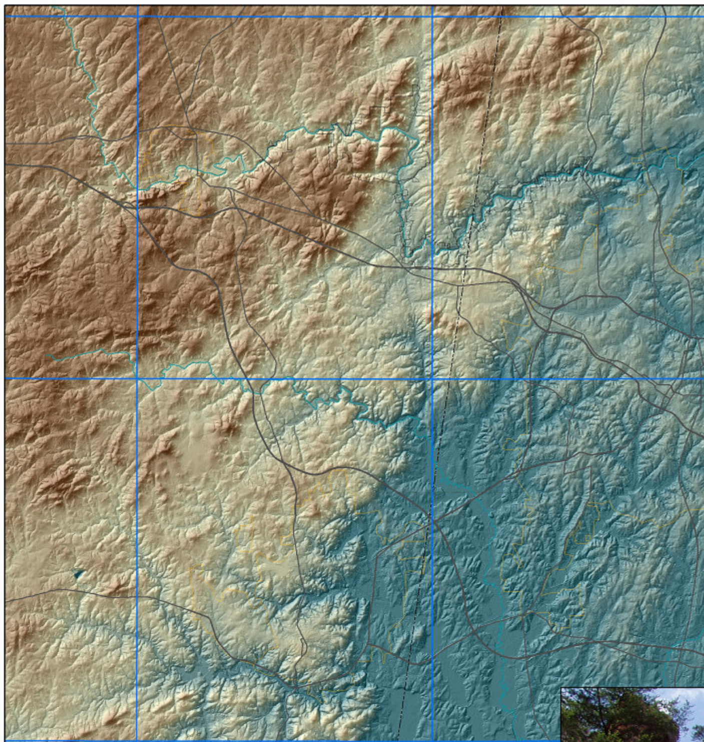
The Geology of the Chapel Hill, Hillsborough and Efland 7.5-minute Quadrangles, Orange and Durham Counties, Carolina Terrane, North Carolina



Carolina Geological Society
Annual Field Trip
November 4-5, 2006

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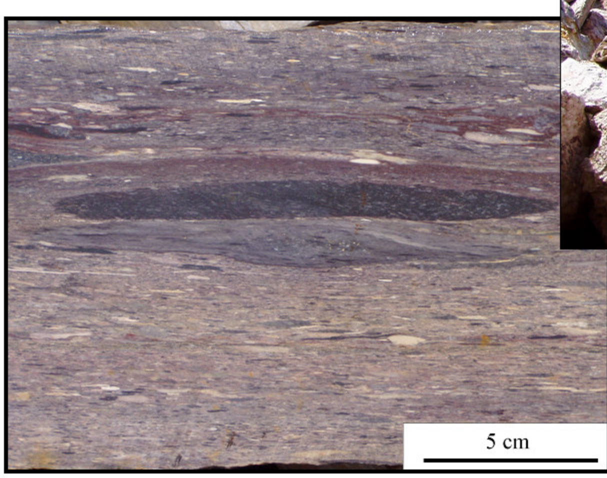
Philip J. Bradley and Timothy W. Clark



Field Trip Leaders:
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CONTENTS

AN OVERVIEW OF NEW GEOLOGIC MAPPING OF THE CHAPEL HILL, HILLSBOROUGH AND EFLAND 7.5-MINUTE QUADRANGLES, CAROLINE TERRANE, NORTH CAROLINA

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ABSTRACT

The Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles are underlain by weakly metamorphosed Late Proterozoic volcano-sedimentary and intrusive rocks of the Virgilina sequence. The environment of deposition of the volcano-sedimentary sequence is interpreted to have been dominantly shallow marine with locally emergent (subaerial) volcanic centers approximately 630 million years ago. Intrusive rocks, which include the Chapel Hill pluton, complexly intrude the volcano-sedimentary sequence. During the Virgilina deformation (ca. 600 ma) the rocks were metamorphosed to the greenschist facies and folded into an anticlinorium, generally parallel to the Virgilina Synclinorium, with an axial plane dipping steeply toward the northwest. A mixture of dominantly primary pyroclastic rocks and lavas of the Hyco formation are exposed in the core of the anticlinorium with epiclastic lithologies of the Aaron formation dominating the flanks of the anticlinorium. The East Farrington pluton intrudes the folded and metamorphosed Virgilina sequence. Faults, whose latest movement appears to be brittle, cut the folded lithologies. Hydrothermally altered volcanic rocks with pyrophyllite deposits are concentrated along the informally named Cane Creek fault. The Cane Creek fault extends for at least 20 miles (30 kilometers) through the Hillsborough, Efland, White Cross and Saxapahaw 7.5-minute quadrangles. Brittle faults, attributed to Mesozoic continental rifting, separate sedimentary rocks of the Durham sub-basin from crystalline rocks of the Carolina terrane. Additional brittle faults are located within Carolina terrane lithologies.

INTRODUCTION

The geology of the Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles, Orange and Durham Counties, North Carolina is the focus of the 2006 Carolina Geological Society (CGS) field trip (Fig. 1). The rocks of Orange, Chatham and Randolph Counties were the focus of the 1964 CGS field trip by Bain et al. (1964). In 1964, the understanding of the Carolina terrane was in its infancy with most of the Carolina terrane mapped only at the reconnaissance scale. The next time the rocks near the subject area were the focus of the CGS field trip was in 1985 by Harris and Glover (1985). The time span from 1964 to 1985 saw advances in the understanding (and development of controversies) of Carolina terrane geology, principally with the identification of an uncomformity separating rocks in the Roxboro-Durham-Ramseur areas from the rocks of central North Carolina (Albemarle area).

Figure 1: Study area location map.

This article presents new detailed geologic mapping in the Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles, provides a brief review of past investigations in the area and presents updated interpretations of the area geology. Detailed geological mapping, funded through STATEMAP, a component of the USGS National Cooperative Mapping Act program, was initiated in 2003 to provide a detailed geologic framework to this rapidly growing area. In the three years of mapping (Bradley et al., 2004; Bradley and Gay, 2005; and Bradley et al., 2006), the understanding of the rocks has increased greatly and their interpretations have evolved to the current state. This article presents a snap-shot of tentative interpretations that will surely evolve as additional areas are mapped. Long-range mapping plans of the North Carolina Geological Survey include detailed mapping of the entire I-85/I-40 and US 64 corridors from the Durham Triassic basin to Greensboro and Asheboro.

PREVIOUS INVESTIGATIONS

The earliest work in the Chapel Hill area was published in the Elisha Mitchell Science Society Journal. Eaton (1908 and 1909), Fry (1911) and Smith (1916, 1917a, b and c) all described rocks in the vicinity of the University of North Carolina at Chapel Hill campus. More modern geologic mapping activities of Harrington (1951), Kirstein (1956), Clarke (1957), Hayes (1962), Mann (1965) and Wagener (1965) mapped the plutonic rocks in the area but did not differentiate the volcano-sedimentary sequence. Butler (1963 and 1964) published the initial detailed descriptions and chemical analyses of the volcano-sedimentary rocks of Orange County. Allen and Wilson (1968) published the Geologic Map of Orange County in which the volcano-sedimentary sequences were differentiated at the reconnaissance scale. Geologic mapping by several graduate students (Bland, 1972; Wright, 1974; McConnell, 1974; Hauck, 1977; Wilkinson, 1978; Newton, 1983; and Chiulli, 1987) further differentiated the plutonic and volcano-sedimentary sequences and further developed the interpretation of the Chapel Hill-Hillsborough-Durham area as an ancient volcanic center. Newton (1983) interpreted the rocks of the Hillsborough area as part of a resurgent cauldron with present day dimensions of approximately 27 x 8.5 miles (45 x 14 km).

REGIONAL SETTING

Carolina Terrane

The Chapel Hill-Hillsborough-Efland area straddles crystalline rocks of the Carolina terrane, part of the Carolina Zone (Hibbard and Samson, 1995), and the sedimentary rocks of the Durham sub-basin of the Deep River Triassic basin. Hibbard et al. (2002) provides an extensive review of past work in the Carolina terrane and the Carolina Zone. Much of the information in this section was taken from Hibbard et al. (2002) and should be referenced for detailed information. The Carolina terrane on the western flank of the Deep River Triassic basin is separated into two main sequences in North Carolina: 1) the older Virgilina sequence and 2) the younger Albermarle sequence (Fig. 2). The Virgilina sequence is composed of Late Proterozoic aged (Wortman et al., 2000) volcanic and intrusive rocks and is unconformably overlain by the Late Proterozoic to possibly Middle Ordovician aged Albermarle sequences (Wright and Seiders, 1980; Koeppen et al., 1995) (Fig. 3).

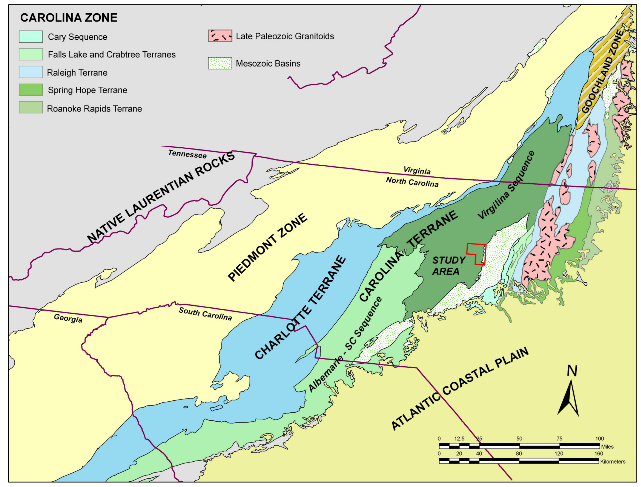


Figure 2: Terrane relationships and study area location after Hibbard et al., 2002.

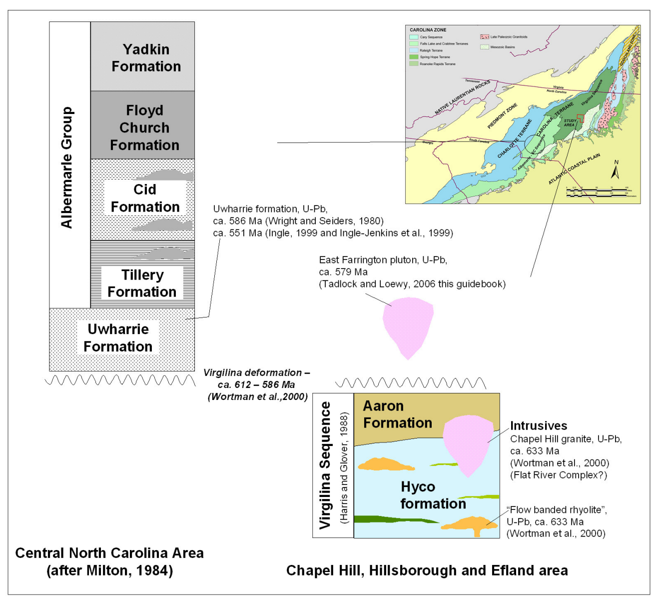


Figure 3: Stratigraphic columns for the Carolina terrane in the Chapel Hill, Hillsborough and Efland, North Carolina areas and central North Carolina area.

Glover and Sinha (1973), Harris and Glover (1985) and Harris and Glover (1988) developed the regional stratigraphy for the area. The study area is located within the Virgilina sequence of the Carolina terrane. The Virgilina sequence is separated into the Hyco formation, Aaron formation and Virgilina formation in the type area in the vicinity of Virgilina, Virginia. Harris and Glover (1988) extended the

regional extent of the Virgilina sequence southwest to the Ramseur, North Carolina area.
Neodium isotopic studies indicate that the Virgilina sequence is composed of juvenile crust derived from the mantle and was likely part of a mature island arc built on oceanic crust (Samson et al., 1995; Mueller et al., 1996; Fullagar et al., 1997). Isotopic and geochronological data indicates that the Albermarle sequence was likely formed above continental crust (Kozuch, 1994; Mueller et al., 1996; Fullagar et al., 1997; Ingle, 1999).

The unconformity separating the Virgilina and Albermarle sequences is interpreted to have been caused by the Virgilina deformation (Glover and Sinha, 1973; Harris and Glover, 1985; Harris and Glover, 1988). The timing of the Virgilina deformation is constrained between 612.4 +5.2/-1.7 Ma and 586 ± 10 Ma (Wortman et al., 2000). According to Glover and Sinha (1973), the Virgilina deformation is interpreted to have caused folding of the Virgilina sequence rocks without foliation development. Glover and Sinha (1973) attributed the regional foliation present in the Virgilina sequence rocks to a middle Paleozoic deformational event (ca. 450 Ma). However, Hibbard and Samson (1995) documented evidence that the Virgilina event was a foliation forming event in the Roxboro, North Carolina area.

Triassic Basin

The eastern one-quarter of the Chapel Hill 7.5-minute quadrangle is underlain by rocks of the Deep River Triassic basin – Durham sub-basin. The Deep River basin is part of the Newark Supergroup (Olsen, 1978 and Luttrell, 1989) and formed during early Mesozoic rifting of the supercontinent Pangea. The lithologies of the Deep River basin in the Chapel Hill area are assigned to the Chatham Group of the Newark Supergroup (Olsen, 1978; Luttrell, 1989). The Chatham Group consists of varying amounts of conglomerate, sandstone, siltstone, claystone, shale, coal and small amounts of limestone and chert. The Deep River basin is bordered on the east by the Jonesboro fault, a west-dipping high-angle, normal fault (Campbell and Kimball, 1923) that separates the Triassic sedimentary rocks from the crystalline rocks of the Carolina Zone. Along the western border of the basin, the Triassic sediments unconformably overlie or are locally in fault contact with the crystalline rocks of the Carolina Zone. In the Chapel Hill quadrangle, the sedimentary rocks along the western border of the basin appear to be largely in fault contact with the crystalline rocks of the Carolina terrane of the Carolina Zone.

The rocks of the Durham sub-basin have been separated into three lithofacies associations (Lithofacies I, II, and III) that are characteristic of certain depositional environments (Hoffman and Gallagher, 1989; and Clark et al., 2000). Lithofacies I (LA I) contains interbedded sandstone and siltstone and is interpreted as braided stream deposits. LA II contains a combination of sandstone interbedded with siltstone and siltstone interbedded with sandstone. LA II is interpreted as a meandering fluvial system surrounded by vegetated floodplain. LA III contains conglomerate, sandstone interbedded with conglomerate and sandstone with interbedded pebbly sandstone. LA III is interpreted as alluvial fan complexes characterized by broad, shallow channels with high sediment concentrations, and locally, high-energy debris flows (Fig. 4).

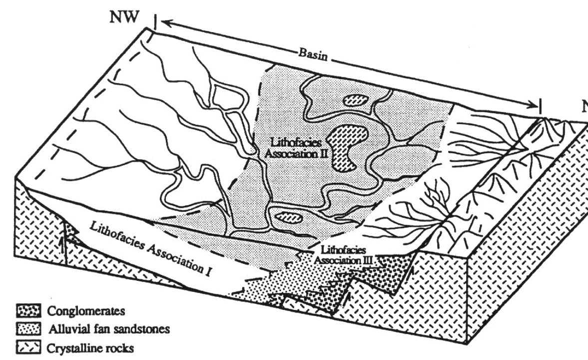


Figure 4: Schematic block diagram of distribution of lithofacies in Deep River Basin (after Hoffman, 1994).

GENERALIZED MAP UNITS:

A composite bedrock geologic map of the Chapel Hill, Hillsborough and Efland quadrangles (Bradley et al., 2004, Bradley and Gay, 2005 and Bradley et al., 2006) is provided as Figure 5. Figure 6 presents a schematic representation of relationships of the bedrock geologic units within the study area. All pre-Mesozoic rocks within the study area have been subjected to at least the chlorite zone of the greenschist metamorphic facies. Many of the rocks display a weak to strong metamorphic foliation. Although subjected to metamorphism, the rocks retain relict plutonic, pyroclastic and sedimentary textures and structures that allow for the indentification of protolith rocks. As such, the prefix "meta" is not included in the nomenclature of the pre-Mesozoic rocks.

Jurassic Diabase Dikes and Sills

Diabase dikes cut rocks of the Carolina terrane and the Durham sub-basin. The dikes are steeply dipping and trend northeast to northwest. Sills of diabase are present within the Durham sub-basin. The diabase is typically black to greenish-black, fine- to medium-grained, dense, consisting primarily of plagioclase, augite and olivine. Diabase occurs as dikes up to 600 ft. wide in the Chapel Hill quadrangle; however, typical dike widths are usually up to 80 ft. Diabase typically occurs as spheriodally weathered boulders with a grayish-brown to orange-brown weathering rind.

Two areas within the Chapel Hill quadrangle in the Durham sub-basin are interpreted to be underlain by diabase sills based on the following: 1) the presence of numerous, randomly distributed boulders of diabase present in the

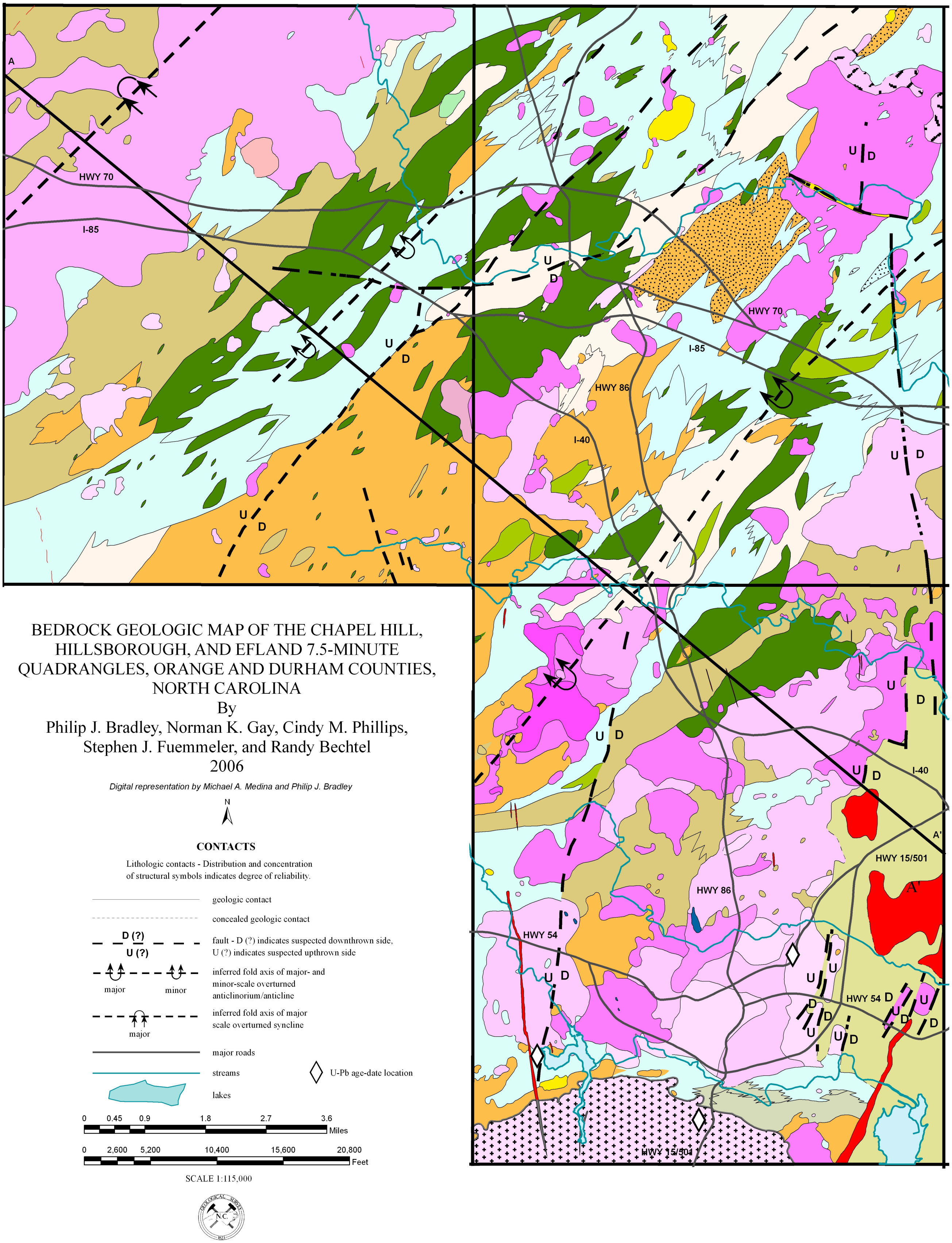
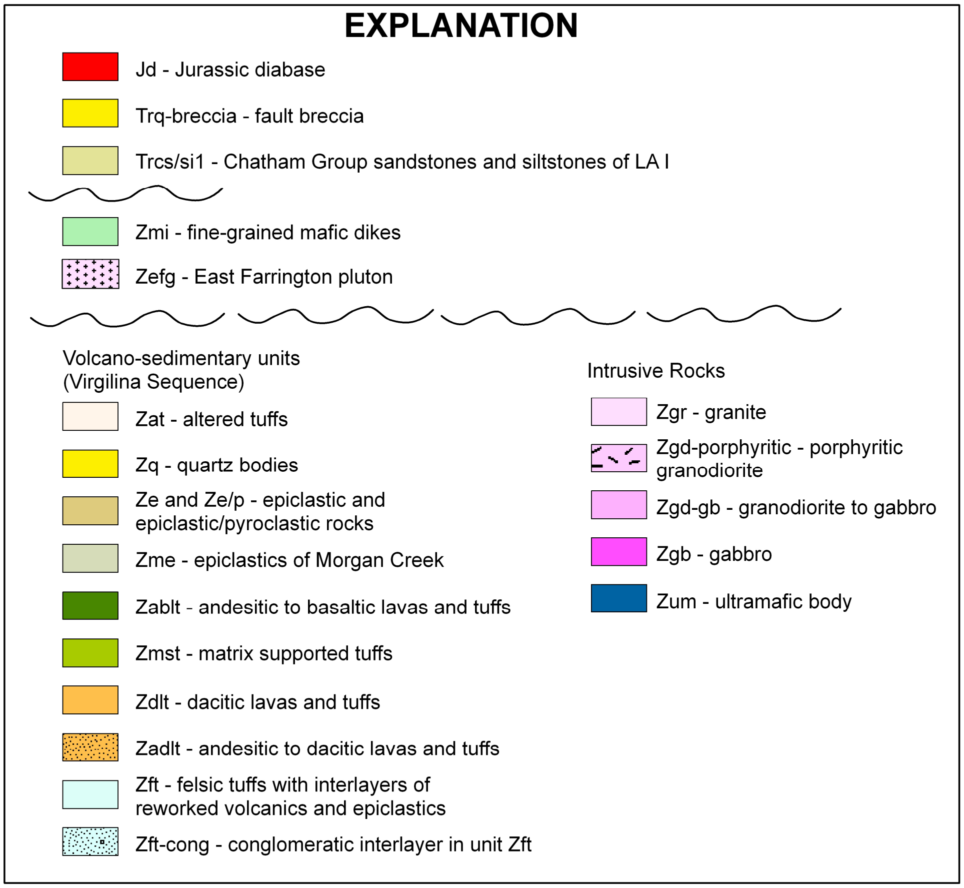


Figure 5: Composite bedrock geologic map of the Chapel Hill, Hillsborough and Efland 7.5 minute quadrangles, Orange and Durham Counties, North Carolina.



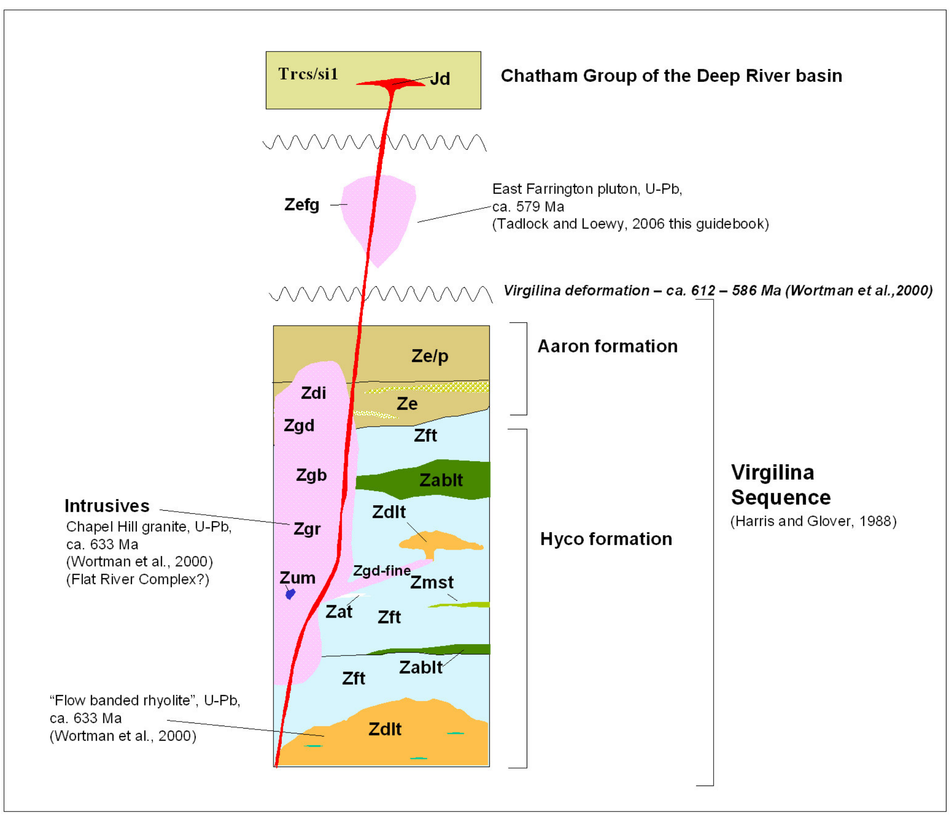


Figure 6: Schematic representation of relationships of bedrock geologic units in the Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles.

Briarcliff subdivision area and 2) Burt et al. (1978) interpreted the presence of a diabase sill directly east of Chapel Hill based on geophysical data presented by of Bain and Harvey (1977).

The distribution of diabase boulders imply a sill in the Chapel Hill quadrangle, however geologic mapping in the adjacent Southwest Durham quadrangle (Hoffman and Gallagher, 1989) and recent field checking indicate diabase is present only as discrete dikes that are on trend and intersect the sills in the Chapel Hill quadrangle. This abrupt change from a sill morphology to dikes may be attributed to diabase magma initially intruding as a swarm of dikes with some magma migrating laterally in between the sedimentary layering coalescing into sill shaped bodies.

Triassic Basin Lithologies

Chatham Group: Lithofacies Association I (Trcs/si_1)

The Triassic sedimentary rocks in the Chapel Hill 7.5-minute quadrangle are assigned to the Lithofacies Association I (LA I) of Hoffman and Gallagher (1989). The sandstones and siltstones of LA I are interpreted to have been deposited in a braided stream fluvial system. In the Chapel Hill quadrangle, the Triassic sediments consist of maroon, micaceous, sandy to slightly sandy, clayey to slightly clayey siltstone. The siltstones appear massive or bioturbated. Burrowing is present as randomly oriented cylindrical structures often filled with pale-green, fine-grained quartz sand. Muscovite is common. The sand fraction in the siltstone is fine- to medium-grained, poorly to moderately sorted, angular to subangular.

Two different sandstones were observed in the mapped area. The first sandstone is white to tan to greenish-gray, fine-grained, well sorted, subrounded to rounded, massive to bedded, quartz sandstone. Bedding is parallel occurring as thick laminations to thinly bedded (0.5 cm to 5 cm). Muscovite and biotite are present in trace to abundant amounts. Feldspar and lithic fragments are rare to absent. The second sandstone observed is gray to pinkish-gray with maroon to brown staining, coarse- to very coarse-grained, poorly to moderately well sorted, angular to subangular, massive to bedded and cross-bedded quartz sandstone, feldspathic arkose, and arkose. Bedding occurs as thin to medium bedded (5 cm to 15 cm), parallel beds; low angle planar cross-beds; and trough cross-beds. Muscovite and biotite are present in trace to minor amounts. Feldspar and lithic fragments are present in trace to common amounts.

Other lithologies observed in the mapped area are brown massive claystone and clayey, poorly sorted, granule to small pebble-size, polymictic conglomerate. Clast types include very fine-grained felsic volcanic rock, micaceous schist, and quartz. The conglomerate is crudely bedded. Due to the generally small size and poor exposure of the outcrops, the stratigraphy between the various lithologies was not seen. Where present, the sandstones appear to be in erosional contact with the siltstones. The larger sandstone outcrops fine upward. The dip of bedding plans are typically at a low angles ranging from 4 to 26 degrees to the southeast. Bedding dips both northwest and southwest proximal to the western border faults.

Carolina Terrane Rock Units

Intrusive Rocks

Intrusive rocks constitute an appreciable portion of the crystalline rocks within the study area, especially within Chapel Hill and northwest of the Town of Efland areas (Fig. 7). Past workers have separated the plutonic rocks within the Chapel Hill, Hillsborough and Durham areas into formally and informally named plutons and intrusive complexes (Wagener, 1965; Black, 1977; McConnell and Glover, 1982; Newton, 1983). Intrusive rocks range from granite to ultramafic in composition.

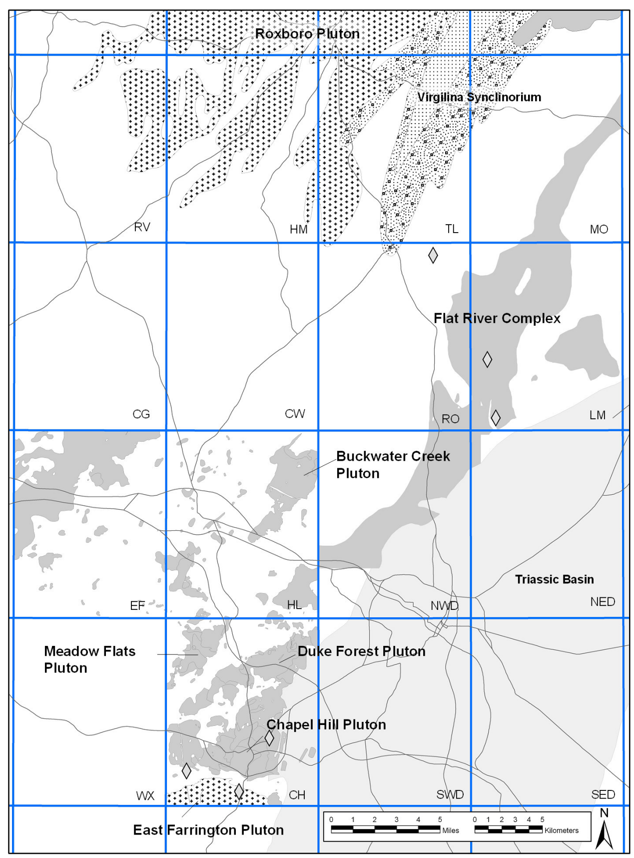


Figure 7: Figure showing unnamed, formal and informal names of plutons and intrusive complex. Diamond shapes indicated U-Pb zircon age-date locations of Wortman et al., 2000 and Tadlock and Loewy, 2006 (This guidebook). Quadrangle names: WX – White Cross, CH – Chapel Hill, SWD – Southwest Durham, SED – Southeast Durham, EF – Efland, HL – Hillsborough, NWD – Northwest Durham, NED – Northwest Durham, CG – Cedar Grove, CW – Caldwell, RO – Rougemont, LM – Lake Michie, RV – Ridgeville, HM – Hurdle Mills, TL – Timberlake, MO – Moriah.

