the location of Line 1-NS (Fig. 16). Representative examples of the two major fault systems in the study area are shown in solid and dashed lines. In this case the more listric solid lines are part of the N-S-trending W-8 fault system, and the more vertical dashed lines are part of the SBPF system. Both fault systems have mixed histories of normal and lateral slip, normal motion dominating. The + indicates fault crossings.

STOP 2: HARRIS LAKE AUXILLARY DAM SPILLWAY OUTCROP

Overview

The purpose of this stop is to observe a well-exposed, heterogeneous sequence of siliciclastic rocks typical of the area, and focus on structural features developed in the hanging wall of the Harris fault (HF). Located on the NW- and SE-banks excavated in the mid-1970's along the spillway for the auxiliary dam, this exposure is about 250 ft (75 m) SE of the known surface trace of the Harris fault, and about 3.5mile (6 km) west of the Jonesboro fault (Figs. 1A, 1B and 6)

The ENE-trending, steeply S-dipping Harris fault was discovered during foundation excavations for the Shearon Harris nuclear power plant in the mid-1970's. Extensive trenching during the investigation traced the Harris fault nearly 3000 ft (900 m) along strike and determined offset to be primarily normal (down to the south) with about 83-98 ft (25-30 m) of vertical displacement (Ebasco Services Inc., 1975). Offset near-vertical, diabase dikes of Early Jurassic age (~200 my), in the vicinity of the power plant give evidence for a minor component of left-lateral displacement along the Harris fault. Radiometric age dating of undeformed zeolites in the fault zone indicated a minimum age of Late Jurassic (~150 my) for the last movement along the Harris fault (Ebasco Services, Inc., 1975). Although not verified by mapping or trenching at the Wake/Chatham site, seismic reflection data can be interpreted as showing that the Harris fault extends along strike to the southwest at least 2000 ft (600 m).

Structure and Fractures

Here the NW-striking, 12° - 20° NE-dipping beds are consistent with the general orientation of strata in the north borrow pit (Figs. 6, 7). Farrell and others (1997a) and Farrell and Clark (1997b) interpret the lithofacies at this stop to represent an assemblage of distal fan and flood basin deposits. Recent 7.5-minute quadrangle mapping (Clark and others, 2001, this volume) places these rocks near the contact between lithofacies associations II (fluvial basin) and III (alluvial fan) (Fig. 2). The five lithofacies described by Farrell and Clark (1997b) include: 1) purplish-gray mudstone with root traces and carbonate nodules; 2) burrowed, reddish-brown siltstones and fine-grained silty sandstones with root traces and carbonate nodules; 3) muddy, sandy conglomerate and muddy, conglomeratic sandstone; 4) a channel deposit defined by a sharp-based, lenticular clast-supported sandstone that fines-upward from a conglomerate base; and 5) tan, clast-supported sandstones. The latter two of the five lithofacies are exposed only across the spillway on the SE bank:

Two dominant, high-angle, systematic fracture sets that occur in the NW-bank are well developed in muddy, sandy conglomerate and muddy, conglomeratic sandstone beds. One is an ENE-striking, 75°-90° S-dipping set and the other is a SSE-striking, 60-90° W-dipping set (Fig. 7). Pale green, bleached fracture walls coated with black, manganese and iron oxide staining are present along both fracture sets. Earlier, reducing fluids along fractures likely produced the bleached fracture walls. Much more recently, near-surface groundwater flux precipitated the coating of black manganese oxides along narrow fractures within the bleached zones.

The ENE-striking set is subparallel to the generalized trace of the Harris fault, and is interpreted to be extensional fractures developed during dip-slip (normal) movement along the Harris fault (Fig. 3C). Locally, pinnate fractures also indicate a left-lateral component of movement for the Harris fault (Figs. 3A and 3C). South of the drainage separating the north and south borrow pits a similar ESE-striking fracture set occurs, which is ascribed to the fracture domain of the ESE-striking, S-dipping south borrow pit fault (SBPF) (Wooten and others, 1996) (Fig. 6).

The orientation and dominant sense of displacement of the Harris fault is similar to that of the W-82 fault, which was discovered and investigated during characterization of the Wake/Chatham site (Bartholomew and others, 1997). ENE-striking fractures observed in the southern part of the south borrow pit are interpreted to be related to the W-82 fault, although the surface trace of the W-82 fault appears to be in the drainage south of the south borrow pit. The origin of the SSE-striking fractures is less clear. Bedding also strikes NNW, subparallel to the SSE-striking fracture set, which is consistent with a similar pattern of NW-striking beds and fractures in the north borrow pit. Wooten and others (1996) interpret fracture sets which strike parallel to bedding to have formed in response to longitudinal (basin-parallel) faulting. NW-striking fractures, which are parallel and associated with diabase

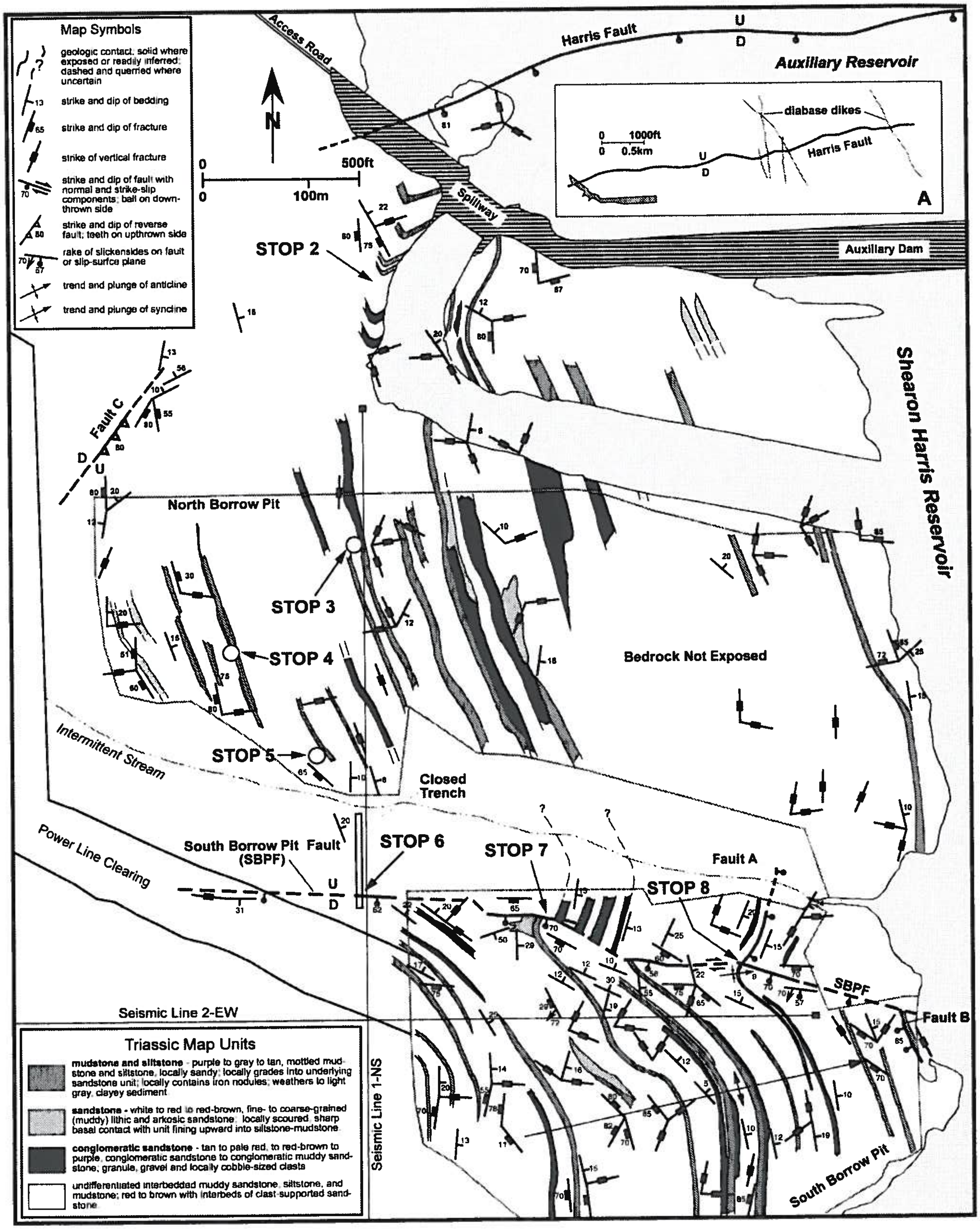


Figure 6. Generalized bedrock geologic map of the north and south borrow pits, and the spillway showing field trip stops 2-8 (adapted from Wooten and others, 1996). Inset A shows the trace of the Harris fault east of the map area (from Ebasco Services, Inc., 1975).

