Neoproterozoic to Mesozoic petrologic and ductile-brittle structural relationships along the Alleghanian Nutbush Creek fault zone and Deep River Triassic basin in North Carolina

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ABSTRACT

The focus of this field trip is the complex lithologic, metamorphic and structural transition between high-grade infrastructural and low-grade suprastructural terranes that define the accreted peri-Gondwanan Neoproterozoic-Cambrian Carolina Zone, an island-arc superterrane in the north-central Piedmont of North Carolina. This transition is now exposed across a metamorphic suite of amphibolite facies layered gneiss plus kyanite-sillimanite zone pelitic schist, and another metamorphic suite of greenschist facies mylonitic and phyllonitic metagranitoids and their undeformed equivalents. A variety of mineral assemblages, fabric elements, and structures within the transition zone may be linked into a progressive sequence recording (1) the transpressional buildup of an Alleghanian collision zone between Laurentia, the Carolina Zone, and Gondwana during Pangean continental amalgamation, and (2) its extensional collapse during the Permo-Triassic through Jurassic rifting and breakup of Pangea.

We will observe the effects of Alleghanian ductile strain superposed on this infrastructural-suprastructural terrane transition, including the interplay between
INTRODUCTION

The starting point for much of the modern geologic mapping in the transition from the eastern to central Piedmont in north-central North Carolina involves the work of Parker (1968, 1978, 1979). He showed that the region is composed of a variety of rock types and metamorphic assemblages that are overprinted by multiple ductile and brittle deformations. Parker’s mapping served as the basis for lithologic contacts in north-central North Carolina on the most recent version of the state geologic map (North Carolina Geological Survey, 1985). It also served as the foundation for a major regional geologic overview by Farrar (1985a, 1985b), who presented a synopsis of the stratigraphy, structure, and metamorphic history of the eastern Piedmont based on his own reconnaissance-level geologic mapping and sampling. In continuity with the regional studies by Farrar, Harris and Glover (1988) provide a synopsis of the stratigraphic, structural, and metamorphic development of the northeastern portion of the central Piedmont based upon regional field studies and stratigraphic correlations.


Since the completion of the regional mapping by Farrar and then by Harris and Glover, the central and eastern Piedmont has been the subject of 27 years of detailed geologic mapping of all or parts of over 50 1:24K quadrangles in the Raleigh and Henderson 1:100K sheets, largely from the efforts of the North Carolina Geological Survey (NCGS). Detailed NCGS geologic mapping under the USGS-administered STATEMAP and EDMAP programs has added clarity to our understanding of rock types and structures in north-central North Carolina. The region lying between the capital city of Raleigh and Kerr Lake Recreation Area located along the North Carolina–Virginia state line has been the primary focus of these mapping efforts. Noted for its 800 miles of shoreline (www.ncparks.gov), Kerr Lake State Recreation Area, together with major southeast-flowing tributaries to the Tar River and Falls Lake–Neuse River drainage basins to its south provide abundant erosional exposures. These will be used on this two-day field trip to examine rocks representing mid-to-upper-crustal levels in cross-strike and along-strike traverses and the geologic transition between the eastern and central Piedmont. Outcrops in this transition expose varying scales of windows into Neoproterozoic to Jurassic crystalline and sedimentary rocks. They also provide a view of the low- to medium-grade metamorphism and ductile-brittle fault zone relationships and structures associated with the transition from Paleozoic transpressional orogenesis to Mesozoic extensional rifting of eastern North America. These events document the final pulses of Laurentian-Gondwanan amalgamation and subsequent breakup of the Pangean supercontinent.

The study area is separated into amphibolite (infrastructural) and greenschist facies (suprastructural) terranes that lie within the orogen-scale, Neoproterozoic-Cambrian Carolina Zone, a peri-Gondwanan island-arc supeterrane (Fig. 1). Specifically, the field trip will focus upon the complex petrologic transition from deeper infrastructural to shallower suprastructural terranes. This transition is now exposed across a suite of amphibolite facies layered gneiss and kyanite-sillimanite zone pelitic schist, and greenschist facies mylonitic and phyllonitic metagranitoids and their undeformed equivalents. We will observe the superposed effects of Pennsylvanian–Early Permian, Alleghanian orogeny ductile-brittle strain on this terrane transition, including the interplay between dextral-slip transpression and generation of syn- to post-kinematic granitic plutons. Finally, the trip highlights ductile-brittle effects of Permo-Triassic normal-slip faulting, and then uplift and rift sedimentation linked to the Durham sub-basin of the Triassic Deep River basin, as well as crosscutting Jurassic intrusive bodies.

From north to south, as well as east to west, field trip stops are located within the John H. Kerr Dam, Middleburg, Henderson, Oxford, Wilton, and Lake Michie 1:24K Quadrangles (Figs. 2, 3, and 4). This field trip honors the 75th anniversary of the establishment of the Carolina Geological Society and its contribution to our understanding of southern Appalachian geology.
Alleghian Nutbush Creek fault zone and Deep River Triassic basin

Figure 1. Tectonostratigraphic element map of suprastructural and infrastructural terranes within the Carolina Zone of the southern Appalachian orogen. Suprastructural elements include the Milledgeville (MT), Augusta (AT), Roanoke Rapids (RR), Spring Hope (SH), Carolina (CT), and Easternmost Carolina (ECT) terranes. Infrastructural elements include the Uchee (UT), Savannah River (SR), Dreher Shoals (DS), Falls Lake (FLT), Triplet (TT), Warren (WT), Raleigh (RT), Crabtree (CRT), and Charlotte (CHT) terranes. VA—Virginia; TN—Tennessee; NC—North Carolina; AL—Alabama; GA—Georgia; SC—South Carolina. Modified from Hibbard and Samson (1995) and Hibbard et al. (2002).

Figure 2. Regional geologic setting of the northeastern Carolina Zone showing tectonostratigraphic terranes, Durham sub-basin (Dsb) of the Deep River Mesozoic rift basin, and major late Paleozoic granitoid plutons (Rolesville (R) and Buggs Island (B)). Suprastructural elements include: Roanoke Rapids (RRt), Spring Hope (SHt), Carolina (Ct), and easternmost Carolina (ECT) terranes. Infrastructural elements include the Falls Lake (FLT), Triplet (TT), Warren (WT), Raleigh (RT), and Crabtree (Cbt) terranes. Terrane-bounding ductile dextral-slip fault zones highlighted by name and arrows include, from east to west, Gaston Dam, Hollister, Macon, Middle Creek, Lake Gordon, Neuse River, Falls Lake, Nutbush Creek; ductile-brittle normal-slip fault zones include the Fishing Creek, Jonesboro, and Upper Barton Creek.
Figure 3. Map showing field trip stops for Day 1 with preliminary bedrock geologic map of the Henderson, southeast portion of the Townsville, Middleburg, and North Carolina portion of the John H. Kerr Dam 1:24K Quadrangles. Select map units identified. Map is compiled from NCGS STATEMAP mapping data.
Figure 4. Map showing field trip stops for Day 2 with preliminary bedrock geologic map of the Oxford, Wilton, Stem, and portions of the Lake Michie, Grissom, Creedmoor, and NE Durham 1:24K Quadrangles. Select map units identified. Map is compiled from NCGS STATEMAP mapping data.
Numerous CGS field trips and discussions in the eastern-to-central Piedmont transition of both North Carolina and South Carolina have helped guide the geologic mapping progression and conceptual interpretations presented here.

**GEOLOGIC SETTING**

**Lithotectonic Elements of North-Central North Carolina**

In north-central North Carolina, the eastern and central Piedmont Physiographic Province of the southern Appalachian orogen exposes a diverse array of meta-igneous, metasedimentary, plutonic, and sedimentary rocks. These rocks and numerous overprinting ductile and brittle faults collectively range in age from the Neoproterozoic to early Mesozoic. A system of north-northeast–trending fault zones known as the Eastern Piedmont fault system (Hatcher et al., 1977; Bobyarchick, 1981; Stoddard et al., 1991) divides pre-Mesozoic rocks into numerous terranes within the larger tectonic realm known as the Carolina Zone (Hibbard and Samson, 1995; Hibbard et al., 2002).

The origin of each terrane appears to be a common Neoproterozoic to early Paleozoic, peri-Gondwanan island-arc setting exotic to Laurentia. From the eastern Piedmont and westward across to the central Piedmont, these tectonostratigraphic terranes include the Roanoke Rapids, Triplet, and Spring Hope terranes, the herein named Warren terrane, and then the Raleigh, Crabtree, Falls Lake, and Carolina terranes (Fig. 1; Blake et al., 2001; Clark et al., 2004; Hibbard et al., 2002; Sacks, 1999). The deeper crustal and infrastructural Raleigh and Warren terranes, and the shallower and suprastructural Carolina terrane are three of the most regionally extensive portions of the Carolina Zone across the eastern-to-central Piedmont transition. Their rocks are the primary focus of the first field trip day.

These terranes are interpreted to record the (1) magmatic and volcaniclastic evolution of this composite, peri-Gondwanan island-arc supeterrane, (2) intra-arc tectonism during the ca. 560 Ma Virgilina deformation (Glover and Sinha, 1973; Harris and Glover, 1988; Wortman et al., 2000), and (3) accretion of the Carolina Zone to eastern Laurentia during the middle Paleozoic Taconic/Cherokee orogeny (Hibbard et al., 2010, 2012). Tectonothermal metamorphism of the eastern Piedmont culminated in the late Paleozoic during Laurentian-Gondwanan continental collision and construction of the Pangean supercontinent (Hatcher et al., 1977; Horton et al., 1994; Blake et al., 2001). As Laurentia merged with Gondwana during the Alleghanian orogeny, oblique convergence deformed the southern Appalachians into a kinematically partitioned, strike-slip and dip-slip continental collision zone of foreland and hinterland rocks (Secor et al., 1986a, 1986b; Hatcher et al., 1989). In the eastern-to-central Piedmont transition, hinterland dextral transpression progressively reactivated antecedent dip-slip structures and produced an anastomosing network of northeast-trending fault zones from the Virginia Piedmont south into North Carolina (Fig. 2; Gates et al., 1988; Bobyarchick, 1988; Hatcher et al., 1977, 1989).

Most faults show dextral-slip displacements, although the Macon and Hyco fault zones in North Carolina and Virginia are partitioned as ductile thrusts (Sacks, 1999; Hibbard et al., 1998). As a group, these Alleghanian faults affect the (1) Mesoproterozoic to Cambrian eastern margin of Laurentia, (2) Neoproterozoic to Cambrian metasedimentary and metavolcanic rocks of the Piedmont Zone, and (3) Neoproterozoic to Cambrian island-arc rocks of the Carolina Zone (Fig. 1; Gates et al., 1988; Costain et al., 1989; Blake et al., 2001).

The area of the field trip also lies along the western flank of the south-plunging Wake-Warren anticlinorium (Fig. 2; Parker, 1979; Farrar, 1985a; Stoddard et al., 1991; Horton et al., 1994), an arch of foliation across a region generally called the Raleigh metamorphic belt. It exposes rocks displaying Alleghanian amphibolite facies metamorphism in its core terranes, and grades outward to greenschist facies to the east and west in the Spring Hope and Carolina terranes, respectively. The Pennsylvanian Rolesville batholith, a large composite granitoid pluton, intruded mainly within the hinge zone and western flank of the Wake-Warren anticlinorium. The weakly to unfoliated nature of large portions of the batholith locally supports a late- to post-kinematic emplacement history during the Alleghanian orogeny. Other portions, especially those injected adjacent to or within dextral ductile shear zones, display strong tectonic overprint, including a progression of proto-mylonitic to mylonitic fabric elements.

On the western flank of the Wake-Warren anticlinorium, individual fault zone strands anastomose around terrane elements to form a 1–10-km-wide dextral-slip fault system that is one of the principal structures of the northeast-trending Eastern Piedmont fault system (Hatcher et al., 1977; Bobyarchick, 1981). This structure is herein termed the Nutbush Creek–Lake Gordon fault system. It has been traced for over 200 km from the North Carolina–Virginia state line into south-central North Carolina (Figs. 2 and 3; Farrar, 1985a, 1985b; Stoddard et al., 1991; Druhan et al., 1994; Blake et al., 2001). Topographic and lithologic lineaments, dextral L-S tectonic fabric, and rock types facilitate mapping each fault zone strand and help to differentiate individual lithotectonic terranes. Linear aeromagnetic anomalies (Casadevall, 1977) also mark the positions of fault zones. They have been used to extend the eastern Piedmont fault system from the North Carolina Piedmont into Virginia and beneath the Atlantic Coastal Plain into the South Carolina Piedmont (Secor et al., 1986a, 1986b).

Permo-Triassic ductile-brittle normal-slip faults, Triassic clastic sedimentary rocks that nonconformably overlap crystalline rocks, and Jurassic diabase dikes, common throughout the Piedmont, and sills within the rift basins, document Mesozoic rifting and the Pangean supercontinent breakup (Olsen et al., 1991; Clark et al., 2001, 2011; Hames et al., 2001). The Jonesboro fault and the Fishing Creek fault zone (FCFZ) overprint the western flank of the Wake-Warren anticlinorium (Figs. 2 and 4). Together, they define the eastern margin of the Durham sub-basin of the Triassic Deep River rift basin and are the focus of the second day of the field trip (Figs. 4 and 5). The basin, associated
ductile-brittle faulting, and a variety of mesoscale extensional structures also overprint and complicate the eastern-to-central Piedmont transition and its underlying terranes (Heller et al., 1998; Blake et al., 2001). The structural development overprinting the eastern-to-central Piedmont transition, as well as the Warren and Raleigh to Carolina terrane boundary in north-central North Carolina marks a late Paleozoic to early Mesozoic ductile-to-brittle structural and tectonic transition as well. This transition links a variety of structures and fabric elements, originally thought to be widely separated in time and space, into a progressive, and relatively coherent deformational sequence reflecting the transpressional buildup of an Alleghanian collision zone between Laurentia, the Carolina Zone, and Gondwana during Pangean amalgamation and its subsequent extensional collapse during Pangean breakup and Wilsonian continental dispersal.

### Infrastructural Terranes

Historically, the Raleigh terrane has been considered to be the easternmost terrane on the western flank of the Wake-Warren anticlinorium. It extends across the hinge zone of this regional fold structure, and contains a mixed assemblage of amphibolite facies igneous and sedimentary protoliths that experienced kyanite-sillimanite zone tectonothermal metamorphism and multiple granitoid intrusion during the Alleghanian orogeny.

The Rolesville batholith has been used to subdivide the Raleigh terrane into two parts across the hinge of the anticlinorium (Fig. 2; Stoddard et al., 1991; Speer, 1994). Southwest of the batholith on the western flank of the anticlinorium, the terrane contains the Raleigh Gneiss, a lithodeme of heterogeneously mixed mafic to granitoid intrusions, minor schist and the

![Image](image-url)

**Figure 5.** Generalized geologic map of the Deep River basin, showing the Durham, Sanford, and Wadesboro sub-basins. The Sanford, Cumnock and Pekin Formations are limited to the Sanford sub-basin. Thin red lines trending north-south to northwest-southeast are Jurassic diabase dikes. CP = Central Piedmont, EP = Eastern Piedmont. Modified from Reinemund (1955), Bain and Harvey (1977), NCGS (1985), Olsen et al. (1991), Hoffman and Gallagher (1989), Watson (1998) and Clark et al. (2001).
regionally distinctive Falls Leucogneiss (Parker, 1979; Farrar, 1985a, 1985b; Stoddard et al., 1991; Horton et al., 1994; Blake et al., 2001). These rocks lie within and east of the Nutbush Creek–Lake Gordon fault system, an integral member of the Eastern Piedmont fault system. To the northeast of the batholith, between the Nutbush Creek–Lake Gordon fault system and Macon fault zone, the anticlinorium hinge zone contains pelitic and mafic to felsic protoliths that are now schist, paragneiss, and orthogneiss (Farrar, 1985a, 1985b; Sacks, 1999). Below, these two domains of rocks grouped as the Raleigh terrane across the Rolesville batholith are discussed separately, and the possibility is raised that they may actually constitute two distinct terranes.

In the southwestern Raleigh terrane, there are complex intrusive relationships among medium- to coarse-crystalline biotite and hornblende-biotite tonalitic to granitic orthogneiss and fine- to medium-crystalline, more mafic biotite ± hornblende ± clinopyroxene gabbroic to dioritic orthogneiss, amphibolite, and biotite ± white mica schist. These relationships produce a distinctive, variably migmatic aspect in the Raleigh Gneiss. Multiple pulses of concordant to discordant intrusions may be seen at cm- to m-scales, forming melanocratic to leucocratic, discontinuous layers. Small, map-scale bodies of meta-ultramafic actinolite-chlorite rock are exposed in the northern portions of the lithodeme (Robitaille, 2004; Stoddard et al., 2002).

Mafic gneiss and schist appear to have formed earlier than more intermediate to felsic gneiss. The mafic rocks form thick layers, thin selvages or enclaves within more differentiated felsic layers. Locally, felsic gneiss layers, and weakly foliated to unfoliated aplite to pegmatitic granite, likely related to the Rolesville batholith, form dikes and veins that truncate sill-like mafic to felsic gneiss. In other exposures, generally farther east, these mafic rocks dominate, but biotite gneiss, hornblende ± biotite gneiss, and amphibolite layers, enclaves, and selvages persist, and with sill-like granitic layers form a lit-par-lit appearance. Accordingly, Parker (1979) called the Raleigh Gneiss “injected gneiss and schist.” Like him, we interpret this zone to show progressive mixing of younger granite with older country rock. In addition, locally intense ductile dextral-slip deformation overprints the Raleigh Gneiss and associated younger granitoid rocks. The deformation is more apparent toward the northern end of the outcrop belt in the Kittrell and Henderson 1:24K Quadrangles as compared to its southern equivalents in the Lake Wheeler and Raleigh West 1:24K Quadrangles (Stoddard et al., 2001; Blake and Stoddard, 2004; Blake, 2008).

One prominent pluton in the Raleigh Gneiss is the Falls Leucogneiss. This leucogranitic orthogneiss forms a narrow, sheet-like pluton 75 km long and up to 2.2 km wide along much of the length of the Crabtree terrane-Raleigh terrane boundary (NCGS, 1985; Farrar, 1985a, 1985b; Horton et al., 1994). The pluton, which records a penetrative L-tectonite fabric and strong linear magnetic anomaly, is located primarily along the western margin of the Raleigh Gneiss (Druhan et al., 1994; Horton et al., 1994). Near Raleigh, the leucogneiss intrudes Raleigh Gneiss amphibolite layers (Blake et al., 2001). Although the leucogneiss was originally thought to be an Alleghanian pluton intruded along the Nutbush Creek–Lake Gordon fault system, its U-Pb zircon age of 542 ± 3.1 Ma (Caslin, 2001) precludes that possibility.