Fine-grained mafic dikes

Fine-grained mafic dikes of basaltic composition are present and cross-cut all pre-metamorphic lithologies. The dikes are typically composed of plagioclase, actinolite (after augite), chlorite and epidote. Dike widths rarely exceed 20 feet. Narrow dikes (<5 feet) are often foliated; wider dikes do not readily display a foliation. One map-scale body of mafic rock, identified as a lamphrophyre by Newton (1983), was mapped in the Hillsborough quadrangle.

East Farrington pluton (Zefg)

The East Farrington pluton outcrops in the southern portion of the Chapel Hill 7.5-minute quadrangle. Rocks assigned to the pluton range from orange pink to pinkish-gray to gray, medium- to coarse-grained, equigranular to slightly porphyritic, unfoliated, hornblende granite to granodiorite. Hornblende content varies from approximately 5 to 10% by volume and occurs locally as elongate crystals up to 1.5 cm long. Grain size becomes finer and dark gray xenoliths of country rock up to 8 cm in diameter are common near the pluton edge. Investigations by Wagener (1965) described the East Farrington pluton as having a granodiorite core with a granitic border. Recent U-Pb zircon geochronologic data (Tadlock and Loewy, this guidebook) indicate that the East Farrington pluton is ca. 579 Ma and records an interval of plutonism within the Carolina terrane after deposition and deformation of the Virgilina sequence.

Granodiorite and diorite (Zgd to Zdi)

Granodiorite and diorite, commonly forming composite plutons, are the predominant intrusive rock types exposed in the study area. Grain size ranges from medium- to fine-grained with equigranular to porphyritic textures. In the granodiorite, mafic minerals consist of biotite partially altered to chlorite and hornblende partially altered to epidote. In the diorite, mafic minerals consist of hornblende altered to actinolite, chlorite and epidote. Feldspars (principally plagioclase) are typically altered to sericite and epidote. Fine- and medium-grained granodiorite and diorite composition plutons within the Hillsborough quadrangle are locally xenolith-rich, contain small (<1 mm to 10 mm) drusy cavities (vesicle-like cavities) and often have margins of hydrothermally altered country rock.

Fine-grained exposures of granodiorite and diorite are often greenish in color due to intense sausseritization of the plagioclase. The intense sausseritization often makes the differentiation of the green fine-grained intrusive rocks and surrounding volcaniclastic rocks difficult. The intrusive texture of the green fine-grained outcrops is discernable only using a 7x or greater hand-lens.

Newton (1983) conducted modal analyses on several intrusive rocks in the Hillsborough and Efland 7.5-minute quadrangles. The modal analyses of Newton (1983) and normalized whole rock analyses from this study plotted on QAP diagrams of Streckeisen (1973) indicate that the rocks generally described as diorites plot in the quartz diorite to quartz monzodiorite fields. Point counts and mode calculations of the intrusive rocks have not been done for this study.

Granite (Zgr)

Rocks of granitic composition occur primarily within the informally named Chapel Hill pluton and an unnamed pluton in the southeast corner of the Hillsborough 7.5-minute quadrangle. The granite is typically massive, fine- to medium-grained with dark green amphiboles (commonly rimmed by epidote and chlorite) and +/- biotite. Light-pink to pink, alkali feldspars are prominent and give the rock a pinkish hue. Grayish-pink to grayish-orange pink, fine-grained aplite with a sub-graphitic texture is present in dikes ranging from centimeters to meters in width and as a map-scale body. Granite of the Chapel Hill pluton has an interpreted U-Pb zircon crystallization age of 633 +2/-1.5 Ma (Wortman et al., 2000). An unpublished U-Pb zircon age of 631.6 +/- 7.9 Ma was also reported by Mehlop (1994) for the Chapel Hill pluton.

Black (1977) separated samples of the Chapel Hill granite into two groups based on thin section analysis. One group displayed interlocking grain margins with a nearly pristine igneous texture. The other group show evidence of recrystallization. The unaltered granite as described by Black (1977) is medium-grained with porphyritic euhedral plagioclase phenocrysts up to 4 mm in a fine-grained (0.5 mm) matrix of quartz, orthoclase, and albite(?). The matrix grains are anhedral to euhedral with interlocking margins and exhibit undulatory extinction. A green to brown, pleochroic amphibole (interpreted to be actinolite) is present as irregular clusters or as single anhedral crystals up to 1 mm. This amphibole is commonly rimmed by epidote or chlorite. Plagioclase phenocrysts are sericitized and/or saussuritized. Some plagioclase phenocryst rims are altered to albite. Accessory minerals include allanite and sphene. The altered granite as described by Black (1977) exhibits a relict igneous texture of broken or corroded plagioclase phenocrysts in a recystallized matrix of fine-grained, euhedral to subhedral crystals of quartz, microcline, and altered plagioclase. Biotite occurs in irregular aggregates up to 4 mm. Stained thin sections indicate only rare orthoclase. Most minerals have uniform extinction and feldspars have little or no twinning.

Gabbro (Zgb)

Gabbro is present as a map scale body within the Meadow Flats pluton. Elsewere, gabbro is typically present intermingled with diorite and granodiorite in composite plutons. In the Meadow Flats pluton the gabbro is coarse- to medium-grained, primarily consisting of plagioclase and augite. Augite grains are commonly 3 - 4 mm in diameter.

When intermingled with diorite and granodiorite, gabbro ranges from fine- to medium grained with augite grains ranging from 1 - 2 mm. Augite is commonly partially altered to amphibole (uralite).

Ultramafic rocks (Zum)

Minor amounts of ultramafic rocks are present as a single map-scale body and as four float localities in the Chapel Hill area. Typically, the rock is black and coarse-grained (5 - 10 mm). Hayes (1962) described the ultramafic rocks of the Chapel Hill area (located east of Iron Mine Hill) as being composed of coarse poikilitic crystals of relict brown hornblende that are partially replaced by actinolite and chlorite. Principal minerals include serpentine, talc, chlorite, actinolite, and opaque minerals. Minor relict orthopyroxene is present. Hayes (1962) interpreted the protoliths of the Chapel Hill ultramafic body as olivine-rich wehrlite (with approximately 50% olivine) and clinopyroxenite. The body is interpreted to be an intrusion of a crystal mush formed by differentiation of gabbroic magma at depth (Butler, 1989).

Mode of emplacement of intrusive rocks

Intrusive rocks in the study area are locally xenolith-rich, locally contain drusy cavities (vesicle-like cavities) and often have margins of hydrothermally altered country rock. These observations are characteristic of high-level subvolcanic intrusions based on the criteria of Thorpe and Brown (2003).

Immediately east and northeast of the Hillsborough and Chapel Hill area, Glover and Sinha (1973), Wright (1974), McConnell (1974) and McConnell and Glover (1982) described intrusive rocks of the Flat River complex (Fig. 7). The Flat River complex is interpreted to have been emplaced at shallow depth (<1 km) and have been eruptive to the surface. The Flat River complex has been interpreted as the igneous center that supplied extrusive volcanic material to the surface. McConnell and Glover (1982) extended the known outcrop of the Flat River complex, from its originally recognized area 40 km to the southwest to the southwestern corner of the Northwest Durham 7.5-minute quadrangle. Harris and Glover (1985), based on the work of Newton (1983), extend the known outcrop of the Flat River complex into the Hillsborough 7.5-minute quadrangle. A hornblende diorite and a hornblende-biotite granite from the Flat River complex have U-Pb zircon crystalliztion ages of 613.9 +1.6/-1.5 Ma and 613.4 +2.8/-2.0 Ma, respectively (Wortman et al., 2000).

The intrusive rocks of the Chapel Hill area are directly on strike with and are similar in composition to the Flat River complex. Granite of the Chapel Hill pluton has an interpreted U-Pb zircon crystallization age of 633 +2/-1.5 Ma (Wortman et al., 2000). The intrusive rocks of the Chapel Hill area may be correlative with the Flat River complex assuming the complex becomes younger to the northeast. Detailed petrographic and geochemical studies are needed to determine if the intrusive rocks of the Chapel Hill area can indeed be correlated with the Flat River complex.

Volcano-sedimentary units (Virgilina Sequence – Hyco and Aaron Formations)

Altered tuffs (includes quartz bodies) (Zat)

Altered rocks are common in the subject area and are interpreted to be formed by the hydrothermal alteration of volcano-sedimentary sequences. Altered rocks commonly occur in close proximity to intrusive bodies, but are also present as mappable units distant from intrusions. Altered rocks also occur locally within all volcano-sedimentary units. Alteration varies from slight, with mild silicification and/or sericitization, with preservation of primary structures; to severe, with completely silicified and/or sericitied rocks with relict structures obliterated.

Altered rocks are typically light-gray to white, sericite-quartz phyllites and silicified rock with red and yellow mottling. Locally, pods of pyrophyllite, and quartz + pyrophyllite rock are present. Deposits of pyrophyllite with andalusite (up to 4 mm) are economically mined on Occoneechee Mountain south of Hillsborough. Map scale to outcrop scale quartz bodies are also present. The quartz bodies are typically massive and locally exhibit a sugary, quartzite-like texture. Stable oxygen isotope geochemistry on altered rocks from the Hillsborough pyrophyllite deposit (Fiess et al., 1993) indicate a meteoric water source for hydrothermal alteration fluids. Spence (1975) and McDaniel (1976) attribute the formation of pyrophyllite in the Hyco formation to hot spring activity during active volcanism and subsequent metamorphism. The altered tuffs unit is assigned to the Hyco formation of Harris and Glover (1988).

Epiclastic and epiclastic/pyroclastic rocks (Ze and Ze/p)

Interlayered tuffeacous siltstones, tuffeacous sandstone, volcanic sandstones, conglomeratic sandstones, conglomerate and phyllite with minor amounts of primary pyroclastic rocks are present within the study area. The rocks are typically grayish-green to greenish-gray in color. Clasts of volcanic rocks are common in conglomerates. The siltstones typically are weakly phyllitic. Sandstone and conglomerate beds often fill scour channels in the siltstones.

The epiclastic rocks are interpreted as correlative with the Aaron formation of Harris and Glover (1988). Harris (1984) interpreted the Aaron formation to have been deposited in a retrogradational (progressing toward the source area) submarine-fan setting, below storm-wave base, where the sediment supply diminished due to erosion of topographic relief in the source area. He interpreted the depositional environment as a deep marine basin marginal to or superimposed on a formerly active volcanic arc.

Felsic tuffs with interlayers of reworked volcanics and epiclastics (Zft)

Dacitic felsic tuffs are abundant in the study area. The tuffs range from massive to foliated; non-welded to welded; plagioclase crystal-rich to crystal poor; fine to coarse tuffs, lapilli tuffs and tuff breccias. Crystal fragments, when present, are dominantly plagioclase up to 3 mm in diameter. Clast types in lapilli tuffs and tuff breccias are typically angular, dark-gray to black; locally magnetic; 1 - 70 mm; cryptocrystalline dacite and porphyritic dacite with feldspar phenocrysts. Other clasts types include various types of fine to coarse felsic and mafic tuff, mafic lava and rarely plutonic rocks. Outcrops and thin sections of welded tuffs show a prominent welding and/or compaction foliation with fiamme-shaped clasts. Minor interlayers of thinly bedded siltstones, volcanic sandstones and reworked tuffs are present.

The felsic tuff unit is interpreted as normal background deposition of air fall tuffs and pyroclastic deposits erupted from both intrabasinal and extrabasinal sources. The reworked tuffs and minor epiclatics are interpreted to represent penecontemporaneous erosion of pyroclastic deposits and sedimentation in a dominantly shallow marine environment. The felsic tuff unit is assigned to the Hyco formation of Harris and Glover (1988).

Matrix supported tuffs (Zmst)

The matrix supported tuffs unit is a distinctive unit of typically green-gray to green; weakly foliated to well foliated; matrix supported; polymictic; lapilli tuff and tuff breccia. Angular to sub-rounded, lithic fragments range from <1 mm up to 1 m in diameter.

This unit is interpreted as a re-sedimented, syn-eruptive, volcaniclastic deposit in which texturally unmodified volcaniclastic debris and entrained texturally more mature accidental clasts are incorporated into a rapidly resedimented package of sediment. These tuffs may be emplaced via submarine mass flows, subaerial landslides and/or lahars. The outcrop in the Few's Ford area of Eno River State Park was interpreted as a lahar deposit (Allen and Wilson, 1968 and Rochester, 1978). The matrix supported tuffs unit is assigned to the Hyco formation of Harris and Glover (1988).

Dacitic lavas and tuffs (Zdlt)

The dacitic lavas and tuffs unit consists of interlayered: 1) distinctive dark-gray to black, siliceous, cryptocrystalline dacite, porphyritic dacite with plagioclase phenocrysts, and flow banded dacite; and 2) welded and non-welded: greenish-gray to grayish-green, coarse plagioclase crystal tuff, lapilli tuff and lithic tuff. Welded lapilli tuff often contains black-colored fiamme, up to 10 cm long, interpreted as flattened pumice. Massive, matrix supported lithic tuff contains angular to rounded, polymictic clasts up to 8 cm. Clast types include: gray and green, microcrystalline to coarse-grained volcanic rock fragments; black porphyritic lava with plagioclase phenocrysts; and black, flow-banded dacite. Minor interlayers of microcrystalline ash tuff are present. Outcrop-scale bodies of mafic tuff and lava; coarse-grained, cross-bedded, litharenite sandstone; and polymictic, pebble and small cobble conglomerate are present in unit. A sample, identified as a flow-banded rhyolite, was collected from a location in the University Lake area in the Chapel Hill quadrangle by Wortman et al., (2000). The outcrop is part of the Zdlt unit of this study and is likely of dacitic composition. Single zircons in the sample yielded an upper intercept age of 632.9 +2.6/-1.9 Ma (Wortman et al., 2000).

This unit is interpreted to represent deposits associated with dacitic domes and composite domes. The dacites are interpreted to represent coherent magma that was extrusive (lavas) or very shallow intrusions. The tuffs are interpreted as episodic pyroclastic flow deposits, air fall tuffs or reworked tuffs generated during eruption of the dome complexes. This unit is assigned to the Hyco formation of Harris and Glover (1988).

Andesitic to basaltic lavas and tuffs (Zablt)

The andesitic to basaltic lavas and tuffs unit consists of green to gray-green to black; amygdaloidal basalt, porphyritic basalt with plagioclase phenocrysts, porphyritic basalt with amphibole/pyroxene phenocrysts, and microcrystalline basalt. Pyroclastic rocks associated with the lavas include: coarse plagioclase crystal tuff, with suasseritized pale green, angular to subrounded plagioclase crystal fragments (up to 3 mm) in a fine-grain matrix of epidote and chlorite; and coarse amphibole/pyroxene crystal tuff with black, prismatic amphibole/pyroxene crystal fragments (up to 3 mm) in a fine-grain matrix of epidote and chlorite. Rounded weathering patterns of outcrops and spheroidally shaped structures in some outcrops of mafic lavas have been interpreted as possible pillow structures by past workers (Wilson and Allen, 1968). Basalts are interpreted to be lava flows or shallow intrusions. This unit is assigned to the Hyco formation of Harris and Glover (1988).

INTERPRETED FACIES ARCHITECTURE OF THE HYCO AND AARON FORMATIONS

A tentative facies architecture (after McPhie and Allen, 1992) has been developed for the rocks of the Hyco and Aaron formation in the Chapel Hill, Hillsborough and Efland quadrangles.

1) Normal background deposition of air fall tuffs erupted from both intrabasinal and extrabasinal sources deposited in a dominantly shallow marine environment is interpreted as the origin of unit Zft. The air fall tuffs are mixed with reworked tuffs and minor epiclastics indicating penecontemporaneous erosion and sedimentation of pyroclastic deposits.

2) Background sedimentation was episodically interrupted by the following:
   a. Construction of dacitic domes with associated lava flows and explosive pyroclastics. The dacitic domes and related pyroclastics are represented by unit Zdlt. The dacitic domes were commonly emergent above local sea level as evident by the common occurrence of red colored lavas and welded tuffs within the unit.
   b. Mass flows of volcaniclastic deposits (subaerial in the form of lahars and shallow submarine in the form of massive, matrix supported monomictic and polymictic tuffeacous deposits) represented by the Zmst unit.
   c. Eruption of mafic lava flows and associated pyroclastic deposits represented by Zablt unit.

3) Synvolcanic intrusions were emplaced at shallow depths with apophyses (off shoots of larger intrusive bodies) that likely feed extrusive equivalents.

4) Synvolcanic intrusions interacted with country rock and heated local groundwater (meteoric water) causing extensive hydrothermal alteration of some lithologies.

5) Secession of major volcanism was followed with the erosion of volcanic highlands and deposition of Aaron formation epiclastics. Episodic intrabasinal and extrabasinal smaller scale volcanism deposited pyroclastic debris interlayered with the dominantly epiclastic lithologies.

GENERALIZED ZONAL SEPARATION OF THE CAROLINA TERRANE IN THE STUDY AREA

The subject area has been separated into three zones (Fig. 8):
1) a central volcanic complex,
2) a northwest volcano-sedimentary sequence and
3) a southeast volcano-sedimentary sequence.

Central Volcanic Complex

The central volcanic complex is a northeast-southwest trending belt approximately 8 miles (13 km) wide and extends out of the subject area to the northeast and southwest. The central volcanic complex contains abundant primary pyroclastic rocks and lava that display nearly pristine volcanic textures and include predominantly feldspar crystal tuffs, pumice-bearing tuffs, feldspar-porphyritic dacitic lavas and amygdaloidal andesitic to basaltic lavas. Dacitic tuffs and lavas are typically interlayed in bodies interpreted to have been domes.

The central volcanic complex contains areas of hydrothermally altered rock. Stable oxygen isotope geochemistry on altered rocks in the area of Hillsborough (Feiss et al., 1993) indicate a meteoric water source for hydrothermal alteration fluids. Coupled with the presence of welded tuffs, red-colored welded tuffs and red-colored lavas, a primarily subaerial environment is interpreted for the central volcanic complex. Minor interlayered, water-lain (probably shallow marine) sedimentary rocks indicate that the central volcanic complex was periodically submerged. The central volcanic complex is correlated with the Hyco formation of Harris and Glover (1988).

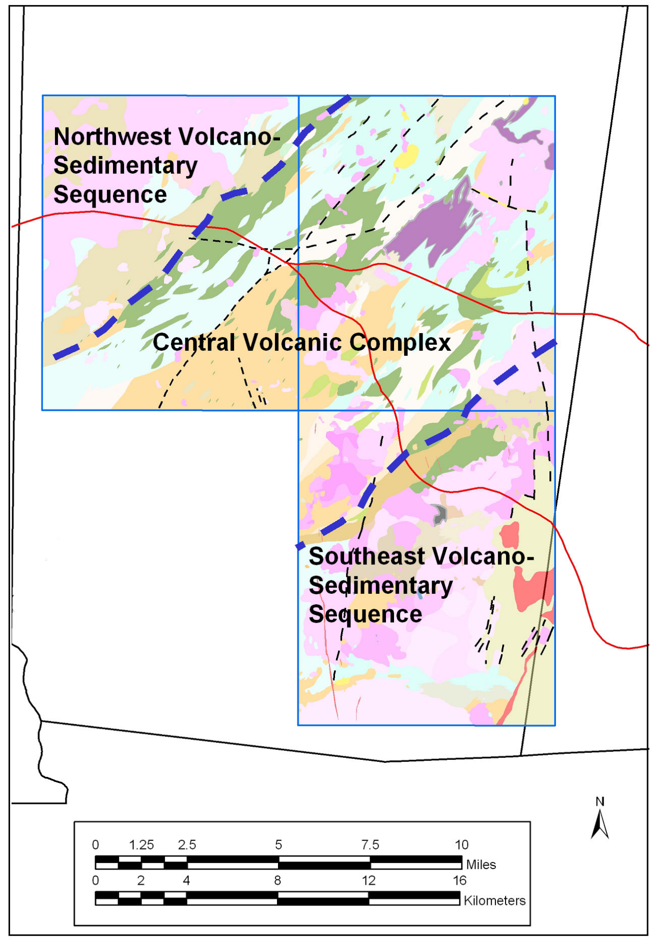


Figure 8: Zonal separation of Carolina terrane rocks in the Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles.

The central volcanic complex is intruded by fine- and medium-grained plutonic rocks ranging in composition from granite to gabbro. Fine- and medium-grained granodiorites and diorites are locally xenolith-rich, contain small (<1 mm to 10 mm) drusy cavities (vesicle-like cavities) and often have margins of hydrothermally altered country rock. These intrusions are interpreted as high-level subvolcanic intrusions based on the criteria of Thorpe and Brown (2003).

Field relationships of the intrusive rocks are similar to relationships described by McConnell and Glover (1982) for the Flat River complex located northeast of Durham, North Carolina. The Flat River complex is a granite, granodiorite, quartz diorite and gabbro intrusive complex interpreted to have been emplaced at a depth of less than 1 kilometer and have broken the surface locally.

Northwest Volcano-Sedimentary Sequence

The northwest volcano-sedimentary sequence is located to the northwest of the central volcanic complex and extends out of the subject area. The sequence is dominated by epiclastic rocks with lesser amounts of primary pyroclastic rocks. Epiclastic rocks include well bedded mudstones, siltstones, sandstones and conglomerate. Interlayed with the epiclastic rocks are lesser amounts of primary pyroclastics similar to rocks of the central volcanic complex. The northwest volcano-sedimentary sequence is intruded by a dominantly granodiorite to diorite composite pluton. The epiclastic rocks are interpreted as correlative with the Aaron formation of Harris and Glover (1988).

Southeast Volcano-Sedimentary Sequence

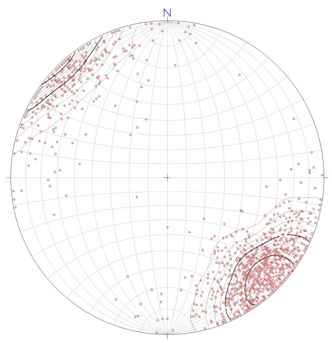
The southeast volcano-sedimentary sequence is located southeast of the central volcanic complex and is generally present as map-scale epiclastic and pyroclastic bodies complexly intruded by granite to ultra-mafic rocks. The southeast volcano-sedimentary sequence is composed of predominately epiclastic rocks with lesser amounts of primary pyroclastics and lavas. The epiclastic rocks are similar to the epiclastics of the northwest volcano-sedimentary sequence and consist of layered siltstones, tuffeaceous siltstones, sandstones, conglomeratic siltstones and sandstones, and conglomerate. The epiclastic rocks are interlayered with primary pyroclastic rocks consisting of dacitic to andesitic tuffs, lapilli lithic tuffs, tuff breccias and lesser lava flows. The intrusive rocks of the southeast volcano-sedimentary sequence are generally medium- to coarse-grained in texture and are in contact with country rock that exhibit lesser amounts of hydrothermal alteration than the intrusives of central volcanic complex. The epiclastic rocks are interpreted as correlative with the Aaron formation of Harris and Glover (1988).

STRUCTURAL GEOLOGY

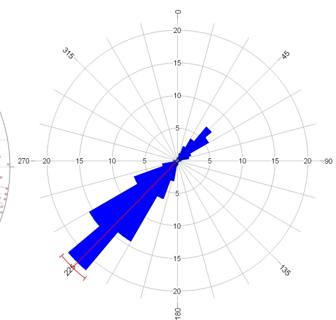
Foliation and Relict Bedding/Layering

Rocks in the subject area display a metamorphic foliation that varies in intensity depending on rock type. The foliation is best displayed in phyllitic epiclastic rocks, altered phyllitic tuffs and mafic to intermediate tuffs. The foliation is typically weakly developed or absent in the plutonic rocks, dacitic tuffs and dacitic lavas. The majority of foliations (Figs. 9a and b), relict bedding and depositional layering (Figs. 10a and b) are steeply dipping to the northwest with lesser amounts dipping to the southeast. The foliation is generally parallel to relict bedding and compositional layering. The foliation was locally observed at an angle to bedding and layering in several outcrops. Relict stratigraphic-up direction was determined in several locations from cross-beds, scour surfaces and grading bedding.

In the southern portion of the Chapel Hill quadrangle, an outcrop of unfoliated, fine-grained diorite dike truncates the steeply dipping cleavage of a siltstone exposed on Morgan Creek. Although undated, the fine-grained intrusive may be related to the circa 579 Ma East Farrington pluton (Tadlock and Loewy, this guidebook). If this intrusion does cut the regional foliation and the intrusion is related to the East Farrington pluton, the regional foliation is related to a pre-circa 579 Ma deformational event (i.e., Virgilina deformation). Hibbard and Samson (1995) interpret the regional foliation in the Virgilina sequence to be attributed to the Virgilina deformation in the Roxboro, North Carolina area.

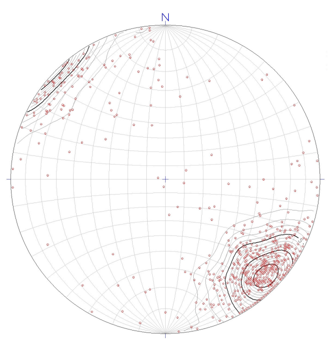


9a.

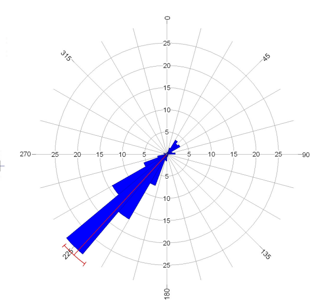


9b.

Figure 9a: Stereonet plot of contoured poles to foliation, cleavage, spaced cleavage, and shear foliations. N=1,172. Figure 9b: Unidirectional rose diagram of foliations, cleavage, spaced cleavage, and shear foliations. N=1,172



10a.



10b.

Figure 10a: Stereonet plot of contoured poles to primary layering, bedding, welding/compaction foliation, and flow banding. N=651. Figure 10b: Unidirectional rose diagram of primary layering, bedding, welding/compaction foliation, and flow banding. N=651

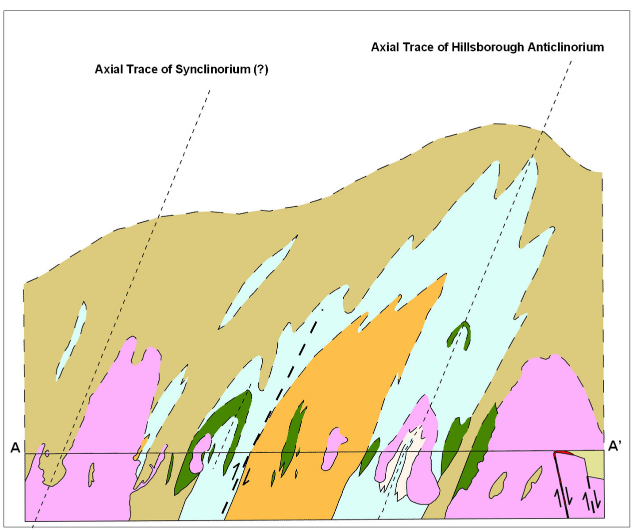
Lineations

Clast lineations are abundant within the primary pyroclastic lithologies. It is unknown whether these clast lineations are attributed to preferential alignment during original deposition or are from tectonic modification (or both). Mineral lineations and clast lineations attributed to tectonic activities are rare in the subject area. When present, the tectonic lineations are typically oriented down-dip, consist of aligned sericite grains for the mineral lineations and consist of down-dip oriented, angular to subrounded lithic clasts for the clast lineations. The lineations are interpreted to be related to strain during folding.

Folds

No outcrop scale folds were observed in the study area. Bedding with stratigraphic-up indicators and cleavage-bedding relationships, from relatively few locations distributed throughout the subject area, appear to indicate the presence of an inferred large-scale asymmetric anticline (possibly an anticlinorium) with an axial trace running through the Hillsborough quadrangle and northwest portion of the Chapel Hill quadrangle (Fig. 5). The position of the axial trace of the anticline is based on the location of chevron-shaped map units in the east-central portion of the Hillsborough quadrangle.

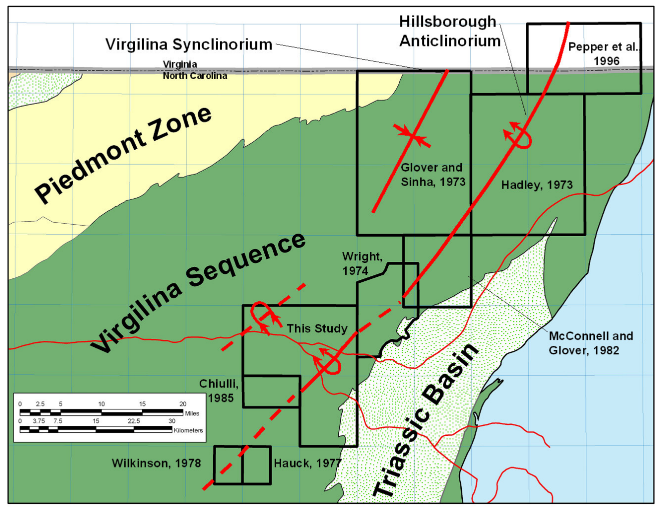
A tentatively placed axial trace of a large-scale syncline, with a northwest dipping axial plane, is mapped in the northwest corner of the Efland quadrangle. The placement of a large-scale syncline is tentative because it is based on two locations of tentatively interpreted overturned bedding in apparent scour contact. A schematic cross-section of the study area with hypothetical fold geometry is provided as figure 11.



Figures 11: Schematic cross-section from A-A' with hypothetical fold geometry. See figure 5 for cross-section line location and explanation of unit colors.

Hadley (1973) and Pepper et al. (1996) identified a regional anticline on trend with the anticline identified in the Hillsborough and Chapel Hill quadrangles. Additionally, McConnell and Glover (1982) described that their units X and Y have southeast dips and are likely located on the southeast limb of the anticlinorium adjacent to the Virgilina synclinorium. Further southwest along the axial trace of the anticline, observations in the M.S. theses of Chiulli (1985), Hauck (1977) and Wilkinson (1978) in the White Cross, Bynum and Silk Hope quadrangles, respectively, collectively indicate the presence of a large anticlinal structure (Fig. 12). This large-scale regional anticline structure is informally designated as the Hillsborough anticlinorium.

A small-scale inferred overturned anticline (probably parasitic to the regional-scale fold) is mapped with an axial trace trending between the inactive (former) and active Duke quarries on the Efland quadrangle. This anticline is based on overturned graded bedding in the active Duke quarry and normally graded bedding in the inactive Duke quarry.



Figures 12: Regional extent of Hillsborough anticlinorium with respect to Virgilina synclinorium and past works study areas.

Faults

On the western boundary of the Durham Triassic basin, Triassic sedimentary rocks are separated from crystalline rocks of the Carolina terrane by either brittle faults or a nonconformity. Fault contacts are interpreted where the contact is linear and/or where fault gouge is present. Contacts between the Triassic sedimentary rocks and crystalline rocks that are not linear and without brittle deformation features are interpreted as a nonconformity.