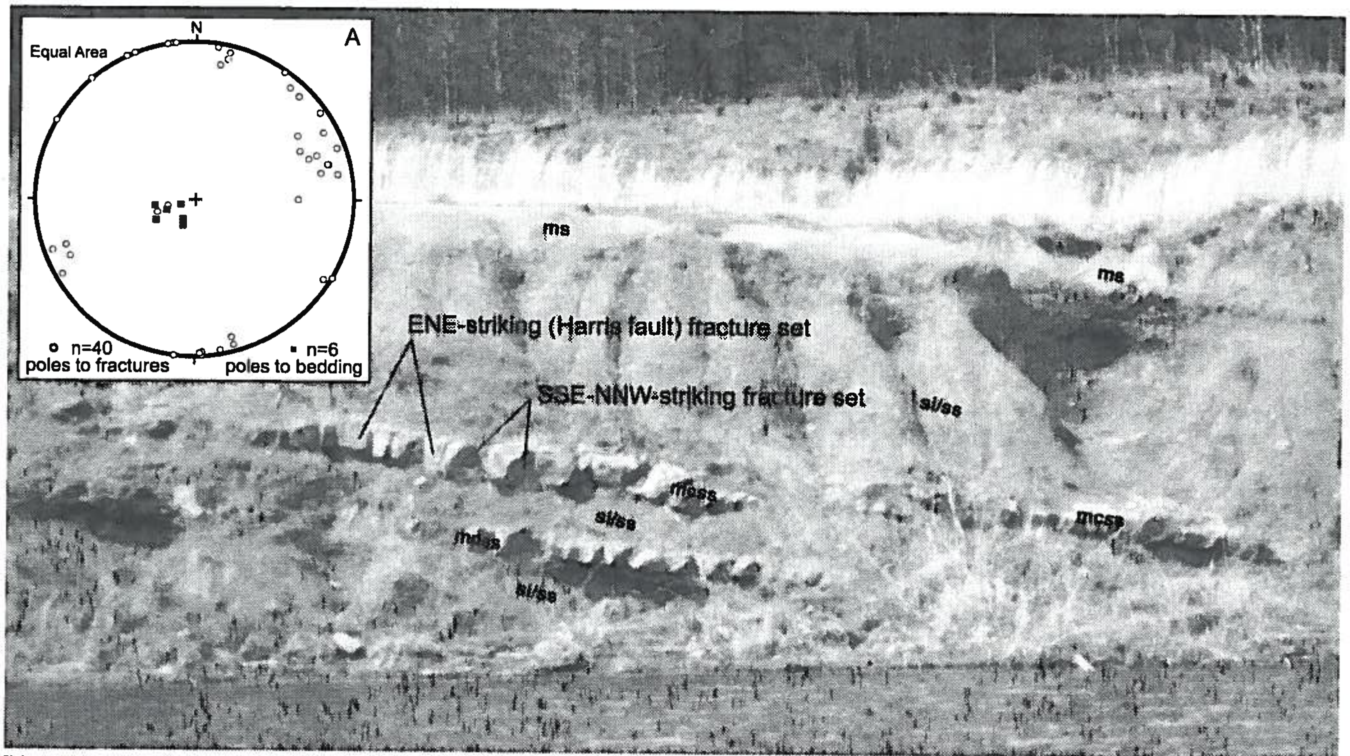


Figure 7. Photograph showing fracture patterns developed in muddy, conglomeratic sandstone (mcss) beds exposed in the NW-bank of the spillway at Stop 2. Interstratified are less resistant beds of purple-gray mudstone (ms) with root traces and carbonate nodules, and red-brown siltstone to very fine-grained, silty sandstone (si/ss). Inset A shows a lower hemisphere, equal area stereonet projection of poles to bedding and fracture planes at this locality. Here beds strike NW and dip 12° to 20° NE. Two high-angle, systematic fracture sets predominate; an ENE-striking set that generally terminates against a SSE-NNW-striking set. The ENE-striking fracture set is sub-parallel to the nearby Harris fault (see Fig. 6). The spillway is upstream and to the right of the photograph.

dikes, are common in the region and are well documented in trench mapping across a diabase dike during studies at the Wake/Chatham site (Chem-Nuclear Systems, Inc., 1993; Bartholomew and Fleischmann, 1993). At this stop, the absence of nearby diabase dikes favors initial formation of these SSE-striking fractures to be related to E-W extension along the Durham segment of the Jonesboro fault and normal faulting along basin-parallel faults within the basin (Fig. 3A). Given that the last displacement on the Harris fault, and related ENE-striking fractures, post-dated both the diabase intrusion and SSE-striking fractures at the spillway, it can be argued that the origin of the SSE-striking fractures at the spillway pre-dates diabase intrusion.

Termination relationships between fracture sets at the spillway vary. In general, however, ENE-striking (Harris fault) fractures terminate against the SSE-striking set indicating the Harris fault fractures are, for the most part, younger. Similar termination relationships occur between SSE-striking and ENE-striking fractures in the north borrow pit. A less dominant NE-striking fracture set present at the spillway probably reflects extensional movement along the Holly Springs segment of the Jonesboro fault (Fig. 3B).

Styles of fracturing differ markedly between sandstone beds and mudstone-siltstone beds. Fracture spacing on the order of 6-18 in (15-46 cm) is typical of the thicker (1.0-1.5 ft; 30-48 cm) muddy, sandy conglomerate and muddy, conglomeratic sandstones beds exposed in the NW-bank. Within similar but thinner (6-8 in; 15-20 cm), sandstone beds however, fracture spacing is on the order of 4-10 in (10-25 cm). More widely spaced high-angle fractures with pale green bleaching and weathering halos cut the thicker mudstones and siltstones in the sequence. The typical fracture pattern in these fine-grained units is a polygonal network of closely spaced, non-systematic fractures. Their polygonal nature and lack of bleaching suggests that these fractures mimic post-depositional pedogenic fabrics overprinted by shrink-swell cracking from modern weathering.

STOP 3: JOINT PATTERNS AND RELATIONSHIPS, NORTH BORROW PIT

Typical age relationships (Fig. 8A) and fracture patterns (Fig. 8B) can be observed along the road west of the telephone pole and south of the road near the telephone pole. NNW-trending bleached joints are generally the oldest set present and terminate against bedding (Fig. 8B). Younger, ENE-trending bleached joints abut against the older set (Fig. 8B). Still younger, non-mineralized, E-trending joints are the youngest set and abut against both older sets. The typical reddish-brown wall-rock of older fractures was commonly altered by reducing fluids and is grayish-green in both core from the site and in deeper clay pits within the Deep River basin. The bleached wall-rock of the fractures, seen here at STOP 3, is the near-surface weathering effect of this alteration by reducing fluids.

The oldest NNW-trending joints are typically 3 to 10 ft (1-3 m) long and spaced from 3 to 10 ft (1-3 m) apart. Younger ENE-trending, bleached joints are necessarily somewhat shorter in length and the youngest, non-mineralized, E-trending set only average about 1 ft (0.3 m) in length. An azimuth versus traverse-distance plot along the road west of the telephone pole showed that this set persist across the north borrow pit parallel to the Harris fault (Bartholomew and Fleischmann, 1993). Another azimuth versus traverse-distance plot, which was done perpendicular to the Harris fault southward across both borrow pits, showed that this youngest, non-mineralized set ceases to be a major component of the fractures about 1000-1200 ft (300-400 m) south of the Harris fault within the north borrow pit. Thus, this set is interpreted to have developed from extension perpendicular to the Harris fault after the rocks were lithified (Bartholomew and Fleischmann, 1993).

STOP 4: LARGE CLAY DIKES, NORTH BORROW PIT

Wide dikes of grayish-green claystone cut through sandstone beds (Figs. 9 and 10A) at numerous locations in different beds between STOPS 4 and 5 and were also observed in core from the site (Bartholomew

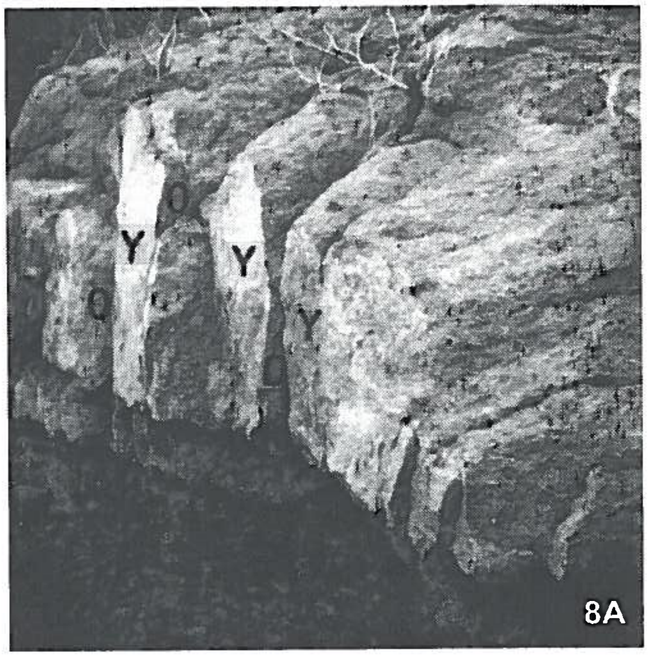


Figure 8. A) Photograph of abutting relationships between older NNW-striking joints (O) and younger ENE-striking joints (Y) at STOP 3 in the north borrow pit. B) Photograph of dominant set of NNW-striking, bleached joints at STOP 3 in the north borrow pit.

and Fleischmann, 1993). Wall rocks of these dikes are bleached, which indicates the presence of reducing fluids at the time of their formation. These NNW-trending dikes are typically 10-30 ft (3 to 10 m) long and individual dikes fill several of the oldest set of joints that become linked together during dike emplacement. They also fill the next younger set of ENE-trending, bleached fractures. These dikes are only found cutting sandstone beds that overlie grayish-green claystones interpreted as lacustrine beds. Matching up blocks across the dikes indicates that they resulted from E-W-extension consistent with slickenlines on low-angle, normal-fault surfaces (Fig. 10B) and with displacement on the Durham segment of the Jonesboro fault (Fig. 3A) (Bartholomew and Fleischmann, 1993). These syndepositional features are interpreted to have developed by earthquake-induced gravity sliding of coherent sandstone beds over water-saturated clay, which then was injected upward along the pre-existing NNW- and ENE-trending fractures.