Farrar (1999) and Farrar and Owens (2001) proposed that bodies of the Falls Leucogneiss, based upon mineralogy and major and trace element characteristics, represent peralkaline granite intruded into the thinned Laurentian margin at the beginning of the Iapetan rifting cycle ca. 600 Ma. These authors infer that the leucogneiss intruded the western edge of the Goochland terrane and was subsequently deformed by Alleghanian ductile dextral-slip faults. This is problematic because the Laurentian margin had entered a rift-drift phase by ca. 550 Ma. (Meert and Torsvik, 2003).

Mesozoic brittle faults truncate the Falls Leucogneiss at its southern termination south of Raleigh (Heller et al., 1998). Along its northern exposures, in the Kittrell and Henderson 1:24K Quadrangles, interlayered mafic to felsic orthogneiss and amphibolite rocks of the Raleigh Gneiss group with arc-related basaltic rocks of the Lake Wheeler and Raleigh West 1:24K Quadrangles (Stoddard et al., 2002; Blake and Stoddard, 2004). Many of these same gneisses also record ductile fault strain. At their northern extent in Henderson, North Carolina, both the Falls Leucogneiss and the Raleigh Gneiss terminate against Alleghanian granitoids between strands of the Nutbush Creek–Lake Gordon fault system.

Farrar (1984, 1985a, 1985b) interprets rocks and metamorphic mineral assemblages of the Raleigh terrane as correlative with the Grenville Goochland terrane in the eastern Piedmont of Virginia. The Goochland terrane, thought to be a portion of the rifted eastern margin of Laurentia, was thrust westward during Paleozoic collisional deformation. Polymetamorphic microstructures north and northeast of the Rolesville batholith indicate that a greenschist to middle amphibolite facies event appears to overprint an earlier metamorphic event that reached at least the sillimanite zone (Farrar, 1985b; Stoddard et al., 1991; Sacks, 1999). This earlier metamorphic event may be correlative with metamorphic mineral assemblages of the Goochland terrane.

However, geochemical data indicate that metamorphosed mafic rocks of the Raleigh Gneiss group with arc-related basaltics on trace-element tectonic discrimination diagrams (Parnell et al., 2006a; Parnell, 2012). Additionally, the ca. 542 Ma zircon date for the Falls Leucogneiss correlates with Stage III plutonism in the Carolina and Charlotte terranes (Hibbard et al., 2002). The bulk of the Raleigh Gneiss appears to represent Neoproterozoic to early Paleozoic, multiply intruded infrastructure to the Carolina Zone that was deformed, metamorphosed and intruded by granitoids during the late Paleozoic Alleghanian orogeny. Limited isotopic dating tends to support this contention (Owens and Buchwaldt, 2009). We also conclude that the Falls Leucogneiss is a deformed, metamplutonic member of the Raleigh Gneiss.

While the original affinity of the Raleigh terrane remains debatable, recent mapping indicates that the Nutbush
Creek–Lake Gordon fault system, deformed Alleghanian granitoids, and the Hylas fault actually separate it from the Goochland terrane (Sacks, 1999). No petrographic correlation of granulite facies assemblages of the Virginia Goochland terrane has been established with those in the Raleigh Gneiss southwest of the Rolesville batholith and east of the Nutbush Creek–Lake Gordon fault system (Stoddard, 1989; see also Blake, 1986; Heller, 1996; Grimes, 2000; Robitaille, 2004). Mineral assemblages of the Raleigh Gneiss best correlate with an Alleghanian greenschist to mid-amphibolite facies metamorphism (Russell et al., 1985). The migmatitic aspect and mafic components of the Raleigh Gneiss southwest of the batholith also appear different from meta-igneous and metasedimentary lithologies northeast of the batholith.

As a consequence of these findings, we here propose that high-grade metamorphic rocks lying between the Nutbush Creek–Lake Gordon fault system and Macon fault zone, which have been heretofore depicted on most regional maps as belonging to the Raleigh terrane, may actually constitute a separate, eastern terrane, herein called the Warren terrane. The newly defined Warren terrane is considered to be distinct from its Raleigh terrane neighbor to the west (Fig. 2). In addition to gneiss located north of the Rolesville batholith and east of the Nutbush Creek–Lake Gordon fault system (and previously designated as part of the Raleigh Gneiss), this new terrane includes the Macon Formation of Farrar (1985a, 1985b) and various schist and gneiss units mapped by Sacks (1996a, 1996b, 1996c; see also Stoddard et al., 2009, 2011). Lithologies include layered biotite, hornblende, and hornblende-biotite orthogneiss similar to parts of the Raleigh Gneiss, but also include pelitic and white mica quartzitic schist and other less common rock types. The Raleigh terrane is defined as the highly strained units of Raleigh Gneiss and Falls Leucogneiss that lie within the Nutbush Creek–Lake Gordon fault system, east of the Crabtree terrane, and west of the Warren terrane.

The justification for defining a new Warren terrane is based on the (1) recognition of the regional significance, along-strike extent, and correlations among individual strands within the Nutbush Creek–Lake Gordon fault system, and (2) occurrence of a considerable proportion of rocks having supracrustal origin in this northeastern part of the eastern Piedmont north of the Rolesville batholith. Rock units having probable supracrustal protoliths include one- and two-mica schist, locally having garnet, chloritoid, sillimanite, kyanite, and rare staurolite or corundum as key index minerals. In addition, quartz-kyanite rock and quartz-sillimanite rock may be high-grade metamorphic equivalents of aluminous, hydrothermally altered felsic metavolcanic rocks such as pyrophyllite-bearing units of the Carolina Zone. Future mapping will also test whether metamorphic rocks north of the Rolesville batholith in the Warren terrane are lithologically or tectonically separate from those in the southwestern portion of the Warren terrane adjacent to the southern end of the batholith (Fig. 2). We will examine rocks of the Warren terrane at Stops 1 and 2 of the field trip.

Suprastructural Carolina Terrane

The easternmost Carolina terrane is the westernmost and structurally highest assemblage of supracrustal rocks that span the eastern-to-central Piedmont transition along the western flank of the Wake-Warren anticlinorium. The Triassic Deep River rift basin and associated normal-slip Jonesboro fault and FCFZ separate these rocks from the main portion of the Carolina terrane in the central Piedmont (Fig. 1, 2, and 4; Secor et al., 1983; Butler and Secor, 1991; Hibbard et al., 2002). In general, the easternmost Carolina terrane contains felsic to mafic, and locally ultramafic plutonic rocks, and felsic to mafic volcanic and volcanioclastic rocks now metamorphosed to the lower to upper greenschist facies and chlorite-biotite-garnet zone (Farrar, 1985a, 1985b; Stoddard et al., 1991). A prograde west-to-east gradient in regional metamorphism across the easternmost Carolina terrane increases metamorphic grade from the chlorite-biotite zone of the greenschist facies to the biotite-kyanite zone rocks of the amphibolite facies. This metamorphic gradient overprints earlier metamorphism. It also marks the Alleghanian metamorphic overprint that defines the western flank of the Wake-Warren anticlinorium, the western limit of the Nutbush Creek–Lake Gordon fault system, and the east-to-west transition from mid-to-upper crustal rocks rock types and structures. It also corresponds to the eastern-to-central Piedmont transition (Fig. 2).

Field and petrographic relationships among the metamorphosed mafic to felsic flows, tuffs, dikes, volcanioclastic rocks, and their subvolcanic plutons reflect the exposure of multiple centers of bimodal volcanism that are Neoproterozoic to early Paleozoic in age. The metamorphosed volcanic and plutonic rocks share similarities in mineralogical and geochemical characteristics (Blake et al., 2001; Parnell et al., 2006a; Parnell, 2012). Although these rocks are exposed at different metamorphic grades due to folding and faulting, similarities in lithology, protoliths, and geochemical signatures suggest links between volcanogenic rocks of the easternmost Carolina terrane and those of the Falls Lake, Crabtree, Spring Hope, and the newly defined Raleigh and Warren terranes (Stoddard et al., 1996). Easternmost Carolina terrane rocks appear to be generally correlative with metamorphosed Neoproterozoic to Cambrian calc-alkaline volcanic, volcanioclastic, and plutonic rocks in the Carolina terrane west of the Deep River basin that are inferred to be the products of island-arc magmatism above a peri-Gondwanan, perhaps western Amazonia, subduction zone (Hibbard et al., 2002; Parnell et al., 2006a; Pollock and Hibbard, 2006; Pollock, 2007; Rhodes et al., 2011).

At the northern termination of the Durham sub-basin south of Oxford, eastern Piedmont rocks merge with similar-grade rocks of the Virgilina sequence of the main Carolina terrane in the central Piedmont (Glover and Sinha, 1973; Hadley, 1973; Harris and Glover, 1988; Hibbard et al., 2002) across the FCFZ (Blake et al., 2007). Complex syn-depositional interlayering of felsic and mafic pyroclastic rocks, flows, and their volcanioclastic sedimentary equivalents are primarily exposed west of the field trip area in the central and western Lake Michie 1:24K
Quadrangle. A suite of metamorphosed gabbro and calc-alkaline granitoids, including the informal Stem tonalite-granodiorite pluton and Oxford granite plutons of this field trip, intrudes and includes small and large enclaves of these metamorphosed volcanic and sedimentary rocks. These plutons become the primary rock types exposed from the eastern Lake Michie 1:24K Quadrangle, across the northern Stem 1:24K Quadrangle, and into the Wilton and Oxford 1:24K Quadrangles (Fig. 4; Hadley, 1973, 1974; McConnell, 1974; McConnell and Glover, 1982; Harris and Glover, 1988).

North of Oxford, the Carolina terrane is essentially unbroken across the eastern-to-western Piedmont transition, although the northern tip point for the FCFZ (the westernmost of the two major Mesozoic faults that bound the northeast border and sedimentary portion of the Triassic Durham sub-basin) has yet to be found. High-strain crystalline rocks along strike of the FCFZ continue north from the Oxford 1:24K Quadrangle to at least the central Stovall 1:24K Quadrangle (Parnell, 2012).

In the north-central Grissom 1:24K Quadrangle, the FCFZ apparently terminates against the Jonesboro fault, which extends northeastward from the Triassic basin, further complicating the lithologic and structural transition from the eastern-to-central Piedmont. The Jonesboro fault coincides with the outcrop trace and overprints the western portion of the Nutbush Creek–Lake Gordon fault system. There, the Jonesboro fault separates lower greenschist facies Carolina terrane metaplutonic rocks to the west from their amphibolite facies Falls Lake, Crabtree, and Raleigh terrane equivalents to the east.

North of the truncation of the FCFZ against the Jonesboro fault zone in the Wilton, Oxford, Kittrell, Henderson, Townsville, and Middleburg 1:24K Quadrangles (Figs. 2, 3, and 4), metaplutonic rocks dominate the Carolina terrane. From south to north, the major plutonic bodies are the Gibbs Creek pluton, Tabbs Creek complex, and the Vance County pluton, all of tonalitic to granodioritic bulk composition (Parker, 1963; Cook, 1963; Carpenter, 1970; Hadley, 1973; Farrar, 1985a; Grimes, 2000; Parnell et al., 2006b; Stoddard et al., 2002; Blake et al., 2003a). The eastern boundary of the Carolina terrane actually lies to the east of the FCFZ along the western boundary of the Nutbush Creek–Lake Gordon fault system. Between the FCFZ and Nutbush Creek–Lake Gordon fault system, these Carolina terrane metaplutonic rocks are complexly dissected by a network of anastomosing, ductile-brittle normal-slip fault zones.

The Gibbs Creek pluton, a metamorphosed porphyritic to equigranular tonalite and granodiorite, contains many cm- to m-scale enclaves of greenstone, and foliated and folded amphibolite and granitoid, as well as four map-scale meta-ultramafic bodies of serpentinite and talc + actinolite + chlorite rock up to several km long. Along its northern perimeter, the Gibbs Creek pluton intrudes greenstone, metagabbro, and more dominant metatonalite to metagranodiorite, collectively grouped as the Tabbs Creek complex (Grimes, 2000; Parnell et al., 2006b; Parnell, 2012). Locally, greenstone in the complex preserves relict basaltic and conglomeratic textures suggesting portions may have a mixed flow and clastic sedimentary origin. This greenstone appears to be wall rock to both the Gibbs Creek and Tabbs Creek complex metagranitoids.

Traversing eastward and northeastward across the suite however, greenstone outcrops become very fine-crystalline metagabbro. Swarms of metagranitoid dikes invade both greenstone types and produce an array of enclave relationships. In many outcrops, metagabbro enclaves and contacts between the metagabbro and metagranitoid preserve rounded to lobate shapes rather than angular boundaries; this may indicate a warm, malleable material behavior for the mafic plutons during felsic injection (Grimes, 2000).

The Vance County pluton is a metamorphosed granodiorite to trondhjemite batholith having a ca. 571 Ma zircon crystallization age (LeHuray, 1989; Farrar, 1985a; Druhan et al., 1994). In the Henderson, Townsville, and Middleburg 1:24K Quadrangles, it consists of medium- to coarse-crystalline, locally porphyritic biotite ± hornblende tonalite, granodiorite, granite and trondhjemite that commonly contains greenish saussuritized plagioclase and blue quartz. Enclaves of finer-crystalline foliated and unfoliated rocks are common. Westernmost exposures are less deformed, but toward the Nutbush Creek–Lake Gordon fault system to the east, outcrops of the Vance County pluton display increasing intensity of deformation that produced protomylonitic, mylonitic, ultramylonitic, and phyllonitic rocks. The Tabs Creek complex and Vance County pluton are in fault contact with the Crabtree and Raleigh terranes and with deformed granitic rocks across the Nutbush Creek–Lake Gordon fault system adjacent to the North Carolina–Virginia state line (Druhan et al., 1994; Grimes et al., 1997; Grimes, 2000; Blake et al., 2001).

Pennsylvanian-Permian Granitoid Rocks

The Rolesville batholith is a large, composite granitoid intrusion that lies generally along the hinge zone of the Wake-Warren anticlinorium, just east of the field trip area (Figs. 1 and 2). Field evidence indicates that plutons of the Rolesville batholith injected during or after the peak of regional metamorphism, and very limited radiometric age-dates indicate that they crystallized and cooled during the Pennsylvanian and Permian periods (Fullagar and Butler, 1979; Horton and Stern, 1994; Schneider and Samson, 2001).

Previous studies dealing with the Rolesville batholith include those of Parker (1968), Becker and Farrar (1977), Farrar (1985a, 1985b), Speer (1994), Speer et al. (1994), and Speer and Hoff (1997). Speer (1994) has demonstrated that, at least in the Raleigh 1:100K sheet, granitoid phases of the Rolesville batholith may be distinguished, based upon petrographic features, enclaves, and field relationships. Mapping in the Henderson 1:100K sheet has been able to continue that approach, and has revealed a much more extensive plutonic compositional range than heretofore recognized for the batholith, indicated by the occurrence of small pods of granodiorite, quartz diorite, diorite, and gabbronite.
within the western and perhaps deeper (?) portion of the batholith (Gaughan and Stoddard, 2003; Stoddard, 2011).

Several smaller Pennsylvanian and/or Permian granitic plutons are present throughout the eastern Piedmont (Speer, 1994; Horton et al., 1994). One of the largest of these, the Wise pluton, lies mainly in the unmapped Warrenton 1:24K Quadrangle, just to the east of the field trip route. The Wise granite is a medium-crystalline, two-mica granite within the field trip area and is considered to be a late syn-kinematic to post-kinematic pluton (Farrar, 1985a, 1985b; Sacks, 1996a). Alleghanian dextral-slip deformation ascribed to the Nutbush Creek–Lake Gordon fault system overprints granitoid rocks at the northern and northwestern margins of the Rolesville batholith across a corridor several km in width. Undefomed granite crosscuts mylonitic granitoid gneiss, indicating that pulses of Pennsylvanian-Permian magma intruded both syn- and post-kinematically with respect to Alleghanian deformation throughout the eastern Piedmont.

Late Paleozoic Fault Zones

The Alleghanian ductile dextral-slip fault zones crossingcutting north-central North Carolina define the individual high-strain elements of the Eastern Piedmont fault system and include from east to west, the Gaston Dam, Hollister, Macon, and Middle Creek (?) fault zones on the eastern flank and within the hinge zone of the Wake-Warren anticlinorium. On the western flank and in its type locality within the Kerr Lake Recreation Area (Casadevall, 1977), the historically known Nutbush Creek fault zone is defined as the dextral-slip fault zone that separates amphibolite-facies infrastructural Raleigh terrane rocks to the east from the greenschist-facies suprastructural Carolina terrane rocks to the west. Reconnaissance mapping from the type locality of the Nutbush Creek fault at the Virginia state line southward originally designated the southern extension of the fault to be the zone of highest observed strain.

However, NCGS STATEMAP results over the past 10 years have identified other zones of high strain that were assigned various fault names (e.g., Leesville fault zone). Our current mapping has necessitated some renaming of individual fault strands across the eastern-to-central Piedmont transition to retain consistency in the original definition of fault strands based upon field relationships while maintaining the established terrane terminology. Using recent mapping, the true southern extension of the Nutbush Creek fault zone from its type locality lies to the west of its currently defined location (e.g., Stoddard et al., 1991; Druhan et al., 1994), on the western flank of the Wake-Warren anticlinorium, as originally suggested by Farrar (1985a, 1985b). The newly named terrane-bounding strands now include, from east to west, the Lake Gordon, Neuse River, Falls Lake, and regionally known Nutbush Creek fault zones (Fig. 2; Hatcher et al., 1977; Boryarchick, 1981; Sacks 1999; Stoddard et al., 2009).