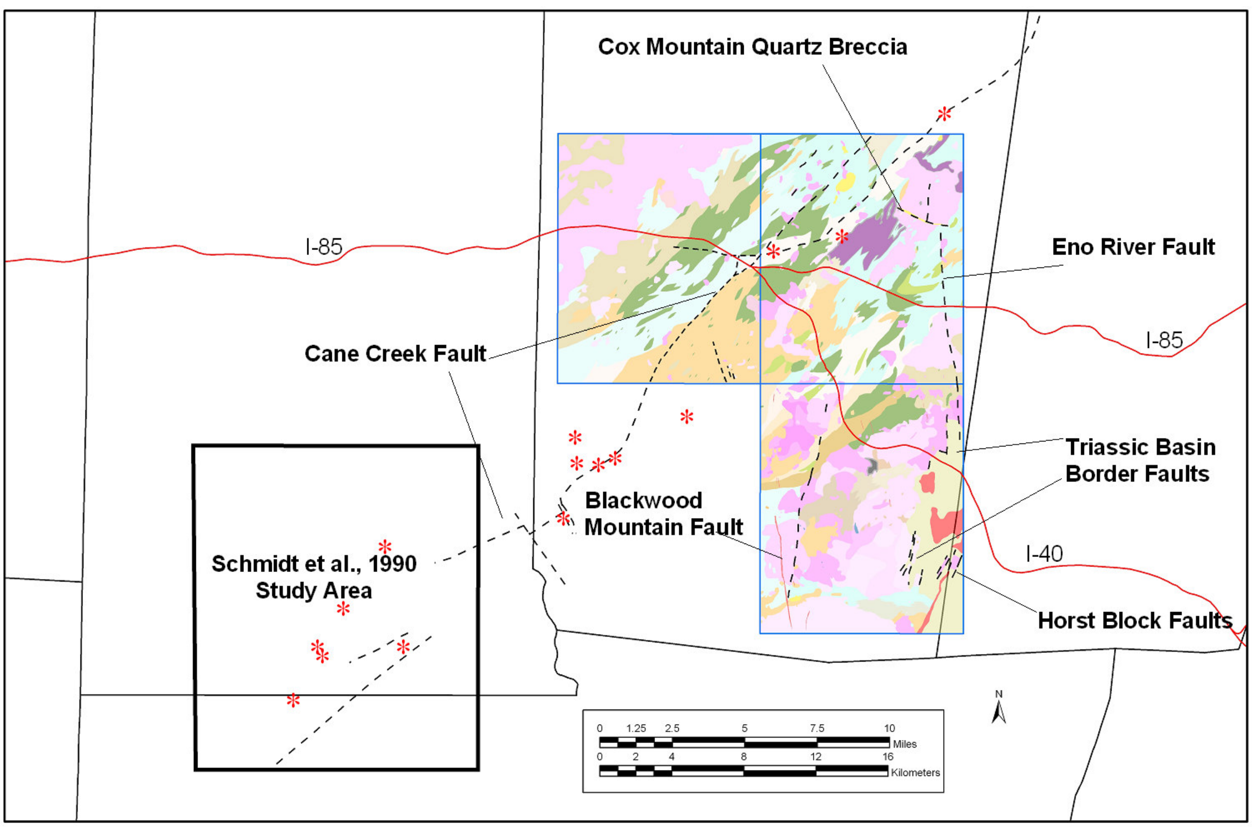
Additional faults, away from the Triassic/crystalline rock contact, have been interpreted based on a combination of features including: 1) conspicuous quartz breccia outcrops and float; 2) local fault gouge; and 3) the apparent offset of lithologic units. Quadrangle-scale lineaments present on Light Detection and Ranging (LiDAR) imagery often occupy the trace of the faults. The latest movement on the faults is interpreted to have been brittle due to the presence of quartz breccia and local presence of gouge. The relative motion on faults is speculative due to a lack of kinematic indicators and is based on apparent offset directions of units or a general assumption that the down-dropped block is on the east side of the fault. Foliated intrusive rocks and strongly foliated hydrothermally altered rocks (locally with shear bands) are present along the trace of some of the interpreted faults. The foliated intrusives and intensely foliated volcanogenic rocks along the trace of the faults may indicate that some of its movement history may have been ductile in nature. Figure 13 displays the locations of interpreted faults in the study area and nearby areas.

Cane Creek Fault

Detailed mapping in the Efland quadrangle indicates a fault within the trace of a regional scale lineament coincident with Cane Creek. Informally named the Cane Creek fault, this fault is interpreted to extend to the northeast where it is defined by a zone of hydrothermally altered rock (which includes the Hillsborough pyrophyllite deposit) and bodies of foliated diorite. LiDAR lineament data and work by Schmidt et al. (1990) in the adjoining Saxapahaw, Silk Hope and Crutchfield Crossroads quadrangles indicate the trace of the Cane Creek fault continues to the southwest into a zone of extensive hydrothermal alteration (Snow Camp area). The Cane Creek fault is interpreted to extend for at least 20 miles through the Hillsborough, Efland, White Cross and Saxapahaw quadrangles (Fig. 13). An additional en echelon fault, approximately 7 miles long, was mapped by Schmidt et al. (1990) in the Silk Hope and Crutchfield Crossroads quadrangles. Sykes and Moody (1978) indicate that the Hillsborough pyrophyllite deposit is located in a major fault zone. Additionally, the trace of the Cane Creek fault through portions of the Efland and Hillsborough quadrangles coincides with the western inner ring-fracture of Newton (1983).

The interpreted main trace of the Cane Creek fault is located approximately 1000 ft and 3000 ft, respectively, northwest of the abandoned quarry on Occoneechee Mountain and the active pyrophyllite mine on the northern end of Occoneechee Mountain (south of the Town of Hillsborough). The quarries are interpreted to be located in a splay of the Cane Creek fault that trends toward the northeast. The trace of the splay is defined by foliated intrusive rocks, chlorite phyllites in a basaltic unit (Zablt) and strongly foliated hydrothermally altered rock. The splay is also on trend with the Murray pyrophyllite prospect in the Caldwell quadrangle to the north of Hillsborough.

Shear bands in the abandoned quarry on Occoneechee Moutain indicate a reverse sense of motion with tops to the southeast. The motion on the Cane Creek fault is tentatively assigned a reverse motion with the upthrown block on the west. Deformation along the Cane Creek fault may be wider in less competent lithologies such as pyrophyllite and sericite phyllites and may account for the deformation in the Occoneechee abandoned quarry & active mine. Kink bands,



Figures 13: Location of informally named faults in the Chapel Hill, Hillsborough and Efland Areas. LiDAR lineament data indicate that the Cane Creek fault may extend toward the southwest into study area of Schmidt et al., 1990. Asterisk indicates approximate locations of pyrophyllite prospects and/or mines.

multiple generations of fractures in the active pyrophyllite mine (Sykes and Moody, 1978), and shear bands in the abandoned quarry indicate a long and probably complicated movement history on the Cane Creek fault or perhaps a system of intersecting faults of varying ages.

Broadhurst and Councill (1953) interpreted the setting of pyrophyllite deposits (like the deposit south of Hillsborough) as being situated on a hanging wall of a fault flanked by "sheared volcanic rock". The Glendon pyrophyllite deposits in Moore County are located along the Glendon Fault (Stuckey, 1928 and Conley, 1962). The Glendon Fault exhibits reverse motion and is a locus of pyrophyllite alteration for a distance of over 30 km (18 miles). The Cane Creek fault may be similar to and on the scale of the Glendon fault.

ACKNOWLEGEMENTS

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ISOTOPIC CHARACTERIZATION OF THE FARRINGTON PLUTON: CONSTRAINING THE VIRGILINA OROGENY

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ABSTRACT

The exotic Carolina Zone is an amalgamation of isotopically juvenile and evolved provinces that experienced a complex tectonic history prior to its Paleozoic collision with Laurentia. The Neoproterozoic Virgilina Orogeny, observed in the Carolina terrane of the Carolina Zone, may record the collision of two or more of these provinces prior to their accretion to Laurentia. The timing is constrained between 612 and 546 Ma by U/Pb crystallization ages of pre and post-Virgilinian plutons (Wortman et al., 2000). New U/Pb data for the post-Virgilinian East Farrington Pluton yields an age of 578.7 +/- 5.5 Ma. This new age: 1) distinguishes the East Farrington Pluton from the older, adjacent Chapel Hill Pluton, 2) identifies a phase of magmatism in the Virgilina Sequence of the Carolina Terrane that previously had not been clearly identified, and 3) minimizes the window during which the Virgilina Orogeny could have occurred.

Sm/Nd signatures and U/Pb zircon data from pre-Virgilinian rocks of the Virgilina Sequence indicate that they had a juvenile source, whereas similar analyses from post-Virgilinian rocks indicate incorporation of older crust. Based upon these observations Hibbard and Samson (1995) proposed that the Virgilina Orogeny resulted from the collision of the isotopically juvenile Virgilina oceanic arc with an unknown continental fragment. Identification of a crustal component in the post-Virgilinian East Farrington Pluton would support this hypothesis. New Sm/Nd and U/Pb data for the East Farrington Pluton indicate a juvenile source and thus, do not constrain the timing of incorporation of older crust into the Carolina Terrane.

INTRODUCTION

The Carolina Zone, which spans the east coast of the U.S. from Virginia to Georgia, is the largest of the Appalachian exotic blocks. It appears to be composed of multiple volcanic arcs that amalgamated to form the larger zone prior to collision with Laurentia during the Paleozoic (Hibbard et al., 2002). Subsequent Paleozoic deformation has obscured this early tectonic history. Consequently, the timing of amalgamation and the sources of these arcs are not well-constrained. Deciphering the early tectonic history of the Carolina Zone will enable us to better understand its role in the formation of the late Paleozoic supercontinent, Pangea.

The Carolina Zone is divided into terranes based on apparent differences in proportions of rocks types, isotopic signatures of magmatic rocks and tectonothermal histories (Hibbard et al., 2002). The largest, least deformed, and, thus, best-understood terrane within the Carolina Zone is the Carolina terrane. Within the Carolina terrane there is evidence of a Neoproterozoic orogeny, referred to as the Virgilina Orogeny (Glover and Sinha, 1973, Harris and Glover, 1988). The timing of this event is constrained to a period of 66 million years, by the U/Pb ages of pre- and post-Virgilinian plutons (Wortman et al., 2000). Hibbard and Samson (1995) suggest that the Virgilina Orogeny was the result of the collision between a juvenile island arc and an older continental fragment. This conclusion was based on an observed shift in the Nd isotopic signatures of pre- and post-Virgilinian igneous rocks.

This manuscript presents new U/Pb geochronology and Nd isotopic data for the East Farrington Pluton, a post-Virgilinian intrusion in the Carolina terrane, to better constrain the timing of the end of the Virgilina Orogeny and test Hibbard and Samson (1995)'s hypothesis.

BACKGROUND

The Carolina terrane is divided into four metavolcanic-dominated sequences, the Virgilina, Albemarle, South Carolina, and Cary sequences. The Virgilina Sequence is the oldest, containing plutons and volcanic rocks with ages ranging from 633-612 Ma (Wortman et al., 2000). The oldest known rocks in the other sequences in the Carolina terrane yield ages of ca. 580 Ma or younger (Hibbard et al., 2002). One younger pluton in the Virgilina Sequence has been precisely dated; the Roxboro Pluton yields an age of 546.5 +/- 3 Ma (Wortman et al., 2000). These two pulses of magmatism in the Virgilina Sequence correspond with Stages I (> 600 Ma) and III (< 550 Ma) of Hibbard et al. (2002)'s characterization of magmatism throughout the entire Carolina Zone. No evidence of Stage II (590-560 Ma) magmatism has been clearly identified in the Virgilina Sequence. A less-precise Rb/Sr age of 566 +/- 46 Ma was reported for the Parks Cross Road granodiorite (Tingle, 1982). The large analytical uncertainty of this age prevents correlation of the granodiorite with one of the three magmatic stages.

The Farrington Igneous Complex is undeformed and intrudes the deformed Virgilina Sequence, near Chapel Hill, NC. It is exposed adjacent to the Chapel Hill Pluton, which yielded a U/Pb zircon age of 633 +/- 2 Ma (Wortman et al., 2000). The complex consists of a dominant East Farrington Pluton and the younger, smaller West Farrington Pluton (Wagener, 1964). Rb/Sr data for the East Farrington yields an age of 517 +/-76 Ma and for the West Farrington yields an age of 541 +/- 84 Ma (Fullagar, 1971; McSween et al., 1991).

The timing of the Virgilina Orogeny in the Virgilina Sequence is constrained between 612 Ma, the youngest of the Stage I plutons, the Osmond biotite-granite gneiss, and 546 Ma, the age of the Stage III Roxboro Pluton. Several researchers suggest that the Albemarle Sequence was unconformably deposited upon the Virgilina Sequence (as referenced in Wortman et al. 2000). The Uwharrie volcanics, the lowest member of the Albemarle Sequence, yields a U/Pb crystallization age of 586 +/- 10 Ma (Wright and Seiders, 1980). If this depositional relationship between the Virgilina and Albemarle Sequences is correct, then the age of the end of the Virgilina Orogeny is constrained to ca. 580 Ma. However, the crystallization age of the post-Virgilinian East Farrington Pluton would constrain the timing of the end of the Virgilina Orogeny without requiring the interpreted relationship between the Virgilina and Albemarle sequences.

Rocks of the Virgilina Sequence generally have a high positive initial E_{Nd} (E_{Ndi}) values and Neoproterozoic T_{DM} ages, whereas Post-Virgilinian rocks of the Albemarle (and a few from the Virgilina) Sequence tend to have lower or negative E_{Ndi} values and older T_{DM} ages (Samson et al., 1995; Mueller et al., 1996; Fullagar et al., 1997). An E_{Ndi} value is the normalized $^{143}Nd/^{144}Nd$ ratio of a rock at the time it crystallized. The values for the ca. 630 Ma Virgilina-Sequence rocks are similar to the range of values predicted for the mantle at that time ($E_{Nd\ mantle\ @\ 630\ Ma} = 0$ to $+7$) suggesting a mantle (juvenile) source. The lower E_{Ndi} values of the ca. 580 Ma Albemarle-Sequence rocks reflect incorporation of materials with lower E_{Nd} values, "evolved" older continental crust (Fig. 1). A T_{DM} age is the calculated time at which the Nd isotopic composition of a rock matched that modeled for the depleted mantle (DM). Similarity of T_{DM} and U/Pb crystallization ages implies that the rock was derived from the depleted mantle. A T_{DM} age that is older than the U/Pb crystallization age implies that the rock contains a component of older crust. The Neoproterozoic T_{DM} ages of the ca. 630 Ma Virgilina-Sequence rocks imply that they are mantle-derived, but Mesoproterozoic T_{DM} ages of the ca. 580 Ma Albemarle-Sequence rocks indicate that they contain some component of Mesoproterozoic or older crust. Additionally, U/Pb zircon analyses indicate that Virgilina-Sequence rocks do not contain inherited zircon (zircon xenocrysts derived from pre-existing crust), whereas Albemarle-Sequence rocks contain xenocrysts that appear to be Mesoproterozoic (Mueller et al., 1996). Assuming that the analyzed compositions of the arc rocks reflect all the available magma sources, these data indicate that pre-Neoproterozoic continental crust was only available after the Virgilina Orogeny. Thus, the shift from juvenile Nd compositions without inherited zircon in pre-Virgilinian rocks to more evolved (crustal) Nd compositions with inherited zircon in post-Virgilinian rocks support the hypothesis that the Virgilina Orogeny was the collision between a juvenile arc and older continental crust. This older crust must lie at depth, as no known pre-Neoproterozoic crust is exposed in the Carolina terrane. (Hibbard et al., 2002) Evidence for the incorporation of older crust in the post-Virgilinian East Farrington Pluton would help constrain the time at which older crust was introduced to the Carolina terrane. However, a mantle source for the East Farrington Pluton would indicate either of two possibilities. 1) Continental crust was not present in the Carolina terrane at that time. 2) Continental crust was present, but was not incorporated into the magma of the East Farrington Pluton. Two existing Sm/Nd analyses from the Farrington Igneous Complex imply a juvenile source (Fullagar et al., 1997). New U/Pb zircon and whole rock Nd data will add to this small dataset.

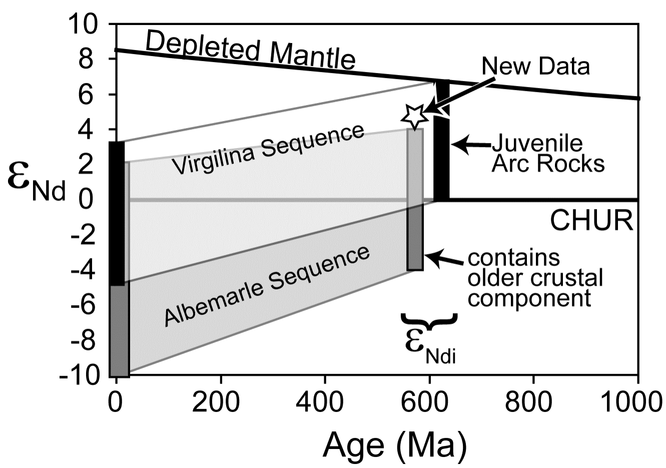

Figure 1. Schematic comparison of Nd data. E_{Ndi} values are calculated at 630 Ma for the Virgilina Sequence, 580 Ma for the Albemarle Sequence and 579 for the East Farrington Pluton (new data). Data sources: Samson et al., 1995; Mueller et al., 1996; Fullagar et al., 1997. Nd isotopic data are normalized to CHUR (chondritic uniform reservoir).

METHODS

U/Pb geochronology was completed at the University of North Carolina at Chapel Hill. Sample FP-AP-05 was crushed and milled and the zircons were separated using standard separation techniques, using a Rogers™ table, heavy liquids, and a Frantz™ Isodynamic Magnetic Separator. Grains were hand picked from the nonmagnetic fraction. Selected grains were separated into fractions annealed for 60 hours at 850ºC, leached in HF for 12 hours at 210ºC, cleaned, and then spiked with a $^{205}Pb/^{233-236}U$ mixed spike. Individual fractions were dissolved in HF and HNO_3

in Teflon™ dissolution bombs at 210°C for five days. U and Pb were isolated from dissolved zircon using anion exchange techniques. The isolated elements were loaded onto zone-refined Re filaments using silica gel (Pb) and regular Re filaments using graphite slurry (U). Fractions were analyzed on a GV Sector 54 Thermal Ionization Mass Spectrometer (TIMS) using the single Daly collector in peak-hopping mode. ISOPLOT (Ludwig, 2001) was used to determine the linear regression through the data.

Whole rock samples, FP-BH-05 and FP-PMC-05, were crushed then pulverized in a Shatterbox™ Puck Mill. For Sm/Nd analysis, 300 mg aliquots of the pulverized powders were spiked with a ^{149}Sm/^{150}Nd mixed spike and dissolved by a two stage process, using HF/HNO_3 and 6N HCl, in Teflon™ dissolution bombs. Rare earth elements were isolated using REE-SPEC column chemistry. Nd and Sm were then separated from other rare earths using LN-SPEC column chemistry. Nd aliquots were loaded onto Re filaments with 2N HCl and analyzed with the VG Sector 54 TIMS in a triple filament configuration using a three cycle dynamic acquisition. Sm aliquots were loaded onto Ta filaments with 2N HCl and analyzed with the VG Sector 54 TIMS using static acquisition.

DATA

U/Pb Geochronology

One sample of the East Farrington Pluton was analyzed for U/Pb geochronology. Sample FP-AP-05, collected in Arlen Park of Southern Village Neighborhood (N035º 53' 05.3", W 079º 03' 53.4"), is a medium grained granodiorite. Zircons from this sample ranged in size from 50 to 250 µm, were typically subhedral, and a few contained minor inclusions. The six analyzed fractions were small samples, each containing one to six zircon grains. All six analyses yield nearly concordant data (Table 1, Fig. 2).

The weighted average ^{207}Pb/^{206}Pb age is 578.7 +/- 5.5 Ma (MSWD = 1.30, n = 6). A linear regression through the data, yields an upper intercept age of 570.5 +/- 4.6 Ma and a lower intercept age of -529 +/- 560 Ma (MSWD = 0.26, n=6). The ages calculated by the two methods overlap within the uncertainties of the analyses. Although the linear regression yields better precision, we prefer the weighted average ^{207}Pb/^{206}Pb age. The slope of the linear regression is defined by a tight cluster of data with the two most distant data points (controlling the slope) having the least precision and the resulting lower intercept age (-529 +/- 560 Ma) is erroneous. This relatively precise new age (578.7 +/- 5.5 Ma) for the East Farrington Pluton is older than that determined by Rb/Sr work, but overlaps the larger uncertainties (517 +/- 76 Ma and 541 +/- 84 Ma) of the Rb/Sr ages. There is no evidence for incorporation of xenocrystic zircons (inheritance).

Whole-Rock Nd Compositions

Two other samples of the East Farrington Pluton were analyzed for whole-rock Nd isotopic compositions. FP-BH-05, collected at Boothe Hill Road (N035º 49' 38.4", W 079º 03' 36.9"), is a medium-grained potassium feldspar-rich granite. FP-PMC-05, collected at Pritchard's Mill Creek (N035º 52' 44.5", W 079º 06' 15.3") is a medium-grained quartz-rich granite. Nd isotopic compositions of these two samples yield nearly identical E_{Ndi} values (@ 579 Ma, E_{Ndi} = 4.90 and 4.92) and T_{DM} ages (715 Ma and 720 Ma) (Table 1, Fig. 1). These positive E_{Ndi} values and low T_{DM} ages indicate that the East Farrington Pluton was dominantly, if not completely, derived from a juvenile source. This data is consistent with two previously analyzed samples of the East and West Farrington plutons (Fullagar et al., 1997).

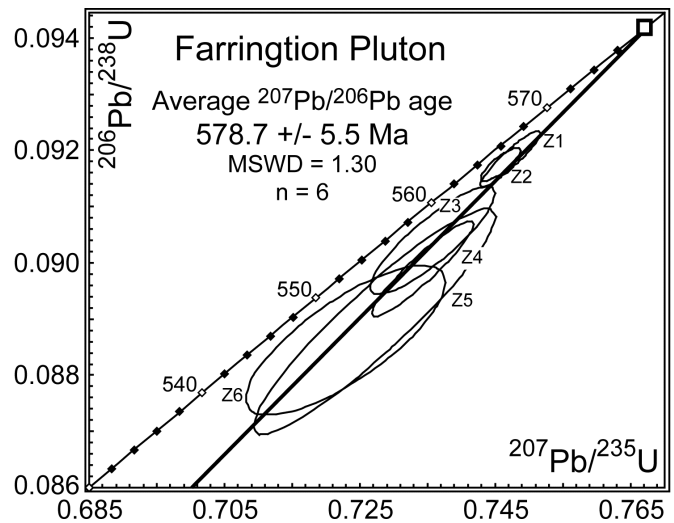

Figure 2. Concordia plot of zircon data from FP-AP-05. Z5 and Z6 contained a slightly larger component of common Pb. The uncertainty in the common Pb correction results in the slightly larger ellipse. Plot generated and age calculated using PbMacDat. All data lie near the crystallization age (ca. 579 Ma), suggesting that no xenocrystic zircons were analyzed. This data provide no evidence for incorporation of older crust.

DISCUSSION

The U/Pb age of 578.7 +/- 5.5 Ma is 54 million years younger than that of the adjacent Chapel Hill Granite (633 +/- 2 Ma), confirming that the East Farrington Pluton formed during a distinct, later magmatic event. It is also 33 million years older than that of the Roxboro Pluton, the only precisely-dated post-Virgilinian, Neoproterozoic pluton in the Virgilina Sequence. Thus, the intrusion of the Farrington Pluton at ca. 579 Ma defines a distinct magmatic event that has not been previously identified in the Virgilina Sequence. The timing of this event is coeval with the Stage II (590-560 Ma) magmatism (Hibbard et al., 2002) present in other sequences within the Carolina Zone, suggesting that these sequences may have been juxtaposed prior to a Stage II event.

U/Pb data

FP-AP-05 Fractions	Mass[1] (mg)	Concentration U (ppm)	Pb (ppm)	Measured 206 Pb / 204 Pb	CORRECTED RATIOS 208 Pb / 206 Pb	206 Pb / 238 U	2s % err	207 Pb / 235 U	2s % err	207 Pb / 206 Pb	2s % err
Z1	0.0076	47.28	5.85	859.45	0.508	0.09153	(.54)	0.74759	(.59)	0.05924	(.23)
Z2	0.0130	61.48	7.62	1585.07	0.514	0.09144	(.32)	0.74617	(.39)	0.05918	(.22)
Z3	0.0017	66.34	7.96	376.08	0.482	0.09009	(1.06)	0.73612	(1.25)	0.05926	(.62)
Z4	0.0048	32.10	3.75	416.32	0.451	0.08958	(.95)	0.73464	(1.02)	0.05948	(.37)
Z5	0.0024	58.15	6.62	185.87	0.431	0.08865	(2.27)	0.72754	(2.47)	0.05952	(.90)
Z6	0.0035	41.49	4.74	277.54	0.440	0.08831	(1.51)	0.72327	(2.04)	0.05940	(1.29)

U/Pb data

FP-AP-05 Fractions	AGES (Ma) 206 Pb / 238 U	207 Pb / 235 U	207 Pb / 206 Pb	corr. coef.	Common Pb (pg)	Estimated Blank (pg)	Pb*/ Pbc	DISCORD-ANCE
Z1	**564.6**	**566.8**	**575.7**	0.922	2.5	2.5	17.9	2.02
Z2	**564.0**	**566.0**	**573.9**	0.830	3.0	3.0	33.4	1.78
Z3	**556.1**	**560.1**	**576.8**	0.868	1.8	1.8	7.5	3.75
Z4	**553.1**	**559.3**	**584.5**	0.932	2.2	2.2	8.1	5.61
Z5	**547.5**	**555.1**	**586.3**	0.930	4.7	4.7	3.4	6.90
Z6	**545.5**	**552.6**	**581.8**	0.774	3.2	3.1	5.3	6.50

[1] Masses are estimated based on measured volumes.

[2] Ratios have been corrected for spike, blank, fractionation and common Pb.

Measurements of NBS981 indicate a fractionation correction factor of 0.15%/AMU

Sm/Nd data

Sample	143/144	147/144	E_{Nd} today	T_{DM} (Ma)	E_{Ndi}
FP-BH-05	0.51255	0.1071	-1.74	715	4.90
FP-PMC-05	0.51257	0.1113	-1.40	720	4.92

Initial E_{Nd} calculated at 579 Ma

Table 1.

The timing of the Virgilina Orogeny was previously bracketed between 612 and 546 Ma by the crystallization ages of the Osmond biotite-granite gneiss and the Roxboro Pluton (Wortman et al., 2000). The new age for the East Farrington Pluton tightens the window in which the Virgilina Orogeny could have occurred from 66 million years to 33 million years (ca. 612-579 Ma). Within uncertainty, the 578.7 +/- 5.5 Ma age overlaps the 586 +/- 10 Ma age determined for the earliest volcanism in the Albemarle Sequence.

U/Pb and Nd data yield no evidence for incorporation of older crustal material in the East Farrington Pluton. We can not distinguish between the two possible explanations: 1) there was no continental crust in the Carolina terrane at the time the East Farrington Pluton formed, or 2) there was continental crust, but it was not incorporated in the East Farrington Pluton. Thus, these new data provide no insight with respect to when pre-Neoproterozoic crust became part of the Carolina terrane. Further U/Pb and Nd analysis of other post-Virgilinian plutons may better constrain regional distribution of plutons that incorporated older continental crust and more precisely determine when this crust was first incorporated into Carolina terrane magmas.

Summary

New zircon U/Pb analyses yield a more precise crystallization age for the East Farrington Pluton of 578.7 +/- 5.5 Ma. This age distinguishes the pluton from the adjacent Chapel Hill Granite and identifies a phase of magmatism that was not previously identified in the Virgilina Sequence. The timing of this phase of magmatism is equivalent to Stage II magmatism (590-560 Ma) of Hibbard et al. (2002), recognized in other sequences and terranes in the Carolina Zone and, thus, supports juxtaposition of the Virgilina Sequence and these other sequences and terranes by this time. This new age better constrains the timing of the Virgilina Orogeny between 612 Ma and 579 Ma.

The lack of inherited zircon components, high positive E_{Ndi} values and Neoproterozoic T_{DM} ages imply a juvenile source for the East Farrington Pluton. The new data do not constrain when pre-Neoproterozoic crust was incorporated into the Carolina terrane.

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OCCONEECHEE MOUNTAIN ROCKSLIDE OF FEBRUARY 17-18, 2001, ENO RIVER STATE PARK, ORANGE COUNTY, NORTH CAROLINA

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ABSTRACT

A ~2,500 cubic yard rockslide occurred near the Occoneechee Mountain observation deck sometime between 6:00 P.M., February 17 and 8:00 A.M. February 18, 2001. Boulders in the slide debris stripped bark and limbs to a height of 20 feet from trees along the 200-foot slide path. Larger boulders snapped and uprooted eight-inch diameter trees. The rockslide originated in a promontory composed of foliated and fractured quartz, sericite phyllite within an altered volcanic tuff unit. The dominant F1 foliation that dips 55°-70° northwest out of the quarry face acted as the main slip surface. Fractures served as planes of separation allowing the block to detach from the rock mass. The primary factor leading to the instability of the rock mass was the over-steepening of the rock slope during past quarry excavation. Gravitational creep, repeated freeze-thaw and frost wedging, and rainfall infiltration were probably contributing factors to the rockslide over the decades since quarry operations ceased. Slope movements along the quarry walls will continue to occur. Some movements will involve the slow, gravitational movement of rock and debris. Other movements, such as rockslides, rock fall, and debris slides will be rapid (i.e., movement rates of feet/second), and could involve volumes of material comparable to the February 17-18 rockslide. The rapid slope movements, that occur with little or no warning, pose a threat to public safety, both for people on the quarry rim and within the quarry.

INTRODUCTION

A major rockslide occurred on the northwest slope of Occoneechee Mountain sometime between 6:00 p.m., February 17 and 8:00 a.m. February 18, 2001. Figure 1 shows the general location of the rockslide in relation to other slope movements and slope movement deposits in the North Carolina Geological Survey (NCGS) database. The rockslide originated within the altered tuffs map unit (Zat) delineated by Bradley and Gay (2005) in the geologic map of the Hillsborough 7.5-minute quadrangle.

The text and figures in this paper are adapted from the report by Wooten and Clark (2001) prepared for the North Carolina Division of Parks and Recreation (NCDPR). The purpose of the 2001 report was to provide the NCDPR with a geologic assessment of the stability of the slopes in the vicinity of an observation deck adjacent to the rockslide. At that time, the NCDPR had recently acquired the property with the deck from the town of Hillsborough. The 2001 report also provided a number of general stabilization concepts for the NCDPR to consider. The NCDPR has since removed the observation deck because of the potential for slope instability that could have affected the deck.

ROCKSLIDE CHARACTERISTICS

The main scarp of the rockslide marking the detachment area of the rock block is about 30 feet northeast of an observation deck that has since been removed. The top of the scarp is along the rim of a northwest-facing slope excavated during development of the now abandoned quarry. NCDPR staff members indicate that the rock block formed a promontory along the quarry face prior to movement (fig. 2). Rock excavation during quarrying, perhaps dating back the Civil War era, produced a ~20-foot high, nearly vertical face on the promontory with areas of overhang.