STOP 5: FRACTURE INTENSITY IN DIFFERENT LITHOLOGIC UNITS, NORTH BORROW PIT

This location shows the relationship of fracture intensity to lithology (Fig. 11). The intensity of both fractures and fracture intersections is similar in coarse-grained and fine-grained sandstones. Siltstones generally have a fracture intensity similar to sandstones, but fracture lengths are somewhat shorter. As the clay content increases in mudstones, the intensity of fractures diminishes. Claystones and claystone paleosols have very few fractures. Thus, vertical and lateral permeability due to interconnected fractures is possible within the stratigraphically repetitive sequences of sandstones and siltstones. However, the presence of numerous mudstones and claystones may inhibit the vertical movement of groundwater from one sandstone-siltstone sequence to another.

STOP 6: TRENCH LOG ACROSS SOUTH BORROW PIT FAULT (SBPF)

In 1995, the south borrow pit fault (SBPF) was trenched (Fig. 12) at STOP 6 along the N-S seismic line (Fig. 16) and a fracture map was made across the fault in the adjacent borrow pit (Fig. 13A) in order to determine the principal sense of displacement on the fault (Fig. 3) and the sequence of joint formation and

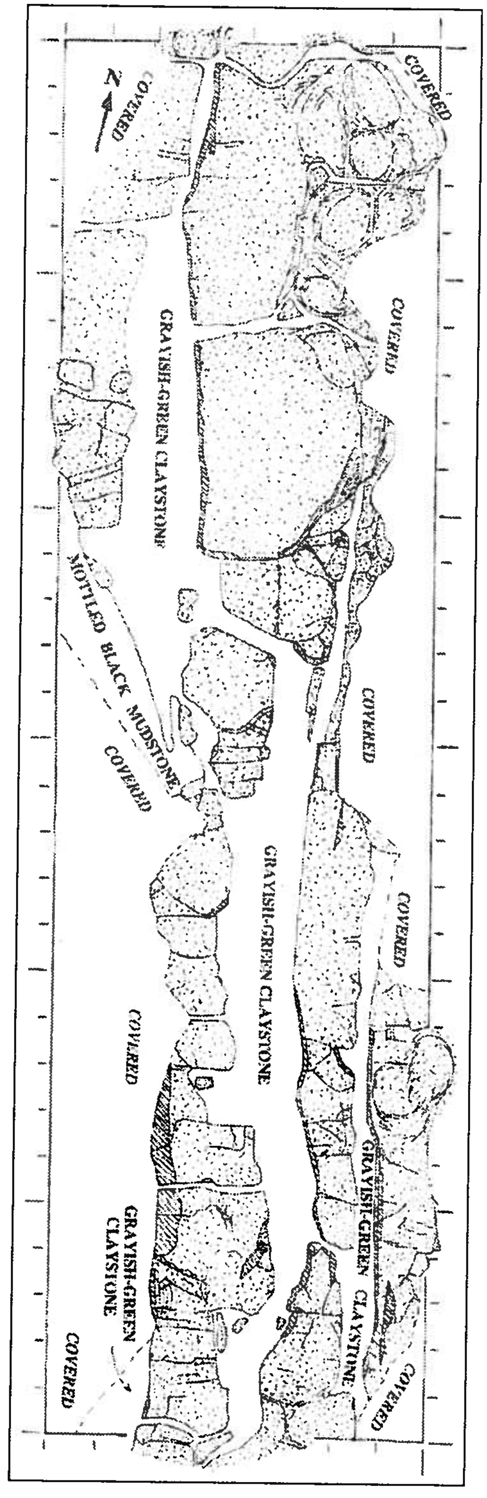


Figure 9. Map of large claystone dikes at STOP 4 in the north borrow pit. Diagonal-lined areas are joint surfaces; sandstone dotted; spheroidal weathered sandstone shown by short curved lines. Mapped by M. J. Bartholomew and K. H. Fleischmann.

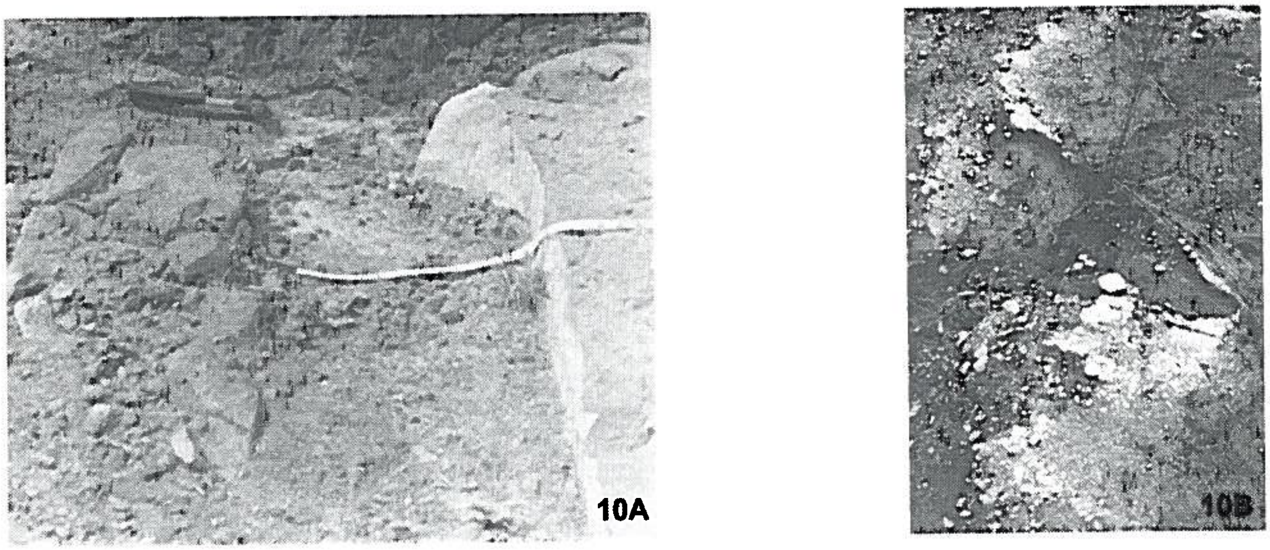


Figure 10. A) Photograph of wide claystone dike with bleached wall-rock contact west of STOP 5. B) Photograph of low-angle extensional fault south of STOP 7 in south borrow pit. Slickenlines, which are parallel to pencil in foreground, indicate E-W-displacement.

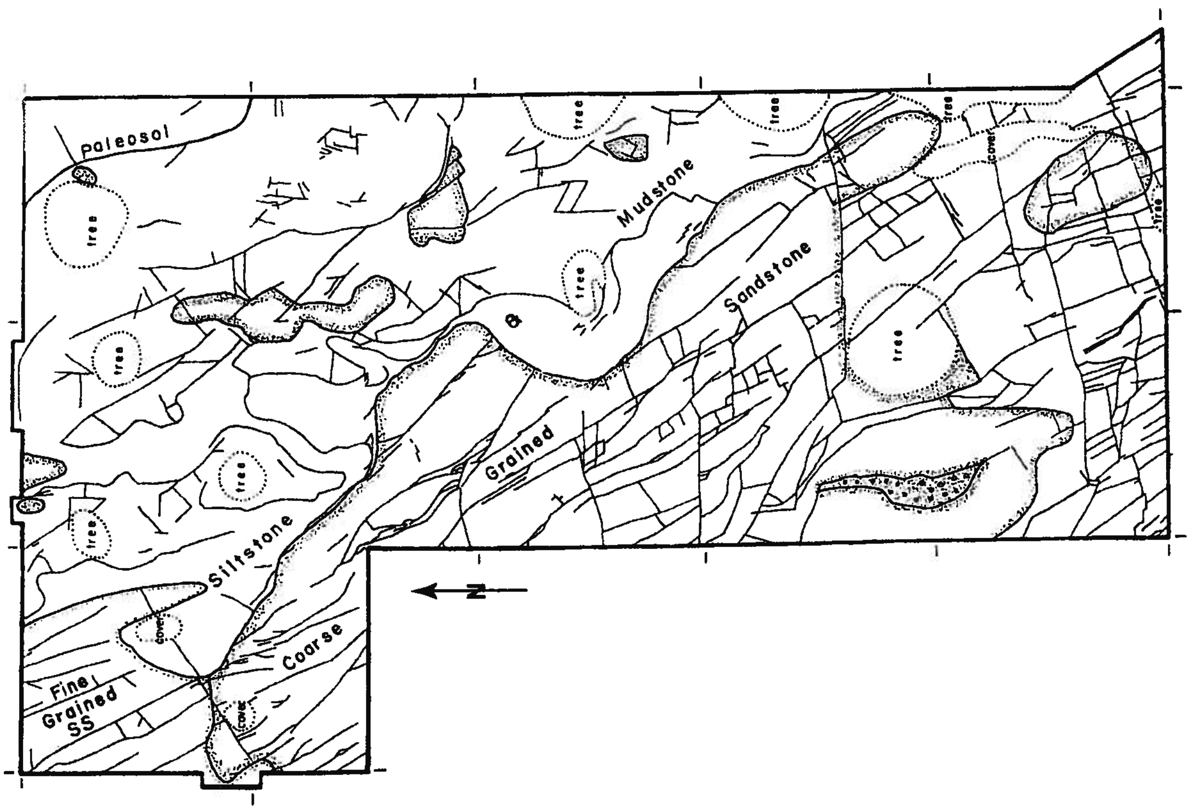


Figure 11. Fracture map at STOP 5 in the north borrow pit showing typical polygonal fracture pattern observed in coarser-grained rocks. Tick marks around border are at 5-ft intervals. Mapped by M. J. Bartholomew, R. D. Heath and B. M. Brodie.