In the John H. Kerr Dam, Middleburg, Townsville, Henderson, Kittrell, and Wilton 1:24K Quadrangles, the Nutbush Creek fault zone separates metaplutonic rocks of the Carolina terrane from the Ruin Creek gneiss and foliated felsic gneiss of the Crabtree terrane (Figs. 2 and 3). In the Wilton 1:24K Quadrangle, the Jonesboro fault truncates a portion of the Nutbush Creek fault zone. South of the Jonesboro fault in the Creedmoor and Bayleaf 1:24K Quadrangles, the western boundary of the Falls Lake terrane with the easternmost Carolina terrane is a dextral normal-slip fault informally named the Upper Barton Creek fault zone (Horton et al., 2004). Down-dip-oriented fabric elements of Permian(?)-Mesozoic fault zones (Hames et al., 2001) may overprint the dextral dextral elements of the Nutbush Creek fault zone, but field relationships are equivocal and additional mapping is needed.

From the Raleigh West 1:24K Quadrangle south to Harnett County where it has been mapped in detail, the Nutbush Creek fault zone (formerly the Leesville fault zone) continues southward and separates greenschist-facies suprastructural rocks of the Cary sequence in the easternmost Carolina terrane from the Crabtree terrane to the east. The relocation and renaming of the Leesville fault zone to the Nutbush Creek fault zone is compatible with its mapped position between high grade and low grade rocks north of the Jonesboro fault. The Nutbush Creek fault zone continues south to at least the south side of the Cape Fear River before it and the easternmost Carolina and Crabtree terranes are obscured by Coastal Plain sedimentary rock cover in the Mamers and Lillington 1:24K Quadrangles.

As such, in the Henderson 1:24K Quadrangle east of the Nutbush Creek fault zone, recent mapping indicates that the fault zone which has been previously identified as the Nutbush Creek is actually a different zone of high strain within the Nutbush Creek–Lake Gordon fault system herein renamed the Neuse River fault zone (Fig. 2). From the northeastern Henderson 1:24K Quadrangle where they truncate against highly deformed Alleghanian granitoids of the Rolesville batholith, the Crabtree terrane, Neuse River fault zone, and a thin sliver of the redefined Raleigh terrane including the Raleigh Gneiss and the Falls Leucogneiss continue southward to the Wilton 1:24K Quadrangle.

There, the Neuse River fault zone overprints the eastern portion of the Crabtree terrane and the Alleghanian Wilton granite pluton that intrudes it (Figs. 2, 3 and 4). The Wilton pluton in turn, truncates the northern boundary between the Falls Lake and Crabtree terranes which is the dextral-slip Falls Lake fault zone. This strand of the Nutbush Creek–Lake Gordon fault system continues southward from the Wilton pluton to the northern Raleigh West 1:24K Quadrangle where it merges with the newly redefined Nutbush Creek fault zone. It is likely that both the Falls Lake and Nutbush Creek faults zones are overprinted by the Upper Barton Creek normal-slip fault zone here.

From the Pennsylvanian Wilton granite in the Wilton 1:24K Quadrangle south to the Lake Wheeler 1:24K Quadrangle in southern Wake County, the Neuse River fault zone (former location of the Nutbush Creek) marks the boundary between the amphibolite-facies infrastructural Crabtree and Raleigh terranes. The L>S tectonite of the Falls Leucogneiss still characteristically marks the location of this high-strain terrane boundary along
most of its length. In the southern Lake Wheeler 1:24K quadrangle, the Neuse River fault zone joins with the Lake Gordon fault zone and terminates the Raleigh terrane. South of this fault zone branch point, the Neuse River fault zone (former Nutbush Creek) continues southward as the dextral-slip fault zone separating the infrastructural Crabtree terrane to the west from the suprastructural Spring Hope terrane to the east (Fig. 2).

The Lake Gordon fault zone, originally defined by Horton et al. (1993a, 1993b) and Butler and Horton (1995), trends northeast-southwest through southern Virginia and lies parallel to and east of the Nutbush Creek fault zone (Sacks, 1999). The deformed Pennsylvanian Buggs Island granitoid pluton separates the two fault zones in the southern Piedmont of Virginia and defines a much narrower Nutbush Creek–Lake Gordon fault system than in North Carolina. The Lake Gordon fault zone continues into North Carolina and marks the boundary between highly deformed Pennsylvanian-Permian granitoid plutons and amphibolite facies, infrastructural schist and gneiss of the newly named Warren terrane just south of the Virginia–North Carolina state line. It continues south from the John H. Kerr Dam 1:24K Quadrangle separating individual deformed plutons of a larger, composite Alleghanian Rolesville batholith. South of the Kittrell 1:24K Quadrangle to its branch point with the Neuse River fault zone in the Lake Wheeler 1:24K Quadrangle, the Lake Gordon fault zone separates the Raleigh and Warren terranes and helps define the high strain character of the western flank of the Wake-Warren anticlinorium (Fig. 2).

Strands of the Nutbush Creek–Lake Gordon fault system, as newly defined, appear to overlap along much of the length of the western flank of the Wake-Warren anticlinorium, thus potentially constituting an along-strike zone of dextral-slip releasing offset. Kinematic indicators in rocks affected by these faults record a progressive ductile strain history having transitional strike-slip and dip-slip components during the late Paleozoic and early Mesozoic, suggesting an evolution from crustal transpressional (contraction or shortening) to dextral simple shear strain, and then, perhaps to dextral transtension and finally to extension. The transpressional component may have enabled the injection of deformed and undeformed mafic facies of the Pennsylvanian-Permian Rolesville batholith and similar Alleghanian orogeny plutons along the length of the Wake-Warren anticlinorium. The extensional component resulted from Triassic rifting and facilitated Jurassic diabase intrusions.

**Mesozoic Rift Basin and Magmatism**

Early Mesozoic rocks in the eastern Piedmont of North Carolina consist of two types: (1) Triassic sedimentary rocks of the Deep River rift basin, and (2) Early Jurassic diabase dikes and sills intruding both the Triassic sedimentary rocks and the crystalline rocks of the western flank.

The Deep River basin formed as a result of late Paleozoic (?) to early Mesozoic rifting of the supercontinent Pangaea (Fig. 5). This rifting created a series of irregularly shaped half-grabens and local full grabens along the Atlantic margin of North America. The Deep River basin is the southernmost exposed of these basins. During rifting, the basin filled with a variety of Triassic clastic sediments, their depositional environments strongly controlled by local basin tectonics. 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 deposits of the Deep River basin were buried and lithified, and are now recognized as the Chatham Group, part of the Newark Supergroup as defined by Olsen (1978), Luttrell (1989), and Weems and Olsen (1997). 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. 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.

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 of the Wake-Warren anticlinorium (Parker, 1979; North Carolina Geological Survey, 1985; Blake et al., 2001). The total amount of displacement along the fault is unknown, but a minimum estimate of 3.0–4.5 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 m wide gouge zone of clay and foliated breccia in the footwall.

Several intra-basinal faults, both synthetic and antithetic to the Jonesboro fault, are also recognized throughout the basin (Wooten et al., 2001). Along the western margin of the basin, Triassic sedimentary rocks unconformably overlie Neoproterozoic and Cambrian metavolcanic and metasedimentary rocks of the Carolina terrane (Butler and Secor, 1991). Locally, minor faults also form the basin boundary along the western border.

From north to south, the Deep River basin is subdivided into three smaller basins, the Durham, Sanford, and Wadesboro sub-basins, respectively. The boundaries of these smaller, component sub-basins are undefined. The width of the Deep River basin dramatically narrows at the Colon cross-structure, a basement high that separates the Durham sub-basin from the Sanford sub-basin (Campbell and Kimball, 1923).
The Colon cross-structure is well constrained by field mapping and seismic reflection data. Analyses of these data suggest it formed by differential subsidence of the Durham and Sanford sub-basins (Reinemund, 1955; Bain and Harvey, 1977; Dittmar, 1979). Slightly different lithologies occur on either side of the Colon cross-structure, suggesting it may have acted as a barrier to sedimentation. A similar structure, the Pekin cross-structure, has been proposed between the Sanford and Wadesboro sub-basins. The existence of the Pekin cross-structure is speculative due to a thin veneer of Atlantic Coastal Plain sedimentary rocks that blankets the area, as well as a lack of well constrained subsurface data.

Bain and Harvey (1977) proposed the first map units internal to the Durham sub-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 sub-basin (Southeast and Southwest Durham 1:24K 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 et al. (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 sub-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 may exist 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 terminology used by Hoffman and Gallagher (1989) for individual lithofacies (Smoot et al., 1988) names each 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 sub-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 noted by subscript numerals (i.e., Trcs/si₁ versus Trcs/si₂).

Watson (1998) extended some of the lithofacies of Hoffman and Gallagher (1989) into the central Durham sub-basin in the Green Level 1:24K Quadrangle. Clark (1998) also utilized the lithofacies system in the southern Durham sub-basin in the Cary, New Hill, Apex, and Cokesbury 1:24K Quadrangles. Clark found two lithofacies of Hoffman and Gallagher (1989), Trcs (sandstone) and Trsc (pebbly sandstone), were so intermixed in map pattern that he combined them into one mappable unit, Trcs/sc (interbedded sandstone and pebbly sandstone). All other map units are consistent with Hoffman and Gallagher (1989) and Watson (1998).

A complete description of the lithofacies of the Durham sub-basin, as well as the Sanford sub-basin to the south, can be found in Clark et al. (2001).

**Early Jurassic Intrusive Rocks**

Early Jurassic diabase intrusions occur throughout the North Carolina Piedmont, 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-crystalline 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 exposed 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 et al. (1986), Stoddard (1992), and Sacks (1999). A thorough discussion of the dike petrology is provided by Ragland (1991). Previous K-Ar and Ar-Ar dating attempts resulted in a wide range of ages between 160 and 203 Ma; however, recent ⁴⁰Ar/³⁹Ar work by Hames (2000, personal 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 in southwestern Wake County. Several of these dikes were observed to be laterally offset 0.5–4 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 et al. (2001) 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 unconformably
overlie the Jonesboro fault. However, no attempts have been made to document fault offset at these locations. Snipes et al. (1993) and Steve and Stephenson (1995) studied a similar Triassic basin, the Dunbarton basin, along the South Carolina–Georgia border. The Dunbarton is buried by ~350 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 as a reverse fault, offsetting the Coastal Plain sedimentary units 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.

FIELD TRIP STOPS

Purpose and Objective

The purpose of this two-day field trip is to provide (1) a regional geologic synopsis of a portion of the north-central North Carolina Piedmont, and (2) a tectonic overview of some of the interrelationships among lithologic, metamorphic, structural, and magmatic components of the transition from Pangean amalgamation to its initial breakup within the Carolina Zone (Figs. 1 and 2). We will focus on a corridor of 1:24K quadrangles mapped along the Alleghanian Nutbush Creek–Lake Gordon fault system and the northern Durham sub-basin of the Triassic Deep River rift basin. A regional overview of the field trip stops is provided on two composite geologic maps of the Henderson, Townsville, Middleburg, and North Carolina portion of the Kerr Dam 1:24K Quadrangles for Day 1 (Fig. 3) and the Oxford, Wilton, Stem, Lake Michie, Creedmoor, and Bayleaf 1:24K Quadrangles for Day 2 (Fig. 4). Mileages were determined using the ruler tool in Google Earth©. All stops are georeferenced using latitude and longitude coordinates (WGS84).

DAY 1. CHARLOTTE TO KERR LAKE AND THE NUTBUSH CREEK FAULT ZONE

Directions to Stop 1. Depart the Charlotte Convention Center, driving north on E. Stonewall St. Turn left (west) on S. Church St, and then merge right onto I-77 North. Drive 0.5 mile and merge right onto I-77 North. Travel 4 miles north on I-77 to the interchange with I-85 East at Exit 13. Merge right onto I-85 North and travel 185 miles to Exit 223 at Manson-Drewry Road (CR 1237). Turn right (east) from the off-ramp traveling 0.9 miles to Manson. Turn right (south) on U.S. 1 and drive 0.5 miles to Kimball Road. Turn left (east) onto Kimball Road (Manson-Axtell Road, CR 1100), cross the railroad tracks, and travel 2.1 miles to Fishing Creek and park on the right just north of the bridge. Walk carefully past the riprap to exposures along an old sewer line that follows the north bank of the creek. This is Stop 1 [latitude 36.39908°, longitude −78.26567°].

Stop 1. Layered Mafic Gneiss of the Warren Terrane

Location: Abandoned sewer line excavations and roadway, north side of Fishing Creek, downstream from Manson-Axtell Road bridge, extending ~300 m downstream to where the creek bends to the right (south); southeastern corner of the quadrangle.

Map: Middleburg 1:24K Quadrangle.

Metamorphic rocks east of the Lake Gordon fault zone include a mix of gneiss and schist that have been considered to be parts of the Raleigh Gneiss by Farrar (1985a, 1985b) and other workers (Fig. 3). At Stop 1, rocks are exposed along Fishing Creek and along a parallel roadway that was excavated for a sewer line during the early 1970s. The line runs to a small, now defunct, wastewater treatment facility located about one km downstream from the bridge. The project was intended to serve the planned community of Soul City, brainchild of civil rights leader Floyd B. McKissick. Legislation enacted during the administration of President Lyndon Johnson made federal assistance available that allowed the initial development of Soul City and its infrastructure, but economic conditions and politics prevented the concept from achieving fruition (see Strain, 2004; Biles, 2005). The property is now privately owned.

Here we are in a unit consisting primarily of mesocratic to melanocratic, medium- to coarse-crystalline, typically layered hornblende and hornblende-biotite gneiss (Figs. 6A, 6B). Clinopyroxene is common, generally as a later phase and locally part of a mineral assemblage showing granoblastic texture. Some of the orthogneiss in this unit is clearly metagabbroic, having large relic plagioclase phenocrysts and a color index of ~50; mylonitic overprint in places yields a porphyroclastic texture from the relic plagioclase phenocrysts. In addition to green hornblende, biotite, intermediate plagioclase, and clinopyroxene, epidote/clinozoisite and titanite are common mineral constituents (Fig. 6C). Middle to upper amphibolite facies conditions are inferred, locally overprinted by hornblende hornfels facies. No orthopyroxene has been observed, and in thin section, clinopyroxene appears to have formed after hornblende, indicating that at least at this stop, the rocks did not achieve the granulite facies (Fig. 6D).

Other layered portions are suggestive of a metasedimentary component. For example, this unit is in contact to the west with fine- to medium-crystalline quartzofeldspathic gneiss. The unit also contains fine- to medium-crystalline felsic gneiss ± biotite, and very rare diopside-rich calc-silicate hornfels or granofels ± microcline. A major unit of white mica schist is exposed to the west of the quartzofeldspathic gneiss. In the northern Middleburg and southern John H. Kerr Dam 1:24K Quadrangles, stringers of the white mica schist are associated with the hornblende-biotite gneiss unit. We will examine a garnet sillimanite white mica schist exposure at Stop 2. Orientations of gneissic layering are quite variable here, but typically strike to the west of north and dip moderately to steeply west or southwest. Early isoclinal folds are locally visible, overprinted by upright open folds.

Locally, sills and dikes of granite and pegmatite, possibly related to the Pennsylvanian-Permian Wise pluton just to the east,
Alleghanian Nutbush Creek fault zone and Deep River Triassic basin

are abundant. As such, exposures in this unit strongly resemble the Raleigh Gneiss near Raleigh, which has been referred to as an “injection complex” adjacent to the Rolesville batholith (Parker, 1979). In fact, ~200 m downstream from the bridge at Stop 1, near where a small tributary enters Fishing Creek, granitic injections become abundant. However, in many other exposures, such as some of the more upstream outcrops here, there is much less felsic plutonic material. Here, the rock is layered amphibolite or metagabbroic orthogneiss, and may perhaps be representative of a larger meta-igneous component to the protolith for parts of the Warren terrane. Some of this material, especially metaplutonic protoliths may have originated as mafic substrate for part of the Carolina Zone. The type area for the Raleigh terrane contains little if any schistose, metasedimentary rocks and does not have protoliths that resemble these Warren terrane rocks.

Directions to Stop 2. Depart Stop 1 and continue north on Manson-Axtell Road ~0.6 miles to Soul City. Turn right (east) on Liberation Road (CR 1113) and drive 2.1 miles to the T-intersection. Turn left (north) on Axtell-Ridgeway Road and drive 1.9 miles to U.S. Highway 1/158. Turn right (northeast) and drive 1.2 miles, passing through Ridgeway, North Carolina. Turn left (north) on St. Tammany Road (CR 1210) and drive 3.6 miles, passing over I-85 at Oine, North Carolina. Turn left (west) on Martin Road (CR 1217), drive 1.1 miles and turn right (north) on Russell Union Road (CR 1206). Drive 0.9 miles to the bridge over Smith Creek. Park and follow the path to the right (downstream) on the north side of the creek to exposures on a low ridge at the edge of the floodplain. Stop 2 [latitude 36.50374°, longitude −78.25078°].

Stop 2. Pelitic Schist of the Warren Terrane

Location: Low ridge on north side of Smith Creek ~0.15 miles downstream (east) from Russell Union Road Bridge, southeastern corner of quadrangle.
Map: John H. Kerr Dam 1:24K Quadrangle.

A map unit of pelitic mica schist is mapped continuously from the southern edge of the Middleburg 1:24K Quadrangle and into the southeastern corner of the John H. Kerr Dam 1:24K Quadrangle (Fig. 3). It lies mainly to the west of the

Figure 6. Outcrop and petrographic relationships at Stop 1. (A) Float block at Stop 1 showing thinly layered hornblende and hornblende-biotite gneiss with infolded fine gneissic granitoid compositional layer. Hammer handle for scale. (B) Leucosome showing tight folding in mafic gneiss at Stop 1. (C) Photomicrograph of hornblende-biotite orthogneiss from Stop 1. Hornblende+biotite-rich layer at lower right. Plane-polarized light, scale bar is 1 mm. (D) Photomicrograph of clinopyroxene-bearing hornblende metagabbro from the hornblende gneiss unit, about two km north of Stop 1. Pyroxene appears to have formed after hornblende, and is thus interpreted to be Alleghanian. Cross-polarized light. Scale bar is 1 mm.
hornblende-biotite gneiss unit seen at Stop 1 and the intervening felsic gneiss unit, although there are some intercalations among these three lithologic units. The schist enters the southwestern portion of the Bracey 1:24K Quadrangle, where it was mapped by Sacks (1996a) as part of his biotite gneiss unit. For most of its map length, the western margin of the schist carries a strong phyllonitic fabric and is in contact with granitoid mylonite. We interpret this contact as the eastern edge of the Lake Gordon fault zone and the Nutbush Creek–Lake Gordon fault system.