A rough estimate of the in-place volume of the main detached rock block was about 2,500 cubic yards, weighing nearly 5,100 tons. Once in motion, the sliding or toppling block broke into numerous boulders, probably upon impact with the quarry bench below. Sliding, rolling and bouncing boulders stripped bark and limbs from trees to a height of ~20 feet along the 200-foot slide path that ended in the quarry floor. Larger boulders, some weighing nearly 125 tons with a volume of about 60 cubic yards, snapped and uprooted eight-inch diameter trees in their path (figs. 3 and 4). At the widest point, the swath of rock debris measures about 100 feet.

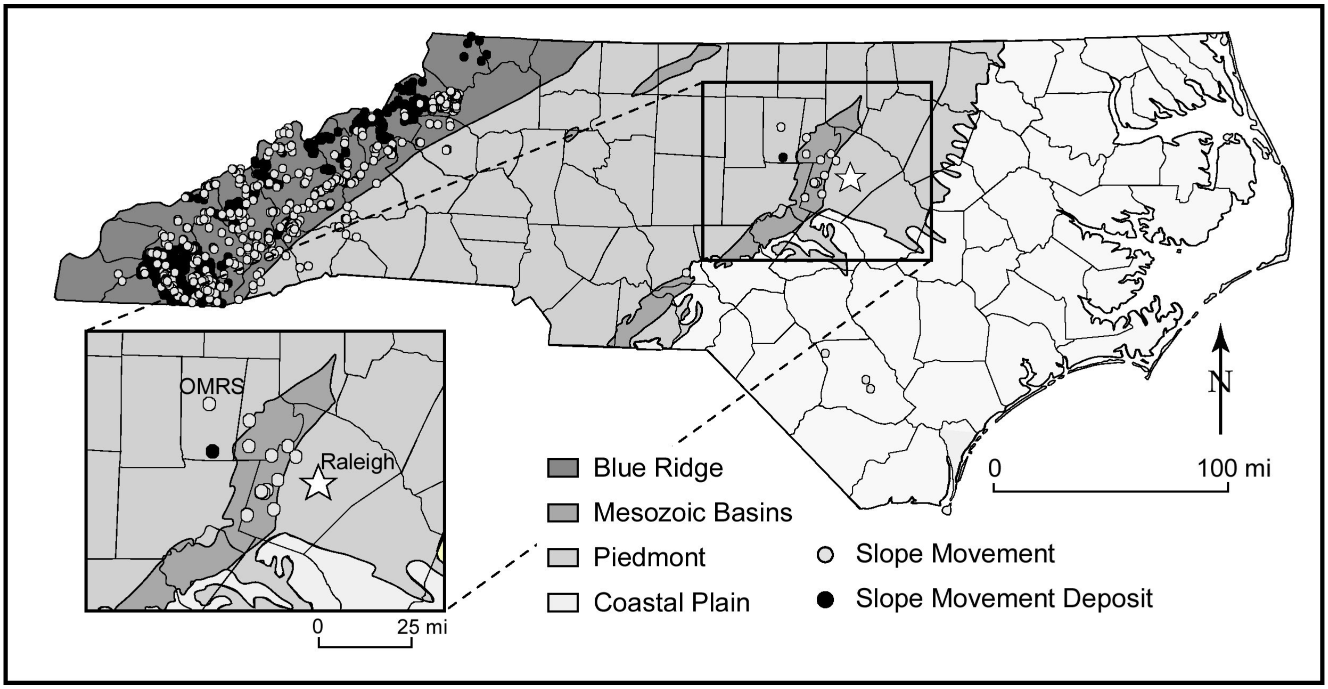

Figure 1. Map showing the location of the Occoneechee Mountain rockslide (OMRS in inset map) in relation to major geologic provinces and other slope movements and slope movement deposits in the NCGS database as of October 2006.

Figure 2. Photograph of quarry face prior to the February 17-18, 2001 rockslide showing the estimated pre-failure extent of the rock block. The solid line approximates the failure surface along F1 foliation planes; dashed line outlines the approximate pre-failure perimeter of the rock block. Arrows show the general movement direction. View looking the northeast. Photograph courtesy of Duncan Heron.

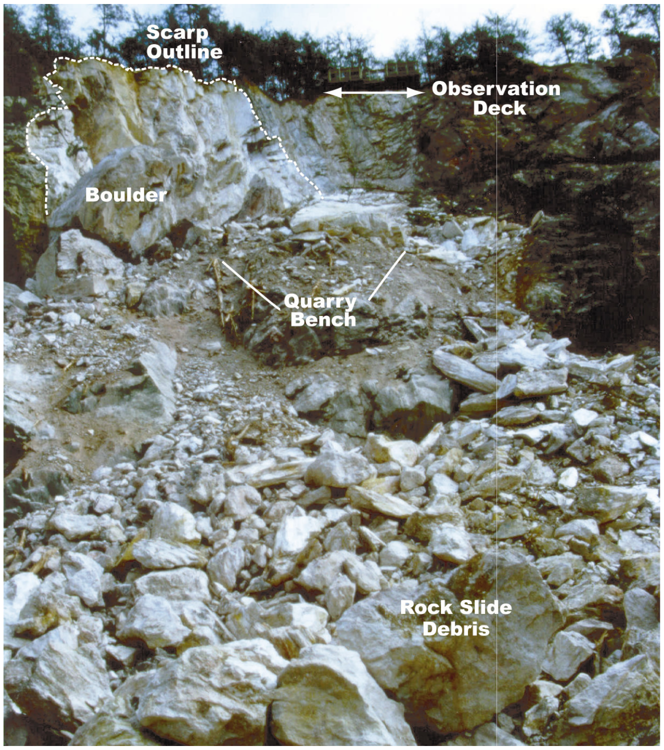

Figure 3. Photograph of the February 17-18, 2001 rockslide path showing the scarp and resulting boulder deposit. For scale, the observation deck located near the quarry rim at the time was about 25 feet wide.

Figure 4. Rockslide boulders and downed trees in the quarry floor near the terminus of the 2001 rockslide. Geologist standing on boulder in middle of photograph for scale.

Communications with NCDPR staff indicated that the rockslide occurred without any prior signs of movement. Given the degree of damage to trees and the steepness of the rockslide path below the scarp, major movement of the rockslide mass probably occurred in a matter of seconds.

GEOLOGIC CONDITIONS

The promontory where the rockslide originated is comprised of foliated and fractured quartz, sericite phyllite (QSPh) (figs. 5, 6 and 7). A less foliated, but highly fractured sericite-bearing siliceous rock unit (SQR) is structurally below the phyllite unit, and holds up the higher slopes of Occoneechee Mountain.

Through-going, planar discontinuities in the quarry related to the rockslide in the vicinity of the observation deck are grouped into five categories based on their orientation and origin. Three foliations (F1, F2, and F3) defined primarily by the planar alignment of sericite and possibly pyrophyllite are present. Two joint sets (fractures) are also present (J1 and J2) in both the QSPh and SQR units. Both joint sets cut across, and are therefore younger than, foliations F1, F2, and F3.

All three foliation surfaces dip toward the northwest, and out of the quarry face. Foliation 1 (F1) corresponds to the primary failure planes of the 2001 rockslide, and dips about 55° to 70° northwest. In the vicinity of the deck piers, F1 is generally subparallel to compositional layering in the rock, and the contact between the two rock units. Foliation 2 (F2) is less steep than F1, and dips about 35° to 45° northwest. F1 and F2 intersect to form the saw tooth pattern on the quarry face immediately below the previous deck location. Foliation 3 (F3) is a younger shear (C) surface that cuts across and deforms both F1 and F2. F3 dips about 15° to 35° northwest. From the tectonic perspective, the shear bands defined by the F1 and F3 foliations indicate reverse movement with tops toward the southeast, consistent with the interpretation of the quarry being within a splay of the Cane Creek fault as shown in Bradley and Gay (2005).

Two joints (fractures) cut across the three foliations and act as planes of separation or release surfaces within the rock mass. Yellow-brown iron oxide staining along the joint surfaces indicates that the fractures are pathways for water infiltration. Black, locally iridescent goethite coatings along numerous fracture surfaces probably resulted from late stage, near surface mineralization rather than relatively recent weathering processes. Joint set 1 (J1) dips about 55° to 60° southeast into the quarry face, and is well exposed in the main scarp of the 2001 rockslide. Joint set 2 (J2) dips about 72° to 82° southeast, oblique to the quarry face. The trace of J2 can be observed as the high-angle dark lines in the quarry face immediately below the observation deck. Dilation (opening) can be observed along some segments of J2. Joint sets J1 and J2 do not dip towards the quarry face; therefore, they will likely act as release surfaces in future rockslides.

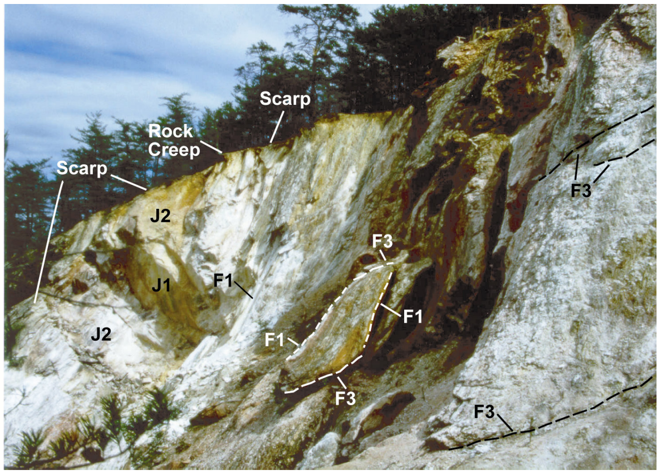

Figure 5. Photograph of the February 17-81, 2001 rockslide scarp along the quarry face. F1 = foliation plane 1 and rockslide failure surface; F3 = foliation plane 3 (C- tectonic shear surface); J1 = back release fracture plane; and J2 = right lateral release fracture plane. F1 and F3 foliations delineate a dislodged boulder in the foreground. The long dimension of this boulder is about 9 feet. Examples of in-place F3 tectonic shear surfaces are labeled in black in the foreground.

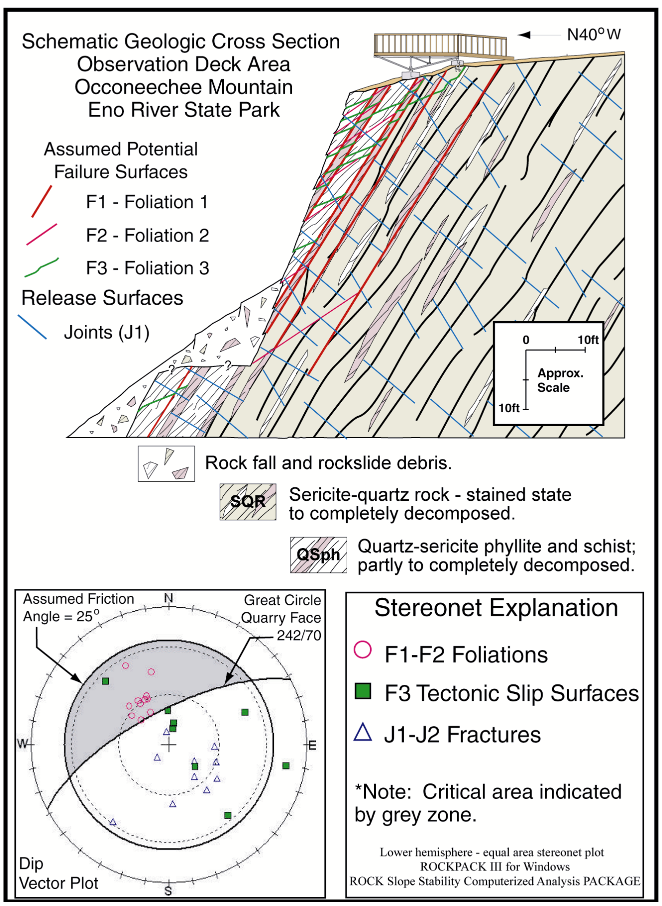

Figure 6. Top center - schematic geologic cross section through the slope below the observation deck. Bottom left – stereonet plot showing kinematic stability analysis. Dip vector plots of foliation surfaces within the gray zone indicate potential failure surfaces. The cross section and stereonet plot illustrate the potential for further sliding. The observation deck has since been removed.

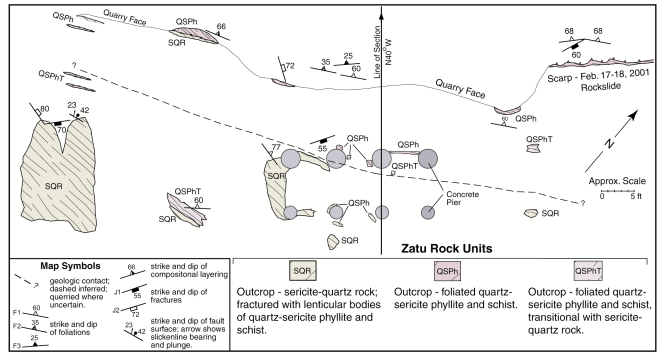

Figure 7. Schematic geologic outcrop map in the vicinity of the observation deck and February 2001 rockslide. Mapping shows that three of the concrete piers for the observation deck are founded in the potentially unstable quartz, sericite phyllite rock unit.

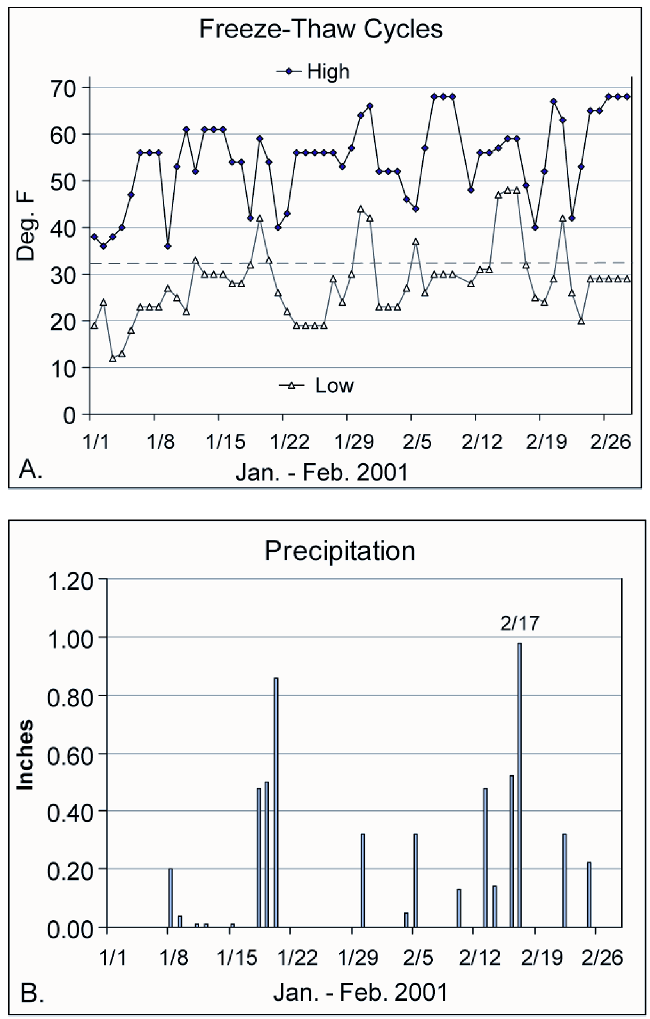

Figure 8. A. Chart of daily high and low temperature recorded at Eno River State Park showing repeated freeze-thaw cycles during January-February 2001. **Note:** Constant high and low temperatures over 2-4 day periods reflect gaps in recorded data. **B.** Chart of daily precipitation data recorded at Eno River State Park during January-February 2001. Trace precipitation is plotted as 0.01 inches. **Note:** Precipitation total recorded over intervals greater than one day are plotted on the last day of the reported interval. Temperature and rainfall data provided by the NCDPR, Eno River State Park.

Extensive iron oxide staining was conspicuously absent on freshly exposed slip surfaces along F1 foliation planes immediately following the rockslide. This contrasts with the ubiquitous staining and iron oxide mineralization along the joint (fracture) surfaces. Staining and mineralization along these surfaces is evidence of infiltrating water; therefore, its absence suggests that infiltrating water along the slip surfaces over the long term was not a major contributing factor in triggering the rockslide. In contrast, precipitation infiltrating along the fractures followed by successive freeze-thaw cycles over the long term may have dilated the fracture openings thereby contributing to the instability.

ROCKSLIDE CAUSES AND TRIGGERS

The primary causal factor leading to the 2001 rockslide was the past quarry excavation that over-steepened the rock slope. The excavated slope intersected three sets of foliation planes that dip out of the slope. The F1 foliation has the steepest dip (55° to 70° northwest) and was the primary slip surface in the 2001 rockslide.

Not surprisingly, a kinematic stability analysis using RockPack III software (Watts and others, 2003) indicates that foliation planes dipping out of the quarry face are potential slip surfaces for future failures (see stereonet plot in figure 6). For this analysis a friction angle of 25° was estimated using RocLab software that utilizes the Hoek-Brown failure criterion for rock masses (Hoek and Brown, 1997). This method incorporates estimated values of the intact uniaxial compressive strength, geological strength index, Hoek-Brown constant, and the disturbance factor to predict the strength parameters for a rock mass. The assumed friction angle of 25° estimated for foliation planes in the sericite phyllite is probably an upper limit for stained state and visually fresh rock, whereas a lower friction angle would be more appropriate for partly- or completely-decomposed rock. Rock weathering state descriptors used here are in general accordance with the unified rock classification system of Williamson (1984).

Evidence of rock creep was observed in the upper two feet of the rock mass in the main scarp immediately below the soil zone as indicated by foliation planes deformed in the down slope direction (figure 6). Although not directly related to the 2001 rockslide, the near-surface rock creep does show the long-term gravitational effect on the weaker phyllite and schist units.

Repetitive freeze-thaw cycles over decades and frost wedging along fractures and other discontinuities, probably contributed to the forces destabilizing the rock mass. Another likely destabilizing factor was infiltrating rainfall that resulted in a build-up of water pressure primarily along fracture planes. Figures 8A and 8B show that numerous freeze-thaw cycles during January and February 2001 preceded a 0.98-inch rainfall on February 17, 2001. These weather patterns in the weeks preceding February 17-18, 2001 were the likely triggering mechanisms for the rockslide.

CONCLUSIONS

The development of promontories and reentrants along the quarry rim, in conjunction with abundant rock and soil debris on the bench, slopes and floor of the quarry indicate that various types of slope movements (e.g., rockslides, rock fall, and debris slides) have occurred over the decades since mining ceased. Slope movements along the quarry walls will continue to occur. Some movements will involve the slow, gravitational movement of rock and debris. Other movements, such as rockslides, rock fall, and debris slides will be rapid (i.e., movement rates of feet/second), and could involve volumes of material comparable to the February 17-18, 2001 rockslide. Rapid slope movements can occur with little or no warning pose a threat to public safety, both for people on the quarry rim, and those within the quarry.

ACKNOWLEDGEMENTS

Charles H. Gardner and Dr. Kenneth B. Taylor, reviewed the initial 2001 report, and their comments and suggestions improved the report significantly. The historical information and field guidance provided by Eno River State Park Superintendent, David Cook is gratefully acknowledged. William L. Moore, III provided valuable comments and insight during the 2001 field review. Digital photographs of area supplied by Duncan Heron and Jean-Michel Margot provided information essential to the report.

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SIGNIFICANCE OF A NEW EDIACARAN FOSSIL FIND AND U-PB ZIRCON AGES FROM THE ALBEMARLE GROUP, CAROLINA TERRANE OF NORTH CAROLINA

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ABSTRACT

The age of the Albemarle Group, one of the major defining units of the Carolina terrane, has been considered to be mainly late Neoproterozoic by most workers. The age of the group, however, has been in question for the past decade because of a report of Late Cambrian and younger fossils from two quarries in the unit. This unconfirmed report potentially has significant ramifications for our conception of the tectonic evolution of the Carolina terrane.

Recently, we recovered the Ediacaran fossil *Aspidella* from Cid Fm. strata in the Jacob's Creek quarry, one of the quarries that purportedly hosts Paleozoic fossils. Rocks in the quarry are stratigraphically ~ 200' below felsic volcanics of the Flat Swamp member of the Cid Fm. for which we have obtained a precise U-Pb zircon age of 547±2 Ma at a nearby locality. The occurrence of *Aspidella* in the Jacob's Creek quarry combined with the new geochronological data lead us to suspect that the strata in the quarry are Neoproterozoic. These new data support a mainly Neoproterozoic age for the Albemarle Group, suggesting that major revision of our understanding of the tectonic history of the Carolina terrane based on the supposed Paleozoic fossils is unwarranted.

INTRODUCTION

The Carolina terrane forms one of the largest and best-known components of Carolinia (Hibbard et al., 2006; in press), one of four major peri-Gondwanan crustal blocks that occur along the eastern flank of the Appalachian orogen. As such, the stratigraphy of the terrane is significant because it forms the main basis for correlation of Carolinia with other peri-Gondwanan crustal blocks in both the Appalachians as well as globally.

The stratigraphy of the Carolina terrane has been problematic in the southern Appalachians (Butler and Secor, 1991). The main unit within the terrane in North Carolina is the Albemarle Group (Conley and Bain, 1965) and it has been the subject of multiple different stratigraphic interpretations (*e.g.* Conley and Bain, 1965; Stromquist and Sundelius, 1969; Milton, 1984); by the early 1990's, the most accepted version was that proposed by Milton (1984) (Fig. 1) (also see Butler and Secor, 1991; Hibbard et al., 2002). In his version of the stratigraphy, the group was considered to be mainly Neoproterozoic in age, and consisted of a succession of four conformable formations, which included from bottom to top, the Tillery, Cid, Floyd Church, and Yadkin formations.

In 1995, workers from the U.S. Geological Survey reported two new fossil locales within the Albemarle Group (Koeppen et al., 1995). One site was within a quarry in the Tillery Formation in Asheboro, NC, and the other was in the Jacob's Creek quarry in the Cid Formation, near the hinge of the New London syncline (Fig. 2). These fossils indicated that the Tillery Formation was no older than early Middle Ordovician and that the Cid Formation was no older than Late Cambrian. Considering that the Flat Swamp member of the Cid Formation had been dated (U-Pb, zircon) as c. 541 Ma (Ingle-Jenkins et al., 1999; Ingle et al., 2003) and that the Floyd Church Formation contained the Ediacaran fossil *Pteridinium* (Gibson et al., 1984), thought to be confined to the Neoproterozoic, the new fossils demanded a major revision of the stratigraphy of the Albemarle Group (Fig. 1). This modification also required a new structural interpretation of the outcrop pattern of the group; Offield (2000) interpreted the contact between the Uwharrie volcanics and the Tillery Formation, as well as the contact between the Flat Swamp member and the underlying Cid Formation (Fig. 2), both formerly thought to be conformable, as representing major thrust faults.

JACOB'S CREEK QUARRY

Jacob's Creek Stone Company, Denton, NC, extracts dimension stone from the quarry near Denton, NC. The quarry was originally operated by a company from the Charlotte, NC, area, which brought the name 'Jacob's Creek' to central North Carolina; there is no geographical feature with this name in the Denton area. The quarry is near the hinge of the regional New London syncline in rocks mapped as mudstone of the upper part of the Cid Formation, just below the Flat Swamp member, the top-most unit in the formation (Fig. 2) (Stromquist et al., 1971). Rocks in the quarry are predominantly fresh, bluish gray tuffaceous argillite and mudstone bedded on a centimeter scale, with local layers of greenish gray coarse volcanogenic sandstone up to 30 cm thick. Bedding throughout the quarry is very regular and planar bedding surfaces allow for easy quarrying of the dimension stone. Koeppen et al. (1995) reported euconodonts from metacarbonate beds in a large loose block of mudstone along the road leading into the quarry (T. Offield, pers. comm., 1998). No carbonate rocks were recognized in the quarry pit during the present study. From a cross section constructed from the geological map of Stromquist et al. (1971), it is clear that mudstone in the quarry is approximately 200' beneath felsic volcanic rocks of the Flat Swamp member (Fig. 3).

NEW EDIACARAN FAUNA

We visited the quarry in early October, 2005, and found a single *Aspidella* specimen. We returned in mid-November, 2005 and found many more specimens of *Aspidella sp. cf. A. terranovica* (Billings, 1872) resembling the flat morph of Gehling et al. (2000) and typical of the Ediacaran fauna. The best specimen is preserved as a flat to slightly concave elliptical disc, with a central concave boss less than one quarter of the diameter of the whole disc (Fig. 4; also see Weaver et al., this volume, fig. 7). Between the rim and the boss, the disc is either smooth or ornamented with faint concentric rings near the outer rim. The elliptical shape of the fossils is most likely the result of regional strain, as the trace of cleavage on bedding is parallel to the long axis of the Aspidella ellipses.

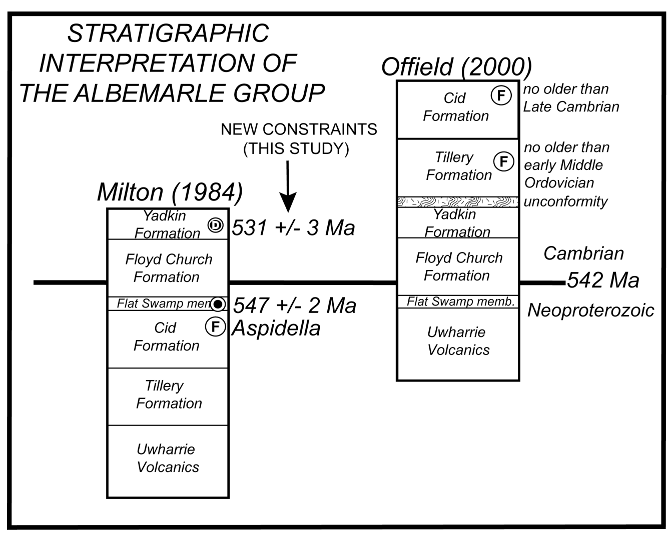

Fig. 1. Stratigraphic interpretation of the Albemarle Group (all units except the Uwharrie Volcanics). Left column depicts the stratigraphy that was generally accepted by the mid 1990's (e.g. Butler and Secor, 1991) with new data from the present study added on the right side of the column; bulls-eye = new geochronological constraint (D denotes detrital zircon age), F = fossil constraint. Right column depicts the proposed modified stratigraphy (Offield, 2000) after the U.S. Geological Survey report of Paleozoic fossils in the Tillery and Cid formations (F). The solid line represents the Neoproterozoic - Cambrian boundary.

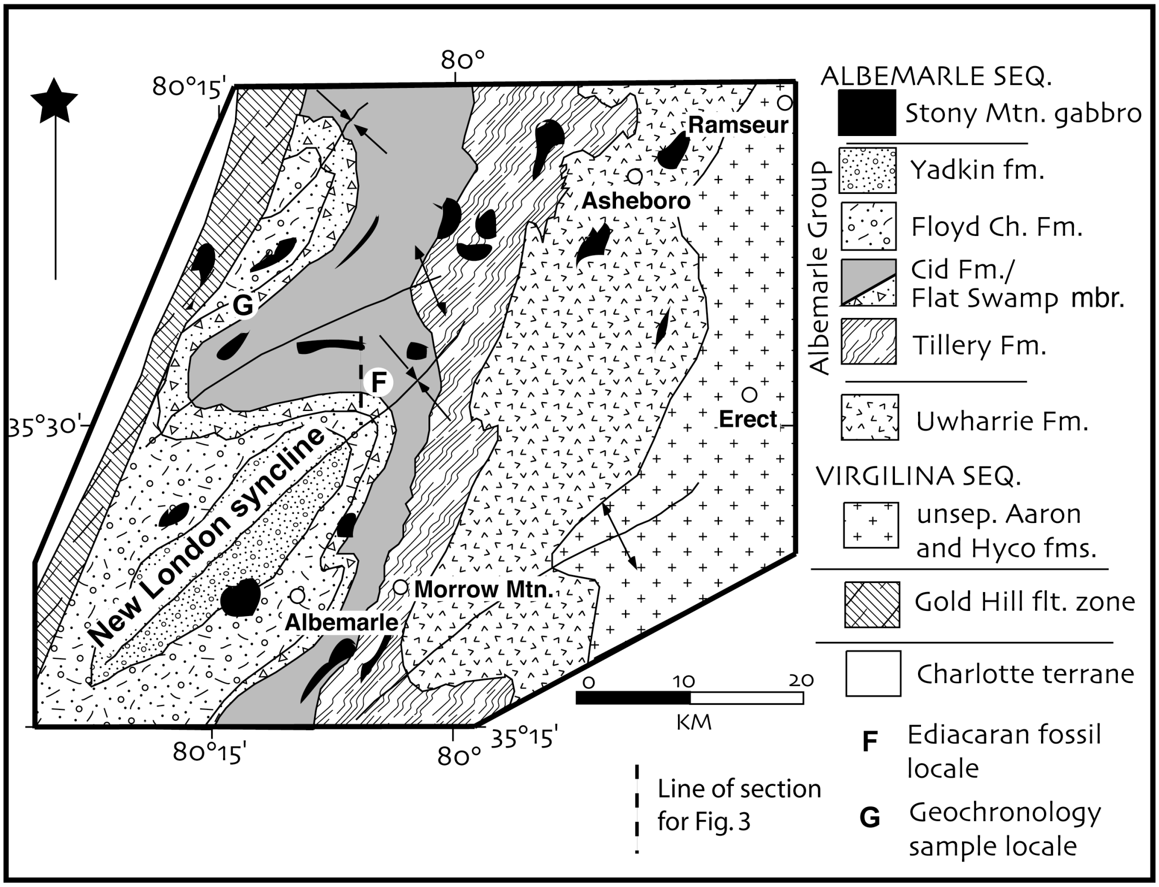

Fig. 2. Geology of a portion of central North Carolina showing the location of the new fossil find at Jacob's Creek quarry and the sample location for the Flat Swamp geochronological sample.