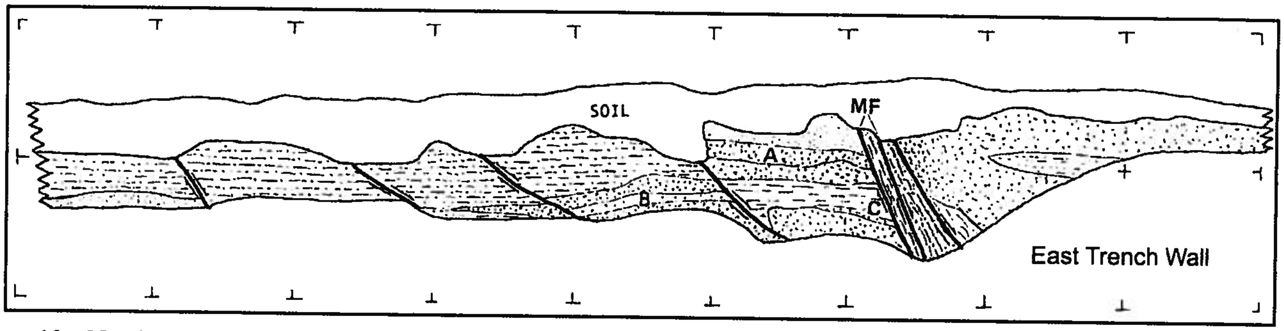


Figure 12. Northern part of trench log across the SBPF at STOP 6 just west of the south borrow pit. Units A, B, and C are coarse-grained, green sandstone; red sandstone (dots), siltstone (dots/dashes), and mudstone (dashes) are not shaded; shaded beds are mottled; MF-main fault; tick marks around border are at 5-foot intervals. Mapped by M. J. Bartholomew and J. Mason.

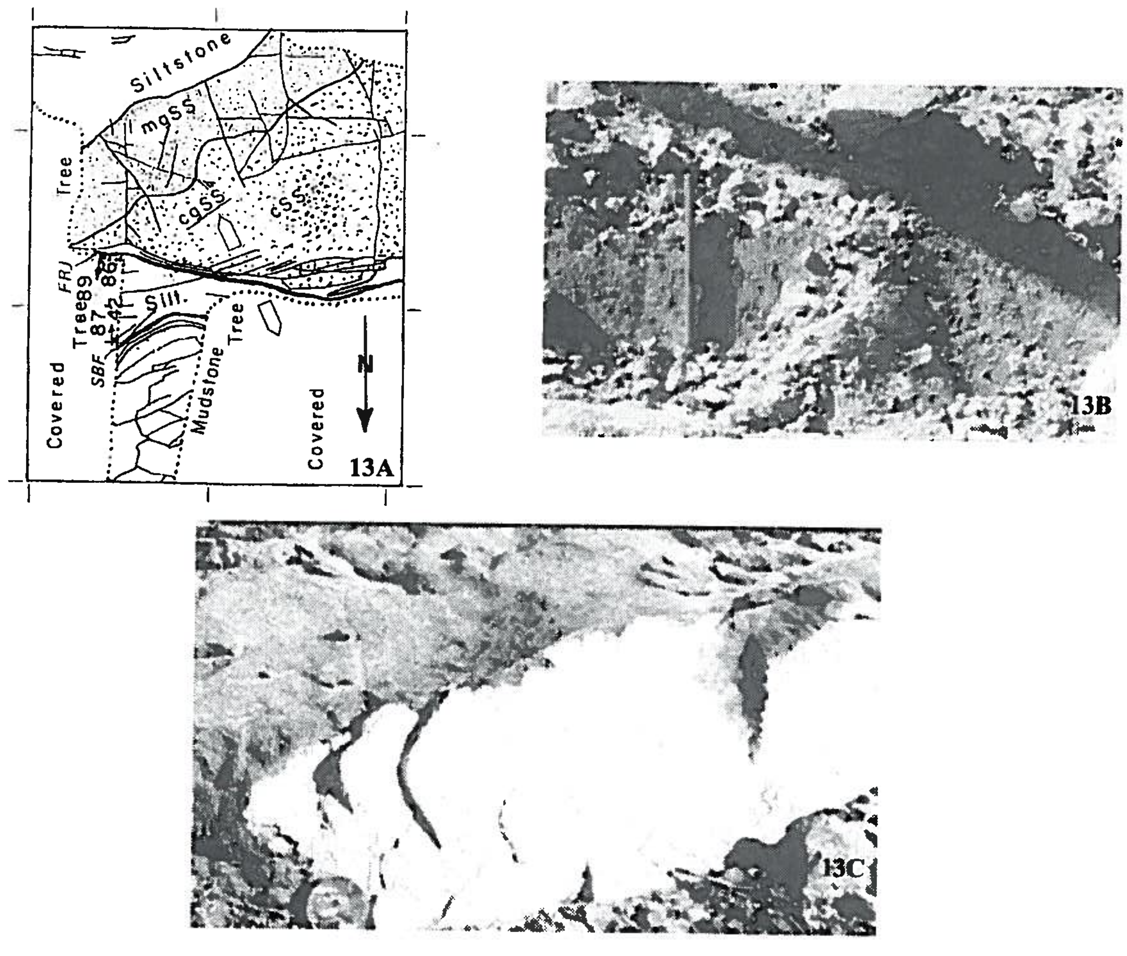


Figure 13. A) Part of the fracture trace map across the SBPF near STOP 7 in the south borrow pit showing large, WNW-striking, mode II, left-lateral pinnate joints (270°, 84°), that indicate N-S extension (large open arrows), along the north side of a coarse-grained sandstone bed. This large joint is related to dip-slip or oblique dip-slip displacement on the SBPF and was later reactivated as a dip-slip normal fault (FRJ). MgSS - medium grained sandstone; cgSS - coarse-grained sandstone; cSS – conglomeratic sandstone; Silt. – siltstone; tick marks around the border are at 5-ft intervals. Mapped by M. J. Bartholomew and S. E. Lewis. B) Photograph of slickensides (parallel to pencil) on the SBPF near STOP 7 indicating dip-slip displacement. C) Photograph of left-lateral, mode II, bleached pinnate joint near the center of the north borrow pit.

reactivation. Slip vectors (Fig. 13B), which were measured on the main fault (Figs. 13A), the five large, nearby faults in the trench (Fig. 12), and fault-reactivated joints in sandstone bed A (Fig. 12), were consistent with the principal displacement directions on the Durham and Holly Springs segments (Fig. 3). These slip vectors are also in agreement with displacement directions on the fault at STOPS 7 and 8 reported by Wooten and others (1997b).

Evidence for right-lateral, oblique-normal displacement was observed at both the trench and the nearby locality (Fig. 14A). This sense of movement is consistent with E-W extension on the Durham segment (Fig. 3A). A minor component of oblique, right-lateral, strike-slip displacement occurred on some fault-reactivated joint surfaces (Fig. 14B), which is consistent with left-lateral, oblique-normal displacement on the SBPF and NW-SE extension on the Holly Springs segment (Fig. 3B). The dominant displacement direction on the SBPF was N-S (Fig. 14C), which is consistent with N-S, oblique-normal, extension on the Holly Springs segment (Fig. 3C). Also at the fracture-map location (Fig. 13A), a near-vertical joint was reactivated as a fault. Small left-lateral pinnate joints (270°, 84°) along this fault-reactivated joint are similar to those observed elsewhere in the borrow pits (Fig. 13C). Here, these pinnates are indicative of N-S extension on the SBPF (Fig. 14C) associated with a component of left-lateral shear on this fault-reactivated joint.

STOP 7: SOUTH BORROW PIT FAULT - WEST EXPOSURE

Overview

This stop is at the westernmost exposure of the SBPF in the south borrow pit. Here, fault-related structures, rock fabric, and fractures have been mapped in detail. The surface trace of the SBPF was delineated though shallow test pits and outcrop mapping beginning in 1994 (see Wooten and others, 1995). Outcrop and fracture-trace mapping delineated internal structures of the fault. More detailed descriptions of this and other exposures along the SBPF are in Wooten and others (1996).

In contrast with the ENE-trending, "left-stepping" trace of the Harris fault (Inset A, Fig. 6), the SBPF has a right-stepping, ESE-trending trace across the south borrow pit. Alternating, nearly E-W-striking and ESE-striking fault-segments delineate the right-stepping

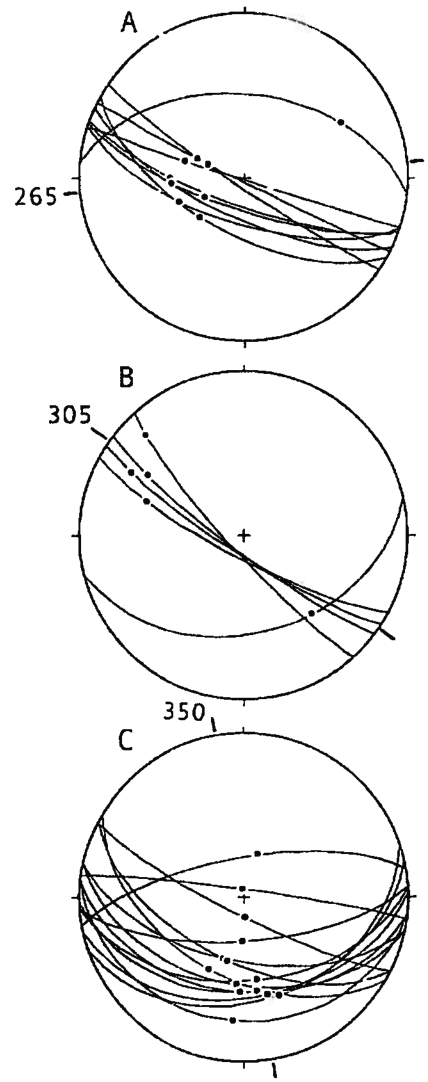


Figure 14. Lower hemisphere equal-area stereographic projections of slickenlines on faults (from Figs. 12 and 13) and fault-reactivated joints (from sandstone bed in Fig. 12) along the SBPF showing relationships to principal directions of displacement on the Durham and Holly Springs segments of the Jonesboro fault (Fig. 3). A) Surfaces with slickenlines indicating right-lateral, oblique-normal displacement, consistent with E-W extension on the Durham segment. B) One fault surface with slickensides indicating left-lateral, oblique-normal displacement associated with normal, right-lateral oblique, strike-slip reactivation of joints, which are consistent with NW-SE extension on the Holly Springs segment. C) Surfaces with slickenlines indicating dip-slip normal displacement, which is consistent with N-S extension on the Holly Springs segment.

surface trace of the SBPF. STOP 7 is located along a nearly E-W-striking segment, that is in transition to a more ESE-strike at the east end of the exposure.