The schist of this unit is typically medium-fine- to medium-crystalline, locally with large garnet porphyroblasts (to 1 cm); it is strongly foliated and locally strongly linedated. Common mineral assemblages are white mica ± sillimanite ± garnet, white mica + chlorite ± sillimanite ± garnet, white mica + biotite + garnet ± sillimanite ± kyanite ± chlorite ± tourmaline. Chlorite typically appears to be retrograde, and in some specimens occurs in clots or sprays and may be pseudomorphic after an earlier porphyroblastic mineral. Sillimanite occurs most commonly in blocky prismatic form along the foliation plane defined by white mica. One unusual specimen, found as float, consists of crenulated white mica schist with kyanite and fibrolitic sillimanite along the foliation, and porphyroblasts of corundum, one of which displays pleochroic blue (var. sapphire) cores in thin section.

Farrar (1984, 1985a, 1985b) argued that sillimanite in the schists of this area is Grenville in age (Mesoproterozoic), belonging to a granulite-grade assemblage overprinted by amphibolite assemblages of late Paleozoic age. It is possible that the prismatic sillimanite was the product of an early metamorphic event and the fibrolitic variety may be the result of thermal overprint. The later event is undoubtedly late Paleozoic in age; the age of the earlier event is unclear, but it also could be late Paleozoic. In thin sections that we have examined which contain both kyanite and sillimanite, the sequence of their growth is ambiguous, except for one specimen in which fibrolitic sillimanite appears to be the later phase. Photomicrographs of samples from the pelitic schist unit are shown in Figures 7A–7D.

Figure 7. Petrographic relationships in samples from the pelitic schist unit seen at Stop 2. (A and B) Photomicrographs of pelitic schist from outcrop in southern Middleburg 1:24K Quadrangle. Assemblage is white mica + garnet + biotite + sillimanite + chlorite. Sillimanite is prismatic and chlorite is retrograde, possibly pseudomorphic. Photo shows sillimanite prisms enclosed in white mica. (A) Plane-polarized light. (B) Cross-polarized light. Scale bar is 0.2 mm. (C and D) Photomicrographs from float sample within pelitic schist unit in south-central Middleburg 1:24K Quadrangle showing a large corundum porphyroblast, partially pseudomorphed by white mica. Assemblage includes blocky kyanite, possibly after prismatic sillimanite, plus later fibrolitic sillimanite. (A) Plane-polarized light. (B) Cross-polarized light. Scale bar is 1 mm.
Directions to Stop 3. Depart Stop 2 and continue ~0.8 miles north on Russell Union Road (CR 1206) to the T-intersection with Burchette Road (CR 1218). Turn right (north) and follow Burchette Road (CR 1218) 2.0 miles to where it ends at Drewry–Virginia Line Road (CR 1200). Turn left (southwest) and drive ~1.0 mile on Drewry–Virginia Line Road (CR 1200) to Kimball Point Road (CR 1204) and turn right (west). Travel 0.9 miles to Boulder Boulevard. Turn right (north) and park at the end of Boulder Boulevard. Walk due north to the lakeshore and proceed west along the shoreline to the rocky bluff outcrops on the point at Stop 3 [latitude 36°53′33″, longitude −78°30′34″].

Stop 3. Late Paleozoic-Mesozoic (?) Brittle Deformation, Kimball Point, Kerr Lake State Recreation Area

Location: Kimball Point Road and north-facing Kerr Lake shoreline just south of the North Carolina–Virginia state line.

Map: John H. Kerr Dam 1:24K Quadrangle.

A common theme along the length of the Nutbush Creek–Lake Gordon fault system in North Carolina is the occurrence of silicified, and locally epidotized, cataclastic fault zones that are oriented subparallel or highly oblique to the regional metamorphic/mylonitic structural grain. These zones range from isolated, resistant linear outcrops to more complex networks of interconnected, lattice-like faults that may be several m to km in length and have moderate to steep dips (e.g., Heller et al., 1998; Stoddard et al., 2002).

This stop provides the opportunity to observe multiple orientations of silicified cataclasite that overprint regional mylonitic rocks (Fig. 3). Here, the surrounding rocks are part of a unit informally called Pg, that is a leucocratic (CI < 10–15), pink-rocks (Fig. 3). Here, the surrounding rocks are part of a unit connected, lattice-like faults that may be several m to km in length and resistant linear outcrops to more complex networks of interconnected, lattice-like faults that may be several m to km in length and have moderate to steep dips. (e.g., Heller et al., 1998; Stoddard et al., 2002).

This stop provides the opportunity to observe multiple orientations of silicified cataclasite that overprint regional mylonitic rocks (Fig. 3). Here, the surrounding rocks are part of a unit informally called Pg, that is a leucocratic (CI < 10–15), pink-tan and white-gray-tan, dominantly fine- to medium-crystalline, well foliated and lineated, biotite white mica granitic mylonitic gneiss. It is part of the suite of mylonitic granitoid gneisses that occupy the space between fault zones of the Nutbush Creek–Lake Gordon fault system and are likely Pennsylvanian-Permian in age and emplaced during the Alleghanian orogeny. In the hillsides and shoreline at this stop, most of the mylonitic gneiss is exposed as saprolite and the topographic relief is caused by the more resistant silicified cataclasite.

Oriented parallel to Boulder Road, a dominant ridge-like boulder field and outcrop fin of silicified cataclasite strikes N15°E, and contains readily apparent fractures striking N20°E and dipping 80°NW (200,80) (Fig. 8A). This fin and boulder ridge has been mapped from the community of Keats, Virginia, at the North Carolina–Virginia line (located ~0.8 km directly north of Stop 4) to the community of Rose Hill, North Carolina, ~2.4 km south of Stop 4. It likely continues further south as indicated by the shaded relief map derived from LiDAR digital elevation model for Warren County and by the reconnaissance mapping of Bob Butler and Bob Druhan who coined the term “Rose Hill fault” (Bob Druhan, personal commun., 2010).

In addition, John M. Parker III (early 1960s?) wrote a short description of the zone entitled “Siliceous Belt north of Drewry” in one of a series of blue pamphlets that were county-based geologic field guides for schoolteachers. Although Parker did not mention a fault, he did trace a silicified zone for ~3.2 km near the community of Drewry, North Carolina, located ~6.4 km south of Rose Hill. In the Kerr Dam and northern Middleburg 1:24K Quadrangles, there are at least five of these northeast-striking silicified cataclasite zones (Buford et al., 2007; Blake et al., 2010).

There are at least two approximately east-west-oriented silicified cataclasite zones connected to the informal Rose Hill fault, and Stop 4 highlights the northern zone that trends along the north-facing shoreline of Kimball Point. The second, southern zone trends N80°E ~0.4 km northeast of the Rose Hill community within eastern coves of Dix Branch on Kerr Lake. Together, these three silicified cataclasite zones are informally referred to as the Rose Hill fault system.

Rounding the shoreline to Stop 3, the north-facing ridgeline contains a wave-cut terrace of cobble and boulder debris, as well as outcrops of vuggy quartz-epidote rock and silicified cataclasite (Fig. 8B). Many chips and flat rock pieces at the east end of the outcrop are white mica biotite schist, which commonly occurs regionally as cm- to km-scale enclaves in the granitic mylonitic gneiss. Shoreline exposures west of the cataclasite are primarily K-feldspar porphyroclastic, biotite-poor mylonitic granitic gneiss. In between these two localities, in-place gneiss is cut by cm-thick quartz veins and is highly epidotized, but continues to preserve the mylonitic foliation (Fig. 8C). Along the terrace, angularity of the debris is attributed to the highly fractured character of the outcrops.

Several obvious fault clasts of epidotized granite, containing relic lumps of K-feldspar and foliation and cut by quartz veins, are apparent in some block outcrops. In addition to the extreme fracturing, quartz-filled vugs in which crystals display rhombohedral terminations stand out in some outcrops. Preliminary lineation measurements on crystal orientation in the vugs show they are subparallel to the regional subhorizontal stretch lineation in granitic mylonitic gneiss. At least one outcrop of quartz-filled vugs in silicified cataclasite in the northern Middleburg 1:24K Quadrangle displays similar crystal-orientation relationships.

While the origin of these silicified cataclasite zones of the Rose Hill fault system is not yet clear, they are common structural features in the Nutbush Creek–Lake Gordon fault system within and along the fault zone boundaries of individual terranes. Multiple pulses of extension and dilational opening of fractures develop multiple east-west–oriented, cataclastic and silicified zones (Fig. 8D). This north-south stretch component tends to be approximately parallel to the regional, finite stretch component preserved as mineral lineation and boudin structure in the mylonitic gneisses and schist enclaves and compositional layering, leading to their east-west orientation. Extension and dilational opening of...
fractures leading to the north-south-oriented silicified zones is roughly orthogonal to this stretch component and parallel to the regional foliation. Where locally preserved, slickenline and vein fiber orientations suggest down-dip displacement on the north-south zones. Similar zones of silicified and epidotized cataclasite define the locations and trends of normal faults related to rift development along the eastern margin of the Triassic Deep River rift basin including the bounding Jonesboro fault and FCFZ.

Directions to Stop 4. Depart Stop 3 and return ~0.9 miles on Kimball Point Road to Drewry–Virginia Line Road. Turn right (south) and continue 2.2 miles to Buchanan Road (CR 1202). Turn right (west) and proceed 0.7 miles to County Line Road. Turn right (north), travel 1.2 miles, and turn right (east) onto County Line Park Road at the T-intersection. Proceed 1.1 miles to the end of the loop road. Walk to shoreline and series of lake level-dependent outcrops at Stop 4 [latitude 36.53232°, longitude −78.3197°].

Stop 4. Mylonitic Alleghanian(?) Granitoids and Gneissic Enclaves, County Line Park, Kerr Lake State Recreation Area
Location: Dix Creek, County Line Park Picnic Area, and its west- and north-facing Kerr Lake shorelines.
Map: John H. Kerr Dam 1:24K Quadrangle.

When the lake level is at or below normal, this stop provides spectacular views of ductile dextral strain of the Nutbush Creek–Lake Gordon fault system. The rocks here were originally mapped as Neoproterozoic to Cambrian inequigranular and megacrystic garnet-bearing biotite gneiss, interlayered with and gradational into mica schist and amphibolite, and containing small masses of granitic rocks (NCGS, 1985). Butler and Druhan (unpublished mapping) traversed the lakeshore and adjacent streams in both the Virginia and North Carolina portions of Kerr Dam 1:24K Quadrangle and mapped the point as layered gneiss and schist of the Raleigh terrane. The notes on their field sheets...
describe biotite gneiss, granitic gneiss, amphibolite, and other compositional layering.

Horton et al. (1993a) remapped the area, classifying County Line Park Point as part of a unit of granitic gneiss lying south of the Late Pennsylvanian Buggs Island granite. On their map, the unit constitutes a large Alleghanian orogeny granitic gneiss that is flanked by the Nutbush Creek fault zone to the west and the Lake Gordon fault zone to the east in the south-central Virginia Piedmont (Horton et al., 1993a; Butler and Horton, 1995; Sacks, 1999; Virginia Division of Mineral Resources [VDMR], 1993).

We have mapped these outcrops as part of the informal Pg1 unit, which is primarily foliated granitic mylonitic gneiss (Fig. 9). The unit as a whole tends to be leucocratic (CI < 10–15), pink-tan and white-gray-tan, dominantly fine- to medium-crystalline, well foliated and lineated, white mica ± biotite granitic gneiss. However, some domains vary in biotite and white mica content (CI up to 25–35). These phyllosilicates join pink-white microcline, plagioclase, and quartz in the mineral assemblage.

Locally, biotite-white mica schist, which may contain fibrolitic sillimanite, and thin felsic gneiss layers form compositional layering oriented parallel to the mylonitic foliation in granitic gneiss. These rocks appear to be enclaves incorporated into the pre- or syn-kinematic magmatic phase. In some cases, the increase in schist enclave abundance seems to locally correspond with some increase in biotite content of the granitic gneiss, perhaps suggestive of enclave digestion and biotite enrichment of the granitic magma, but no clearcut relationships are yet recognized.

In other compositional layers that also may be large enclaves in granitic gneiss, hornblende ± biotite ± epidote ± retrograde chlorite and plagioclase dominate the mineral assemblage of amphibolite, especially at the western point of the park (Fig. 9A). These layers, ranging from cm to m in width and length may consist entirely of melanocratic and leucocratic compositional layers that form internally coherent gneiss layers bounded by granitic gneiss. Several large domains dominated by amphibolite rather than granitic gneiss are inferred to extend across to Kimball Point, another amphibolite-rich locality in this unit.

Other amphibolite layers have pegmatitic granitic gneiss seams intruded along strike of the foliation or are separated and bounded by pegmatitic granitic gneiss into separate amphibolite layers; in each case, the granitic gneiss appears to be a later sill-like injection (Fig. 9B). In several places, these amphibolite and dioritic gneiss assemblages are reminiscent of Raleigh Gneiss exposures farther south in the Henderson and Raleigh 100K sheets.
Compositional layers are variably stretched in the dominant plane of mylonitic foliation, commonly forming pinch and swell structure while others terminate as elongate asymmetric boudins, especially in amphibolite as noted by Butler and Druhan (unpublished mapping). Boudin stretch directions are coincident with the dominant northeast-trending subhorizontal mineral lineation, making it a stretching lineation. Due to compositional strain partitioning, other layers form scale-variable sets of asymmetric fish-like structures. Steeply dipping fins of foliation also display this top-north asymmetric sweep. These features allow S-surfaces, and C- and C′-shear surfaces to be readily identified and measured (Fig. 9C). Also, sigma-type winged K-feldspar porphyroclasts are flattened and rotated and contribute to the composite S-C surfaces and C-C′ surfaces.

Finally, in still other layers, varieties of granitic gneiss produce the compositional variations. In addition to changes in white mica ± biotite content, these layers may vary in (1) original magmatic crystal sizes, (2) degree of penetration of strain that also leads to changes in bulk crystal sizes and formation of rootless isoclinal fold hinges (Fig. 9D), (3) quantity and size of K-feldspar porphyroclast development, (4) number of thin, cm-scale mesocratic versus leucocratic mineral domains that appear to represent relic wallrock(?), (5) layering versus leucocratic dike and sill injections of later intrusive granitoid, and finally, (5) amount of white- to white-pink and red-pink pegmatitic granite and granitic gneiss injections, again as either dikes or sills. While these relationships are apparent at County Line Park, in outcrops to the north at Kimball Point and the point west of Keats, Virginia, pegmatitic granitic gneiss dominates the granitic gneiss, forming m-high, and m-scale elongate fins that preserve multiple and consistent dextral sigma-type porphyroclast relationships.

In fact, the predominance of dextral kinematic indicators significantly contributes to the overall strain character and grain of these outcrops and the granitic gneiss unit as a whole. Overprint of protomylonitic, mylonitic and ultramytonitic fabric elements obscures many contact relationships. Highly transposed, subparallel granitic mineral assemblages and foliation appear to have developed during pre-full magmatic crystallization and crystal-plastic deformation. Truncation of foliation by other highly foliated granitoids highlights the progressive strain history in this fault system (Fig. 9E).

The abundance of planar C-C′ relationships combined with silicified fractures oriented both subparallel and highly oblique to S-C foliation (Fig. 9F) suggests that these outcrops experienced extension similar to Stop 3. Because of their along-strike position in the Nutbush Creek–Lake Gordon fault system, these rocks may be the high strain equivalent of granitoid rocks at optional Stop 8 lying within this large area of granitoid injections into fault zones. Again, we interpret this mixing of granite textures and fabric elements to indicate that magma intruded repeatedly in pulses, during and following the time of shear strain displacements. Whether this northwestern region of the “Rolesville batholith” really belongs to that intrusive phase, or constitutes a different pluton (perhaps even an extension of the Buggs Island) remains to be determined through detailed mapping.

**Directions to Stop 5.** Depart Stop 4 and return to the T-intersection between County Line Park Road and County Line Road. Turn right (west) onto County Line Road. Proceed 0.6 miles and park along the road. Walk north to the rocky Kerr Lake shoreline and Stop 5 [latitude 36.52248°, longitude –78.3301°].

**Stop 5. Jurassic “Devil’s Backbone” Diabase, County Line Park, Kerr Lake State Recreation Area**

Location: Western portion of County Line Park and east-facing Kerr Lake shoreline.

Map: John H. Kerr Dam 1:24K Quadrangle.

Assuming the lake is not too high, here we see an extensive linear boulder field along the lakeshore exposing a coarse-crystalline, two-pyroxene, granophyre- and locally quartz-bearing diabase, texturally and mineralogically distinct from the more common olivine diabase. This dike has been mapped from central Johnston County north for a distance greater than 120 km, crossing the state line into Virginia. In the southern part of its outcrop area near Flowers, North Carolina, the dike trends about N15°W, curving to a N-S direction near Rolesville, and then to approximately N10°E north of Henderson. The dike appears to be between 32 and 40 m in width. Field evidence and magnetic modeling suggests that it dips eastward 75–80° near Middleton.

This dike is particularly well exposed due to large semi-continuous bouldery outcrops (Fig. 10A), including a number of spots where a stream crosses it, and the entire width of the dike may be sampled. There is also a close relationship to geomorphology, with the dike trending parallel to stream courses in some cases, and in others the dike trends along ridge-tops. In the Kittrell 1:24K Quadrangle, just north of the Tar River, an elderly man told one of us all about the dike without knowing any geology. He said he reckoned you could walk on those boulders all the way up to Henderson, and he even knew where the dike crosses several roads on the way. He said “Folks around here call that ‘The Devils Backbone’.”

Where mapped, the dike intrudes granitoid country rocks of the Rolesville batholith and older metamorphic rocks of the Spring Hope and newly defined Warren terranes. The dike also intrudes rocks that have been ductilely deformed within the Nutbush Creek–Lake Gordon fault system, but the diabase shows no evidence of ductile deformation. In several places, the dike is transected by brittle faults at a high angle, and at one location in the southwestern Middleburg 1:24K Quadrangle, the dike is clearly cut and offset along a north-dipping normal fault. Petrographic characteristics include a generally coarser crystal size than most olivine diabase and a low-Ca pyroxene in addition to an augitic, high-Ca pyroxene (Fig. 10B). Plagioclase occurs commonly as rectangular laths, but also locally as large blocky phenocrysts (Fig. 10C). The diabase locally contains a fine granophyric intergrowth of alkali feldspar and quartz (Fig. 10D). The two-pyroxene diabase is quartz normative and shows...
many other indications of being somewhat more evolved than the more common olivine diabase variety. Silica, Ti, alkali elements, Rb, Zr, Th, and U are higher in the quartz-normative dike than in olivine diabase, while Mg and transition metal elements are in lower concentrations than in olivine diabase.