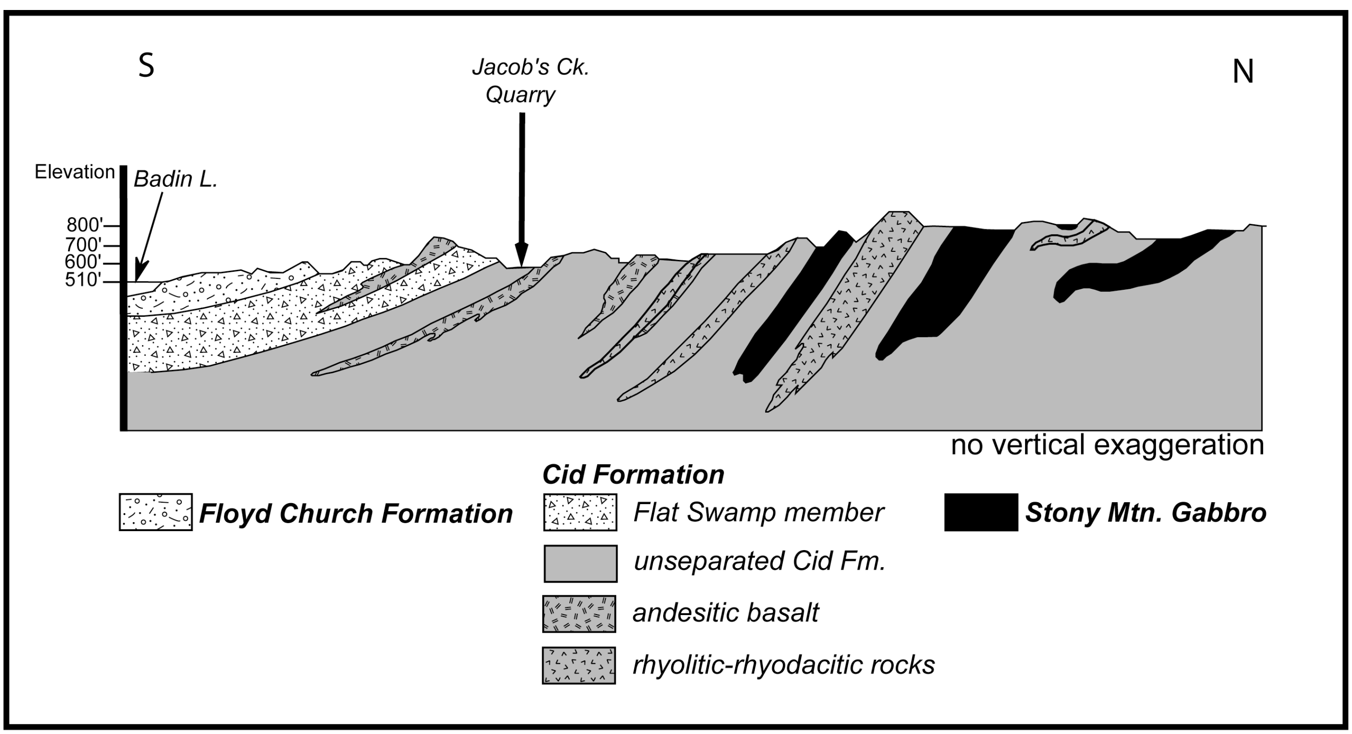

Fig. 3. A north-south geological cross section through the area of Jacob's Creek quarry; details of section from geological map by Stromquist et al. (1971).

Fig. 4. *Aspidella* specimen recovered from Jacob's Creek quarry in June, 2006; numerical scale in cms.

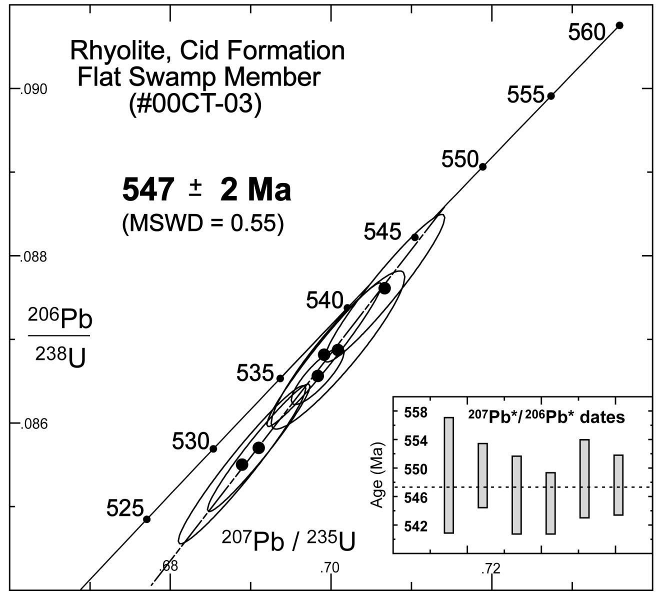

Fig. 5. U-Pb concordia diagram for a rhyolite sample from the Flat Swamp member of the Cid Formation (sample location shown in Fig. 2). Six zircon fractions define an upper intercept age of 547$\pm$ 2Ma (MSWD = 0.55).

The Ediacaran fauna is mainly confined to the time span 600-542 Ma (e.g. Narbonne, 1998; Waggoner, 2003), although the youngest elements are documented as extending into the Early Cambrian (see Waggoner, 2003). Even if the newly discovered Ediacaran fauna at Jacob's Creek quarry extends up into the Early Cambrian, it conflicts with the previous USGS report of Paleozoic euconodonts no older than Late Cambrian purportedly found on the premises.

NEW GEOCHRONOLOGICAL DATA

Felsic volcanic rocks of the Flat Swamp member of the Cid Formation are the stratigraphically closest rocks to the quarry that are readily amenable to U-Pb dating. This top-most unit in the Cid Formation lies approximately 200' above mudstone of the quarry. We collected a sample of the Flat Swamp member from the vicinity of the High Rock Lake dam, approximately 15 km NW from the quarry, where fresh rhyolitic material could be obtained. The sample yielded a high-precision U-Pb TIMS age on six discordant zircon fractions of 547 $\pm$ 2 Ma (Fig. 5), indicating that the Flat Swamp member is uppermost Neoproterozoic in age. This age is consistent with the member being stratigraphically close and above the Ediacaran fauna.

In addition, we conducted high precision U-Pb TIMS analyses of eight detrital zircon grains from the Yadkin Formation (Fig. 1). One concordant grain yielded a U-Pb age of 531 $\pm$ 2.5 Ma, but the suite also included grains at 539-547 Ma, ~ 647 Ma, ~830 Ma, and ~2074 Ma. The Early Cambrian detrital zircon age indicates that the Yadkin Formation must be at least Early Cambrian in age.

CONCLUSIONS

The combination of the Ediacaran fauna in Jacob's Creek quarry and the new late Neoproterozoic U-Pb zircon age on felsic volcanic rocks that lie 200' stratigraphically above the quarry lead us to the conclusion that the upper Cid Formation is late Neoproterozoic in age, contrary to the USGS reports of Late Cambrian or younger euconodonts in the unit. These conflicting data leave us with the following three alternative interpretations of the age of this portion of the Albemarle Group:

1. The quarry area contains rocks of both Neoproterozoic and Paleozoic age, but their interrelationship has yet to be determined.
2. The report of Paleozoic fossils is erroneous.
3. *Aspidella* ranges at least into the Late Cambrian.

In light of our new data, we favor either of the first two interpretations. If the first interpretation proves true, our data indicate that all of the rocks now assigned to the Cid Formation are not Paleozoic. In this case, Ediacaran fossils in the quarry, the late Neoproterozoic age for the Flat Swamp member, and the apparent concordancy of strata in the area at a scale of 1:62,500 (Stromquist et al., 1969) collectively imply that any Paleozoic rocks present would be of limited extent. Likewise, if the second interpretation proves true, then data presented here in conjunction with regional mapping (Stromquist et al., 1969) strongly support a late Neoproterozoic age for the Cid Formation. Thus, in either case, our present study indicates that major modification of our understanding of the Carolina terrane, such as that proffered by Offield (2000), is unwarranted.

In order to refine our choice of alternative interpretations, we are continuing studies in the areas where the Paleozoic fossils have been reported. Matt Brennan (MS candidate, NCSU) is undertaking detailed field, stratigraphic, and sedimentological studies in the area of Jacob's Creek quarry in order to determine the detailed relationships of rock types in the area. We have collected limestone from the Asheboro quarry and processed the first of two samples for microfossils; it has proven to be barren of fossil material. We are also searching for a graduate degree candidate who is interested in establishing the relationship between rocks in the Asheboro quarry and those of Tillery Formation that surround the quarry.

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Carolina Geological Society Field Trip
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EDIACARAN BODY FOSSILS OF SOUTH-CENTRAL NORTH CAROLINA: PRELIMINARY REPORT

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ABSTRACT

Ongoing research at the North Carolina Museum of Natural Sciences has led to the recovery of Ediacaran body fossils of *Sekwia excentrica* Hofmann,1981, from the Floyd Church Formation and ?*Inaria* sp. Gehling, 1988, from the unnamed mudstone member of the Cid Formation, Stanly County, North Carolina. Together with previously published reports of *Pteridinium carolinaensis* (St. Jean, 1973), *Swartpuntia* sp. Narbonne et al., 1997, and *Aspidella* sp. Billings, 1872, also found from Neoproterozoic-Early Cambrian metasediments of the Albemarle Group in south-central North Carolina, the new discoveries give a more complete picture of North Carolina Ediacaran biota. While individual genera have affinity with the Nama Assemblage (Waggoner, 2003), preliminary results from parsimony analysis suggest greater affinity with the White Sea Assemblage (Waggoner, 2003) for the entire North Carolina Ediacaran fauna.

Sample size is still rather small, and assemblage groupings could be a function of depositional environment, paleogeography, age, or preservational bias. Our preliminary results indicate that during late Neoproterozoic, Carolina Terrane was faunally distinct from Avalon Terrane. Supporting recent conclusions by Hibbard et al. (2002) and others that the Carolina Terrane is paleogeographically separate from Avalon.

INTRODUCTION

Over the past several decades there has been much debate over geographic origin of the Carolina Terrane. Hibbard et al. (2002), in their extensive discussion of age, origin and deformational history of the Carolina Terrane, state that one of the first-order outstanding problems is affinity of the fossil fauna as it relates to paleogeographic setting. Ediacaran fossils are known from approximately thirty localities on five different continents (Narbonne, 2005). Recent studies by Waggoner (1999, 2003), Gehling (2001), and Grazhdankin (2004) have divided the global Ediacaran fauna into three environmentally and age related assemblage types: Avalon, White Sea and Nama; characteristics of each assemblage type are given in Figure 1. Until recently North Carolina has not produced sufficient Ediacaran body fossils to compare this fauna with other Ediacaran faunas world-wide.

Recent collecting efforts in the Albemarle Group of Carolina Terrane by Tony Furr and Ruffin Tucker, have yielded two genera not previously known from Neoproterozoic rocks of North Carolina: *Sekwia excentrica*, ?*Inaria* sp. These new discoveries, combined with previously described *Aspidella* sp., *Swartpuntia* sp. and *Pteridinium carolinaensis* (St. Jean, 1973; Gibson et al., 1984; Gibson and Teeter, 2001; McMenamin and Weaver, 2002; Hibbard et al, 2006; Tacker et al., 2006), give a more complete picture of the North Carolina Ediacaran fauna

Assemblage type	Characteristic fauna	Paleoenvironments
Nama	Mineralized and agglutinated taxa: *Cloudina*, *Archaeichnium*, *Namacalathus* Endemic frond-like fossils: *Ernietta* and *Swartpuntia*	Distributary-mouth bar shoal
White Sea	Bilaterally symmetrical forms: dickinsoniids, *Kimberella, Spriggina* Annulated concentric forms: *Kullinga* and *Ovatoscutum* Most known triradially symmetric forms: *Tribrachidium*	Prodelta or low-energy shore face
Avalon	Lobate “medusoid” *Ivesia* Unique frond-like fossils: *Bradgatia* Unnamed spindle	Deeper water, slope apron

Figure 1. Characteristics of Ediacaran assemblage types (adapted from data in Gehling, 2001; Waggoner, 2003; Grazhdankin, 2004).

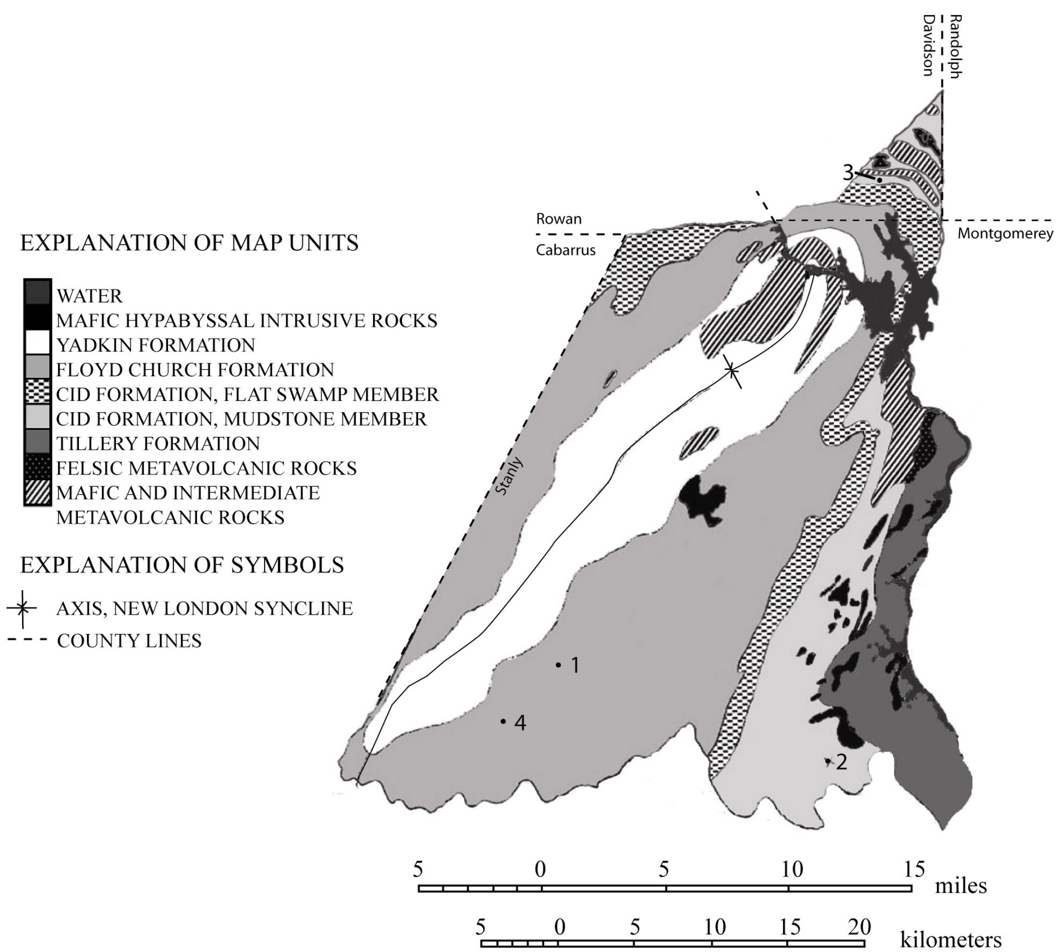

Figure 2. Geologic map of south-central North Carolina (adapted from Goldmith et al., 1988) showing Ediacaran localities (Gibson and Teeter, 2001; Hibbard et al., 2006; Tacker et al., 2006): 1) Gleaning Mission Church, north of Oakboro, Stanly County, 2) Private property near Mount Zion Church, southeast of Cottonville, Stanly County, 3) Jacobs Creek Stone Quarry, Davidson County, 4) Island Creek, east of Stanfield, Stanly County.

which can now, using a branch and bound search to generate parsimony analysis, be compared with other Ediacaran faunas world-wide.

GEOLOGIC SETTING

The Carolina Terrane extends from southern Virginia southwest to Georgia and is considered to be one of several peri-Gondwanan exotic terranes that accreted to the eastern margin of Laurentia during the Paleozoic (Hibbard et al, 2002). Rocks within the Carolina Terrane show a lower green-schist facies grade of regional metamorphism (Gibson and Huntsman, 1988). Stratigraphic reconstruction of the Carolina Terrane in North Carolina has undergone a series of revisions and workers in North Carolina have recognized three main stratigraphic units: the Virgilina Sequence, the Uwharrie Formation and the Albemarle Group (Conley, 1962; Conley and Bain, 1965; Stromquist and Sundelius, 1969; Seiders,1978; Milton, 1984).

Neoproterozoic Ediacaran body fossils have been reported from the Floyd Church Formation (St. Jean, 1973, Gibson et al., 1984, Gibson and Teeter, 2001, McMenamin and Weaver, 2002) and from the unnamed mudstone member of the Cid Formation (Hibbard et al., 2006, Tacker et al., 2006). Neoproterozoic trace fossils have been reported from most of the Albemarle Group except the volcanic Flat Swap Member of the Cid Formation (Gibson, 1989). The new specimen of *Sekwia excentrica* was found lying on the ground of property surrounding Gleaning Mission Church, Stanly County, NC, by Ruffin Tucker, and based on rock type and locality, most likely came from the Floyd Church Formation (Fig. 2). *Pteridinium carolinaensis* has also been reported from this locale (Gibson and Teeter, 2001; McMenamin and Weaver, 2002). The new specimen of ?*Inaria* sp. was found on private property southeast of Cottonville (near Mount Zion Church), Stanly County, North Carolina, by Tony Furr in the same general area from which *Swartpuntia* sp. was reported by Tacker et al. (2006). Based on rock type and locality ?*Inaria* sp. most likely came from the unnamed mudstone Member of the Cid Formation (Fig. 2).

ANALYTICAL METHODS

Two data sets consisting of the “compromise” data set of Waggoner (1999) along with his added information from Jenkins (1995), Gehling et al. (2000), Grazhdankin (2000) Grotzinger et al. (2000), Hagadorn and Waggoner (2000), Hofmann and Mountjoy (2001), Narbonne et al. (2001) and Dzik and Ivantsov (2002) were derived from Waggoner (2003). In order to apply this data set to the Carolina Terrane, several modifications were made: a.) the genus *Sekwia* was added based on locality information from Hofmann (1981), Hofmann et al. (1983) and MacNaughton et al. (2000), and b.) the Carolina Terrane was added with *Pteridinium* (Fig. 3) and *Sekwia* (Fig. 4) recovered from the Floyd Church Formation and *Swartpuntia* (Fig. 5), ?*Inaria* (Fig. 6) and *Aspidell*a (Fig. 7) recovered from the unnamed mudstone Member of the Cid Formation.

The first data set (Appendix 1) consists of 71 genera from 23 localities and treats the Floyd Church Formation and the unnamed mudstone Member of the Cid Formation individually. The second data set (Appendix 2) consists of 71 genera from 22 localities and combines information from the Floyd Church Formations and the unnamed mudstone Member of the Cid Formation into the Carolina Terrane.

Following Waggoner (1999, 2003), PAUP 4.0b10 (Swofford, 2002) facilitated phylogenetic analysis of the data sets in which localities were treated as taxa and genera were treated as characters. A Branch-and-Bound (B and B) algorithm was used to search for optimal trees using the parsimony optimality criterion. The program utilized only those characters considered informative (e.g. found in more than one location). The set of shortest trees from each analysis was re-weighted using rescaled consistency indices of 0.7004 for the Carolina Terrane and 0.7308 for the Floyd Church and the unnamed mudstone Member of the Cid Formation treated as separate entities and the B and B analysis repeated. The process of re-weighting and B and B analysis was repeated until successive analyses yielded a consistent set of trees as judged by number of trees and branch lengths. A consensus tree was then determined using the majority 50 percent rule.

B and B analysis of the Floyd Church and Cid as separate entities yielded 3113 trees initially with a branch length of 124. In this case, four cycles yielded 18 trees for consensus determination with a final branch length of 50. B and B analysis of the Carolina Terrane yielded 4742 trees with a branch length of 123. After three cycles of re-weighting and B and B analysis the yield was 6 trees which were then used in generating a consensus tree with a branch length of 50.

Trees generated from this type of analysis are not used to reflect phylogenetic relationships between branches but rather to show similarities among taxa from different localities. Thus localities with a number of genera in common will appear close to each other on the tree and those with few taxa in common will appear distant from each other.

RESULTS

Consensus trees (Fig. 8) indicate that considering the Ediacaran fauna from the Floyd Church Formation as most closely associated with faunas from Wernecke Mountains and Sekwi Brook of Northwest Canada is most parsimonious.These formations are considered by Waggoner (2003) to be White Sea Assemblage. Consensus trees of the fauna from the unnamed mudstone Member of the Cid Formation suggest that considering it most closely associated with the Swartzrand Group of Namibia and fauna from the Southwestern United States is most parsimonious (Fig. 8). These are considered by Waggoner (2003) to be Nama Assemblage. When the two Carolina Terrane faunas are combined, analysis indicates the overall assemblage to be

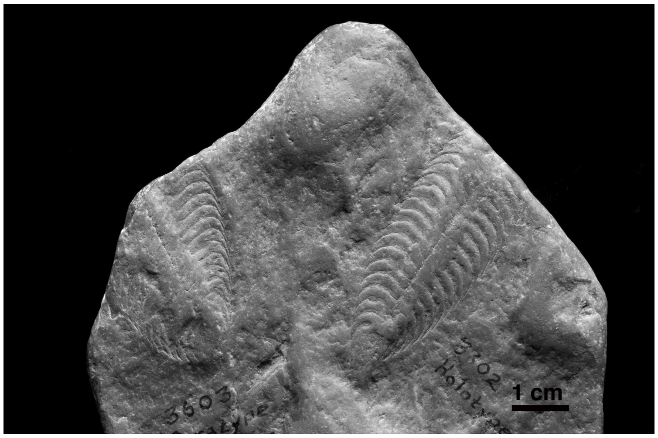

Figure 3. *Pteridinium carolinaensis* (St. Jean, 1973), entire block NCSM 4041, UNC holotype 3062, UNC paratype 3063 recovered from locality 4 of figure 2.

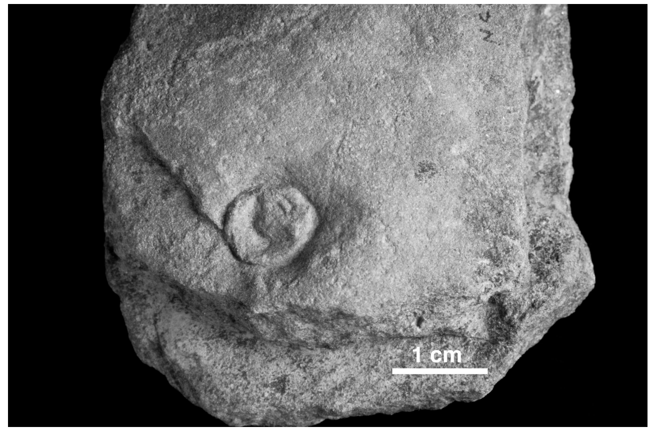

Figure 4. *Sekwia excentrica* Hofmann, 1981, NCSM 9836 recovered from locality 1 of figure 2.

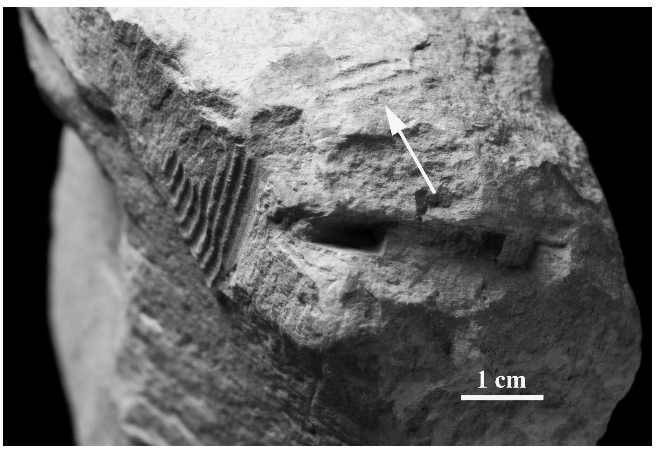

Figure 5. *Swartpuntia* sp. Narbonne, Saylor and Grotzinger, 1997, NCSM 958 recovered from locality 2 of figure 2.

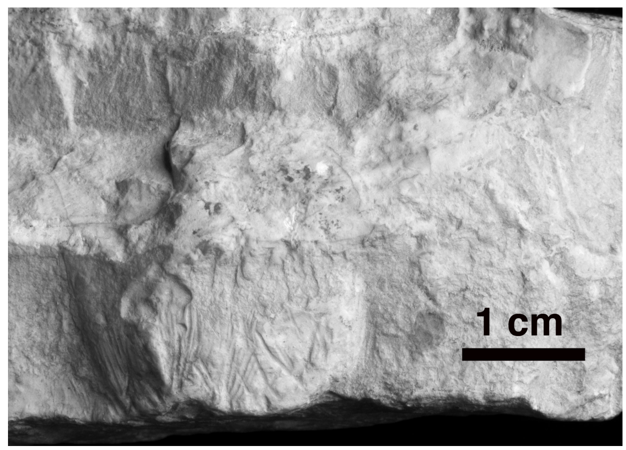

Figure 6. ? *Inaria* sp. Gehling, 1988, NCSM 9714 recovered from locality 2 of figure 2.

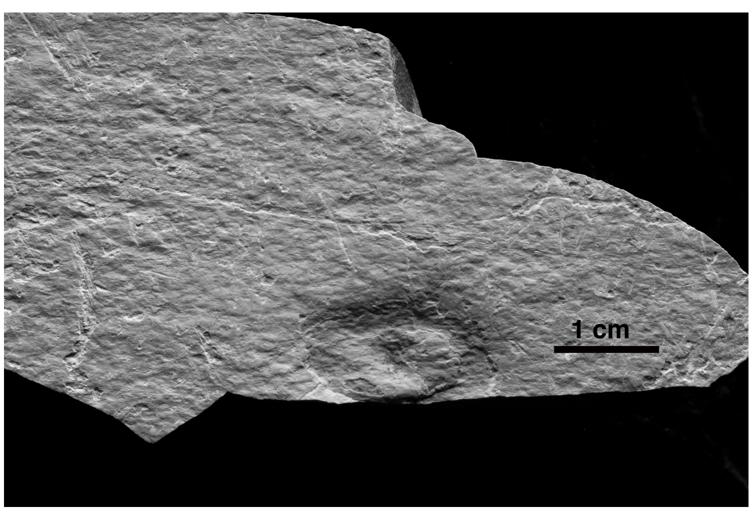

Figure 7. *Aspidella* sp. Billings 1872, NCSM 9713 recovered from locality 3 of figure 2.

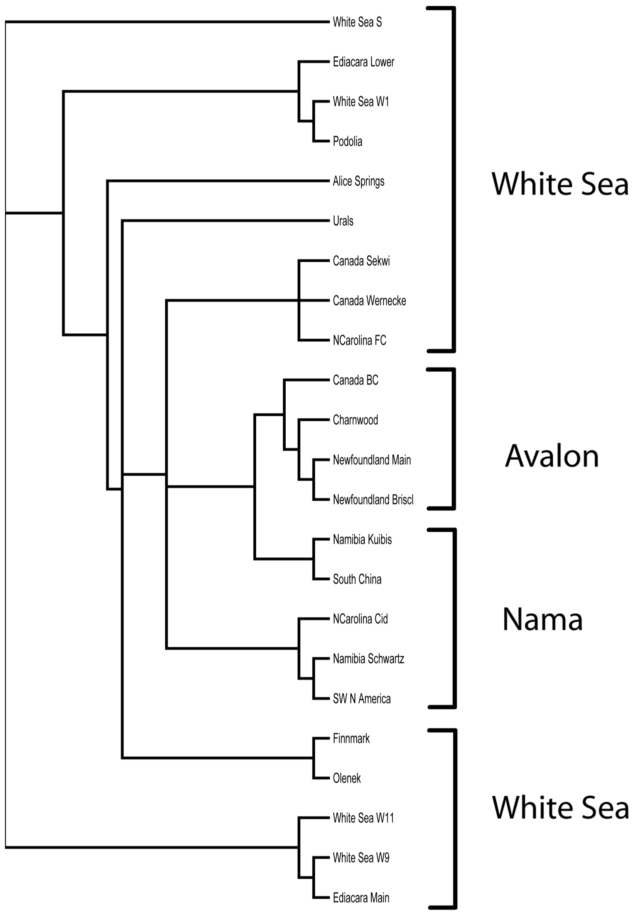

Figure 8. Majority consensus tree showing how the Floyd Church and unnamed mudstone Member of the Cid Formations fit with global Ediacaran assemblages.

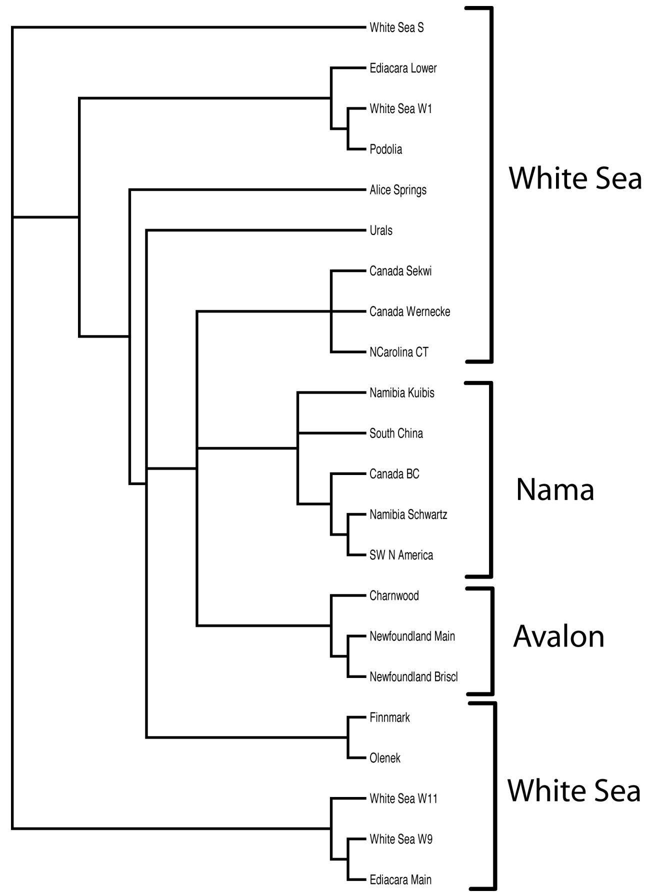

Figure 9. Majority consensus tree combining data from both Floyd Church and the unnamed mudstone Member of Cid Formations into the Carolina Terrane fauna, providing an overall view of how it fits with global Ediacaran assemblages.

White Sea (Fig. 9). Although we are assigning the overall Carolina Terrane fauna to the White Sea Assemblage, we currently consider it as being on the periphery of this biogeographic province because it has not yet yielded core White Sea Assemblage taxa such as *Dickinsonia*, *Spriggina* and *Tribrachidium* as defined by McMenamin (1982).

Overall assemblage groupings of localities generated in this study are generally similar to those of Waggoner (2003). However, as Waggoner (2003) used MacClade 3.08 (Madison and Madison, 1999) to further modify his results (and we did not), our trees look physically different in detail. Addition of the North Carolina faunas also changed the grouping details somewhat, most notably when the Floyd Church Formation and the unnamed mudstone Member of the Cid Formation were treated individually. When this is done, the Ediacaran fauna from British Columbia, moves from a Nama assemblage (Figure 9) to a more characteristicly Avalon assemblage (Figure 8), most likely because the British Columbia fauna contains the genus *Bradgatia*, characteristic of the Avalon assemblage, as well as *Namacalathus*, characteristic of the Nama assemblage.

None of the trees place North Carolina Ediacaran fauna with the Avalon Assemblage. Several factors could have influenced these results: 1) Age. The Avalon Assemblage is significantly older than the White Sea Assemblage and it is possible that organisms like *Swartpuntia* and *Pteridinium* hadn't yet evolved, 2) Preservational bias. The Mistaken Point (Avalon Assemblage) is a death assemblage. If *Pteridinium*, *Swartpuntia*, *Inaria*, and *Sekwia* had lived there they should have been preserved, 3) Lack of published Ediacaran data. Most Ediacaran specimens are enigmatic, difficult to identify or assign to a specific genus. This study relies heavily on published data; as more specimens are identified and published, apparent faunal separation may break down. Based, however, on the available data the Carolina Terrane fauna is distinct from the Avalon Terrane and, 4) Depositional environment may also play a factor in what lived where and what was able to be preserved. The Avalon fauna is considered a deeper water fauna (Misra, 1969; Anderson and Conway Morris, 1982;

Narbonne and Gehling, 2003) than the Carolina Terrane fauna. All of the above factors indicate that, based on available data Carolina Terrane was faunally distinct from Avalon. These faunal distinctions, combined with lithotectonic and isotopic evidence presented by Hibbard et al. (2002), Wortman et al. (2000), and Samson (2004), further bolsters conclusions by these workers that during the Neoproterozoic the Carolina Terrane was geographically separate from Avalon.