Mapping in the south borrow pit identified a map-scale anticline and outcrop-scale synclines in the hanging wall of the SBPF (Fig. 6). The ENE-plunging hanging wall anticline (i.e., rollover anticline as described by Schlische, 1995) is interpreted to have formed in response to N-S extension and dip-slip movement across the SBPF. Strike-slip movement, and possibly drag folding during normal movement, produced the ENE- to ESE-plunging synclines.

Map-scale footwall folds are less well-constrained. Bedding strike changes northward from NNE in the footwall of the SBPF to NNW toward the north borrow pit. This change shows that map-scale folding, and possibly additional faulting occurs along the SBPF system in the wooded drainage between the borrow pits (Fig. 6). Seismic line 1-NS (Fig. 16) indicates faulting to the north of the SBPF we interpret to be part of the SBPF system.

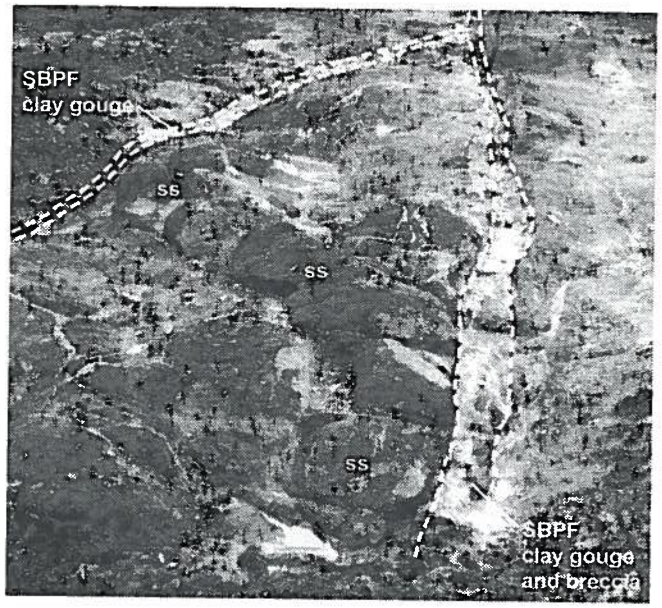


Figure 15. Photograph of deformed and truncated beds between splays of the SBPF at Stop 7 (Fig. 17B). View to the WNW.

Structure and Fractures

The trace of the SBPF was mapped for about 200 ft (60m) along an undulatory E-W- to ESE-strike (Fig. 17A). The SBPF dips 58° S in the west end of the map area and steepens to 70° S at the east end. Slip surfaces in foliated breccia internal to the fault dip as low as 40° S at the west end. Map units in the hanging wall define an outcrop-scale syncline with an ESE-plunging fold axis nearly parallel to the SBPF fault trace. A completely weathered, light gray, arkosic sandstone channel is a distinctive unit on the southern side of the fault. Slip-surfaces, which are sub-parallel to internal stratification within the arkosic sandstone body, show that inter-bed slip accompanied movement along the SBPF. Footwall rocks are not as well exposed, however, a distinctive conglomeratic sandstone crops out at the east end of the map area.

Internal structures exist between two splays of the SBPF (Figs. 15 and 17B) where the SBPF fault dips 68°S to 70°S. Deformed and truncated beds occur between fault splays defined by clay gouge, breccia, and foliated breccia. The sigmoidal shape of the sandstone bed and associated fractures between the splays indicate a right-lateral sense of shear consistent with a Riedel shear model (Fig. 17B). This is in contrast with the pinnate fractures at the eastern end of the map area that indicate left-lateral strike-slip movement (Fig. 13A). Taken together, the kinematic indicators identified along the SBPF indicate a complex movement history dominated by dip-slip (normal) displacement (Fig. 3C) and subordinate components of both left-lateral (Fig. 3B) and right-lateral (Fig. 3A) strike-slip displacements.

ESE-striking, nearly vertical fractures occur throughout the SBPF, and are interpreted to reflect extension roughly orthogonal to the trace of the SBPF (Fig. 3C). Field observations in the south borrow pit indicate that this fracture set increases in intensity near the SBPF, particularly in the hanging wall. Fractures that strike parallel to bedding strike occur throughout the south borrow pit, and their strike appears to mimic the changes in bedding strike in the hanging wall. As at STOP 2, the bedding-strike-parallel fractures here are interpreted to reflect E-W extension and longitudinal (basin-parallel) faulting (Fig. 3A) that predated deformation of the enveloping beds by cross faults, such as the HF, SBPF, and W-82 faults.

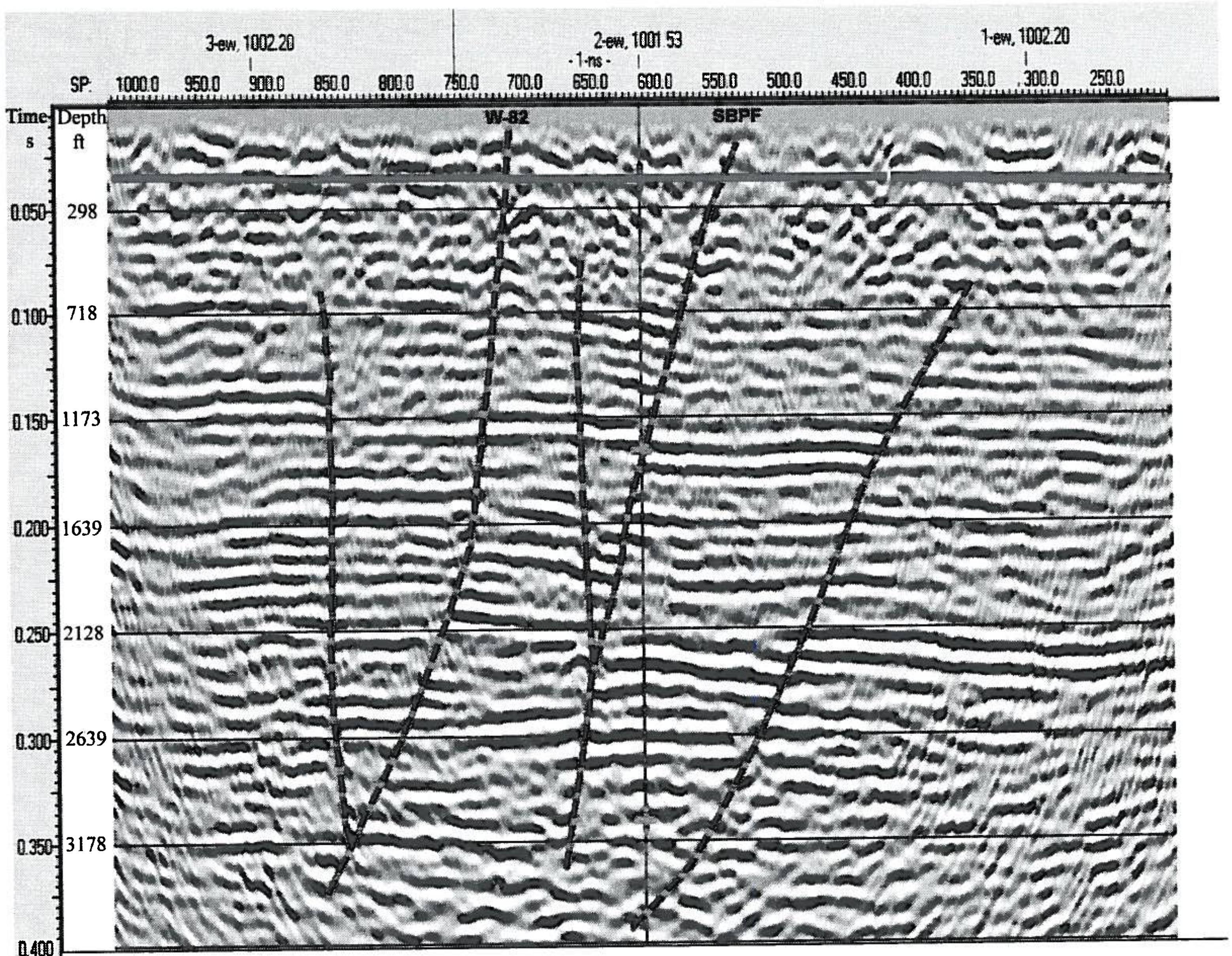


Figure 16. Seismic reflection profile 1-NS. This N-S-oriented strike-profile was gathered and processed in the same fashion as Line 2-EW (described in Fig. 5). In this case the depth in feet was calculated from the average interval velocities (compare to the stacking velocity based depths shown in Fig. 5). Again, signals above 40 ms are processing artifacts. The vertical line at Shot Point 612 shows the location of Line 2-EW (Fig. 5). Representative examples of the south borrow pit (SBPF) and W-82 fault system are shown with dashed lines. The + indicates fault crossings from Line 2-EW.