Directions to Stop 6. Depart stop and return to the T-intersection between County Line Park Road and County Line Road. Turn right (south) onto County Line Road and drive 1.2 miles to Buchanan Road (CR 1202). Turn left (east), driving 0.7 miles back to Drewry–Virginia Line Road (CR 1200), which to the south is called Jacksontown Road (CR 1369). Turn right (south) and travel 6.8 miles to the T-intersection with Jackson-Royster Road (CR 1400). Turn right (west) on Jackson-Royster Road and proceed 1.2 miles to Flemingtown Road (CR 1371). Turn left (south) and proceed 0.9 miles to East Spain–Middleburg Road. Turn left (east) and drive 0.3 miles to the sharp bend in the road and park. Walk south across the stream, uphill, and into the woods ~0.1 mile to Stop 6 [latitude 36.40243°, longitude −78.33972°].

Stop 6. Deformed Pennsylvanian Granitoids, Lake Gordon Shear Zone
Location: Top wall of stone quarry 1.1 km northwest of E.O. Young Elementary School in Middleburg.
Map: Middleburg 1:24K Quadrangle.

Here we visit an excellent exposure in an abandoned quarry of strongly deformed protomylonitic to mylonitic granitic rock (Fig. 3) referred to as Middleburg gneiss by Parker (undated, likely early 1960s). This is one of several small inactive quarries in the vicinity of Middleburg (Ronald Stainback, personal commun., 2011); most of them are now backfilled. Known as the Carroll Quarry, it produced dimension stone as long ago as 1899 that was used for curbing and blocks in Norfolk and Portsmouth, Virginia (Watson and Laney, 1906). The quarry may have also been used during construction of I-85.

The rock is medium-crystalline porphyroclastic biotite granite with a color index of ~10. The rock is less gneissic than

Figure 10. Outcrop features at Stop 5. (A) Lakeshore boulder field exposure of diabase dike looking south along strike. Trains of such boulders gives this dike the local nickname “Devil’s Backbone.” Figures B–D show some petrographic features from dike samples in the Henderson 1:24K Quadrangle. (B) Photomicrograph under crossed polars, showing relatively coarse crystal size and texture of a sample of two-pyroxene diabase. (C) Large plagioclase phenocrysts are commonly strongly zoned, with the core very calcic at An90 (anorthite) and the rim in the An65−70 (labradorite) range. Cross-polarized light. (D) A granophyric intergrowth of alkali feldspar and quartz is another diagnostic feature of this diabase. Cross-polarized light. Scale bars are 1 mm and 0.5 mm, respectively.
many granitoids to the east, and overall appears relatively homogeneous and more penetratively deformed (Figs. 11A, 11B). It carries a strong biotite foliation, flattened and locally ribboned feldspars; these foliations are near-vertical and strike N10°E to N15°E. Rare winged porphyroclasts and a stretch lineation indicate subhorizontal dextral shear strain. We map this exposure near an unnamed fault zone.

A thin section shows alkali feldspar porphyroclasts having cores of relic Carlsbad-twinned perthitic orthoclase mantled by finer microcline derived from the outer portions of the original phenocrysts (Fig. 11C). With Q:A:P of ~30:60:10, this rock is a syenogranite using the IUGS classification. In addition to the aligned dark brown biotite, the rock contains significant unoriented post-kinematic white mica. Allanite is a distinctive accessory phase present in this granite; it has also been found in deformed granite at the western edge of the Vicksboro 1:24K Quadrangle, ~10 km to the south and approximately along strike. Between these two locations, in the northwest corner of the Vicksboro 1:24K Quadrangle, the Greystone Quarry, operated by Vulcan Materials, exposes protomylonitic to mylonitic granite, leucogranite, and pegmatite, with some gneissic varieties and enclaves of biotite gneiss. Foliation defined by oriented biotite and by gneissic layering is variable but averages nearly north-south; there is also a subhorizontal mineral stretching lineation. Also at the quarry, late chlorite films define a steeply east-dipping foliation, and a late brittle fault trending approximately east-west cuts the granitic rocks.

At the latitude of Middleburg, a large region (“sea”) of granitic rocks, most very strongly deformed, lies within the Nutbush Creek–Lake Gordon fault system, from the edge of the Carolina terrane on the west, to the edge of the Warren terrane on the east. Modest petrographic differences have led us to divide them into three parallel map-units, but the distinctions are not major. In the John H. Kerr Dam 1:24K Quadrangle, Horton et al. (1993a) mapped a pre-Alleghanian granitic gneiss unit between the two mylonite zones, whereas we map granitic rocks, presumably late Paleozoic, in the same area, on strike and to the south of where Horton et al. (1993a) showed the Buggs Island pluton ending. Furthermore, we see no definite break in the deformation fabric elements across this zone of granitoids. Whether the granite located at Stop 6 belongs to the composite Rolesville batholith, Buggs Island pluton, or neither, remains to be seen. Continued mapping, petrographic analysis, geochemical, and geochronological study will be necessary to make that determination.

**Directions to Stop 7.** Depart Stop 6 and return to Fleming-town Road (CR 1371) and turn right (north). Proceed 1.0 mile and turn left (west) on Anderson Creek Road (CR 1374). Travel 1.7 miles to the T-intersection with Satterwhite Point Road (CR 1319). Turn left (south) and proceed ~1.4 miles to

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**Figure 11. Outcrop and petrographic features at Stop 6.** Shear sense is tops-north to the right in Figures A and B. (A) Outcrop showing granitoid mylonite. Rock is a biotite syenogranite with prominent alkali feldspar porphyroclasts deformed into ribbons. Surface is nearly horizontal, top of the photo is toward the west. (B) Another area of Stop 6 exposure showing large winged feldspar porphyroclast indicating dextral shear. Top of photo is to the west; hammer is 32 cm long. (C) Photomicrograph from outcrop at Stop 6. Porphyroclasts have Carlsbad-twinned perthitic orthoclase in their cores, mantled by recrystallized matrix containing microcline. Rock contains Q:A:P of ~30:60:10, 8% biotite, 5% white mica, and carries significant allanite as the main accessory mineral. Cross-polarized light. Scale bar is 1 mm.
Nutbush Road (CR 1308). Turn right (west) and drive 3.0 miles to its intersection with NC 39. Turn right (north) and proceed 9.3 miles to the Y-intersection with Rock Spring Church Road (SR 1356). Bear to the right and drive 3 miles to Reverend Henderson Road. Turn right (east) and proceed 1.5 miles into Henderson Point Park and take the first left (north) inside the park. This road leads to a boat ramp on the west side of Kerr Lake, 0.3 miles past the left turn. Walk east to the western shoreline of Nutbush Creek, Kerr Lake and Stop 7 [latitude 36.5371°, longitude −78.34171°].

Stop 7. Phyllonite and Mylonite of the Carolina Terrane, Nutbush Creek Fault Zone, Henderson Point Park, Kerr Lake State Recreation Area
Location: East-facing shoreline of Nutbush Creek and Kerr Lake from a point just west of the boat ramp around to the northern point of the park.
Map: John H. Kerr Dam 1:24K Quadrangle.

When the lake is at or below normal levels, this stop provides spectacular views of ductile dextral strain of the Nutbush Creek–Lake Gordon fault system. The rocks here were originally recognized by Parker (1963, 1968, 1978) as a unique strip of phyllite along the eastern boundary of the Vance County pluton, a tonalite to granodiorite pluton in the Carolina terrane (Fig. 3). Casadevall (1977) reinterpreted the phyllite as fault zone phyllonite and mylonite, noting the correlation between a regional northeast-southwest-oriented, linear aeromagnetic anomaly and the topographic lineament produced by Nutbush Creek along Kerr Lake Recreation Area.

Subsequently, these rocks were described as a linear-tending zone of Neoproterozoic to Cambrian phyllite and schist containing minor biotite and pyrite, and noted for being associated with fault zone phyllonite and sheared metasedimentary and metavolcanic rocks (NCGS, 1985). Butler and Druhan (unpublished mapping) also noted the spectacular structures at this stop, while Druhan (1983) and Druhan et al. (1994) carefully mapped this phyllonite/mylonite zone and then a zone of regionally high strain from the North Carolina–Virginia state line southward. They provided a regional synopsis of the structural character and regional extent of the ductile dextral Nutbush Creek fault zone, now a strand within the Nutbush Creek–Lake Gordon fault system, along the western flank of the Wake-Warren anticlinorium in the North Carolina eastern Piedmont.

The compositional origin of these high strain layers is not clear. As suggested by Druhan et al. (1994) and clearly mapped in the Kerr Dam and Middleburg 1:24K Quadrangles, some layering represents highly deformed portions of the greenschist facies Vance County pluton of Neoproterozoic age (LeHuray, 1989; Druhan et al., 1994). The pluton is a metamorphosed medium- to coarse-crystalline granodiorite and tonalite (CI ~45), which in a high-strain state contributes to the production of many of the white mica + chlorite phyllonite exposures. It also displays multiple crosscutting phases of mesocratic, leucocratic, and holocrystalline granodiorite and tonalite (CI < 5) stocks as observed at the point just west of the boat ramp (Figs. 12A, 12B). The Vance County pluton also preserves xenoliths of both mesocratic and leucocratic plutonic and volcanic rocks, which in a high-strain state contribute to the white mica phyllonite and crystalline and cryptocrystalline felsic mylonite and ultramylonite structures at this point.

We also map this point as part of a significant zone of green-schist facies phyllonite and mylonite that corresponds with the eastern boundary of the northern Carolina terrane in the north-central North Carolina Piedmont. It extends from the state line south to Satterwhite Point State Recreation Area on Kerr Lake in the Middleburg 1:24K Quadrangle. South of that point, the phyllonite becomes a less prominent rock type in the Townsville 1:24K Quadrangle in favor of felsic mylonite from the north-central portion of the Henderson 1:24K Quadrangle to the Wilton 1:24K Quadrangle where it is truncated by the Triassic Jonesboro fault.

The rocks at Henderson Point display scale-variable dextral planar and linear kinematic indicators that are characteristic of this high-strain zone. Planar indicators range from mm to m in length, width, and height in a heterogeneous mix of highly transposed, rotated, and attenuated, northeast-striking and steeply west-dipping compositional layers. Layering produces a scale-variable, ductile fluxion structure as originally described by Druhan et al. (1994). Phyllonite “fins” are predominantly a mixture of phyllosilicate minerals and quartz that vary in their ratio of chlorite to white mica. This change leads to medium green-gray mesocratic and silver-gray leucocratic, laminated color variations in outcrop (Figs. 12C, 12D). Fractures, some silicified, overprint most outcrops, having orientations that are either subparallel with or highly oblique to layering and regional high strain foliation (Fig. 12C).

In more chlorite-rich layers, chemical weathering may be so extreme that asymmetric Fe-oxide and Fe-hydroxide saprolite layers highlight the phacoidal-shaped disks (fish structures) in white mica-rich layers. Some composite white mica fish structures are 0.5–1 m in length and litter the beaches as phacoidal-shaped disks. Other compositional layers contain phacoidal “schools” of cm-scale chlorite fish structures that are consistently displaced in a tops-north, dextral asymmetry as S-C–style, reverse-sense crenulations between more leucocratic ledges. Centimeter-scale quartz ribbons display similar asymmetric geometries interspersed within the phyllosilicate fish. Normal-sense crenulations also bound smaller-scale schools of fish structures, and in some exposures join as cm- to m-scale C–C’ shear band surfaces that are synthetic to the overall dextral shear sense of this phyllonite zone.

In contrast, fine-crystalline leucocratic phyllonite, mylonite, or ultramylonite are composed of a mixture of quartz and feldspar and variable amounts of white mica. These felsic ultramylonitic zones will form individual cryptocrystalline compositional layers in the phyllonite fluxion structure, and larger domains of highly foliated, composite S-C fabric elements. Their higher competence
also allows them commonly to be disharmonically and tightly to isoclinally folded, having hinges that may plunge steeply down dip, or moderately and shallowly to the northeast in accordance with the subhorizontal to moderate northeast-plunging mineral lineation. In numerous exposures along this zone, cm- to m-scale asymmetric isoclinal folds have highly attenuated and/or thrust-faulted eastern limbs leading consistently to tops-north hanging wall displacements. In other exposures, felsic layers form asymmetric, competent boudins in a more phyllonitic matrix, stretched subparallel to the dominant mineral lineation.

**End of Day 1.** Depart Henderson Point Park and return to NC 39. Turn left (south) and proceed 13.5 miles to Henderson, North Carolina, and the I-85 South interchange. Turn left (north) and downhill onto the curved on-ramp and drive 2 miles south to Exit 212 at Ruin Creek Road. Turn right (north) at the traffic light at the top of the off-ramp and then turn immediately left (west) at the next light in front of Maria Parham Medical Center. Bear left (west and south) past the center and proceed 0.1 miles onto the I-85 service road known as Market Street and then into the Sleep Inn parking lot at 18 Market Street, Henderson, North Carolina.

**Directions to Optional Stop 8.** Depart Henderson Point Park and return to NC 39. Turn left (south) and travel 13.5 miles to the I-85 interchange. Proceed 2.1 miles through Henderson on NC 39 (Andrews Ave) to the interchange with U.S. 1 Bypass South. Turn right (south) onto U.S. 1 and merge onto the southbound bypass. Drive 4.5 miles to Cobble Way in the Cobblestone subdivision. Turn left at Cobble Way, then take a left at the T-intersection onto North Cobble Creek Drive, then a right onto Stonehedge Drive. Proceed to the end of the cul-de-sac straight ahead. Park and walk to the pavement exposure. Stop 8 [latitude 36.26334°, longitude −78.4142°].
Stop 8. Late Paleozoic Granitoids on the Western Flank of the Wake-Warren Anticlinorium

Location: Cobblestone subdivision, located in southeast Henderson between U.S. Highway 1 Business and U.S. Highway 1 Bypass, ~0.5 km west of Gill, North Carolina.
Map: Henderson 1:24K Quadrangle.

As portrayed on the State Geologic Map of North Carolina (NCGS, 1985), the Rolesville batholith extends for some 100 km along the generally north-south trend of the Wake-Warren anticlinorium, and for 20–30 km across that trend. The batholith actually consists of a number of mutually intrusive individual plutons that may be distinguished, with some difficulty, on the basis of texture, mineralogy, and enclave characteristics (Speer, 1994). Some other named late Paleozoic intrusive granitic bodies in the region are in contact with the Rolesville (e.g., Castalia and Gupton) and may belong to the batholith; other bodies (e.g., Wise, Wyatt, Lake Benson) are separated from the batholith by metamorphic country rocks.

Mapping along the northwestern margin of the batholith has shown that much of the granitic rock is deformed, and some of it is strongly deformed (Fig. 3). Whereas much of the granite mapped in the Louisburg 1:24K Quadrangle, near the heart of the batholith, is equigranular to very slightly feldspar-phryic (either alkali feldspar or plagioclase may be the phenocryst phase), granitoid rocks to the west and northwest tend to be gneissic, and locally protomylonitic to mylonitic. Toward the west and south of Henderson, gneissic varieties of granite gradually merge with Raleigh Gneiss of the Raleigh terrane.

The state geologic map shows the northern termination of the Rolesville batholith in the center of the Middleburg 1:24K Quadrangle, with a large tract of biotite gneiss and schist extending to the Virginia line (NCGS, 1985). Mapping in Virginia (Horton et al., 1993a; VDMR, 1993) depicts the southern termination of the late Paleozoic Buggs Island pluton just north of the border. Where these maps show metamorphic country rock between these large plutons, we have instead mapped mainly strongly deformed granitoid rocks, locally containing sizable country rock enclaves. We ascribe much of the strain fabric in these rocks to the effects of the Nutbush Creek–Lake Gordon fault system.

Here at Stop 8 we see an exposure of granite that displays an older, locally protomylonitic foliation, showing the effects of major flattening and sparse indications of dextral shear. Subparallel to this major fabric, which strikes about N10°E, are sills and dikes of weakly to strongly foliated granite that lack strong evidence of mylonitization. Still other portions of this outcrop, and nearby roadcuts on the U.S. Highway 1 Bypass, are apparently undeformed, exhibiting equigranular, medium- to coarse-crystalline textures. Figures 13A–13C shows some of these features in outcrop. We interpret this mixing of granite textures and fabric elements to indicate that magma intruded repeatedly in pulses, during and following the time of fault motion. Whether this northwestern region of the “Rolesville” really belongs to the Rolesville batholith, or constitutes a different pluton (perhaps even an extension of the Buggs Island) remains to be seen. At previous stops, we examined the equivalents of these granitic rocks having different and higher degrees of shear strain.

Directions to the Sleep Inn from Optional Stop 8. Return to U.S. 1 and turn right (north). Proceed 0.6 miles to the off-ramp to U.S. 1 Business (Raleigh Road). Turn left (north) on U.S. 1 and proceed 2 miles to the T-intersection with Belmont Drive/Old Country Home Road and turn left (west). Drive 1.4 miles to the new traffic light at the T-intersection with the new Dr. Martin Luther King, Jr. Bypass. Turn right (north) and continue 3.6 miles to the Ruin Creek I-85 exit. Cross over the interstate and turn left at the light in front of Maria Parham Medical Center. Bear left (west and south) past the center and proceed 0.1 miles onto the I-85 service road known as Market Street and then into the Sleep Inn parking lot at 18 Market Street, Henderson, North Carolina.

Day 2. Henderson to the Deep River Triassic Basin and then Charlotte

Directions to Stop 9. Depart the Sleep Inn and proceed to the on-ramp for I-85 South. Drive 6 miles south to Exit 206 and merge right at the top of the off-ramp onto U.S. 158 West. Travel 0.5 miles and turn right (west) at the traffic light onto U.S. 158 Bypass and drive past the Revlon factory ~0.7 miles just across the crest of this broad hill. Park on the right (north) side of the road, cross, and walk south into the woods to Stop 9 [latitude 36.32174°, longitude −78.55862°].

Stop 9. Ductile Mylonite Gneiss and Brittle Silicified Cataclasite in Metagranite, Fishing Creek Fault Zone (a.k.a. The Revlon Outcrop), Oxford, North Carolina

Location: Small ravine tributary to Coon Creek on its west-facing floodplain bluffs just north of the Revlon factory.
Map: Oxford 1:24K Quadrangle.