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DETERMINING THE SOURCES OF LITHIC ARTIFACTS IN THE CAROLINA TERRANE USING PETROGRAPHY

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INTRODUCTION

Are the characteristics of specific rocks from the Carolina terrane sufficiently distinctive that they might be used to determine the outcrop location from which lithic artifacts originated? That question has been addressed in a multidisciplinary study that was undertaken by the Cultural Resources Office at Fort Bragg, NC, to determine the sources of artifacts found on the reservation. The study utilized petrographic and geochemical analyses of outcrop samples collected from known and suspected archaeological quarry sites, followed by a comparison of their characteristics with those of nine of the artifacts. Geochemical analyses included XRF, NAA, ICP-MS, and TIMS techniques to determine concentrations of a large array of major, minor, and trace elements, and of Nd isotopes. Details and results of the project, including the petrographic data and photomicrographs, as well as the companion geochemical studies, are included in the final report (Steponaitis and others, 2006).

This short note summarizes the petrographic study (Tables 1 and 2), and suggests that careful examination of minerals and textures can be effective in a lithic sourcing study, and should probably be undertaken first, due to relative ease and low cost, in comparison with other approaches. Useful petrographic criteria include primary, metamorphic, and other secondary features.

PROCEDURE

The project involved examination of 74 rock samples (and corresponding thin sections) collected from 12 individual quarries or quarry groups, defined as two or more geographically proximal and lithologically similar quarries. Among the 12 are five quarry groups in the Uwharries, four of which were described previously by Daniel and Butler (1996). Rocks from the Uwharrie quarries are all various felsic metavolcanic rocks, with the quarry groups distinguished based upon mineralogy and texture. These quarries sample the Tillery, Cid and Uwharrie Formations (Stromquist and Sundelius, 1969). The seven new quarry sites are in Chatham, Durham, Person, Orange, and Cumberland Counties, and include both metavolcanic and metasedimentary rock types. The Cumberland County quarry occurs in younger sedimentary material derived primarily from the Carolina terrane. Compositionally, most metavolcanic rocks are dacitic, and include flows, tuffs, breccias, and porphyries. Metasedimentary rocks are metamudstone and fine metasandstone.

In the second phase of the study, thin sections were prepared from nine Late Archaic Savannah River points collected on the Fort Bragg Military Reservation. These artifact thin sections were examined for the purpose of comparison with the quarry samples. All nine artifacts appear to have been fashioned from rocks originating in the Carolina terrane. Two are interpreted as metasedimentary and the remaining seven as metaigneous.

PETROGRAPHIC CRITERIA

Rocks examined are either metaigneous or metasedimentary. The metaigneous rocks originated as pyroclastic volcanic deposits, or less commonly, lava flows or shallow subvolcanic plutons. Phenocryst type, shape, size, and relative abundance are important primary criteria for characterizing these specimens. Other primary igneous features include flow banding, spherulites, glass shards, amygdules, and fragmental (pyroclastic) texture. Primary sedimentary features include clastic texture, with clastic grains generally in the sand to silt size. Deposition from water is indicated by parallel bedding planes or laminae (essentially very thin and cyclic beds). More specialized sedimentary structures may be indicative of water depth, current velocity and direction, and/or stratigraphic younging direction. Such features include graded bedding, ripple marks, and cross bedding. In a couple of specimens, small ovoid features may be trace fossils, possibly fecal pellets.

The common preservation of primary igneous or sedimentary features is due to the relatively low-grade metamorphism suffered by the Carolina terrane. Metamorphic minerals in this study include all of the most common greenschist facies minerals, including white mica (muscovite), chlorite, epidote/clinozoisite, albite (Na-plagioclase), actinolite, titanite (sphene), pyrite, and calcite. Less common greenschist facies metamorphic minerals include biotite (both green and brown varieties in

METAVOLCANIC ROCKS				
GROUP/QUARRY	**PHENO-CRYSTS**	**METAMOR. MINERALS**	**TEXTURES**	**ROCK TYPES**
UWHARRIES: EASTERN (Tillary Formation) ***Hattaway, Shingle Trap, Sugarloaf Mts.***	Plagioclase + Quartz	Green Biotite, Stilpnomelane	Quartz-Epidote-Chlorite **clusters**	Dacite flows, Crystal lithic tuffs
UWHARRIES: WESTERN (Cid Formation); ***Wolf Den, Falls Mts.***	Plagioclase,K-feldspar	Green Biotite, no Stilpnomelane	**Spherulites,** no flow banding	Dacite, Rhyodacite
UWHARRIES: SOUTHERN (Tillary Formation) ***Morrow & Tater Top Mts.***	***NONE***	Stilpnomelane	**Spherulites,** banding, cleavage	Dacite, Felsite
UWHARRIES: ASHEBORO (Uwharrie & Tillary Fms); ***Daves and Carraway Mts.***	Plagioclase, Quartz	**Garnet**, brown Biotite, Stilpnomelane	Quartz-Epidote-Pyrite **clusters**, Pumice lapilli	Dacite tuffs and flows
UWHARRIES: SOUTHEAST (Uwharrie Formation); ***Horse Trough & Lick Mts.***	Quartz + Plagioclase	**Actinolite**, Epidote, sphene	Spherulites, **Quartz Amygdules**, Banding	Dacite flows and Porphyries
SILK HOPE (CHATHAM CO.)	Plagioclase, K-feldspar	**Piedmontitie**	Volcanic rock fragments, **Glass shards**, Flow bands	Dacitic Lapilli and Crystal-lithic tuff and breccia
ORANGE COUNTY	**(Coarse)** Quartz + Plagioclase	Calcite, **Low-T Feldspar clots**	No banding, **Saussuritization**	Dacite porphyry, crystal-lithic tuff
METASEDIMENTARY ROCKS				
PITTSBORO (CHATHAM CO.)	Bedding, Laminae, Graded beds, Ripples, Cross-beds		Mudstone, Siltstone, Sandstone	
DURHAM COUNTY	Plagioclase; Rock fragments, Epidote veins, Layering		Dacite tuff, Tuffaceous sandstone	
PERSON COUNTY	Bedding, Graded beds, Trace fossils (?), Pumice(?), Microfaults		Mudstone, Siltstone, Sandstone, Tuff	
METASEDIMENTARY ROCKS				
SILER CITY (CHATHAM CO.):	metasedimentary rocks and crystal-lithic tuff			
CAPE FEAR (CUMBERLAND CO.):	aplite, greenstone, and (meta-) gabbro, basalt, andesite/diorite, lapilli tuff, and heterolithic tuff breccia			

Table 1. Petrographic features of lithic quarry groups, central North Carolina.

NUMBER	PHENOCRYSTS	META. MINERALS	TEXTURES	ORIG. ROCK TYPE	POSSIBLE SOURCE
31Hk182	PLAGIOCLASE	EPIDOTE	FINE GRAINED; SAUSSURITIZATION	ANDESITE	
31Hk100	PLAGIOCLASE (ZIRCON INCLUSIONS)	GARNET, BROWN BIOTITE, STILP?	ALIGNED PLAG LATHS, FLOW BANDING	DACITE	UWHARRIES ASHEBORO
31Hk999	PLAGIOCLASE, QUARTZ	EPIDOTE, ACTINOLITE, OPAQUE MINERALS	FLOW BANDS; ZONED, SAUSSUR. PLAG; MAFIC PSEUDOMORHS; QTZ-EPID AMYGDULES	DACITE CRYSTAL-LITHIC TUFF OR PORPHYRY	UWHARRIES ASHEBORO? UWHARRIES SOUTHEAST?
31Hk737	FINE CLASTS	GREEN BIOTITE	VERY FINE GRAINED	SILTSTONE	*Like 31Hk224?*
31Hk148	PLAGIOCLASE, QUARTZ (RESORBED)	EPIDOTE, POSS PIEDMONTITE	COARSE; CRYSTAL-RICH; MAFIC PSEUDOMORPHS	DACITE PORPHYRY	ORANGE COUNTY
31Hk1408	SPARSE PLAGIOCLASE	BROWN BIOTITE, EPIDOTE, ACTINOLITE, MUSCOVITE	CRYSTAL-POOR; QTZ-EPID AMYGDULE	DACITIC TUFF	UWHARRIES ASHEBORO? UWHARRIES SOUTHEAST?
FLAT CREEK	PLAGIOCLASE (SPARSE, EUHEDRAL)	BROWN BIOTITE, GARNET, EPIDOTE, MUSCOVITE	PLAG LATH FABRIC; BANDING	DACITE	UWHARRIES ASHEBORO? UWHARRIES SOUTHEAST?
31Hk224	PLAGIOCLASE (TINY), CLASTS?	ACTINOLITE, EPIDOTE, BROWN BIOTITE	ALMOST APHYRIC OR FEATURELESS	DACITIC TUFF OR SILTSTONE	*Like 31Hk737?*
31Hk173	QUARTZ, PLAGIOCLASE (SPARSE)	EPIDOTE, BIOTITE, ACTINOLITE, CHLORITE	SAUSSURITIZATION, AMYGDULES?, WEAK ALIGNMENT	DACITIC TUFF	UWHARRIES EASTERN?

Table 2. Summary of petrographic characteristics of Fort Bragg artifacts

different specimens), stilpnomelane, (Mn, Ca-rich) garnet, and piedmontite. Because the growth of metamorphic minerals is also a function of the rock's overall composition, the absence of a particular mineral does not necessarily imply a different facies or conditions. For example, actinolite is typical of metamorphosed basalt in the greenschist facies, but is not found in metamorphosed mudstone. However, the presence of biotite in the Carolina terrane is limited to the western half of the terrane (approximately the Uwharries), and indicates that metamorphic temperatures (and possibly pressures) there were somewhat higher than in the eastern portions of the terrane (Butler, 1991; North Carolina Geological Survey, 1985).

Locally, pervasive alteration has affected phenocryst minerals; examples are saussuritization and sericitization. Saussuritization is more apparent in the more Ca-rich volcanic rock types, especially andesite and basalt, but is also seen in some dacite. Small clusters or clots of associated metamorphic minerals are interpreted as metamorphosed amygdules in some cases and as pseudomorphs after pheocrysts in other cases, depending on the shape of the original mineral. Veins of epidote, calcite, or quartz occur in a few samples, as do micro-faults and slaty cleavage.

RESULTS

Of the twelve different quarry sites that were studied, ten are sufficiently distinctive that they hold some promise for sourcing. The samples from seven of these ten are inferred to be primarily of volcanic origin, while those from the remaining three are metasedimentary. Each of the seven metavolcanic quarry groups is texturally and mineralogically distinctive. Relict volcanic textures include porphyritic texture, flow-banding, amygdules, inferred glass shards, spherulites, and pyroclastic material. Metamorphic textures include phyllosilicate cleavage. Relict minerals are quartz, plagioclase, and K-feldspar phenocrysts; metamorphic minerals include chlorite, biotite, epidote, calcite, actinolite, titanite, pyrite, garnet, stilpnomelane, and piedmontite. The three metasedimentary quarries preserve relict sedimentary textures including laminations, ripples, and graded bedding. Possible cross-bedding and trace fossils are present.

Of the nine lithic artifacts, three bear strong resemblance to quarry sites and are tentatively correlated with two quarries in the Uwharries region and a third in Orange County. The other artifacts have moderate resemblance to one or more quarries, or are dissimilar to the characterized quarries.

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GEOCHEMICAL CORRELATIONS AND TECTONIC SETTING OF THE NORTHEASTERN CAROLINA ZONE IN NORTH CAROLINA

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ABSTRACT

This study examined a total of 181 samples of which 156 are new major and trace element analyses for samples from portions of the central and eastern Piedmont of North Carolina. These samples were collected in conjunction with the USGS funded National Cooperative Geologic Mapping Program-STATEMAP and EDMAP projects conducted in a series of 7.5-minute quadrangles adjacent to the eastern, northern, and western boundaries of the Mesozoic Durham basin in the Raleigh, Henderson, Greensboro, and Chapel Hill 30 x 60-minute sheets. This rift basin structurally and geographically separates greenschist facies metavolcanic and metaplutonic rocks of the northeastern Carolina terrane in the easternmost central Piedmont from greenschist and amphibolite facies metavolcanic and metaplutonic rocks of the Cary sequence (herein called the Cary terrane) in the westernmost eastern Piedmont. Major and trace element data presented here establish links among these Late Proterozoic to Cambrian age rocks, and are used to compare these two terranes to lithotectonic sequences from the main portion of the Carolina terrane in Virginia, North and South Carolina, and Georgia. In addition, trace element petrogenetic indicators permit an assessment of tectonomagmatic origins for these metavolcanic and metaplutonic rocks and allow for a refinement of the evolution of the Carolina Zone in the central and eastern Piedmont of North Carolina.

Silica histograms display a bimodal, Daly gap distribution of mafic, intermediate, and felsic rocks. Standard Harker SiO_2, AFM, and CaO-Na_2O-K_2O major element diagrams suggest that the samples follow generally linear crystal fractionation trends, having tholeiitic to calc-alkaline compositions, and that intermediate and felsic rocks substantiate the eastern portion of the Carolina Zone as being a sodic, K-deficient region. Chondrite-normalized REE diagrams have enriched light rare earth elements (LREE) generally flat heavy rare earth element (HREE) patterns with a low to moderate negative slope. Trace element multielement discrimination diagrams show an enrichment of large ion lithophile elements (LILE) relative to high field strength elements (HFSE) and both LREEs and HREEs, and strongly depleted HFSEs for Nb (Ta) and Ti, as well as fluctuations of Y that mimic the HREEs with respect to N-MORB compositions. REE and trace element data substantiate field correlations among rock types within and between the northeastern Carolina and Cary terranes as well as published geochemical analysis from the Virgilina, Albemarle, and South Carolina sequences in the main Carolina terrane in south-central Virginia, central North and South Carolina, and northeast Georgia. These data reinforce a subduction-related, island-arc origin for all terranes. In addition, mafic and felsic petrogenetic discrimination diagrams are compatible with an island-arc affinity for most samples, while geochemical trends on specific diagrams suggest that this peri-Gondwanan island-arc was built on dominantly oceanic substrate. However, continental contamination or continental arc formation, within-plate sources, and back-arc-basin rifting may have been involved in the evolution of some northeastern Carolina and Cary terrane lithodemes. The significant overlap of these geochemical signatures among the northeastern Carolina and Cary terranes with volcanogenic sequences of the main Carolina terrane establishes the Cary terrane as a structurally isolated portion of the main Carolina terrane on the eastern side of the Durham rift basin.

INTRODUCTION

The central and eastern Piedmont Province of the southern Appalachian orogen provides abundant exposures of a diverse group of metamorphosed igneous rocks. These rocks and numerous ductile and brittle faults that overprint them collectively range from the late Proterozoic to at least the early Mesozoic in age. In North Carolina, all crystalline rocks exposed east of the Central Piedmont shear zone comprise the central Piedmont, while the eastern Piedmont contains the easternmost crystalline rocks exposed west of onlapping drift-related sedimentary rocks of the Atlantic Coastal Plain and east of the Mesozoic Deep River rift basin.

Detailed mapping and supporting analytical work, as well as orogenic-scale compilations completed over the past three decades have strengthened our understanding of the lithotectonic framework in the central and eastern Piedmont of central Virginia, North and South Carolina, and northeastern Georgia (e.g. Bobyarchick and Glover, 1979; Farrar, 1984; Dallmeyer and others, 1986; Secor and others, 1986a,b; Secor, 1987;Gates and Glover, 1989; Hatcher, 1989; Horton and others, 1989; Maher and others, 1991; Hibbard and others, 2002). Integration of local projects with regional reconnaissance and correlation-based projects provided the basis of our knowledge for the North Carolina eastern Piedmont (e.g. Hatcher and others, 1977; Farrar, 1985a, b; Gates and others, 1988; Stoddard and others, 1991; Stoddard and Blake, 1994; Samson and others, 1995; Sacks, 1999). Over the last decade, NCGS STATEMAP mapping and geochemical studies have enhanced our understanding of the tectonic development of the central and eastern Piedmont in North Carolina.

In the easternmost portion of the central as well as the eastern Piedmont in North Carolina, a complex tectonothermal history is superimposed upon primarily metaigneous rocks that, from west to east, are subdivided into the Carolina, Falls Lake, Crabtree, Raleigh, Spring Hope, Triplet, and Roanoke Rapids terranes (Horton and others, 1994; Blake and others, 2001; Hibbard and others, 2002). Together, rocks in these second-order tectonstratigraphic elements document the suprastructual and infrastructural evolution of the easternmost part of a Late Proterozoic to early Paleozoic, peri-Gondwanan island-arc system known as the Carolina Zone. This island arc is a first-order tectonstratigraphic element in the southern Appalachian orogen (Fig. 1; Hibbard and Samson, 1995; Hibbard and others, 2002).

These rocks also record the accretion of the Carolina Zone to the eastern Laurentian continental margin during the middle Paleozoic. Laurentian-Gondwanan continental collision and construction of the Pangean supercontinent in the late Paleozoic culminated in the formation and dispersal of the individual terranes along regional ductile dextral fault zones (Hatcher and others, 1977; Horton and others, 1994; Sacks, 1999; Blake and others, 2001). Sedimentary rocks that crop out within and overlap these terranes combined with the formation of ductile/brittle normal faults document Mesozoic rifting and the eventual breakup of Pangea (Olsen and others, 1991; Clark and others, 2001).

However, it is not clear whether all rocks of the North Carolina Piedmont fall into this Carolina Zone designation. Farrar (1985b, 2001) considers the Raleigh terrane to be the southern extension of the Grenville Goochland terrane of south-central Virginia, a possible Laurentian-affinity continental fragment. Farrar (1985b, 1999, 2001), Glover and others (1997), and Farrar and Owens (2001), contend that the Goochland and Raleigh terranes represent a Grenville crustal block that was detached from the eastern Laurentian margin during Late Proterozoic rifting and subsequently reattached during mid-Paleozoic arc-continent collision. Hibbard and others (2002) also recognize the Laurentian affinity of Goochland terrane rocks and designate them as another first-order tectonostratigraphic element called the Goochland Zone, although they continue to group the Raleigh terrane with Carolina Zone elements. Thus, the uncertain affinity of the Piedmont terranes complicates our understanding of the tectonic history of this portion of the southern Appalachian hinterland (Stoddard and others, 1996).

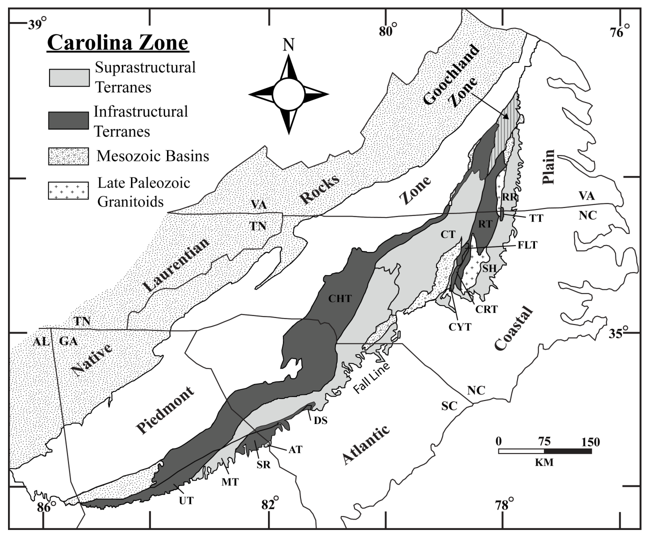

Figure 1: Tectonostratigraphic superstructural and infrastructural terrane map for the Carolina Zone. Suprastructral elements include the Milledgeville (MT), Augusta (AT), Roanoke Rapids (RR), Spring Hope (SH), Carolina (CT), and Cary (CYT) terranes. Infrastructural elements include the Uchee (UT), Savannah River (SR), Dreher Shoals (DS), Falls Lake (FLT), Triplet (TT), Raleigh (RT), Crabtree (CRT), and Charlotte (CHT) terranes. Modified from Hibbard and others (2002).

The purpose of this study is to provide insight into regional correlations among Carolina Zone meta-igneous rocks that may assist in future reconstructions of the tectonic history of the easternmost central and eastern Piedmont of North Carolina. In order to investigate the geochemical aspect of terrane correlation in the easternmost central and eastern Piedmont of North

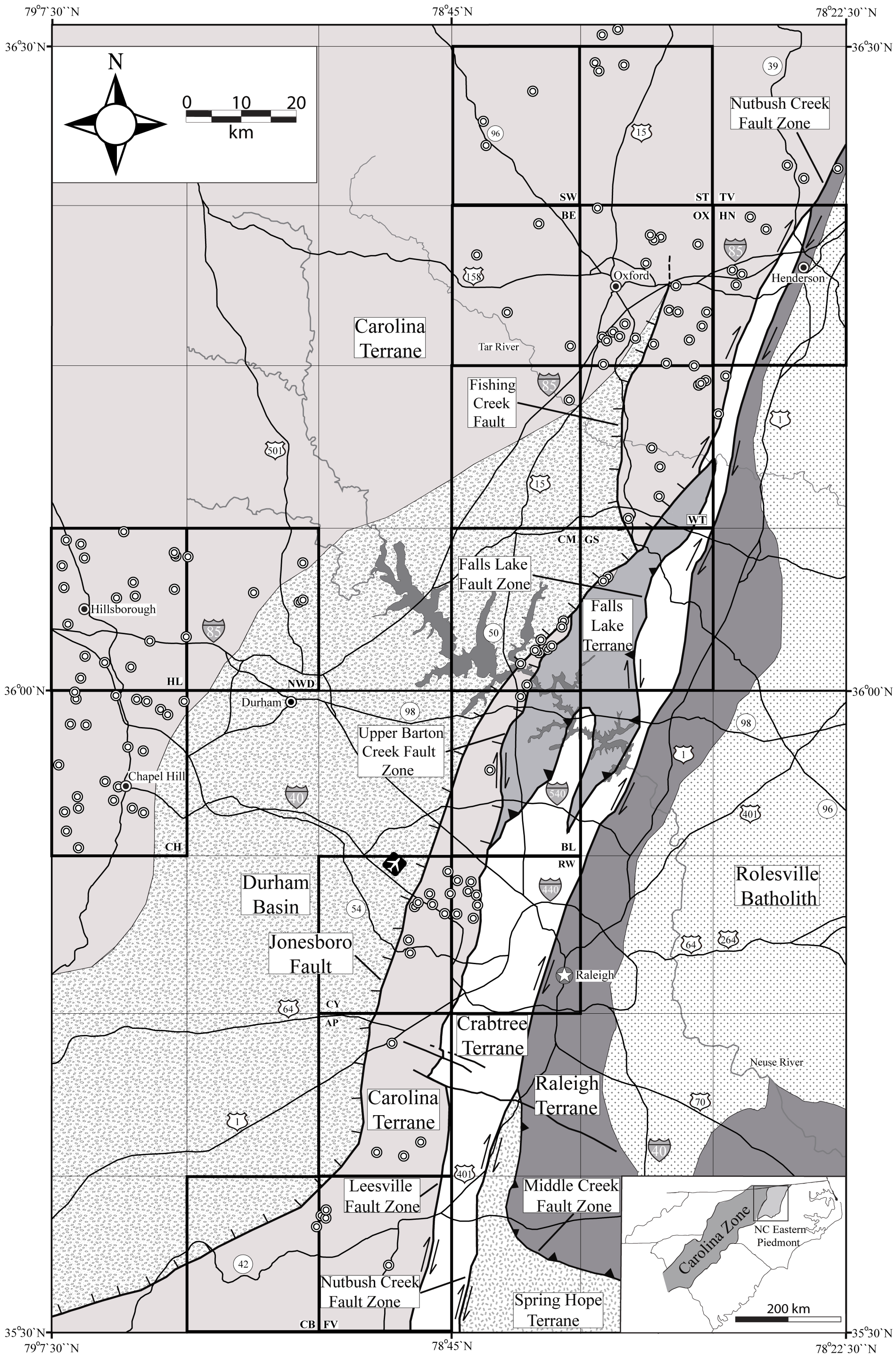

Figure 2: Regional setting of the northeastern Carolina Zone showing tectonostratigraphic terranes, late Paleozoic to Mesozoic faults, and the Late Triassic Durham basin in the easternmost central and westernmost eastern North Carolina Piedmont. Inset map depicts the Carolina Zone and the study region in the hinterland of the southern Appalachian orogen. Hatchures indicate the location of the Mesozoic Jonesboro normal fault and the Fishing Creek normal fault to its north, as well as the ductile normal attributes of the Upper Barton Creek fault zone. The 7.5-minute quadrangles mapped for U.S.G.S. STATEMAP and EDMAP programs in the North Carolina central and eastern Piedmont include Cokesbury (CB), Fuquay-Varina (FV), Apex (AP), Cary (CY), Raleigh West (RW), Bayleaf (BY), Creedmoor (CM), Grissom (GS), Wilton (WT), Oxford (OX), Henderson (HN), Townsville (TV), Northwest Durham (NWD), Hillsborough (HL), and Chapel Hill (CH). Open circles represent station locations for the 181 collected samples from this study and Hadley (1973). Modified from Stoddard and others (1991), Horton and others (1994), Hibbard and Samson (1995), Blake and others (2001, 2004, 2005, 2006), and Clark and others (2004).and subordinate felsic and mafic metavolcanic rocks dominate these formations (Butler and Ragland, 1969; Seiders, 1978; Butler and Secor, 1991; Kozuch, 1994, Ingle, 1999; Ingle and others, 2003).

Carolina, analysis of 181 whole-rock geochemical samples from a portion of the Carolina terrane (Fig. 2), the largest intact member of the Carolina Zone, have been used to address three broad questions that have evolved from the mapping efforts. 1) What are the representative major and trace element geochemical signatures of, and links among greenschist facies metaplutonic and metavolcanic rocks within the northeastern Carolina terrane in the region surrounding the Mesozoic Durham basin? 2) How does the geochemical data from the northeastern Carolina terrane compare with published analyses from the main Carolina terrane in south-central Virginia, central North and South Carolina, and northeast Georgia? 3) What are the geochemical characteristics of these rocks that serve as potential petrogenetic indicators of tectonic environments of formation?

REGIONAL SETTING

Lying along the eastern flank of the southern Appalachian orogen, the Carolina Zone contains metaigneous and metavolcaniclastic, fault-bounded terranes derived from a peri-Gondwanan, Late Proterozoic to early Paleozoic island-arc system (Fig. 1; Hibbard and Samson, 1995; Hibbard and others, 2002). In the central Piedmont from Virginia to Georgia, the Charlotte and Carolina terranes represent portions of the amphibolite facies infrastructure and the greenschist facies suprastructure of the Carolina Zone, respectively. In the eastern Piedmont from east-central Virginia to northeastern Georgia, the amphibolite facies infrastructure of the Carolina Zone includes the Triplet, Raleigh, Falls Lake, Crabtree, Dreher Shoals, Savanna River, and Uchee terranes, while the Roanoke Rapids, Spring Hope, Augusta, and Milledgeville terranes represent its greenschist facies suprastructure (Fig. 1). A transition between greenschist facies suprastructural metavolcanic and metaplutonic rocks of the northeastern Carolina terrane in north-central North Carolina is the focus of this geochemical correlation study (Fig. 2).

In North Carolina, arc-related rocks of the Carolina terrane exposed in the central and eastern Piedmont are subdivided into the Virgilina and Albemarle sequences and the Cary sequence, respectively (Butler and Ragland, 1969; Glover and Sinha, 1973; Seiders, 1978; Parker, 1979; Rogers, 1982; Harris and Glover, 1988; Butler and Secor, 1991; Hibbard and others, 2002). In the central Piedmont of South Carolina, the arc-related sequence may be correlative with the Albemarle sequence of North Carolina, although definitive geochemical links have not yet been established (Secor and others, 1986; Maher, 1987; Secor, 1987; Hibbard and others, 2002).

The Virgilina sequence contains metavolcaniclastic rocks of the Aaron Formation that overlie the basal felsic and intermediate metavolcanic rocks of the Hyco Formation. Metabasalt of the Virgilina Formation overlies both these formations (Glover and Sinha, 1973; Harris and Glover, 1988; Hibbard and others, 2002). The Albemarle sequence of the Carolina terrane contains the Albemarle Group that overlies the basal Uwharrie Formation of primarily felsic metavolcanic rocks having minor metamafic and metasedimentary members. The Albemarle Group consists of, from structurally lowest to highest, the Tillery, Cid, Floyd Church, and Yadkin Formations. Submarine epiclastic metasedimentary rocks,

Some of the larger metaplutonic bodies that range from diorite to granite in composition include the Vance County and Gibbs Creek plutons (Farrar, 1985a), Tabbs Creek complex (Grimes, 2000), Roxboro metagranite (Glover and Sinha, 1973; Wortman and others, 2000), and the East and West Farrington plutons (Ragland and Butler, 1972; Tadlock and Loewy, this guidebook). Numerous metagabbro and metabasalt dikes and sills (Butler and Secor, 1991) intrude rocks from the Virgilina and Albemarle sequences and include such bodies as the gabbro of Tar River (Carpenter, 1970; Robitaille, 2004) that crosscuts the Gibbs Creek pluton and the Stony Mountain Gabbro (Pollock and Hibbard, this guidebook).

In the structurally lower portion of the Cary sequence (Hibbard and others, 2002), also known as the Cary series (Parker, 1979) and the Cary Formation (Farrar, 1985a), metabasaltic and metagabbroic rocks of the Turkey Creek Amphibolite are in structural contact with rocks of the Crabtree terrane across the Leesville fault zone (Blake and others, 2001; Clark and others, 2004). Structurally above this mafic lithodeme, the Big-Lake Raven Rock Schist and Cokesbury Phyllite (formerly the Coles Branch Phyllite) lithodemes have chiefly felsic pyroclastic and subordinate felsic volcaniclastic protoliths. Metabasalt and intermediate to mafic metavolcaniclastic rocks of the Sycamore Lake Greenstone are interlayered with these metamorphosed pyroclastic rocks. Bodies of metamorphosed ultramafic and mafic rocks of the informal Umstead metaintrusive suite and Beaverdam and Buckhorn Dam metaintrusive suites, and felsic rocks of the Reedy Creek granodiorite and smaller metagranitoid plutons are intrusive lithodemes that have the Cary sequence as their wall rocks (Parker, 1979; Farrar, 1985a; Clark and others, 2004).