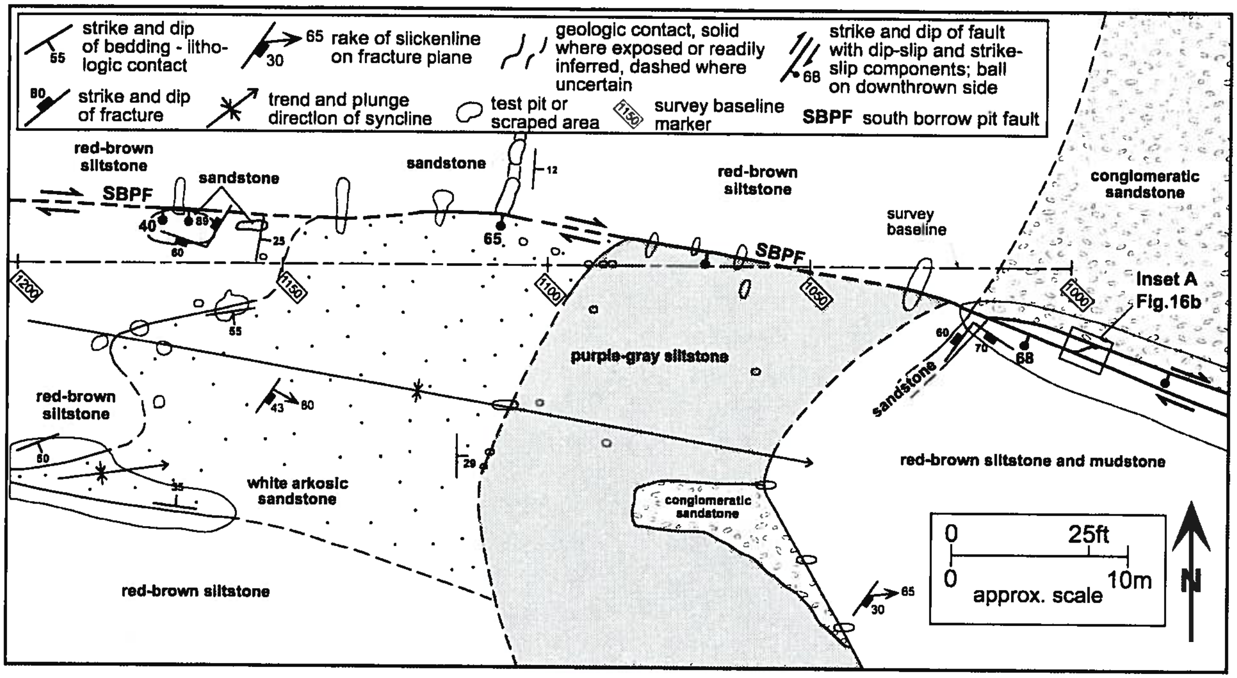


Figure 17A. Geologic outcrop map of the SBPF at STOP 7. Fig. 17B shows the detailed mapping for the area of Inset A. Adapted from Wooten and others (1996).

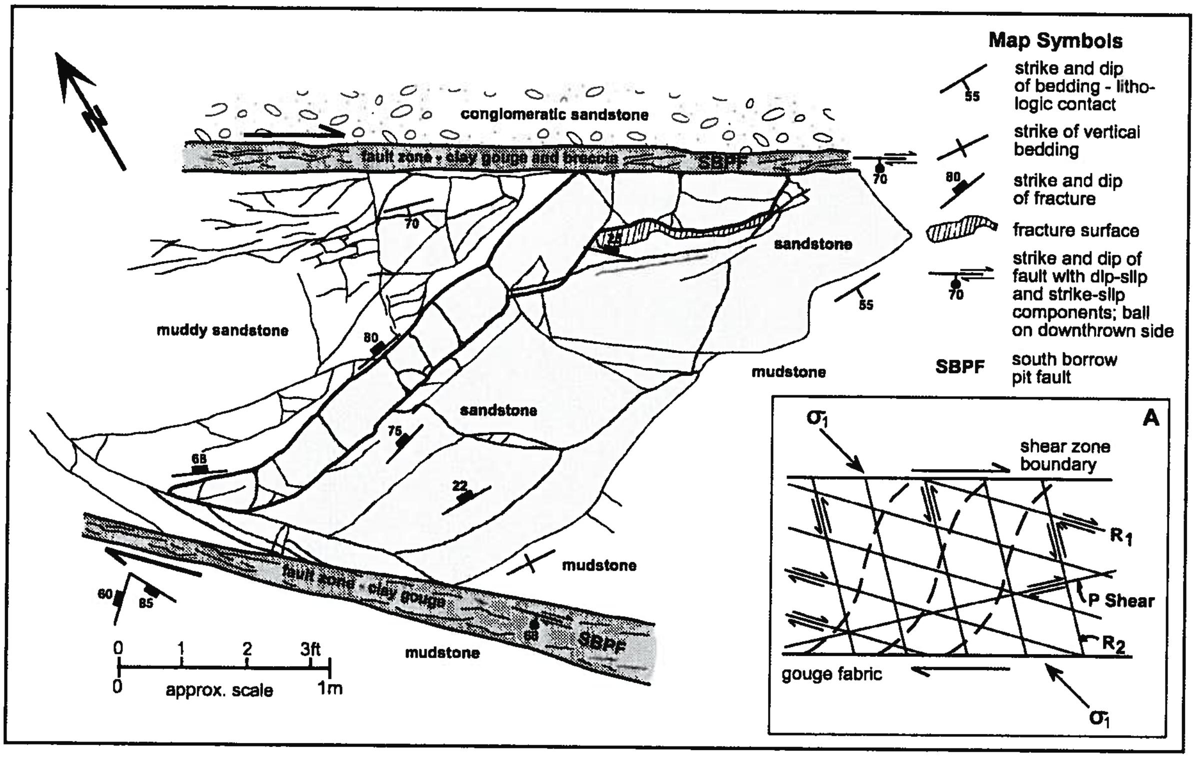


Figure 17B. Outcrop geologic map showing internal structures between splays of the SBPF exposed at STOP 7. Deformed and truncated beds occur between fault splays defined by clay gouge, breccia, and foliated breccia. The sigmoidal shape of the deformed sandstone body and associated fractures between the splays indicate a right-lateral component of shear consistent with the Riedel shear model (Inset A) (modified from McClay, 1987). Faults converge to the northwest (see Figs. 15 and 17A). Adapted from Wooten and others (1996).

STOP 8: SOUTH BORROW PIT FAULT – FAULT-A EXPOSURE

Overview

STOP 8 is located in the east side of the borrow pit (Fig. 6). Here, outcrop-scale structural relationships show that the NE-striking, SE-dipping fault A terminates against the ESE-striking SBPF. Also exposed is a fault-related syncline in the hanging wall of the SBPF (Fig. 19). Fault-related fabrics, folding, and fracture patterns in the hanging wall and footwall of the SBPF are reported in more detail in Wooten and others (1996).

Figure 18. Photograph of the SBPF and fracture trace mapping grid (approx. 1ft grid) at STOP 8. The fault trace follows the low relief area separating the footwall (FW) and hanging wall (HW). Compass points north.

Fracture-trace mapping conducted along the SBPF at this location (Figs. 18 and 19) revealed fracture patterns in the hanging wall of the SBPF that contrast with those in the footwall. Here fracture patterns related to the SBPF occur in two distinct rock units; a fine grained, red to brown, sandstone that defines the hanging wall syncline; and a brown to red, medium to coarse-grained sandstone in the footwall (Fig. 20).

Hanging Wall Sructures

The change in bedding from NW to NE as one approaches the SBPF from the south defines and outcrop-scale syncline within the hanging wall of the SBPF. The beta diagram constructed from bedding data defines a fold axis of 83° at 9° (Fig. 20B). The change in bedding strike was used to divide the hanging wall part of the fracture-trace map into four domains (I, II, III, and IV).

Two primary fracture sets occur in the hanging wall of the SBPF here: a set striking nearly parallel to the SBPF (Set A); and a set at a high angle to the SBPF (Set B). Inset table 20C summarizes properties observed at this location for fracture Sets A and B. Generally, both fracture sets dip greater than 80°. Set A maintains a constant ESE-strike that is subparallel to the SBPF. The fracture map and corresponding equal-area stereonet projections show a change in the trend of Set B from NNW in domains I and II, to NNE in domains III and IV. This change to a more NE strike in Set B, when approaching the SBPF from the south, mimics the strike change of the bedding units in the syncline.

Crosscutting and termination relationships of fractures in the hanging wall suggest that Set A, which is parallel to the SBPF, is generally younger than Set B. This conclusion is based on several observations: 1) Set A terminates against Set B in many cases; 2) Set A fractures locally offset Set B fractures; and 3) the strike of Set B fractures changes orientation near the SBPF similar to the stratigraphic units defining the outcrop-scale syncline. In contrast, the strike of Set A maintains a constant orientation indicating that synclinal folding did not affect Set A, but did reorient Set B.

The geometry of the hanging-wall syncline suggests it formed by drag either related to right-lateral, strike-slip displacement along the SBPF (Fig. 3A) or during normal displacement (Fig. 3C). The orientation of the synclinal fold hinge (83°, 9°NE), however, appears consistent with the shortening direction expected in a right-lateral strike-slip system.