One of the major tectonic events affecting the Carolina Zone involves early Mesozoic rifting of the Pangean supercontinent (Olsen et al., 1991; Stoddard et al., 1991; Hibbard et al., 2002). The formation of the Triassic Deep River rift basin between the eastern and central Piedmont records this episode of crustal extension and continental breakup (Clark et al., 2001, 2011). Its development and the petrology of bounding crystalline rocks and basin sedimentary rocks are the focus of the second day of the field trip.

From south to north, the Wadesboro, Sanford, and Durham sub-basins are formal subdivisions of this irregularly shaped, half-graben rift basin (Figs. 2, 4, and 5). The ductile-brittle Jonesboro normal fault forms the eastern boundary of the Wadesboro, Sanford, and southern portion of the Durham sub-basins (Olsen et al., 1991; Clark et al., 2001, 2011). The Fishing Creek fault zone (FCFZ) forms the eastern boundary of the northern Durham sub-basin. These half-graben sub-basins structurally separate the easternmost Carolina terrane consisting of the Cary sequence and its associated metagranitoid plutons in the eastern Piedmont.
from the Virgilina and Albemarle sequences and their associated metagranitoid plutons in the main portion of the Carolina terrane in the central Piedmont (Farrar, 1985b; Harris and Glover, 1988; Blake et al., 2001; Hibbard et al., 2002).

Historically, the mapped occurrences of Triassic clastic rocks have been used to mark the areal extent of the Deep River rift basin (NCGS, 1985). However, recent mapping by Parnell et al. (2006b) and Parnell (2012) indicate that basin-bounding ductile-brittle fault structures extend past the northernmost mapped occurrences of Triassic sedimentary rocks as the FCFZ continues northward. LiDAR data shows a strong topographic lineament along Coon Creek in the central portion of the Oxford 1:24K Quadrangle. This lineament supports the mapping data that underlying structures control topography and that ductile-brittle phyllonite and cataclasite continue north of the last mapped Triassic clastic sedimentary rock outcrops.

As such, the informally named FCFZ forms the structural boundary for the north portion of the Durham sub-basin. In the region surrounding this stop, three tectonite units define the FCFZ northward along Coon Creek and into the Stovall 1:24K Quadrangle just to the north. From south to north, schist, phyllonite, and mylonite (εZphc), foliated felsic meta-intrusive suite (εZgrf), and foliated chlorite-biotite metagranodiorite (εZfgd) are interpreted as deformed equivalents of plutonic protoliths of granite (εZg), intrusive granitoid (εZgr), and diorite-tonalite (εZdito). Similar rock compositions, close unit contacts, and transitional structural boundaries provide the basis for these correlations (Hadley, 1973, 1974; Farrar, 1985b; Parnell et al., 2006b; Parnell, 2012).

Entering into the woods here, random float blocks of the meta-intrusive suite mark the underlying unit. Stocks of granite, leucogranite, granodiorite, tonalite, and trondhjemite are the rock types that primarily comprise this heterogeneous lithodeme. Rock samples range in color from pale pink or tan to light gray and white on fresh surfaces, and yield dark brown to red-brown colors on weathered surfaces. Compositions range from leucocratic (CI = 10–15) to locally hololeucocratic (CI = 5–10). They are phaneritic and medium- to coarse-crystalline. K-feldspar phenocrysts locally range up to 10 mm in diameter in granitic compositions. Locally, finely crystalline microdiorite enclaves are randomly distributed in the plutons.

The foliated equivalent of the intrusive granitoid unit occurs in outcrop just to the north of this stop. It is leucocratic (CI ~ 10), pale green and pink to green-gray and consists of chlorite-white mica phyllonite and protomylonite. These rock types define the FCFZ along Coon Creek. East of the FCFZ, several subparallel anastomosing shear zones in granite range from approximately several m-wide up to a half a km-wide. This unit also includes silicified varieties found in and adjacent to domains of brittle deformation in and near the FCFZ. It has a pale pink and green,
to green-gray color on fresh surfaces and a brown-gray color on weathered surfaces. Locally, domains of epidotized rock exist in this unit, forming large boulders and resistant outcrops within the FCFZ for much of its length.

Moving down the ravine, large outcrops of silicified rock are part of a linear ridge of multiply fractured and silicified cataclaseite defining the western margin of the FCFZ. Greenish gray to gray-white clasts are very angular, consisting of both silicified non-foliated granitoids (Fig. 14A) and foliated phyllosilite and protomylonite equivalents of this unit (Fig. 14B) that range from mm-to-m in diameter. Locally, vuggy xenomorphic to idiomorphic quartz occurs in open void spaces between angular rock clasts or produces drusy coatings on the cataclastic fragments.

At the bottom of the ravine and in many creek bottoms along the FCFZ, there are light green-gray to dark green subvertically oriented phacoidal folia that protrude up from the creek bottom in a manner analogous to shark fins. These rocks include chlorite schist, chlorite white mica phyllosilite, and felsic protomylonite. These rocks have composite S-C high strain foliations that overprint a relict phaneritic texture. Typically, S-C fabric development is more prevalent in phyllosilite portions of the unit where abundant chlorite and lesser white mica occur. Alignment of white mica, biotite, quartz ribbons, and minor chlorite define the dominant gneissic foliation $S_{1c}$. Plagioclase and K-feldspar $\sigma$-type porphyroclasts display wings of white mica, dynamically recrystallized quartz, and small amounts of plagioclase. These wings form a monoclinic mortar microstructure that suggests a tops-down-to-the-west sense of displacement in oriented thin sections (Fig. 14C).

The west-dipping alignment of chlorite, white mica, and biotite also defines an $S_{1s}$ schistosity oriented oblique to $S_{1c}$, especially adjacent to porphyroclasts of plagioclase and K-feldspar porphyroclasts. $S_{1s}$ is not readily observed at the mesoscale; however, at the microscale, the dominant and more evolved fabric element is the penetrative metamorphic mineral foliation, $S_{1c}$, which overprints the $S_{1s}$ foliation and deflects it into a tops-down-to-the-west

Figure 14. Structural features from Stop 9 at the Revlon Outcrop. (A) Outcrop photograph of silicified cataclaseite containing non-foliated clasts of metagranite ($\mathbf{\varepsilon}$Zgr). Scale bar is ~10 cm. (B) Outcrop photograph showing foliated phyllosilite clasts ($\mathbf{\varepsilon}$Zphc) contained within silicified cataclaseite. Pencil is 14 cm for scale. (C) Photomicrograph of winged sigma-type porphyroclast of plagioclase in foliated metagranite ($\mathbf{\varepsilon}$Zgrf). Sense of displacement is down-dip to the west. View is to the south, but rotated 90° to the left. Magnification 2.5x. Field of view 9 mm. (D) Photomicrograph of composite S-C fabric element development in $\mathbf{\varepsilon}$Zphc. Sense of displacement is down-dip to the west. View is to the south, but rotated 90° to the left. Cross-polarized light. Magnification 5x. Field of view is 4 mm.
parallelism with the $S_{hc}$ (Fig. 14D). A penetrative mineral alignment lineation, $L_1$, formed from the long axis of quartz ribbons and aggregates or films of platy white mica and chlorite lies in the $S_{hc}$ surface. $L_1$ typically has a dip-slip to oblique, down-dip orientation. Locally, brittle deformation dominates silica-rich domains where quartz defines a stair-stepped vein-fiber lineation and more minor slickenlines aligned parallel to the ductile $L_1$ lineation.

Based upon similar field relationships, compositions, and positions along the eastern and western side of the FCFZ, granitoid rocks observed on opposite sides of this extensional structure may represent different structural levels within the same plutonic body. Distinguishing between them across the FCFZ becomes more difficult in the northern mapped limits of this structure. The apparent west-side-down offset of the FCFZ progressively becomes less significant northward from Oxford and may explain the similarities between the two lithodemes. In the vicinity of the field trip stop, the west-side-down offset of the FCFZ appears sufficient to establish separate lithodemes based on variations in composition, texture, and outcrop pattern.

Detailed and reconnaissance-level mapping by Parnell (2012) has determined that basin-bounding structures of the FCFZ extend a minimum distance of 10 km past the northernmost occurrence of Late Triassic clastic sedimentary rocks (Fig. 15) and are most likely represented by the foliated felsic meta-intrusive suite ($CZgrf$). Because these structures continue northward and extend out of the study area, a tip point for the FCFZ structure was not determined in his study. Furthermore, Parnell (2012) indicates that the termination of these sedimentary rocks does not necessarily mark the northern termination of the structural and sedimentary basin at its time of formation. The current
 Alleghanian Nutbush Creek fault zone and Deep River Triassic basin

basin shape, mapped based upon present occurrences of Triassic clastic sedimentary rocks, may potentially be a lower structural level of the basin, compared to the basin at the time of formation and sedimentary deposition.

The continuation of these structures suggests that the Triassic Deep River basin may have been larger during the time of formation, and perhaps clastic sedimentary rock extended farther northward and westward. The continuation of the FCFZ structures implies that the extent of the presently mapped basin may be a smaller erosional remnant of a larger basin. However, due to the present inability to establish a tip point for these structures, only a minimum basin size can be determined based upon the nature of the structures that define the FCFZ and the minimum distance they extend northward from Triassic clastic sedimentary rocks.

**Directions to Stop 10.** Turn around and proceed back to I-85 South on U.S. 158. Merge onto I-85 south and travel 2 miles south to the interchange with NC 96 at Exit 204. At the top of the off-ramp turn right (south) and proceed 1.2 miles on NC 96 to the Y-intersection with Fairport Road (CR 1609). Turn left (south), drive 0.6 miles and park on the right side of the road. Outcrops are exposed in the north-facing slopes of the roadside creek. Stop 10 [latitude 36.27269°, longitude −78.57129°].

**Stop 10. Polymictic Conglomerate Marking the Northernmost Exposures of Triassic Sedimentary Rocks of the Durham Sub-Basin along the Fishing Creek Fault Zone**

Location: Western tributary to Coon Creek and its north-facing floodplain bluffs along Fairport Road. Map: Oxford 1:24K Quadrangle.

Along the right or south side of the highway and across the roadside ditch serving this tributary to Coon Creek, a stretch of nearly continuous outcrop of Triassic polymictic conglomerate and feldspathic sandstone mark the most accessible and approximately northern limit of sedimentary rocks of the rift basin exposed along the FCFZ (Fig. 4). The last outcrops of coarse conglomerate and interlayered coarse conglomerate and sandstone within the basin have been mapped by Rick Wooten of the NCGS (initially located on one of Bob Butler’s unpublished field sheets) just to the north of this outcrop across the open field, as well as a small patch just south of I-85 in the Coon Creek drainage basin (Parnell et al., 2006b). No Triassic sedimentary rock was encountered in mapping north of I-85 (Parnell, 2012).

The easternmost exposure provides the best example of the coarse clastic nature of this rock unit (Figs. 16A, 16B). The coarse conglomerate is mostly reddish-brown, typical of Triassic sedimentary outcrops, containing a mixture of clast types in massive and chaotically bedded horizons having coarse sandstone to gravelly sandstone matrix. Some small beds and lenses of finer sandstone and mudstone are preserved in the matrix as well, and have an attitude of approximately N20°E and a 10–20° dip to the southeast (020,10–20), typical of the strata that dip toward the east side of the Durham sub-basin (Clark et al., 2001, 2011). This stop is mapped as part of the Trcc lithofacies that is in contact with the Trcs/c lithofacies of Lithofacies Association III described by Hoffman and Gallagher (1989), Clark (1998), and Clark et al. (2001, 2011). Trcc lithofacies is primarily an irregularly bedded, poorly sorted, clast-supported to matrix-supported, boulder to cobble conglomerate. It typically has a micaceous matrix of orange-red gravelly sandstone and reddish-brown siltstone. Trcs consists of reddish-brown to dark brown, irregularly...
bedded to massive, poorly to moderately sorted, medium- to coarse-grained, muddy lithic arkosic to pebbly sandstone.

To the south along the Jonesboro fault, units of Trcc are interpreted to be alluvial fan and/or bajada complexes. They are thought to have been generated by progressive dip-slip displacement combined with erosion and canyon dissection through the significant topographic gradient and fault scarp marking the east side of the Durham sub-basin in the Carolina and Falls Lake terranes. The alluvial fans adjacent to the Jonesboro fault are inferred to have prograded westward from the mouths of crystalline rock canyons into deepening alluvial depocenters in the Durham sub-basin rift valley (Blake et al., 2001; Clark et al., 2001, 2011).

At this stop, a number of the larger clasts are reminiscent of the weathered intrusive granitoids surrounding the Oxford area just to the north at the last field trip stop. The arkosic mineralogy of the feldspathic arenite here and in outcrops between here and Stop 11 is similar to the metatplutonic rocks of the Carolina terrane of the central Piedmont exposed just to the west of the Durham sub-basin in the Stem 1:24K Quadrangle. Consequently, these outcrops of Lithofacies Association III appear to have been derived from the west or northwest side of the sub-basin. Bedding and clast relationships suggest an ~10-m-thick, coarsening-upward succession for the outcrop from west to east.

The relatively smaller clast size and potential nearby source area may indicate that conglomerate, sandstone, and siltstone units collectively were deposited in a mixed alluvial fan, debris flow and sandy, braided stream environment. They appear to have derived from and were deposited directly onto metatplutonic, metavolcanic, and metasedimentary rocks that bound the western border of the sub-basin (Hoffman and Gallagher, 1989; Clark et al., 2001, 2011; Blake et al., 2003a, 2009). There, the proximal Carolina terrane source rocks of the central Piedmont and the half-graben geometry of the Durham sub-basin is more readily apparent. The sedimentary-crystalline contact is a regional nonconformity that extends from the Oxford region southward through at least the Durham–Chapel Hill region. Only locally do fracture zones in crystalline rocks and minor post-depositionai (?) faults form the basin boundary along the western border of the sub-basin (Clark et al., 2001, 2011; Blake et al., 2009). The lithologic character of the sedimentary rocks forming this nonconformity in the northwestern portion of the Durham sub-basin is the topic of Stop 14.

**Directions to Stop 11.** Return to NC 96 and turn left (south). Travel 3.4 miles south on NC 96 past the crossroads of Clay and look for a small utility service road on the right (west) side of the highway. Turn into the circular drive around the substation and park. Walk south along NC 96 0.1 miles to the second grassy lane into the woods to the left (east) side of the highway. Proceed along it to the crest of the hill ~0.25 miles into a clearing, then turn immediately left (north) and enter into the woods from the clearing. A faint trail will lead down the right side of the ravine to the rocky, knife edge outcrops lining the southern cutbank of Fishing Creek. If the creek is in flood stage, walk back to NC 96 and turn left (south) on the highway. Either walk or drive to the first broad dirt driveway on the left (east) side of the road just south of the long stretch of timber that is oriented parallel to the NC 96. Park in the driveway and walk ~0.1 miles eastward to the outcrops on the left (north) side of the gravel driveway. Stop 11A [latitude 36.23795°, longitude ~78.57964°] and Stop 11B [latitude 36.23328°, longitude ~78.58364°].

**Stop 11.** (A) Quartz Diorite-Tonalite Protomylonite and Chlorite-White Mica Phyllonite in the West-Dipping Fishing Creek Fault Zone; (B) Disharmonic Folding of Chlorite-White Mica Phyllonite of the Fishing Creek Fault Zone and the Eastern Contact of the Triassic Durham Sub-Basin

**Location:** Western tributary to Fishing Creek and northwest-facing floodplain bluffs adjacent to NC 96.

**Map:** Wilton 1:24K Quadrangle.

Along the length of the FCFZ as initially described for Stop 9, the development of both ductile and brittle structures marks the northeastern border of the Durham sub-basin. At this stop and in outcrops exposed fairly continuously downstream southward to the Tar River, the composite fabric element relationships and mineralization associated with anastomosing strands of this basin-bounding fault zone are well preserved. Reaching up to a km in width east of basin sedimentary rock exposures, most of the FCFZ is comprised of phyllite, schist, and gneiss that are actually shear zone phyllonite, protomylonite, and mylonite. The fault zone rock type depends upon the metagranitoid protolith type, which ranges from gabbro-diorite to tonalite-trondhjemite and granodiorite-granite. The modal amount and degree of recrystallization of chlorite versus white mica also influences the rock type produced along this structure. Downstream, large hydrothermal, fine-crystalline domains of epidotization and quartz silicification stand out as large unfoliated bluff outcrops within the FCFZ.

Specifically at this stop and Stop 11B, gray-green chlorite–white mica phyllonite and protomylonitic gneiss are well exposed as steeply west-dipping outcrops of tens of cm-to-m-scale foliation fins (Fig. 17). The surrounding rocks have been mapped as the foliated equivalents of the tonalite of Gibbs Creek, informally known as the Gibbs Creek pluton. In fact, much of the southern portion of the wedge-shaped block between the FCFZ and Nutbush Creek fault zone to the east (Figs. 2 and 4), as described at Stop 9, is underlain by this pluton, its foliated equivalent, and its northern and eastern border zone, the Tabbs Creek complex (Farrar, 1985b; Grimes, 2000; Blake et al., 2003a; Robitaille, 2004).

In hand sample, the Gibbs Creek pluton is a gray-green, fine- to medium-crystalline, unfoliated hornblende biotite tonalite and locally granodiorite. Chlorite, white mica, and epidote recrystallization of the primary igneous minerals marks the greenschist facies metamorphic overprint. Within the pluton, enclaves of microdiorite, foliated amphibolite, meta-ultramafic rocks, and foliated metagranitoid crop out in random locations.
The occurrence of microdiorite enclaves is a common theme among metamorphosed plutons exposed in this portion of the northeastern Carolina terrane and they may be derived from co-magmatic plutonic bodies. Diorite-gabbro bodies are exposed just to the northwest in the Lake Michie, Stem, and Oxford 1:24K Quadrangles. The foliated metagranodiorite enclaves appear to be an early deformed equivalent of the tonalite that chiefly comprises the Gibbs Creek pluton. In contrast, the origins of smaller foliated amphibolite enclaves and four large pods of serpentinite, soapstone and talc-actinolite schist, and actinolite rock are more problematic. A geochemical analysis obtained from an amphibolite enclave from the Gibbs Creek pluton has an ocean-floor MORB signature and is discussed further by Robitaille (2004). The enclaves may represent some form of oceanic substrate sampled by this calc-alkaline pluton during the magmatic construction of the Carolina Zone island-arc crustal section.