The South Carolina sequence consists of, from structurally lowest to highest, the Persimmon Fork, Asbill Pond, and Richtex Formations. They comprise the southernmost exposures of the Carolina terrane (Secor and others, 1986; Butler and Secor, 1991; Dennis and Shervais, 1996; Shervais and others, 1996; Hibbard and others, 2002). The Persimmon Fork Formation is predominantly metamorphosed intermediate to felsic pyroclastic rocks while the Asbill Pond Formation contains quartz-rich metasedimentary rocks interlayered with intermediate to felsic pyroclastic metavolcanic rocks. Metavolcaniclastic rocks and greenstone inferred to be intermediate to mafic tuff and/or flow breccia and mafic dikes and sills comprise the Richtex Formation (Bulter and Secor, 1991; Dennis and Shervais, 1996; Shervais and others, 1996). In the northwestern South Carolina Piedmont, metaigneous rocks are correlative with Charlotte terrane infrastructure rocks

(Dennis and Shervais, 1991, 1996; Hibbard and others, 2002).

Tectonic History

Three major tectonic events describe the construction, emplacement and subsequent deformation of portions of the Carolina Zone (Blake and others, 2001; Hibbard and others, 2002). The first event is the development of the island arc on a juvenile oceanic, or perhaps older orogenic volcanic crustal substrate in a peri-Gondwanan setting and then its subsequent accretion to Laurentia (Nance and Thompson, 1996; Hibbard, 2000; Hibbard and others, 2002). Based on early Paleozoic faunal assemblages exotic to Laurentia (Secor and others, 1983; Butler and Secor, 1991; Nance and Murphy, 1996; Hibbard and others, 2002), the Carolina Zone appears to be a far-traveled assemblage of island-arc rocks.

Hibbard and others (2002) characterize the tectonic history of Carolina Zone arc magmatism into three broad stages. Stage I magmatism occurred prior to 600 Ma and reflects the formation of a juvenile, felsic-rich island arc most likely built on oceanic substrate. The Virgilina sequence is the oldest island-arc sequence in the Carolina terrane of the central Piedmont and best represents Stage I magmatism. Stage II magmatism and deposition took place between 590-569 Ma., and represents a period of possible intra-arc or back-arc rifting as proposed by Feiss (1982), Feiss and others (1993), and Dennis and Shervais (1991, 1996). The Cary sequence provides a good example of Stage II magmatism in the Carolina terrane (Hibbard and others, 2002).

Stage III magmatism occurs post 569 Ma, and documents intrusions of large mafic to ultramafic volcanic arc plutons that may also be rift-related such as the Beaverdam and Buckhorn Dam metaintrusive suites of the Cary sequence (Moye, 1981; Phelps, 1998; Clark and others, 2004) and the northwestern South Carolina Piedmont (Dennis and Shervais, 1991, 1996; Hibbard and others, 1996). In other places in the Carolina Zone, dominantly sedimentary sequences with minor felsic and mafic magmatism in the Albemarle and South Carolina sequences of the Carolina terrane mark Stage III magmatism (Hibbard and others, 2002).

Early to middle Paleozoic tectonism during the Taconic orogeny led to the accretion of this magmatic-arc system (Hibbard, 2000; Hibbard and others, 2002). This orogeny juxtaposed the Carolina Zone island-arc with Laurentia, producing a regional greenschist to amphibolite facies metamorphism and small-to regional-scale folding, thrust faulting, and foliation formation (Farrar, 1985, Secor and others, 1986; Stoddard and others, 1991; Hibbard and others, 2002).

The second major tectonic event to affect the easternmost central and the eastern North Carolina Piedmont involves late Paleozoic metamorphism, magmatism, and ductile faulting due to the collision of Gondwana with Laurentia during the Alleghanian orogeny. This collision formed the supercontinent Pangea, resulting in dextral transpression as evidenced by the formation of macroscale and mesoscale folding and ductile dextral faulting. The fault structures overprint the arc and dissect it into the suprastructure and infrastructure terranes throughout the Carolina Zone (Secor and others, 1986; Gates and others, 1988; Stoddard and others, 1991; Blake and others, 2001; Hibbard and others, 2002).

The third major tectonic event affecting the Carolina Zone involves the latest Paleozoic to early Mesozoic rifting of Pangea (Olsen and others, 1991; Stoddard and others, 1991; Hames and others, 2001). In North Carolina, the easternmost central and eastern Piedmont record an episode of extension expressed by the formation of the Deep River basin (Clark and others, 2001). From south to north, the Wadesboro, Sanford, and Durham basins subdivide this irregularly shaped, half-graben rift structure. The brittle-plastic Jonesboro normal fault forms the eastern boundary of Wadesboro, Sanford, and southern portion of the Durham basins (Olsen and others, 1991; Clark and others, 2001). The informally named Fishing Creek fault zone forms the northeastern boundary of the Durham basin (Blake and others, 2002, 2003, 2006). These faults structurally separate the easternmost portion of the Carolina terrane containing the Cary sequence from the western and northeastern portions of the main Carolina terrane containing the Virgilina and Albemarle sequences (Fig. 2).

GEOCHEMISTRY DATA

A suite of 181 samples from the northeastern Carolina terrane have been geochemically analyzed from two regions in the easternmost central and eastern Piedmont of North Carolina (Fig. 2). The Mesozoic Deep River basin and its basin-bounding brittle-ductile normal faults geographically and structurally separate the two regions. Greenschist facies rocks of the easternmost Carolina terrane lie east of the Deep River basin and west of the Leesville and Upper Barton Creek ductile dextral and normal fault zones that separates them from amphibolite facies rocks of the Crabtree and Falls Lake terranes, respectively (Fig. 2). The easternmost Carolina terrane includes rocks that Hibbard and others (2002) have defined as the Cary sequence. In an effort to simplify the nomenclature and to be consistent with eastern Piedmont terrane terminology used on the western flank of the Wake-Warren anticlinorium (Horton and others, 1994; Blake and others, 2001; Hibbard and others, 2002), the easternmost Carolina terrane is informally referred to here as the Cary terrane.

The northeastern Carolina terrane in this study includes metavolcanic rocks of the Virgilina sequence and their metaplutonic equivalents mapped in the Chapel Hill-Hillsborough and Oxford-Henderson areas (Bradley and others, this guidebook). A majority of the sample exposures in this region lie to the west and north of the Durham basin (Fig. 2). South of Oxford, a subset of samples lie in a wedge-shaped area east of the Durham basin and Fishing Creek fault zone and west of the Jonesboro fault and ductile Alleghanian Nutbush Creek fault zone (Blake and others, 2001). In this region, field relationships suggest that the Jonesboro fault truncates the Fishing Creek Fault and overprints the Nutbush Creek fault zone (Grimes, 2000; Blake and others, 2002, 2003; Blake and Stoddard, 2004).

Figure 2 shows the sample distribution from the Cary and northeastern Carolina terranes. From north to south, lithodemes in the Creedmoor, Bayleaf, Raleigh West, Cary, Apex, Fuquay-Varina, and Cokesbury 7.5-minute quadrangles of the Cary terrane provide representative samples. These samples include the metamorphosed equivalents of 1) pyroxenite, gabbro, diorite, and granodiorite from the Beaverdam metaintrusive suite; 2) granitoids of the Reedy Creek granodiorite and the Umstead metaintrusive suite; 3) felsic pyroclastic rocks from the Big Lake-Raven Rock Schist that yield a 575 ± 12 Ma $^{207}Pb/^{206}Pb$ zircon crystallization date (Goldberg, 1994); 4) basalt and gabbro from the Sycamore Lake Greenstone and Turkey Creek Amphibolite; and 5) granitoids of the Sunset Lake, Burt Creek, Duncan, and Avents Creek plutons (Clark and others, 2004).

In the northeastern Carolina terrane, outcrops in the Middleburg, Henderson, Oxford, Wilton, Northwest Durham, Hillsborough, Efland, and Chapel Hill 7.5-minute quadrangles provide representative samples (Fig. 2). This data set also includes 25 samples previously collected by Hadley (1971) in the Berea, Clarksville South, Oxford, Satterwhite, Stem, and Stovall 7.5-minute quadrangles. Samples from the northeastern Carolina terrane include the metamorphosed equivalents of 1) tonalite, granodiorite, and granite from the Vance County, Gibbs Creek, Chapel Hill, Meadow Flats, Duke Forest, East Farrington, and smaller, unnamed plutons; 2) diorite, quartz diorite, and gabbro from local, unnamed plutons; 3) dacitic and rhyolitic pyroclastic rocks, and basaltic lavas from the Hyco and Aaron Formation in the Virgilina sequence; and 4) greenstone enclaves exposed in various granitoid plutons. The granite of Chapel Hill yields an interpreted zircon crystallization age of 633 +2/-1.5 Ma (Wortman and others, 2000), while the Vance County yields a of 571 Ma U-Pb date on a zircon (LeHuray, 1989). The informal Meadow Flats and Duke Forest plutons are part of the same pluse of plutonism associated with the granite of Chapel Hill (Bradley and others, this guidebook). Recent geochronologic data (Tadlock and Loewy, this guidebook) indicate that the East Farrington pluton is ca. 579 Ma, records an interval of plutonism within the northeastern Carolina terrane after deposition and deformation of the Virgilina sequence, and is a stage II magmatic pulse of Hibbard and others (2002).

Sampling and Methods

In this study, 156 new whole-rock geochemical analyses are reported, including analyses from Heller (1996), Phelps (1998), Grimes (2000), and Robitaille (2004). There are also 25 major element analyses from Hadley (1973). The sample distribution yields 130 analyses from the northeastern Carolina terrane and 51 analyses from the Cary terrane. All samples except those of Hadley (1971) and one sample from Phelps (1998) were analyzed between 1993 and 2006 for 11 major and 49 trace elements by SGS Minerals (formerly XRAL Laboratories) of Toronto, Canada. SGS Minerals uses multi-method, multi-element quantitative techniques involving X-ray fluorescence, ICP, neutron activation analysis, ICP/MS, and AA spectrophotometry. Whole-rock sample preparation involved the facilities at XRAL and the Petrology Preparation Laboratory of the Department of Geography and Geology at the University of North Carolina Wilmington. Powdering of fresh samples followed a standard procedure to avoid contamination, and each sample had all weathered and Fe-stained faces and joint surfaces removed.

To conduct this test for potential geochemical links, synoptic diagrams and fields of major and trace element data from the Virgilina, Albemarle, and South Carolina-Georgia lithotectonic sequences are included here for comparison. Butler and Ragland (1969), Hadley (1973), Seiders (1968), Weigand (1969), Whitney and others (1978), Green and others (1982), Kreisa (1980), Harris and Glover (1988), and Samson and others (1995) provide major element data. The studies of Allen and Wilson (1968), Black (1977), Paulson (1980), Kozuch (1994), Dennis and Shervais (1996), Shervais and others (1996), and Ingle (1999) yielded both major and trace element data.

Major Elements

The QAP classification diagram of Figure 3 displays CIPW normative quartz-alkali feldspar-plagioclase percentages derived from the whole-rock analyses for 181 samples and follows Streckeisen (1976) and Le Maitre (2002). The normative minerals illustrate a continuous linear compositional trend for northeastern Carolina and Cary terrane plutons, volcanic flows, and pyroclastic tuffs that range from gabbro-diorite (basalt-andesite) to granodiorite-granite (dacite-rhyolite). The suite may be further subdivided into 57 mafic samples (42-52 wt% SiO_2), 60 intermediate samples (52-66 wt% SiO_2), and 64 felsic samples (66-78 wt% SiO_2).

Upgrading the silica frequency histogram originally established by Black (1980) and Feiss (1982), silica analyses compiled from northeastern Georgia to south-central Virginia during the last 35 years resulted in the silica frequency histogram of Figure 4a for the entire Carolina terrane. Following subdivisions of Hibbard and others (2002) for the Carolina terrane, sample occurrences within the Virgilina, Albemarle (North Carolina), and South Carolina-Georgia sequences, along with several samples from the Charlotte terrane serve to subdivide the silica data. Only silica contents between 45-80 wt% SiO_2 that represent standard magmatic compositions are reported.

When the 508 analyses are evaluated together, the Carolina terrane sequences display a bimodal "Daly Gap" signature with a complete range in silica distribution, although compositions between 50-55 wt% SiO_2 and 70-75 wt% SiO_2 dominate. Given the number of analyses, this distribution does not appear to be an artifact of sample bias, and suggests a lower relative abundance of intermediate composition rocks in the Carolina terrane. The distribution displays a compositional trough at 62 wt% SiO_2 that is slightly higher than the midpoint value of intermediate compositions at 60 wt% SiO_2.

The 181 analyses from the northeastern Carolina and Cary terranes have a corresponding range in silica between 45-78 wt% SiO_2, and a similar, although weaker increase in frequency of mafic composition rocks between 45-55 wt% SiO_2, and felsic compositions between 65-75 wt% SiO_2 (Fig. 4b). The frequency histogram shows a compositional trough between 60-65 wt% SiO_2, that closely approximates the midpoint value of intermediate compositions at 60 wt% SiO_2. Figure 4c combines the Carolina terrane silica histograms of Figure 4a and 4b with all currently unreported NCGS STATEMAP silica data from the Crabtree, Falls Lake, Raleigh, and Spring Hope terranes in the North Carolina eastern Piedmont. This synoptic histogram for a large portion of the Carolina Zone is very similar to that for the Carolina terrane. The histogram further demonstrates the bimodal and "Daly Gap" signature (e.g. Baker, 1968; Chayes, 1977; Clague, 1978 Bonnefoi and others, 1995) of this first order tectonostratigraphic element, and is compatible with the analytical results of Stoddard and others (1996) that suggest much of the Carolina Zone may comprise a bimodal suite of metaigneous rocks.

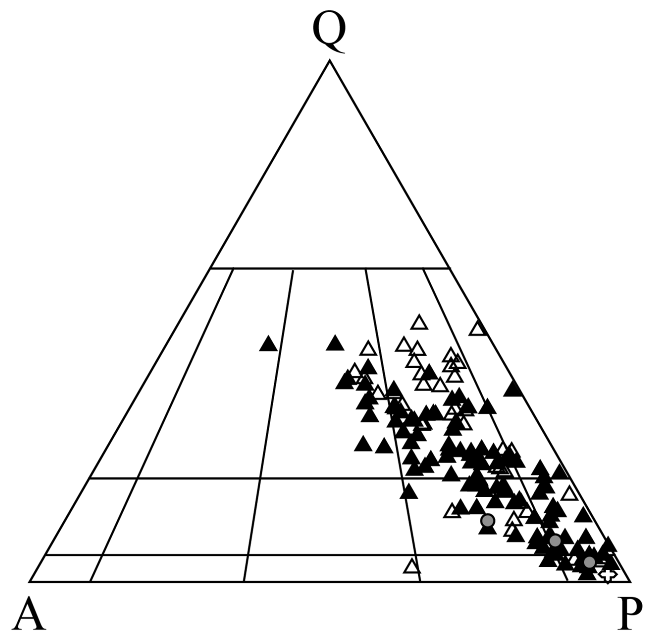

Figure 3: QAP diagram for all rock samples after Streckeisen (1976) and Le Maitre (2002). Symbols: filled triangles represent samples from the northeastern Carolina terrane; open triangles represent samples from the Cary terrane; shaded circles represent greenstone enclaves. The single open cross sample near the P apex represents a cross cutting gabbroic dike in the Gibbs Creek pluton.

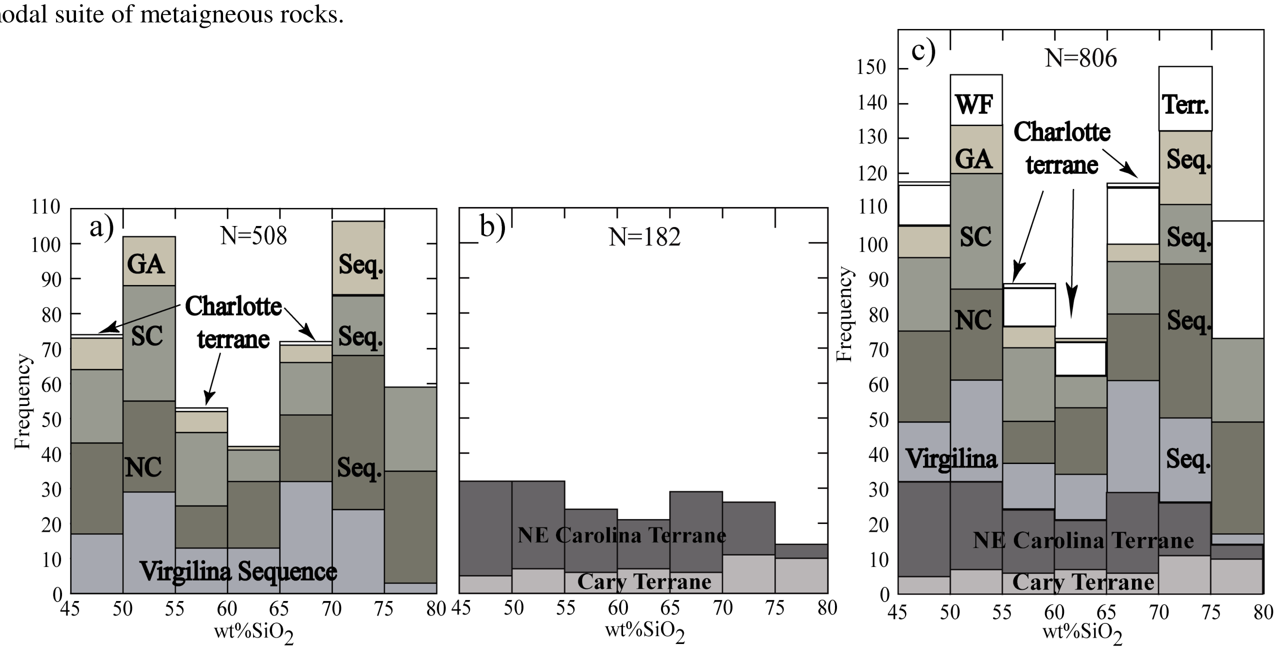

Figure 4: Silica histograms for: a) main sequences of the Carolina terrane from Allen and Wilson (1968), Seiders (1968), Butler and Ragland (1969), Weigand (1969),Hadley (1973), Whitney and others (1978), Black (1977), Kreisa (1980), Paulson (1980), Green and others (1982), Harris and Glover (1988), Kozuch (1994), Samson and others (1995), Dennis and Shervais (1996), Shervais and others (1996), and Ingle (1999). b) Rocks of the northeastern Carolina and Cary terranes from this study. c) Histograms a) and b) combined with all available unreported NCGS STATEMAP data including samples from the Falls Lake, Raleigh, Crabtree, and Spring Hope terranes.

Standard Harker variation diagrams (Fig. 5) combine sample scatter and linear trends for the population as a whole. SiO_2 values for the entire suite range from 42-78 wt%. Oxide wt% for Fe_2O_3* (total Fe reported as Fe_2O_3), MgO, TiO_2, MnO, Al_2O_3, and CaO all decrease with increasing wt% SiO_2, while K_2O and Na_2O wt% show increased values with increase in wt% SiO_2. Concentrations of Fe_2O_3 (1-14 wt%), MgO (0.5-9 wt%), Al_2O_3 (11-20 wt%), CaO (0.1-14.5 wt%), and Na_2O (0.5-7 wt %) vary across the suite, while TiO_2 (0.2-2 wt%), MnO (0.01-0.45 wt%), and K_2O (0.5-4.5 wt%) have slightly narrower ranges. Scatter on the Fe_2O_3, MgO, TiO_2, Al_2O_3, and CaO plots generally occur at SiO_2 concentrations less than 50-55 wt% SiO_2, demonstrating the compositional diversity of mafic metaigneous rocks. For major element concentrations greater than 50-55 wt% SiO_2, the data define linear trends up to 78 wt% SiO_2 except for K_2O and Na_2O. Both the Na_2O and K_2O diagrams display the most significant scatter, attesting perhaps to problems in open-system mobility of these two elements during subsequent metamorphism and/or weathering. Results from Harker diagrams of Seiders (1978) in the Albemarle sequence, and Shervais and others (1996) in the South Carolina sequence show comparable trends.

A K_2O-Na_2O-CaO ternary diagram (Fig. 6a) for samples having greater than 60 wt% SiO_2 suggests that felsic plutonic and volcanic rocks primarily have sodic compositions similar to that noted by Whitney and others (1977) in northeastern Georgia, and Butler and Ragland (1968), Seiders (1978), and Kozuch (1994) for Albemarle Group strata and samples from the Virgilina sequence. This diagram is in accord with field and petrographic analysis that suggests most of the metamorphosed “granitoid” plutons and felsic pyroclastic rocks are diorite, quartz diorite, and granodiorite instead of granite, and dacite rather than rhyolite, respectively. Plotting samples from northeastern Carolina and Cary terrane on an AFM diagram (Fig. 6b), mafic rock compositions display a broad Fe-enrichment trend that straddles the tholeiitic and calc-alkaline dividing line of Irvine and Baragar (1971), that are analogous to the results of Butler and Ragland (1968) in North Carolina, and Shervais and others (1996) in South Carolina. Intermediate and felsic rocks define a tightly clustered population that forms a compositionally expanded, linear calc-alkaline, I-type magmatic trend.

REE Patterns

Because of generally similar major element characteristics of metaigneous rocks in the northeastern Carolina and Cary terranes with the Virgilina, Albemarle, and South Carolina sequences, a comparison of trace elements further evaluates potential lithotectonic correlations. Dennis and Shervais (1996), Shervais and others (1996), Kozuch (1994), and Ingle (1999) report trace element geochemistry for a suite of Carolina terrane metaigneous rocks from the South Carolina sequence and the northwestern South Carolina Piedmont, and the Virgilina and Albemarle sequences, respectively. These studies provide data with which to construct three rare earth element and three trace element concentration fields for comparison with the northeastern Carolina and Cary terranes. REE data are chondrite-normalized after Nakamura (1974), while trace element multielement discrimination diagrams are N-MORB normalized to present-day oceanic crust after Sun and McDonough (1989).

Figure 7a-h shows REE and trace element diagrams for mafic, intermediate, and felsic metaplutonic and metavolcanic rocks of the northeastern Carolina and Cary terranes, as well as for greenstone enclaves within various metagranitiod plutons in the northeastern Carolina terrane. The suite as a whole displays enriched light rare earth element (LREE) La/Sm ratios, generally flat heavy rare earth element (HREE) Gd/Lu ratios, and a low to moderate negative slope, depending upon whole-rock composition. Felsic rocks display a La_N/Lu_N that ranges between 2x and 14x chondrite (Fig. 7a). They have moderate to high La_N concentrations (28x-198x chondrite), and a relatively broad range of Lu_N concentrations (4x-43x chondrite) as compared to intermediate and mafic rock compositions. All sample LREE and HREE concentrations fall within the boundaries of the fields for the Virgilina, Albemarle, and South Carolina sequences and the northwestern South Carolina Piedmont (Kozuch, 1994; Dennis and Shervais, 1996; Shervais and others, 1996; Ingle, 1999). Slight variations in enrichment or depletion of Eu concentrations occur in felsic compositions for both metaplutonic and metavolcanic samples.

Intermediate rocks display a similar range of La_N/Lu_N between 2x and 14x chondrite (Fig. 7b). They have moderate La_N concentrations (24x-126x chondrite) and a smaller range of Lu_N concentrations (5x-19x chondrite). As a group, intermediate rock compositions display the most restricted range of LREE and HREE concentrations in the northeastern Carolina and Cary terranes, which fall within the boundaries of the fields for the Virgilina, Albemarle, and South Carolina sequences and the northwestern South Carolina Piedmont. Slight variations in depletion of Eu concentrations occur in intermediate metaplutonic and metavolcanic samples.

Mafic rocks have the lowest range of La_N/Lu_N between 1x and 10x chondrite, having a mean of 3x chondrite for the 42 analyzed samples (Fig. 7c). They have low to moderate La_N (3x-99x chondrite), a range of Lu_N concentrations (2x-18x chondrite), and weak Eu_N depletions. Shervais and others (1996) suggest parallel and crossing patterns represent some magma similarities within, but clearly multiple magma sources between the metamafic samples. Most compositions fall within the fields defined for Carolina terrane sequences. However, magmas of the Beaverdam metaintrusive suite are the least enriched, which is compatible with their primary pyroxenite, gabbro, and diorite field associations (Moye, 1981; Phelps, 1998), and tend to plot in the lower range or out of the fields defined for Carolina terrane sequences.

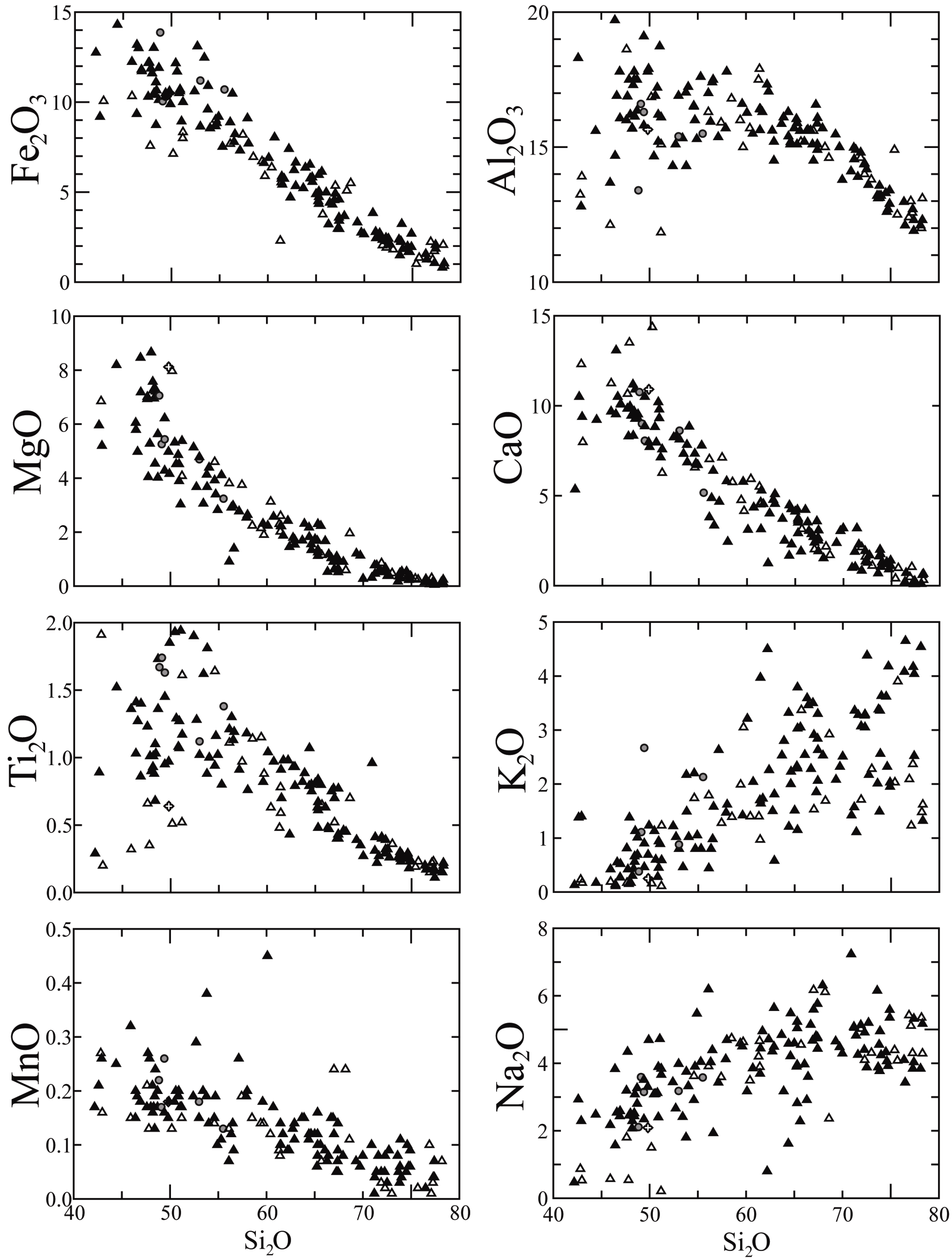

Figure 5: Harker variation diagrams for Fe_2O_3*, MgO, TiO_2, MnO, Al_2O_3, CaO, K_2O, and Na_2O versus SiO_2. All oxides shown in wt%. Symbols: filled triangles represent samples from the northeastern Carolina terrane; open triangles represent samples from the Cary terrane; shaded circles represent greenstone enclaves. The single open cross sample represents a cross cutting gabbroic dike in the Gibbs Creek pluton.

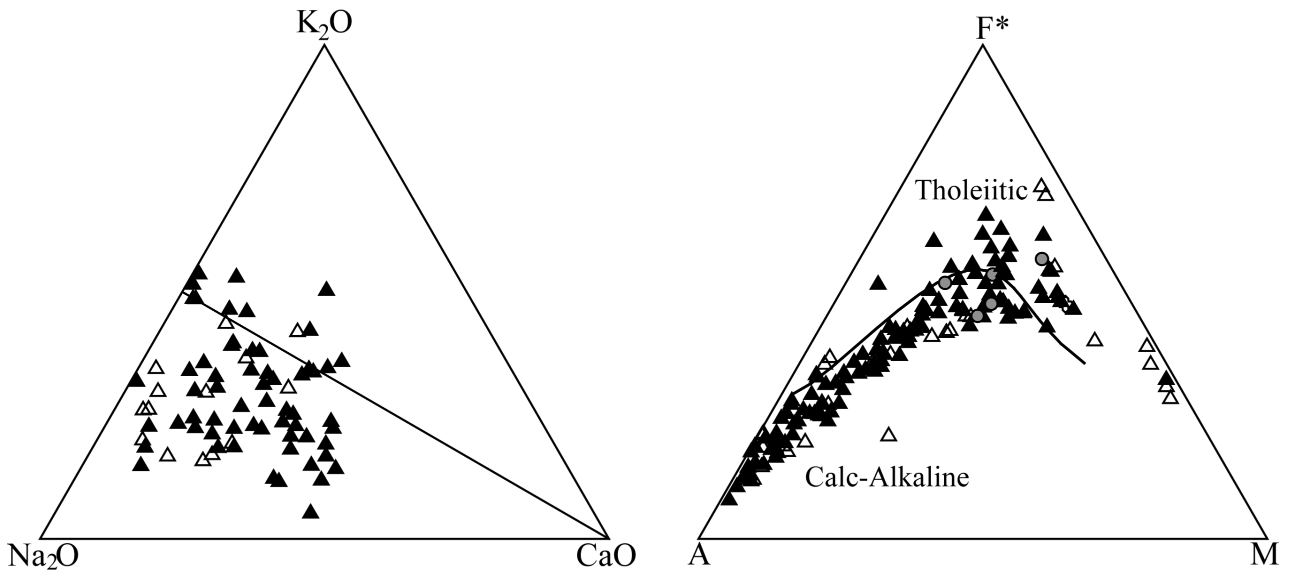

Figure 6: a) K_2O-Na_2O-CaO diagram after Kozuch (1994) displaying samples having greater than 60 wt% SiO_2. Dividing line crosses 50% K_2O and Na_2O, with N=74. Symbols: filled triangles from the northeastern Carolina terrane; open triangles from the Cary terrane. b) AFM diagram for all samples in the northeastern Carolina and Cary terranes. A= total alkalies, F*= total iron reported as Fe_2O_3, M= MgO. Symbols: filled triangles represent samples from the northeastern Carolina terrane; open triangles represent samples from the Cary terrane; shaded circles represent greenstone enclaves. The single open cross sample represents a cross cutting gabbroic dike in the Gibbs Creek pluton.