Furthermore, pinnate joints on several E-striking fractures (Set A) are consistent with their formation during right-lateral, strike-slip faulting. In addition, some N-striking, fractures (Set B) are offset in a right-

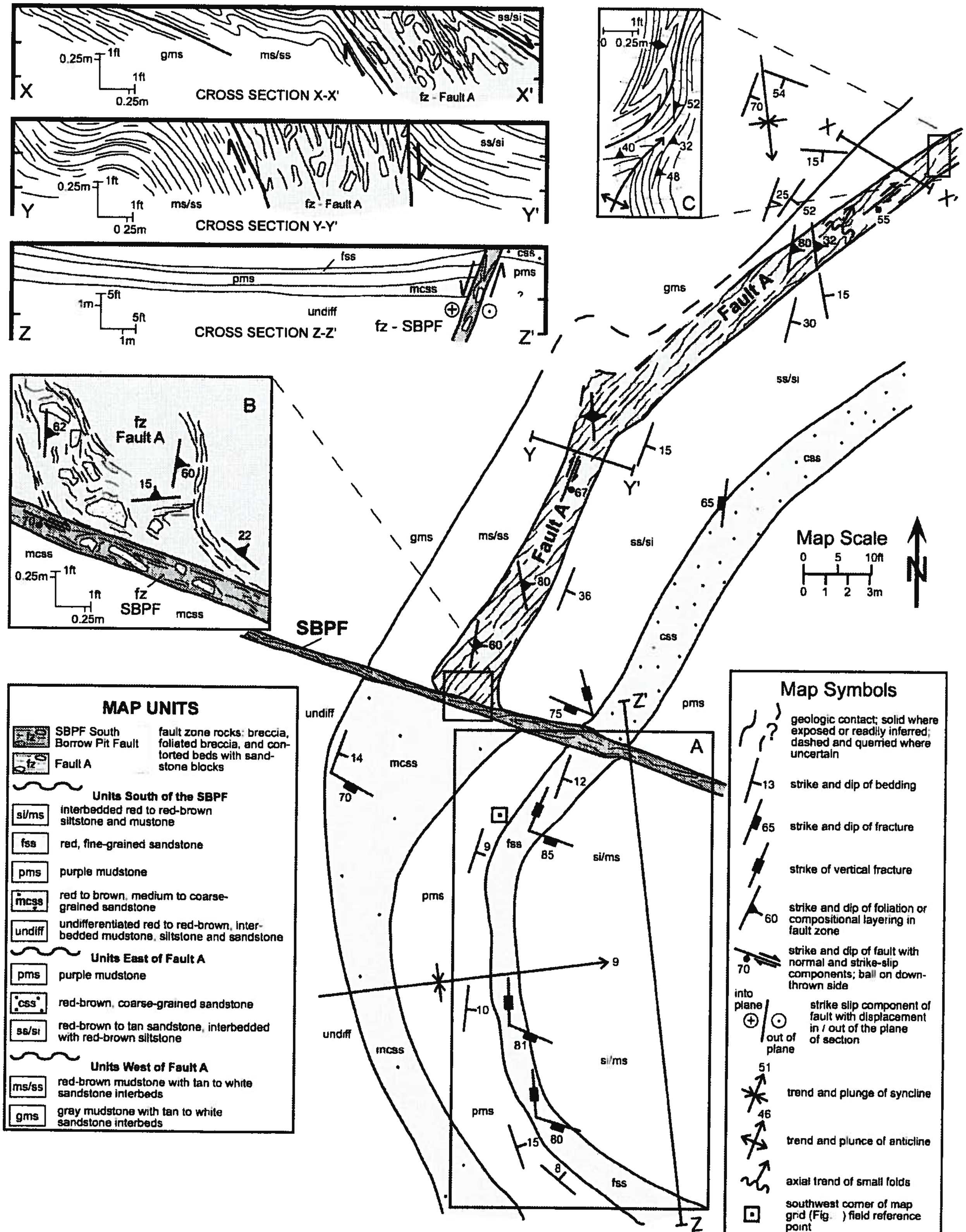
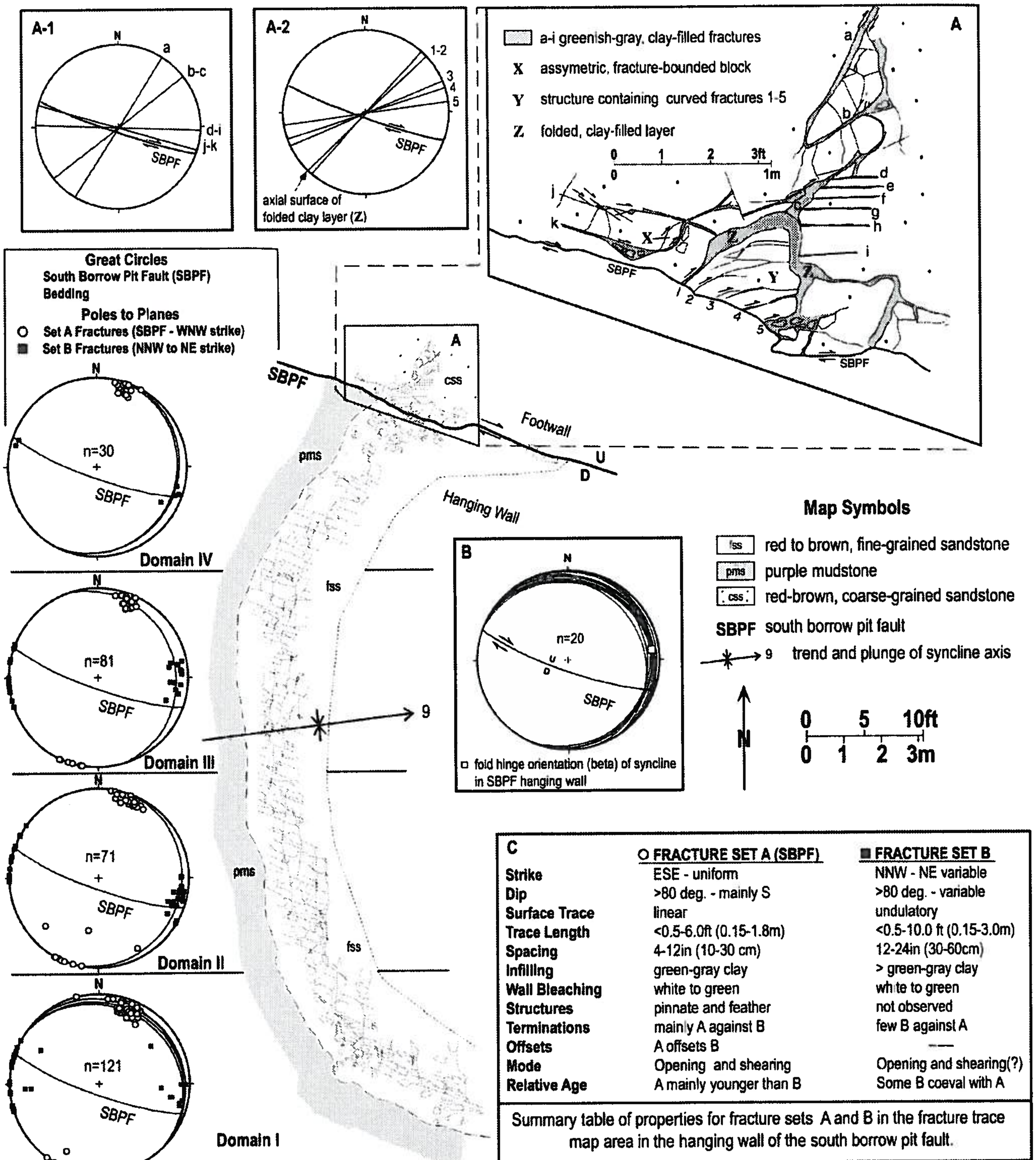


Figure 19. Geologic map and cross sections showing structural relationships where fault A terminates against the SBPF (STOP 8). Inset A) fracture trace map area (Fig. 8). Inset B) detail of fault fabric where fault A terminates against the SBPF. Inset C) schematic detail of deformation fabric within fault A. Adapted from Wooten and others (1996).



C	O FRACTURE SET A (SBPF)	■ FRACTURE SET B
Strike	ESE - uniform	NNW - NE variable
Dip	>80 deg. - mainly S	>80 deg. - variable
Surface Trace	linear	undulatory
Trace Length	<0.5-6.0ft (0.15-1.8m)	<0.5-10.0 ft (0.15-3.0m)
Spacing	4-12in (10-30 cm)	12-24in (30-60cm)
Infilling	green-gray clay	> green-gray clay
Wall Bleaching	white to green	white to green
Structures	pinnate and feather	not observed
Terminations	mainly A against B	few B against A
Offsets	A offsets B	---
Mode	Opening and shearing	Opening and shearing(?)
Relative Age	A mainly younger than B	Some B coeval with A

Summary table of properties for fracture sets A and B in the fracture trace map area in the hanging wall of the south borrow pit fault.

Figure 20. Fracture trace map and lower hemisphere equal-area stereonet projections of the SBPF, bedding, and fracture data (STOP 9). Insets A, A-1, and A-2 are a map showing structures, and stereonet projections of structural data in the footwall of the SBPF. Inset B) stereonet projection of bedding, fault orientations, and the synclinal fold hinge orientation from the hanging wall of the SBPF. Hanging wall map is divided into domains I-IV based on changes in bedding strike. Inset C) summary table of properties from fracture sets A and B in the footwall of the SBPF. Adapted from Wooten and others (1996); fracture trace mapping and analysis by T. L. Davis.

lateral sense by fractures of set A, which are interpreted as fault-reactivated joints. The change in orientation of N-striking fractures in the syncline (Set B, Fig. 20) is also consistent with a component of right-lateral, strike-slip displacement.