Deformed examples of the Gibbs Creek pluton and associated metagranitoids at this stop and Stop 11B become phyllonite and porphyroclastic protomylonite and mylonite that develop a moderately to steeply west dipping, composite planar-linear fabric striking approximately N10–25°E (010–025). Chlorite, white mica, and biotite again define an S₁s schistosity oriented oblique to an S₁c, especially adjacent to porphyroclasts of large blue-quartz and plagioclase porphyroclasts. At the mesoscale S₁s primarily has the shallower dip of the two foliations in this dip-slip shear zone (Figs. 17A–17D). The dominant and more evolved fabric element is the penetrative metamorphic mineral foliation, S₁c. It overprints S₁s and deflects it into a tops-down-to-the-west parallelism with S₁c, similar to C′ extensional shear bands. When the spacing between these two foliations reaches cm-scale, large down-dip “fish-like” phacoids of protomylonite are developed.

A penetrative mineral aggregate lineation, L₁, is preserved from the long axis of quartz ribbons and aggregates or films of platy chlorite and lesser white mica. L₁ develops on the composite S₁s–S₁c surfaces. It typically has a dip-slip to oblique, down-dip-to-the-south orientation. Locally, brittle deformation dominates silica-rich domains where quartz defines a stair-stepped vein-fiber lineation and more minor slickenlines aligned parallel to the ductile metamorphic L₁ lineation. On the chlorite foliation surface, some vein fibers display an up-dip sense of slip, indicating a reverse component of fault displacement, while shallow-dipping, brittle fault surfaces display a normal sense of vein-fiber growth. Differential, late ductile to brittle dip-slip adjustments accommodated some FCFZ displacements.

At Stop 11B, the fish-like phacoids, dominant S₁s–S₁c shear foliations, and L₁ lineation are also well preserved, but deviate from the regional trend. In the ditch cut and adjacent small knob, easily observed with Google Earth©, the phyllonite foliation swings in an arcuate shape from a northeast strike to west-northwest strike with moderate dips to the southwest. In the ditch, a few 5–10 cm wavelength multilayer folds of the foliations can
be observed (Fig. 17E). Changes in interlimb fold style may be observed down the length of individual fold hinges. Because of the deviations in foliation orientations, L1 also fluctuates from the northwest to southwest trends and variable plunges. The outcrop is also highly and variably fractured (Fig. 17F). Quartz-chlorite tension gashes and vein fill permeate the exposure as well.

The deviation in shear foliation orientation from the regional trend and the highly fractured character of the phyllonite here is interpreted to be caused by rigid-block rotation and transitional-tensile fracturing during late-stage brittle failure immediately adjacent to the fault contact. Just to the west of this exposure and north of the culvert to the north-flowing stream, the actual contact between weathered phyllonite and sandstone and pebbly sandstone is knife-edged and may be depositional or structural. This portion of crystalline rocks forms a small, disoriented rider block in the FCFZ on the eastern border of the Durham sub-basin. Similar geometries have been observed to the south along the Jonesboro fault in the Raleigh-Cary region (Bartholomew et al., 1994; Blake and Clark, 2000; Clark et al., 2001, 2011).

Numerous anastomosing shear zones crop out in the wedge-shaped region east of the FCFZ. Similar to this stop, those shear zones record tops-down-to-the-west sense of displacement of composite planar elements, and dip-slip to slightly oblique-to-the-south mineral lineation and vein fibers. A small population of subhorizontal lineations exists when structural data from Parnell et al. (2006b), Robitaille (2004), and Parnell (2012) are analyzed. Figure 18 shows an interpreted 3-D view of these shear zones lying east of the Durham sub-basin and FCFZ along the northern portion of this rift basin.

Directions to Stop 12. Return to NC 96 and continue south. Travel 5.9 miles to the T-intersection with Philo White Road (CR 1623) on the left (east) side of NC 96. Turn left (east) and drive 1.8 miles to the Y-intersection with CR 1630. Merge right onto CR 1630 and proceed 0.3 miles to the intersection with Flat Rock Road (CR 1629). Turn right (south) and travel 1.9 miles to the base of Mayfield Mountain and the driveway to the Strothers’ property on the left (north) side of Flat Rock Road marked by the sign. Drive up the gravel road leading to the top of Mayfield Mountain and park on the right-hand side of the driveway between the large, black eagle sculptures. Walk 0.1 miles north to the outcrops at the ridge crest. Stop 12 [latitude 36.14427°, longitude −78.53809°].

Stop 12. Silicified and Fractured Cataclasite along the Jonesboro Normal Fault Zone and a Panorama of the Rift-Related Horst-and-Half-Graben System of the North-Central North Carolina Piedmont
Location: Heights of Mayfield Mountain and its west-facing rocky bluffs on the Strothers’ property.
Map: Wilton 1:24K Quadrangle.

In southeastern Granville County, the brittle normal-slip character of the Jonesboro fault is well exposed along a northeast-oriented string of silicified and fractured cataclasite ridges. They are best exposed just northeast of where this fault is in contact with the southern tip point of the FCFZ (Fig. 4). The Jonesboro fault comprises perhaps the most obvious map-scale brittle structure in pre-Mesozoic rocks in the eastern to central Piedmont transition. These ridges, highlighted at Mayfield Mountain, were originally described by Carpenter (1970) and then Heller et al. (1998), Grimes (2000), Blake et al. (2003a), and Robitaille (2004). Each mapped a silicous zone along this regional ridge line for a distance of ~8 km. Carpenter (1970) also mapped a short silicous zone along the FCFZ just north of its juncture with the Jonesboro fault. Because the Jonesboro fault is the basin-bounding structure on the east side of the Durham sub-basin, it has generally been assumed to be the fault bounding the entire length of Triassic sedimentary rock outcrops.

However, mapping in the crystalline rocks east and north of the Durham sub-basin indicates that the Jonesboro fault continues on a N50°E trend out of the basin, crosscutting older crystalline rocks of the Crabtree terrane (Heller et al., 1998; Grimes, 2000; Blake and Stoddard, 2004). This structural relationship then makes the FCFZ become the basin-bounding fault for Triassic clastic sedimentary rocks along the northeastern portion of the Durham sub-basin. Grimes (2000) and Robitaille (2004) demonstrated that the brittle fault here extends for at least two km to another northeast-trending ridge (Fig. 4), locally referred to as “Little Egypt Mountain.” Just beyond that point, the fault...
approaches the N10–15°E orientation of the Nutbush Creek fault zone (Heller et al., 1998). That Alleghanian dextral-slip fault zone and its ductile-brittle and petrologic relationships were the focus of our Day 1 trip stops.

At its top and flanks, multiply fractured and silicified cataclasite underlie Mayfield Mountain (Figs. 19A–19C). The rocky ledges here are massive milky quartz. Subvertically oriented fractures appear to fall into two main clusters, averaging about N23°E and N15°W, and highlight the tabular nature of the outcrops. A minor group of fractures strike nearly east-west. The fracture orientation is roughly parallel to the FCFZ, and also similar to trends of diabase dikes in the region.

Commonly, fracture-filled vugs and cavities in outcrop and especially float are lined with radiating syntaxial quartz crystals. These vuggy and locally drusy cavities may also contain the outlines of silicified breccia clasts in the vug walls (Fig. 19D). Much of the soil here is littered with small milky quartz pieces and small crystals. In thin section, fractures cut large quartz crystals, while brecciated quartz occurs with recrystallized quartz as the matrix between larger unfractured and fractured silicified quartz clasts. While no vestiges of the host rock to the silicification event can be identified along the top of the mountain, at lower elevations to the west, brecciated, catalastic and silicified clasts of Carolina terrane greenstone have been identified (Robitaille, 2004).

Mesozoic and younger (?) brittle faults are more widespread in the Piedmont than the impression conveyed on published geologic maps. Garihan and his co-workers have documented an impressive family of faults in the western Piedmont of South Carolina and North Carolina since the early 1990s (e.g., Garihan et al., 1993). Heller (1996) and Heller et al. (1998) document a network of brittle faults in the Lake Wheeler 1:24K Quadrangle south of Raleigh within the Nutbush Creek–Lake Gordon fault system. The most extensive of these faults trends about N70°W and has been mapped eastward through the Lake

Figure 19. Outcrop and petrographic relationships at Mayfield Mountain and Stop 12. (A, B) Brittle normal-slip character of the Jonesboro fault is visible along northeast-oriented silicified and fractured cataclasite rocky ledges. Subvertically oriented transitional-tensile fractures highlight the tabular nature of the outcrop and ridgeline. Tyler Stewart, University of North Carolina Wilmington geology undergraduate student, kneeling for scale in (A). Kenny Robitaille and Brian O Shaughnessy, UNCW geology students, standing for scale on the ridgeline of Mayfield Mountain just north of Stop 12 in (B). (C, D) Multiply fractured and silicified cataclasite domains on the western slopes of Mayfield Mountain, and mineral-filled vugs and cavities in outcrop and especially float at the top of the ridgeline lined with radiating syntaxial quartz crystals. Vuggy and locally drusy cavities may also contain the outlines of silicified breccia clasts in the vug walls. Hammer head is 12 cm wide in (C). View to the east. Hand samples in (D) are ~5 cm in width; tips of fingers in lower left.
Wheeler and into the Garner 1:24K Quadrangle for ~12 km (Heller et al., 1998).

Reconnaissance mapping by McDaniel (1980) in the northern portion of the eastern Piedmont showed numerous occurrences of “quartz breccia” and other presumably brittle features, suggesting the presence of other regional brittle faults. Since that work, numerous silicified cataclasite and silica-rich ridges and extensional strike-parallel and strike-normal faults have been mapped along the length of the Nutbush Creek–Lake Gordon fault system (Phillips et al., 2002; Stoddard et al., 2002; Buford et al., 2007; Blake et al. 2010), including Stop 3 yesterday. In many places, these brittle faults and possibly extensional crack-fill are also expressed topographically by these relatively sharp, but discontinuous ridges. Silicified breccia and microbreccia are common along such faults, but usually the only evidence is rugged outcrops of milky quartz, syntaxial quartz veins, or linear arrays of vein quartz, silicified cataclasite and locally vuggy quartz float. Cataclasite in the Lake Wheeler region contains clasts of country rock also interpreted to be derived from a level above the present erosion surface (Heller, 1996). Slickenlines and fibers are observed locally (Heller et al., 1998).

Looking north and west from Stop 12, the topographic expression and horst-half graben geometry of the northern terminus of the Durham sub-basin is evident. To the very far west, prominent ridges of the Carolina terrane in the central Piedmont are visible along the skyline in the Stem and Lake Michie 1:24K Quadrangles, the location of our next two stops. The most prominent conical peak is Bowling Mountain near Tallyho. Weathering resistant pyrophyllite- and silica-enriched hydrothermal deposits within metamorphosed dacitic metavolcanic rocks of the Hyco Formation underlie that peak (Sexauer, 1983; Rhodes and Blake, current unpublished STATEMAP mapping). These 630–615 Ma Virgolina sequence pyroclastic and volcanogenic sedimentary rocks underlie most of the region in the western distance. Lithodemes of post–613 Ma metamorphosed calc-alkaline intrusions as viewed at Stop 9 underlie the region in the northwestern distance. These metamorphosed plutons form a belt of magmatism that extends northeastward past the Oxford region and then to Kerr Lake as the 571 Ma Vance County tonalite-granodiorite pluton emphasized yesterday at Stop 7.

The depression between those far peaks and the north-south ridge in the near distance is occupied by Triassic rift-related clastic sedimentary rocks and is the Durham sub-basin. We will travel across this basin to the next two stops. The horst block to the sub-basin half-graben lies along this near distance north-south ridge just west of Mayfield Mountain. The green-schist facies Gibbs Creek pluton and its plethora of metamorphosed mafic and ultramafic enclaves underlie it. This region is the wedge-shaped block located between the FCFZ on the far west side of this ridge and the Jonesboro fault–Nutbush Creek fault zone between this stop and Stop 7 yesterday (Figs. 2, 3, 4, and 18). The Jonesboro fault continues to the north of Mayfield Mountain as a cataclastic structure for at least 25 km to Red Bud Creek in the central Henderson 1:24K Quadrangle. There, cataclastic blocks of foliated felsic Little Creek gneiss of the Crabtree terrane mark the apparent northern tip point for the Jonesboro fault.

The Wilton pluton is a Pennsylvanian-Permian granite that intrudes both the Falls Lake and Crabtree terranes (Carpenter, 1970; Stoddard et al., 1991; Blake et al., 2003a, 2003b; Robitaille, 2004). It is exposed in the fault block to the east. It forms part of the amphibolite facies horst block to the green-schist facies half-graben block to the west underlain by the Gibbs Creek pluton. A small quarry across the road from the Strothers’ driveway exposes an undeformed portion of this pluton. Carpenter (1970) observed brecciated granite in at least one locality along its western margin. Along its eastern margin ~2 km to the east, the granite records a subhorizontal stretch lineation. This L-tectonite marks the western boundary and strain gradient into the renamed Neuse River fault zone. This structure extends southward as the Falls Lake fault between the Falls Lake terrane to the west and the Crabtree terrane to the east (Stoddard et al., 1986, 1991, 1994).

In older models of the Piedmont, the Jonesboro fault would mark the boundary between the Raleigh metamorphic belt and the Carolina slate belt along the western flank of the Wake-Warren anticlinorium. Recent mapping supports the concept that this fault is a fundamental lithologic break and metamorphic discontinuity between an infrastructural block to its east and a series of suprastructural blocks to its west (Robitaille, 2004; Parnell, 2012; Blake and Stoddard, 2004). Older maps and field guides have proposed that the supracrustal block was perhaps a green-schist facies equivalent of the infrastructural Falls Lake terrane to its south. This hypothesis was based on the similarity in contact relationships among metamorphosed mafic and ultramafic enclaves and pods in matrix. Thus, Stoddard et al. (1997) originally proposed that the Jonesboro fault juxtaposed two different structural and stratigraphic levels of the same terrane, perhaps the Falls Lake terrane.

Leaving Mayfield Mountain, the field trip heads westward on NC 56 over Falls Lake terrane schist, gneiss and meta-ultramafic rocks, a bluff slope of silicified cataclasite marking the Jonesboro fault, and then the Gibbs Creek pluton and associated mafic and meta-ultramafic enclaves (Fig. 4). Another slope break marks the FCFZ, and sequentially westward across the Durham sub-basin, units of Lithofacies Association III and then II are crossed all the way to the Butner-Stem region. There, the Jurassic Butner diabase sill underlies much of the town of Butner (NCGS, 1985; Gottfried et al., 1991) and rounded boulder debris lines many of the local roads. The Sunrock Group’s Butner quarry of diabase “trap rock” is located on the outskirts of southeastern Butner. Some samples removed from that quarry indicate coarse crystal accumulation in the interior of the Butner sill including 5–10-cm-long prismatic clinopyroxene crystals. In most outcrops, the melanocratic diabase is medium crystalline containing up to 3–4 mm tabular subidiomorphic plagioclase prisms, xenomorphic intergranular clinopyroxene and opaque minerals including pyrite, and very minor olivine.
Locally, some diabase is finely aphyric, especially on the rims of sills or some small dikes.

**Directions to Stop 13.** Return on the gravel driveway to Flat Rock Road and turn left (east). Travel 1.0 mile to the T-intersection with Grove Hill Road (CR 1625). Turn right (south) and drive 0.4 miles to the intersection with NC 56. Turn right (west) and drive 9.3 miles straight through the crossroads of Wilton, downtown Creedmoor and NC 50 to the T-intersection with U.S. 15. Turn left (south) at the traffic light onto NC 56/U.S. 15 and then immediately right (west) at the next traffic light, staying on NC 56. Continue 2.6 miles westward on NC 56 to the town of Butner, North Carolina, and the I-85 corridor. Proceed 0.6 miles across I-85 and past the Asian King restaurant on the right to the traffic light at S. 33rd Street. Turn right (north) and proceed 2.1 miles to the intersection with Butner Road/Old 75 Hwy (CR 1004). Turn right (north) and drive 1.2 miles to the left (west) turn with Barham Eason Road and Camp Eason Murdoch. If the yellow gate to Camp Eason Murdoch is closed, walk 0.5 miles west down the road, and just before the facility and its gate, turn immediately right (north) and walk into the woods and toward the steep bank of the creek. Stop 13 [between latitude 36.17906°, longitude −78.76353° and latitude 36.17951°, longitude −78.76082°].

**Stop 13. Ductile-Brittle Fabric Elements and Faulting in the Neoproterozoic (?) Stem Tonalite-Granodiorite Pluton along the Western Boundary of the Triassic Durham Sub-Basin at Lake Butner**

**Location:** Eastern tributary to Lake Butner off Barham Eason Road below Camp Eason Barham, formally Murdoch.

**Map:** Lake Michie 1:24K Quadrangle.

Underlying much of the stop here and to the east in the Stem 1:24K Quadrangle, metamorphosed tonalite and granodiorite of the Stem pluton is leucocratic (CI < 10), light tan gray-white, bluish-gray-white, or pinkish-white depending upon weathering and amount of primary biotite, hornblende, or metamorphic chlorite, and then K-feldspar content. White-tan plagioclase and blue-gray quartz are dominant phenocrysts. Porphyritic outcrops containing plagioclase, blue quartz, and large pink K-feldspar phenocrysts define magmatic domains of granodiorite in the tonalite. Dikes of trondhjemite, monzonite and granodiorite locally crosscut the tonalite. All plutonic types appear to contribute significantly to the arkosic composition of sandstone that nonconformably overlie them ~1 km just to the east in the Durham sub-basin. This relationship is the topic of Stop 14A. In addition, cm-to-m-scale enclaves of greenstone, either very fine-crystalline microdiorite or andesite, are conspicuous throughout the pluton. This relationship appears in many of the 613–571 Ma Carolina terrane calc-alkaline plutons exposed from here eastward to its eastern terrane boundary at the Nutbush Creek fault zone.

At the west end of this series of stream bluffs along this unnamed tributary just before it deepens into Lake Butner, undeformed hillside outcrops belong to the informally named Stem pluton (Fig. 20A). Moving east away from the lake, south-side slope outcrops and cobble float becomes progressively foliated and fractured into a non-penetrative ductile-brittle fault zone. The creek cuts obliquely across this fault zone for ~0.25 km. Upstream, undeformed tonalite becomes the dominant rock and appears to mark the eastern boundary of this structure.

In between its two boundaries, discrete steeply to sub-vertically east- and west-dipping planar shear zones of composite white mica-chlorite foliation, subparallel fractures, and crosscutting fractures overprint tonalite of the Stem pluton (Fig. 20B). In some exposures, discrete planes of recrystallized white mica and chlorite along with tensional fractures subdivide the tonalite into large fin-like phacoidal shapes as they anastomose through the rock (Fig. 20C). Strikes of these surfaces vary from N15°W to N15°E. In other outcrops, the phyllosilicate planes become finely spaced, and anastomose to form lenticular to wedge-shaped domains of recrystallized and relic quartz-feldspar, basically a gneissic protomylonitic structure analogous to the FCFZ rocks observed at Stops 9 and 11. These wedge shapes are elongated in both the strike-slip and dip-slip direction, further highlighting the composite nature of the steep foliations.

As microdiorite enclaves are encountered locally, they become dark green white mica-chlorite phyllonite. When the strain in the pluton and enclaves is penetrative, these zones will erode as subvertically oriented fins protruding up from the creek bottom. The prominent foliation surfaces also contain a felsic rod and white mica-chlorite aggregate mineral lineation. Oriented with dip-slip and oblique-slip plumes, the mineral alignment appears to be a stretch lineation in these anastomosing shear zones. Transitional-tensile fracture surfaces may also record this lineation as vein fibers of white mica-chlorite, felsic rods, and Fe-oxide-hydroxide coatings.

Preliminary analysis indicates that the shear-sense population is tops-down in both east- and west-dipping surfaces in this zone and similar zones regionally. Local populations of up-dip vein-fiber shear sense similar to that at the FCFZ may be encountered. In addition, fractures and crosscutting veins may be lined with quartz prisms or multiple layers of wall-lining quartz mineralization in a crack-seal, syntaxial growth pattern (Fig. 20D). The fault zone also appears to serve as a conduit for a Jurassic diabase dike. The dike has been mapped for at least 3 km north and south of Stop 13 at an acute angle to this structure.

This fault zone extends ~2 km northeast from the Lake Michie into the Stem 1:24K Quadrangle. There, it continues for at least another 4 km before apparently reaching a tip point nestled in between a series of northeast-trending, ductile-brittle fault zones. Within both the Stem and Lake Michie 1:24K Quadrangles, a series of these ductile-brittle fault zones having an en echelon distribution are beginning to be recognized on the northwestern side of the half-graben marking the Durham sub-basin. They typically have high-angle dips and are N15°W-N15-30°E–trending. They contain both subvertically to steeply
east- or west-dipping composite shear foliation-fracture surfaces, as well as overprinting silicified cataclastic structures and variably mineralized zones.

In the Stem pluton, and diorite and granodiorite of the Butner stock to the west just across Lake Butner, along-strike domains of silicification, epidotization, and sulfide, primarily pyrite, mineralization overprint the northeast-striking phyllonite and protomylonitic to mylonitic composite foliation and down-dip lineation of white mica, quartz ribbons, plagioclase, and orthoclase. Locally, highly altered, stained and leached outcrops of pyrite, Fe-oxide-hydroxide, and silica mark these zones. Further to the west, composite facies of trondhjemite, granodiorite, and granite of the 613–614 Ma Moriah pluton may be foliated or non-foliated. Both types display some silicification or significant sericite-silica and leaching overprint.

Other outcrops additionally display heavy Fe-oxide-hydroxide staining. Recently, another series of these fault zones has been discovered. They have a northeast strike in the northeastern Lake Michie 1:24K Quadrangle (Rhodes et al., 2012). They crosscut the northeastern border zone of the Moriah pluton, large bodies of microdiorite, and the country rock Hyco Formation dacite lavas and tuffs unit (Zdlt) exposed east of the pluton. They also affect the hydrothermally altered equivalent of this dacite unit, especially across the top of Bowling Mountain. There pyrophyllite phyllonite is exposed. The fault zone from this stop has been traced at least as far north as these faults just east of Bowling Mountain. The origin of these ductile-brittle fault zones is not yet clear and they have the potential to be younger structures, perhaps related to Taconic, Alleghanian, or more likely, Permo-Mesozoic extensional deformation.

**Directions to Stop 14.** Return to Butner Road/Old 75 Hwy and proceed south for 1.6 miles to the T-intersection with Range Road on the right (north). Pass Range Road and drive another 0.3 miles, crossing Knap of Reeds Creek, and park in the small gravel/grass driveway on the right (north) side of the highway and on the east side of the NCSU Umstead Agricultural Field Research Unit. Walk 0.1 miles back (east) to Knap of Reeds Creek and proceed upstream to the rocky bluffs on the left (west) side of the creek and Stop 14A [latitude 36.15684°, longitude −78.77468°].

Then, walk 0.1 miles west past the 3 abandoned houses of the Umstead Facility to the north-oriented, grass-covered access road on the east side of the Umstead Facility. Proceed up the grass road to the 2 large rock blocks and then turn immediately left (west). Proceed downstream to the outcrops on the right cutbank and Stop 14B [latitude 36.15531°, longitude −78.78218°].
Stop 14. (A) Bluff-Scale Alluvial Fan Crossbeds in Triassic Pebby Arkosic Sandstone of Lithofacies II, Durham Sub-Basin of the Triassic Deep River Rift Basin; (B) Cutbank of Triassic Sedimentary Breccia of Metamorphosed Hyco Formation Microdacite-Diorite in Mudstone Matrix

Location: (A) Prominent west-facing rocky bluffs on Knap of Reeds Creek in the northwest quadrant of the intersection between Range Road and Butner Road, and (B) Hillside and cut-back outcrops on southeast facing outcrops of an unnamed creek and the Umstead Facility and North Carolina State Game Lands access road.

Map: Lake Michie 1:24K Quadrangle.

When hiking to Stop 14A and Knap of Reeds Creek, turn right (southeast) and look across Old 75 Highway at the broad lobate topography upon which the large agricultural barns of the Umstead facility are built. This broad hill is the remnant of a shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone. It is tentatively ascribed to the sandstone with interbedded siltstone shallowly east-southeast–dipping slope of arkosic sandstone.

The small rocky slope at the creek is weathered arkosic sandstone similar to the lobe across the road. Turning left (northwest), an east-dipping layer of Triassic mudstone is exposed in the brush that lines the steep creek bank. It is primarily reddish-maroon in color, but is variegated in pale green colors at a high angle to the thinly laminated bedding planes. The mottled coloring suggests that paleobioturbation is now recorded as Fe-oxidized regions surrounded by pale green, greenish-blue, or gray reduced Fe-domains within the mudstone. Walking just upstream from the mudstone, a 6–7-m-high, subvertically oriented cutbank and a 3–4-m-wide and flat, lobate stream outcrop of arkosic sandstone are well exposed. Along much of the length of this nonconformity in the Lake Michie and Stem 1:24K Quadrangles, arkosic sandstone is the consistent pediment rock type deposited upon variable crystalline basement rock types. It also appears to be the dominant rock type along the northwestern border of the Durham sub-basin.

Here, the sandstone is coarse grained, poorly sorted and poorly rounded. It is pinkish-gray, light gray or light tan in color. The matrix assemblage includes blue-gray quartz, white-tan plagioclase, minor K-feldspar, white mica, and biotite. Cleavage surfaces on both feldspar types and conchoidal fracture of blue-gray quartz are clearly preserved in single minerals. Some matrix clasts are actually metagranitoid rock fragments containing one or more of these minerals so that in part this unit is lithic arkosic sandstone. Individual grains and clasts straddle the sand-to-gravel-sized transition, having lengths up to 2–4 mm. Randomly scattered and small-scale domainal accumulations of angular to subrounded monomineralic quartz pebbles are also preserved within this coarse-grained matrix. They are reminiscent of some of the quartz veins and tension gashes overprinting meta-intrusive rocks just to the west such as the Stem and Moriah plutons and Lake Butner stock (McConnell and Glover, 1982; Blake et al., 2009). The coarse grain size and composition of the matrix would also be indicative of the coarse crystal size and composition of its source region rocks, also likely to be these metamorphosed granitoid rocks.

While there is a distinct pink coloration to some of the feldspars, it is not clear whether all such hues are due to the actual color of orthoclase feldspar or a secondary mineral overprint. The term “pinking” is commonly used to describe secondary recrystallization and alteration of plagioclase feldspar to K-feldspar or perhaps other minerals due to hydrothermal geochemical diffusion, fluid migration, and cation exchange (e.g., Bartholomew et al., 2009; Dennis, 2010). “Pinking” of feldspar is common in eastern Piedmont granitoid rocks of North and South Carolina and Virginia. Alleghanian plutons display a strong hydrothermal overprint of feldspar “pinking,” especially along or adjacent to the borders of the Mesozoic rift basins. The Pennsylvanian-Permian Lilesville granite pluton, which is exposed adjacent to the Triassic Wadesboro sub-basin in the southern portion of the Deep River rift basin, and the Pennsylvanian-Permian Petersburg granite, which lies along the eastern flank of the Richmond rift basin, both record strong, late-stage overprinting “pink” events.

In these arkosic sandstone samples, there are clearly small, pink grains that display Carlsbad twinning. However, domains of white-tan plagioclase transition into domains of “pinking” and many are coated with Fe-hydroxide mineralization, making visual estimates of mineral percentages a challenging task. In fact, along the nonconformity, the proximity and mineralogy of the source rocks combined with indurating silica-clay mineral cement makes sandstone outcrops resistant to erosion. When combined with the “pinking” mineralization, sandstone can be confused with equigranular granitoids in small pavement outcrops that lack larger identifying pebbles right along the nonconformity contact. Some form of “pinking” is evident in the matrix to the arkosic sandstone at this stop. It contributes to the overall pink coloration of the steep cutbank bluff. Perhaps the local association of diabase sills and meteoric waters contributed to a weak hydrothermal “pink” overprint of this arkosic sandstone.

In any case, large-scale stratification of the pink-white arkosic sandstone is a well preserved sedimentary structure here. Bounding surfaces of individual crossbeds reach sizes of 2–3 m. They may have their forest and bottomset beds lined with individual and accumulations of pebble-sized clasts in this subvertically oriented, 2-D bluff view. Accumulations of pebbles in the large, flat stream outcrop may be adding to a 3-D record of this sedimentary structure on shallow east-dipping forest and bottomset surfaces. These crossbeds appear to be large, subaqueous dune structures.
possibly deposited in a mixed alluvial fan, debris flow and sandy, braided stream environment. Paleocurrent directions derived from the crossbeds and the N20–40°E (020–040) strike and shallow east dip of beds suggests that the sediments were derived from the west side of the Durham sub-basin (Figs. 21A, 21B).

Just upstream to the north, just below the lowermost set of crossbeds in this arkosic sandstone layer, a thick layer of maroon micaceous mudstone to fine muddy sandstone is exposed. The orientation of thicker bedding laminae and fissility in thinly bedded layers, as well as the disconformable sandstone-mudstone contact, further attest to the shallow east dips of the sedimentary rocks here. This mudstone can be traced around the bend of Knapp of Reeds Creek to a small south-flowing tributary. There, the mudstone appears to disconformably overlie sedimentary breccia. Clasts that range from several mm to 10s of cm are primarily angular to subrounded and are randomly distributed in a red-brown mudstone matrix. Many of the clasts are metamorphosed diorite or its highly silicified and epidotized equivalent. Some clasts are rounded vein quartz.

Just upstream metamorphosed, locally fractured, and then foliated plutonic rocks of the Butner stock crop out. They are mesocratic to melanocratic (CI = 40–70), greenish-gray to grayish-green to green, fine- to medium-crystalline diorite, microdiorite and quartz diorite. Textures range from equigranular to porphyritic. Hypidiomorphic to xenomorphic granular plagioclase and hornblende phenocrysts range up to 1–3 mm in tabular length. Plagioclase crystals are highly saussuritized and to a lesser degree sericitized. Some crystals display evidence of epidote-enriched Ca-rich cores and sericite-enriched Na-rich rims at both the meso- and microscales. Hornblende may be recrystallized to

![Figure 21. Outcrop relationships at Stops 14A and 14B. (A, B) Large-scale stratification of pink-white feldspathic arenite well preserved as the dominant sedimentary structure at Stop 14A. Bounding surfaces of individual crossbeds reach sizes of 2–3 m. Upstream, just below the lowermost set of crossbeds in this feldspathic arenite layer, a thick layer of maroon micaceous mudstone to fine muddy sandstone is exposed. Location is interpreted to be part of Lithofacies Association II. Paleocurrent directions derived from the crossbeds and the N20–40°E (020–040) strike and shallowly east-dipping beds suggests that the sediments were derived from the west side of the Durham sub-basin. Todd LaMaskin, University of North Carolina Wilmington geology professor, is 1.8 m tall for scale. Both views to the southwest. (C) Intermixed Triassic sedimentary breccia and conglomerate of Lithofacies Association III at Stop 14B. Clasts range from several cm to over 50 cm in length. Clasts are chiefly metamorphosed aphanitic and weakly porphyritic hornblende and plagioclase dacite underlying the stream bluff and land immediately to the north of the creek. Hammer is 28 cm in length. View to the southwest.](image)
chlorite, epidote, and actinolite-opaque minerals. Locally, some outcrops contain 5%–10% quartz, classifying them as a quartz diorite. Where foliated, chlorite and white mica highlight the overprinting composite phyllonite foliation-fracture.

Now return to the north-northwest-oriented, grass-covered access road on the east side of the Umstead facility. Continue southwest down Old 75 Highway 0.2 miles to the grassy access lane on your right (north). It will be located immediately across the road from the lobate sandstone hillside and the large barns and offices of the Umstead Agricultural Facility on the south side of the road. Turn immediately right (north) and walk up this grassy lane. It is clearly marked as the unimproved road on the Lake Michie 1:24K Quadrangle. Travel ~0.25 miles until you encounter several very large blocks of aphanitic gray-green metadacite on the left (west) side of the lane. Turn immediately left (west) and cross the small floodplain to the unnamed south-flowing tributary to Knop of Reeds Creek and Stop 14B.

Along the western cutbank of this stream, intermixed Triassic sedimentary breccia and conglomerate are well exposed (Fig. 21C). Clasts range from several cm to 30 cm in length. Some clasts are over 50 cm in length. The larger clasts primarily have angular to subangular shapes. Smaller clasts tend to be more sub-rounded to rounded or oblate in shape as if tumbled and transported farther. These clasts are chiefly the metadacite encountered on the grassy lane. It underlies the stream bluff and land immediately to the north of this creek. Many clasts are mesocratic (CI = 30–40), gray-green, aphanitic and weakly porphyritic hornblende and plagioclase dacite, indicating a proximal source area. Hornblende and plagioclase phenocrysts are not ubiquitous in metadacite and some blocks and local outcrops are micro-quartz diorite based upon mineralogy and texture observed in thin section. Oblate clasts are foliated and represent deformed equivalents of metadacite and mixed volcanogenic sedimentary and pyroclastic rocks. One of the northwest-striking, ductile-brittle lent of metadacite and mixed volcanogenic sedimentary and pyroclastic rocks formed in highly similar depositional environments. Deposition appears to include, from west-to-east into the sub-basin, pediment and then a transitional and laterally changing gravel- to sand-sized alluvial fan, debris or braided stream, and/or intermittent stream system, including subaqueous dune deposits.

As currently mapped, these outcrops in the Lake Michie and Stem 1:24K Quadrangles have been grouped with the regionally, and northern sub-basin–dominant Trcs/si, unit of Lithofacies Association II (Hoffman and Gallagher, 1989; Clark et al., 2001, 2011; Blake et al., 2009). This unit contains sandstone with interbedded siltstone. The sedimentary sequence distribution is attributed to lateral point bar aggradation within a meandering fluvial system. Vegetated floodplains are interpreted to have surrounded this depositional environment. Abundant K-feldspar and white mica and the coarse- to very coarse-grain size indicate a proximal granitic source area.

In the south-central Lake Michie 1:24K Quadrangle just southwest of this stop, the Trcs/si, unit is in contact with the Trcs/si, unit of Lithofacies Association I (Hoffman and Gallagher, 1989; Clark et al., 2001, 2011; Blake et al., 2009). This unit contains sandstone with interbedded siltstone as well. The sandstone sequences are interpreted to represent sandy braided streams, perhaps in an alluvial floodplain environment. Thick sequences of heavily bioturbated siltstone surround these braided streams. Their interlayering is interpreted to indicate channel avulsion on a muddy floodplain, perhaps as these braided alluvial fan streams prograded eastward.

Along the northern border of the Durham sub-basin, similarities in sedimentary facies characteristics, lateral interlayering of sediment supply and alluvial-fluvial depositional environment blurs the ability to make a sharp distinction between these two lithofacies association units. Because these sedimentary similarities can be traced northeast to their termination against the FCFZ, evident at Stop 11B, much of the very northern portion of the Durham sub-basin is underlain by sedimentary rocks formed in highly similar depositional environments. In these units, basal layers of coarse sedimentary conglomerate and breccia are also a significant component along the border nonconformity (Parnell et al., 2006b). The sub-basin geometry, structure, and sedimentary characteristics highlight the central Piedmont and northeastern Carolina terrane, and their underlying calc-alkaline metagranitoids as a principal source area and rock types for the influx of clastic material into this growing rift basin. Mapping here is compatible with earlier interpretations of basin growth and lithofacies association development in the northern portion of the Durham sub-basin and the Triassic Deep River rift basin in general (Hoffman, 1994; Hoffman and Gallagher, 1989; Olsen et al., 1991; Clark et al., 2001, 2011).

**End of Day 2.** Return to vehicles on Butner Road/Old 75 Hwy and proceed north for 0.7 miles back to the T-intersection with 33rd Street. Turn right (east) on 33rd Street and then immediately right (south) on Central Avenue. Proceed east along Central Avenue 1.2 miles to the stop sign at Veazey Road. Turn left (east), continuing to follow Central Avenue straight through...
downtown Butner. There are several rest facilities and convenience stores in Butner. Drive 1.8 miles to the east side of Butner and the interchange with I-85 South at Exit 189. Merge right down the on-ramp and travel 151 miles to Exit 38 and I-77 South. Follow the traffic flow and signs for I-77 South. Merge onto I-77 South and travel 4 miles to Exit 9 and I-277. Follow the signs for I-277 and U.S. 74 East and proceed 1.2 miles to South College Street. Merge right and onto the off ramp. Then travel east on South College Street to the Charlotte Convention Center and the end of the field trip.

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