Foot Wall Structures

The SBPF footwall structures (Fig. 20A) contrast with those in the hanging wall. A primary difference is that the pervasive, rectilinear, hanging wall fracture Sets A and B are absent in this portion of the footwall.

Structural features observed in the footwall do, however, suggest a component of right-lateral, strike-slip displacement along the SBPF. Fractures at location j are interpreted as either pinnate joints or conjugate shear fractures indicative of right-lateral shearing. Structure X is interpreted as a fault-bounded block (e.g., horse block) and its S-shape asymmetry also supports right-lateral, strike-slip shearing.

Structure Y is interpreted as a contractional, strike-slip duplex that is analogous to those described by Woodcock and Fischer (1986) and also indicates a right-lateral sense of displacement. Fractures 1-5 (Fig. 20A) comprise the duplex and are interpreted as slip surfaces that sole into the SBPF. The angle between each slip surface and the SBPF increases from 5 to 1. This change in angle reflects the steepening of earlier slip surfaces (e.g., 1) during emplacement of later faults (2-5) in a forward-breaking sequence similar to that observed in foreland thrust systems. Right-lateral, strike-slip, fault-reactivation of pinnate joints, which were developed during earlier left-lateral displacement, would likely produce a structure similar to Y as well. This left-lateral component is consistent with the slip data recorded along the SBPF at STOP 6.

The formation and geometry of the folded clayey layer (Z on Fig. 20A) is likely to be related to the duplex structure Y. The geometry of the folded clayey layer S, including its vertically plunging fold hinge (45°at 90°), the axial surface orientation, and the sense of asymmetry or vergence suggests right-lateral, strike-slip displacement.

Initial movement along fault A is interpreted as normal displacement antithetic to the Durham segment of the Jonesboro fault (Fig. 3A), and predating movement along the SBPF. E-tilting of beds and the development of fracture set A relects this phase of faulting and E-W extension. Reactivation during movement along the SBPF probably contributed to the complicated internal fabric observed within fault A (Fig. 20). Kinematic indicators such as small-scale sigmoidal sandstone layers suggest a right-lateral component of movement on fault A consistent with similar movement on the W-8 fault (Figs. 3B and 3C).

The map-scale anticline in the hanging wall of the SBPF (Fig. 6) and in the seismic reflection data (Fig. 16) formed during normal (down-to-the-S) displacement on the SBPF. This model assumes that the curved patterns of beds that delineate the hanging wall anticline resulted from anticlinal folding of an E-dipping sequence of rocks. The outcrop-scale syncline in the hanging wall of the SBPF (Figs. 19 and 20) is interpreted to have formed during subsequent right-lateral, strike-slip displacement on the SBPF.

We interpret the relative magnitude of normal displacement along the SBPF to be significantly greater than the magnitude of strike-slip movement along the SBPF, given the hanging wall anticline (inferred to the result of normal displacement) is a map-scale feature in contrast to the smaller, outcrop-scale syncline related to strike-slip movement.

DISCUSSION

The focus of this trip was to show how trenching and detailed geologic mapping of individual beds, thin stratigraphic units, and structural features contained therein can be combined with structural analyses and interpretation of seismic reflection profiles to gain a better understanding of fault systems near the Colon cross structure (Bain and Harvey, 1977). These studies shed light on how these faults behaved during early Mesozoic rifting when the Jonesboro fault and the associated Deep River basin formed along with many other brittle faults in the Piedmont (Garihan and others, 1993).

Furthermore, these investigations provide insight into the spatial distribution of faults and the related folding and fracturing important to conceptual models of groundwater flow in fractured rock aquifers within faulted, Triassic sedimentary rock (Fig. 21). Hydrologic testing conducted at the site during the GM-1 pilot study (Harding Lawson and Assoc., 1997), confirmed that nearly all of the groundwater flow anomalies detected in boreholes were associated with fractures, including intensely fractured rock in the hanging wall of the W-8 fault, and strata-concordant flowing zones. At the site scale, fracture orientation and intensity can be related to the structural domains of local

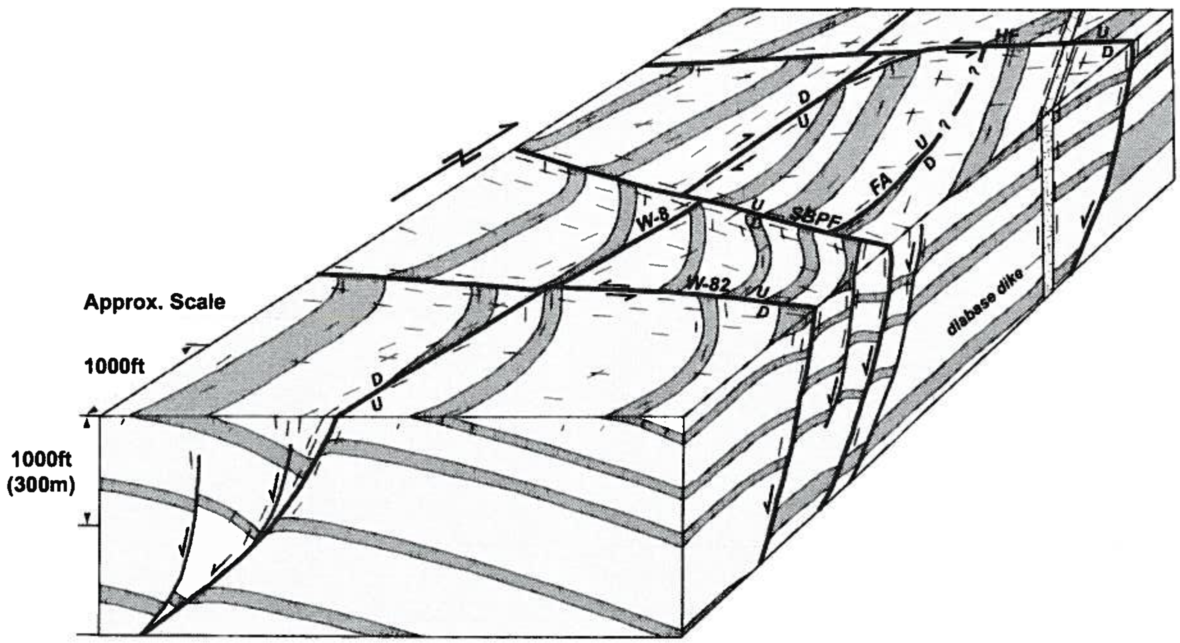


Figure 21. Schematic block diagram showing a conceptual structural model for the site and vicinity. Continuous stratigraphic sequences are shown only to depict structural trends. Structural relationships at fault intersections are uncertain. Dominant movement on all faults is dip-slip, normal displacement. Both right-lateral and left-lateral displacement occurred on the south borrow pit fault (SBPF). The location of the diabase dike is schematic to illustrate relationships with the Harris fault (HF). (FA = fault A; W-8 = W-8 fault; W-82 = W-82 fault.)

faults that formed in response to movement along the basin-bounding, Jonesboro fault. Bedding and fracture orientations can also vary considerably both within and across fault-bounded blocks. At the local scale the trend of beds do not necessarily correspond with the trend of lithofacies associations delineated through 7.5-minute quadrangle mapping.

We did not have access to structural data collected along the Harris fault at the time that the Shearon Harris facility was constructed, but were able to glean some structural information from the detailed maps that were made then (Ebasco Services, Inc., 1975). Moreover, neither the Harris fault nor the SBPF were trenched at multiple locations within the site like theW-8 and W-82 faults, thereby limiting the amount of structural data available for analysis. The Harris and W-82 faults have similar orientations (Figs. 16 and 21) supporting the interpretation that they had similar displacement histories. The SBPF is sub-parallel to these faults (Fig. 21) and shared a similar normal and oblique-normal displacement-history with them related to the two dominant displacement directions on the Holly Springs segment (Figs. 3B and 3C). The younger sets of ENE- and E-W-trending joints are also related to these displacement directions.

Bartholomew and Fleischmann (1993) showed that the trends of sections of the Harris fault are consistent with its development as a strike-slip fault with both Reidel R1 (left-lateral) and P (right-lateral) secondary shears (e.g., Petit, 1987; Mawer, 1992). The ESE-trend of the SBPF is similar to the trend of P-shears along the Harris fault. This orientation is consistent with the opposite (right-lateral) sense of strike-slip displacement on the SBPF (Wooten and others, 1996) during normal displacement along the Durham segment when the Harris and W-82 faults experienced left-lateral, strike-slip displacement (Figs. 3A and 21). Although the dominant displacement on all three faults was actually normal (down to the S or SE), the steep dips (70°-90°) along parts of these faults suggest that they actually originated as strike-slip faults accommodating displacement at the southern end of the Durham segment (Fig. 3A).

In contrast, the dip of the W-8 fault is about 60° or less (Fig. 4B) and it is listric at depth (Figs. 5 and 21). Its major sense of displacement is also normal (down to the W) and it strikes sub-parallel to the Durham segment. Thus, the W-8 fault is interpreted to have formed

formed as a normal fault related to normal displacement on the Durham segment (Fig. 3A). The N- to NNW-trending (oldest) joints and large clay dikes are also related to this displacement direction. Normal displacement on the Holly Springs segment then reactivated the W-8 fault as a right-lateral, strike-slip fault.

ACKNOWLEDGEMENTS

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END OF FIELD TRIP; RETURN TO RALEIGH FOR WELCOMING PARTY OF THE 50th ANNUAL SE GSA MEETING.

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