In addition, a fine-grained metagabbro, which intrudes tonalite of the Gibbs Creek pluton, has a La_N/Lu_N of 1x chondrite, a La_N concentration of 11x chondrite, and a flat REE slope (Fig. 7d). This concentration corresponds with the lowest value reported from a metabasalt in the Carolina terrane by Kozuch (1994). This crosscutting dike most likely developed from a distinctly different mafic magma.

Greenstone enclaves, all from the northeastern Carolina terrane, have and La_N/Lu_N between 1x and 4x chondrite, low to moderate La_N (11x-76x chondrite), a range of Lu_N concentrations (10x-21x chondrite), and relatively flat REE slopes with weak Eu_N depletions, while plotting in the fields defined for Carolina terrane sequences (Fig. 7d). Two of the enclaves from southwest Oxford have higher wt% silica contents and fall into the range of intermediate compositions. They may represent quartz dioritic (basaltic andesitic) rocks incorporated into later granitoids.

Two of the enclaves, one from the Gibbs Creek pluton and another from the Tabbs Creek complex, exhibit field and petrographic evidence for mineralogical layering, and hornblende displays a weak preferred orientation. The enclave of Gibbs Creek displays the lowest La_N/Lu_N of 1x chondrite and the lowest La_N concentration of 11x chondrite for all six enclaves. The enclave of Tabbs Creek falls in the La_N/Lu_N concentration range of the other four enclaves. The cause of the mineralogical layering is not clear, and the truncation of layering at enclave/granitoid contacts indicates that it must pre-date enclave incorporation in both Late Proterozoic to early Paleozoic plutons.

N-MORB Normalized Trace Elements

Northeastern Carolina and Cary terranes rocks are also similar in terms of N-MORB-normalized trace element data, their anomalies, and general concentration patterns, to those of the Virgilina, Albemarle, and South Carolina sequences and the northwestern South Carolina Piedmont (Kozuch, 1994; Dennis and Shervais, 1996; Shervais and others, 1996; Ingle, 1999). These rocks produce patterns on trace element multielement discrimination diagrams that show generally comparable concentration variations among rocks in all mapped units (Fig. 7e-h). Mafic, intermediate, and felsic compositions are enriched in large ion lithophile elements (LILE; Cs, Ba, Rb, Th, K, and LREE) relative to high field strength elements (HFSE) and HREEs, and have higher concentrations of LILEs relative to the LREEs. Elemental concentration scatter, including Nd and Sm, are most noticeable in finer grained metavolcanic rocks. Sr shows small positive anomalies in mafic rocks and small to significantly large negative anomalies in intermediate and felsic rocks. All compositions of metaigneous rocks also display strongly depleted HFSE for Nb (Ta) and Ti, and fluctuations of Y that mimic the HREEs with respect to N-MORB compositions. Where analyzed Nb concentrations are below detection limits, normalized plots use a detection limit value of 2 ppm.

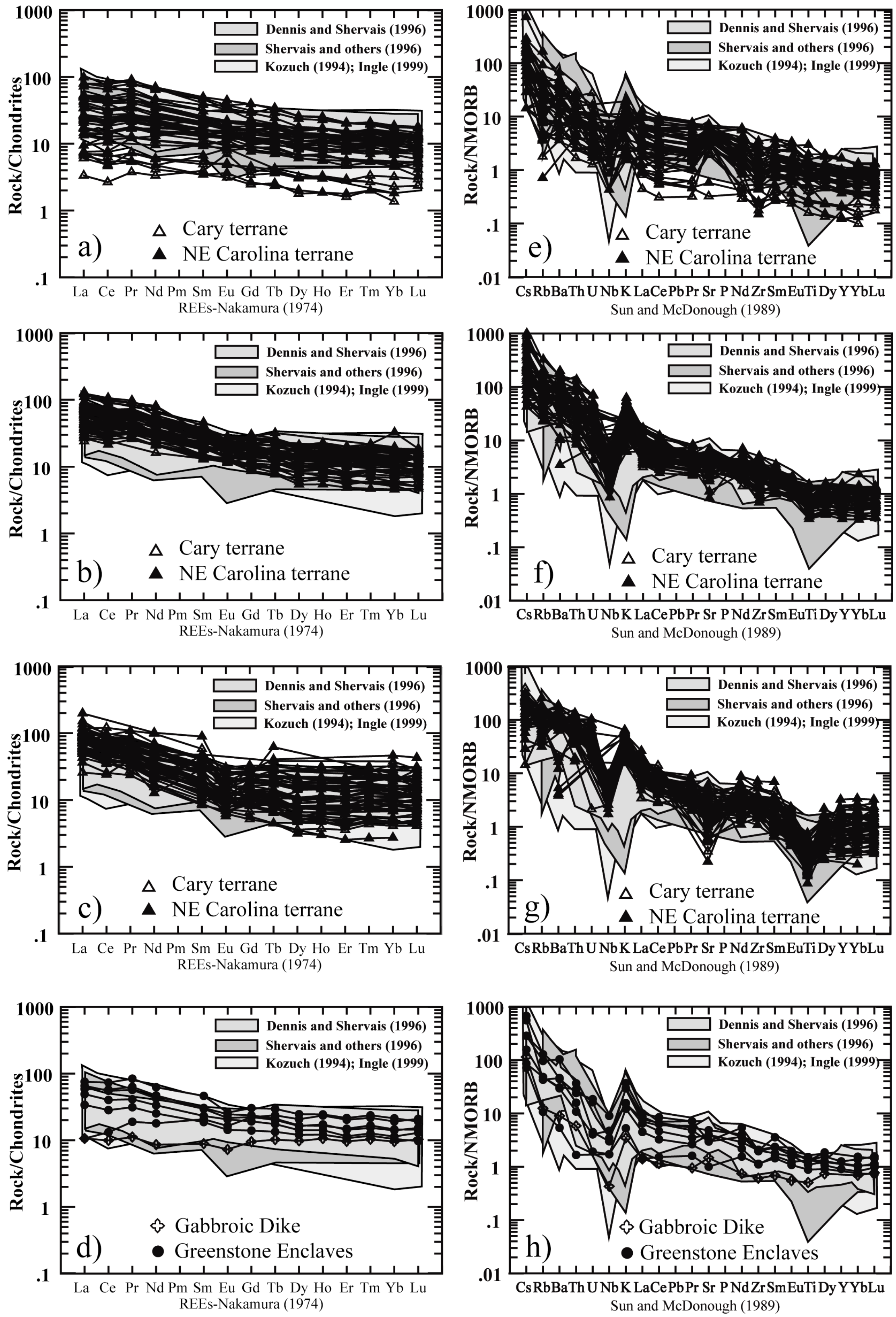

Figure 7: Chondrite-normalized REE diagrams (after Nakamura, 1974) for a) mafic samples, b) intermediate samples, c) felsic samples, and d) greenstone enclaves and the gabbroic dike of the Gibbs Creek pluton. N-MORB normalized trace element diagrams (after Sun and McDonough, 1989) for e) mafic samples, f) intermediate samples, g) felsic samples, and h) greenstone enclaves and the gabbroic dike of the Gibbs Creek pluton. Three REE and three trace element concentration fields for comparison with the northeastern Carolina and Cary terranes based upon data from Kozuch (1994), Shervais and others (1996), Dennis and Shervais (1996), and Ingle (1999).

Foliated and unfoliated greenstone enclaves from the Vance County and Gibbs Creek plutons, the Tabbs Creek complex, and the Oxford area display trace element multielement discrimination diagrams that are enriched in LILE relative to HFSEs and HREEs, and have higher concentrations of LILEs relative to the LREEs (Fig. 7h). Enclaves display strong to moderate Nb depletions while Sr shows small depletions and enrichments. All enclave samples also display minor depletions in Zr. In addition, the fine-grained metagabbro dike that intrudes the felsic Gibbs Creek pluton has a significant Nb trough, a slight Sr enrichment, and the lowest concentrations on the multielement discrimination diagram (Fig. 7h). This crosscutting dike most likely developed from a distinctly different mafic magma source.

Petrogenetic Variation Diagrams

Broadening the elemental characterization of protolith relationships suggested by REE and trace element multielement discrimination diagrams, trace element discrimination diagrams test the tectonic setting for the Carolina Zone terranes. Limited trace element data from Allen and Wilson (1968), Black (1977), and Paulson (1980) are combined with data from Kozuch (1994), Dennis and Shervais (1996), Shervais and others (1996), and Ingle (1999) to generate comparison diagrams for the Virgilina, Albemarle, and South Carolina sequences, as well as the northeastern portion of Georgia (Paulson, 1980) and northwestern portion of South Carolina (Dennis and Shervais, 1996).

The relative immobility of incompatible HFSEs and the tendency for Th to be less mobile than other LILEs suggests that these may be used to evaluate protolith characteristics. Use of these elements to assist in the discrimination among metamafic rocks having ocean-floor, island-arc, or within-plate origins prompted the construction of Zr-Ti-Y, Th-Hf-Nb, and Zr-Nb-Y plots after Pearce and Cann (1973), Wood and others (1979), and Mershede (1986). These studies set fourth diagram constraints in which wt% MgO + CaO must be less than 20 wt% and greater than 12 wt%. A suite of 43 samples from this study conform to required constraints and are displayed on the diagrams. To facilitate diagram comparison, where analyzed Nb concentrations are below detection limits, normalized plots use a detection limit value of 2 ppm.

On a Zr-Ti-Y diagram (Fig. 8a), mafic metaplutonic and metavolcanic rocks from the northeastern Carolina and Cary terranes plot mainly in the calc-alkaline field as well as the within-plate field. By comparison, rocks from the Virgilina and Albemarle sequences plot primarily in the fields of calc-alkaline and MORB magmatism. Some sample scatter toward the low-K island arc tholeiite and within-plate fields is also apparent. The South Carolina-Georgia and northwestern South Carolina sequence primarily plot between the fields of low-K arc tholeiite and calc-alkaline mafic magmas. They dominate the field of overlapping arc and MORB magmatism. Few within-plate compositions occur in the South Carolina sequences of the Carolina terrane.

On a Th-Hf-Nb diagram (Fig. 8b), most samples from the northeastern Carolina and Cary terranes and all the sequences fall into the field of arc-basalt. Most rocks from the Virgilina, Albemarle, and South Carolina sequences have enrichments of Th relative to Hf and clear Nb depletions observed on the multielement discrimination diagrams (Fig.7). Th-enrichment trends result in the clustering of metamafic rocks in a portion of the arc-related basalt field implying crustal contamination (Wood and others, 1979; Wilson, 1989). Samples from northeastern Georgia and South Carolina, as well as samples from the Virgilina and Albemarle sequences again predominantly fall into the same arc-basalt fields.

Incorporating Nb data from Paulson (1980) in northeastern Georgia and southwestern South Carolina, a Zr-Nb-Y diagram further demonstrates the compatibility between the northeastern Carolina and Cary terranes with the Virgilina, Albemarle, and South Carolina sequences (Fig. 8c). Samples from all terranes that plot in the overlapping arc and N-MORB basalt field remain the same as the Zr-Ti-Y plot described above. In the main Carolina terrane, the Virgilina sequence does not necessarily show a distinctive within-plate affinity on this diagram because the lack of Nb data precludes the use of a similar population of samples. Most samples define a second cluster in the field of overlapping arc and N-MORB basalts. The South Carolina-northeastern Georgia sequence, as well as the northwestern South Carolina rocks fall in the overlapping volcanic arc and within-plate, and volcanic arc magma fields. However, this diagram displays a much greater sample spread than the Zr-Ti-Y diagram. Several samples plot in the field of E-MORB and within-plate tholeiites, as do a number of northwestern South Carolina rocks.

The strong depletion anomalies observed on trace element multielement discrimination diagrams led to a plot of the variation in Nb/Th versus Y to further illustrate the arc signature of both the northeastern Carolina and Cary terrane rocks (Fig.9a). Jenner and others (1991) suggest that Nb/Th tracks the Nb depletion relative to Th of arc rocks as compared to primitive mantle. Concentrations of Y resemble the HREE behavior and evaluate the extent of mantle source depletion. Northeastern Carolina and Cary terrane sequences predominantly plot in the field of arc rocks well below the primitive mantle reference line of 7.4. Samples plot between 18 and 45ppm Y, and the majority between 32 and 45 ppm Y. These values are similar to the Virgilina, Uwharrie-Albemarle, and South Carolina sequences, although some central North Carolina and northwestern South Carolina rocks show enrichment of Nb relative to Th and pass into the non-arc field.

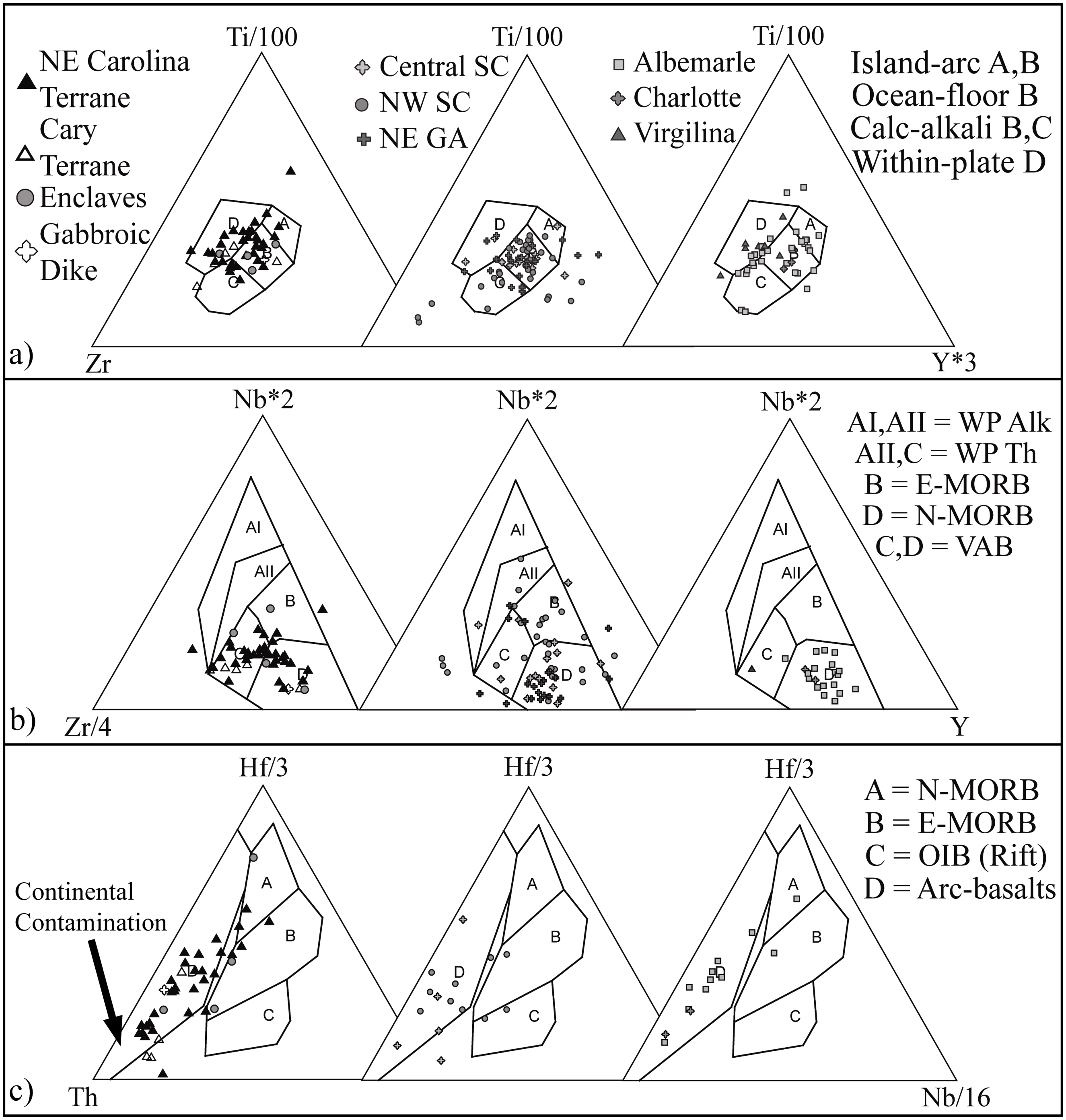

Figure 8: a) Ti-Zr-Y (after Pearce and Cann, 1973), b) Nb-Zr-Y (after Wood and others, 1979), and c) Hf-Th-Nb (after Mershede, 1986) discrimination diagrams for mafic samples, greenstone enclaves, and gabbroic dike of the Gibbs Creek pluton from the northeastern Carolina and Cary terranes totaling 43 samples as compared to samples from northeastern Georgia, northwest South Carolina, and the Albemarle, Charlotte, and Virgilina sequences of the main Carolina terrane.

On a Th/Yb versus Ta/Yb diagram (Fig. 9b), 12 samples from this study are plotted that result from the acquisition of new Ta data with substantially lower detection limits of 0.05 to facilitate use of this diagram. All other samples collected from both the northeastern Carolina and Cary terranes have Ta compositions below reported detection limits of 0.5 ppm. Plotting all samples at a detection limit of 0.5 falsely increases the Ta/Yb ratio and skews the data into the field of continental magmatic arc rocks. 12 samples from the northeastern Carolina terrane plot closely in the field of calc-alkaline oceanic-arc setting and correspond with sequences in northeastern Georgia, South Carolina, and North Carolina. The overall lack of Ta in the northeastern Carolina and Cary terranes should be noted.

On a Ti versus V diagram (Shervais, 1982) for the northeastern Carolina and Cary terranes (Fig. 10a); samples have a MORB to MORB back-arc-basin basalt signature. This is not the case when compared to the main Carolina terrane in Georgia, South Carolina, North Carolina, and Virginia. The main Carolina terrane has a large population falling in the island-arc-tholeiite field, and overlaps into the MORB back-arc-basin basalt field. Metafelsic rocks further support the arc-related signature for lithodemes in the northeastern Carolina and Cary terranes. Following Kozuch (1994), a plot of Rb versus Y + Nb for northeastern Carolina and Cary terrane sequences produces a clustering of samples within the field of volcanic arc granitiods (Fig. 10b). A smaller population from the Virgilina and Uwharrie-Albemarle sequences straddles the boundary between the volcanic arc and within-plate granitoids.

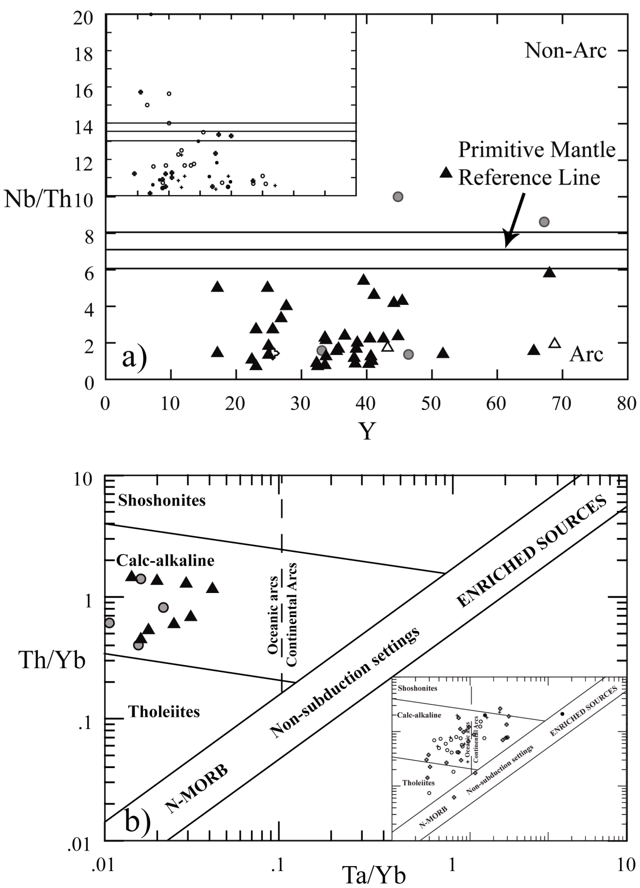

Figure 9: a) Nb/Th versus Y diagram for mafic samples showing the arc affinity of northeastern Carolina and Cary samples. Inset for comparison to samples from the three main Carolina terrane sequences. Units are in ppm, primitive reference line from Jenner and others (1991). b) Th/Yb versus Ta/Yb diagram showing a subset of samples having Ta data that plot in the field of oceanic arc. Inset represents the three main Carolina terrane sequences for comparison. Symbols: filled triangles represent samples from the northeastern Carolina terrane; open triangles represent samples from the Cary terrane; shaded circles represent greenstone enclaves. The single open cross sample represents a cross cutting gabbroic dike in the Gibbs Creek pluton.

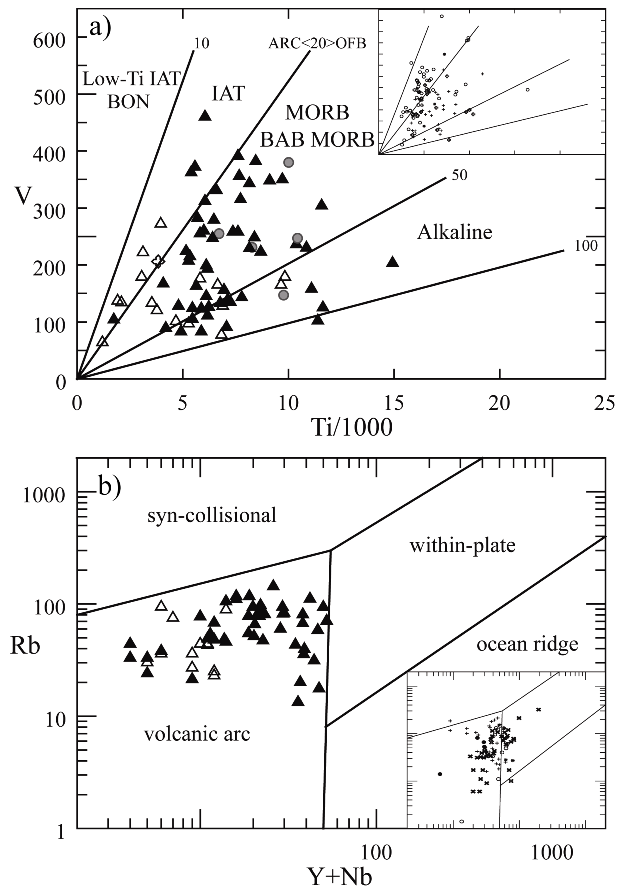

Figure 10: a) Ti versus V diagram for mafic samples that plot dominantly in the field of MORB/back-arc-basin basalt. BON=Boninite, IAT=island-arc tholeiite, MORB=mid-ocean ridge basalt, BAB=back arc basin. Inset represents samples from the main Carolina terrane sequences for comparison, units in ppm. Symbols: filled triangles represent samples from the northeastern Carolina terrane; open triangles represent samples from the Cary terrane; shaded circles represent greenstone enclaves. The single open cross sample represents a cross cutting gabbroic dike in the Gibbs Creek pluton. b) Rb versus Y+Nb discrimination diagram for felsic samples that plot in the field of volcanic arc. Units are in ppm. Open triangles represent samples from the Cary terrane, closed triangles represent samples from the northeastern Carolina terrane. Inset from the three main Carolina terrane sequences for comparison.

DISCUSSION

The northeastern Carolina and Cary terranes record a relatively complex magmatic history in the easternmost central and eastern Piedmont of North Carolina. While it is difficult to document an unequivocal link among lithodemic units because of rock diversity and the effects of overprinting middle Paleozoic through early Mesozoic metamorphism and deformation, a commonality of major and trace element signatures and anomalies does exist between these terranes and data reported from the Virgilina, Albemarle, and South Carolina sequences, and northwestern South Carolina (Kozuch, 1994; Dennis and Shervais, 1996; Shervais and others, 1996; Ingle, 1999). In addition, 1:24,000-scale mapping and petrographic studies suggest that volcanogenic mafic, intermediate, and felsic rocks share similarities in their field, mineralogical, and textural characteristics in the northeastern Carolina and Cary terranes, as well as the main portion of the Carolina terrane.

Together, protoliths for the northeastern Carolina and Cary terranes represent a diverse collection of metamorphosed basaltic, andesitic, dacitic, and more minor rhyolitic tuffs and flows, as well as subvolcanic and deep-seated gabbroic, dioritic and quartz dioritic, granodioritic, and granitic dikes, sills, and plutons based upon field, petrographic, and geochemical criteria. As a whole, the major and trace element diagrams define population scatter and slightly curvilinear to linear trends that overall are overlapping for all rocks of the northeastern Carolina and Cary terranes. When combined, the geochemical characteristics of the suite appear to be consistent with the development of an oceanic island arc that may display the transition between tholeiitic and calk-alkaline magma series.

The scatter of major elements for metamafic rocks on traditional Harker diagrams may provide evidence for multiple mafic magma pulses, diversity in mafic magma source regions, and/or variations in magma chamber processes that erupted lava flows or developed the mafic plutons. Mafic samples tend to straddle the boundary between the tholeiitic and calk-alkaline series on the AFM diagram and may represent the formation of two separate differentiation trends that are superimposed. Field exposures provide evidence for multiple pulses of mafic magma genesis. In the Cary terrane, the pyroxenite, gabbro, and mafic diorite of the Beaverdam, Buckhorn Dam, and Umstead metaintrusive suites, the Sycamore Lake Greenstone which is interlayered with pyroclastic rocks of the Big-Lake-Raven Rock Schist, and the gabbro of Tar River (Clark and others, 2004), combined with the numerous gabbro bodies in the northeastern Carolina terrane (Bradley and others, this guidebook), attest to a spatial and temporal variation in mafic magmatism.

Shervais and others (1996) indicate that crossing of some REE patterns in the South Carolina sequence, which is observed in the northeastern Carolina and Cary terranes, may imply multiple magma series and magma derivation from source regions having variable compositions and residual mineralogies. Other subgroups of mafic metaigneous rocks show parallel trends and in some cases, elemental clusters at nearly coincident concentrations may imply multi-phase partial melting and possibly magma differentiation from similar source regions. Greenstone enclaves in the northeastern Carolina terrane, especially where mineralogically layered, when combined with the local occurrence of metaultramafic enclaves in tonalite of the Gibbs Creek pluton (Robitaille, 2004) and metamafic rocks of the Turkey Creek Amphibolite, may provide evidence for an older mafic-ultramafic substrate, perhaps serving as the platform upon which the Carolina Zone was constructed.

This substrate may have also served as a source of magma genesis and/or perhaps the contamination for later invading mafic magmas. In addition, fractionation of mafic magmas is suggested because of slight variations in enrichment or depeletion of trace elements such as the Eu concentration enrichment and depletions suggesting the accumulation of plagioclase in the magma or fractionation to a source residuum.

In both the northeastern Carolina and Cary terranes, intermediate to felsic samples having elevated SiO_2 concentrations display a tight linear and again overlapping trend for major elements on most standard Harker diagrams. These rocks also define a tightly clustered population that forms a compositionally expanded, linear calc-alkaline, I-type magmatic trend on the AFM diagram. Consistent trends among metaplutonic and metavolcanic samples from both terranes on Harker, AFM, REE, and trace element multielement discrimination diagrams, suggest that fractional crystallization processes may relate these suites of rock and that they are relatively unmodified by extensive crustal contamination.

Field and petrographic studies combined with major and trace element geochemistry suggest that decreases in Fe_2O_3, MgO, TiO_2, CaO, and Al_2O_3 corresponding with higher SiO_2 contents would be compatible with removal of ferromagnesium minerals, magnetite, and/or rutile in differentiating magmas or source region, and changing from calcic to sodic plagioclase compositions in the system. Changing plagioclase compositions are consistent with field and petrographic observations of mineral zoning and core sausseritization in metamorphosed plutonic and volcanic rocks. Again, variations in enrichment or depletion of trace elements such as the Eu concentration troughs for felsic rocks suggest the accumulation of plagioclase in mafic magmas or fractionation to a source residuum. Sr shows small positive anomalies in mafic rocks and small to significantly large negative depletions in felsic rocks, perhaps also as a function of the gain or loss of modal Ca-plagioclase, or a consequence of differentiation, metamorphism, or perhaps interaction with seawater.

Typically, more leucocratic bodies crosscut bodies having higher mineral color indices and may provide further evidence for either a progressively developed calc-alkaline magmatic fractionation trend and/or temporally separated pulses of felsic magma. However, lack of age controls on most intrusions prohibits an absolute assessment of timing relationships in spatially separated plutons and pyroclastic deposits.

For the population as a whole, both the Na_2O and K_2O diagrams display the most significant scatter, attesting perhaps to problems in open-system mobility of these two elements. When combined with trace element data and the positive and negative K concentration anomalies in all sequences, K_2O scatter may reflect the ion mobility of this LIL element during magmatic fractionation and/or the influence of Paleozoic metamorphism and secondary alteration. This K_2O scatter coupled with the scatter of Na_2O could be a consequence of the seritization of plagioclase and K-feldspar in felsic, intermediate, and lesser mafic compositions observed during petrographic analysis. Scatter of Na_2O also generally corresponds with the general sodic compositional trends observed on the K_2O-Na_2O-CaO diagram.

However, the generally bimodal nature of mafic and felsic compositions observed in the field and the linear array of intermediate and felsic magma compositions may indicate that the tight linear trends for these samples represent mixing lines rather than compositional variations due to crystal fractionation. In addition, field relationships suggest that in some exposures, mafic and felsic magmas mingle to form hybrid rocks. Arcuate and lobate contacts between gabbroic and dioritic to granodioritic plutonic bodies suggests the comagmatic intrusion of felsic magmas while the mafic magmas were still warm and malleable (Hill and Abbott, 1989; Grimes, 2000). These data coupled with the silica histograms of Figure 4 may suggest a mixing of felsic and mafic magmas that could explain the bimodal "Daly Gap" (e.g. Baker, 1968; Chayes, 1977; Clague, 1978; Bonnefoi and others, 1995) signature of magmatism in the Cary and Carolina terranes, the compositional spread, and smaller population of intermediate composition rocks in the entire Carolina Zone. Clearly, there is a need for more work on the issue of fractionation versus magma mixing and the apparent Daly Gap for this suite of metaigneous rocks.

Similar calc-alkaline major and trace element enrichment patterns in many of the Cary and northeastern Carolina terrane metaplutonic and metavolcanic rocks combined with their intermingled field relationships imply a cogenetic link among parental magmas. Mafic, intermediate, and felsic intrusions dominate the eastern portion of the Cary and northeastern Carolina terrane, while felsic pyroclastic rocks lie to the west on both sides of the Durham basin. Based upon field and petrographic relationships, as well as the geochemical evidence, it appears that these rocks form a "plutonic belt" or the infrastructure along the eastern margin of these two terranes, and some of the plutons may be the source magmas for suprastructural volcanic rocks cropping out father to their west.

In this case, at least some of the plutons in this "belt" may represent Stage I magmatism of Hibbard and others (2002) given the Virgilina sequence affinity of metavolcanic rocks in the northeastern Carolina terrane north of Chapel Hill, North Carolina (Bradley and others, this guidebook). In the northeastern Carolina terrane, at least two siliceous centers possibly represent higher crustal levels of older volcanic edifices in the Oxford 7.5-minute Quadrangle (Blake and others, 2006). However, other plutons represent Stage II magmatism based upon field relationships and limited geochronology. Together, the "plutonic belt" may be analogous to the infrastructural plutons of the Charlotte terrane.

East of the Jonesboro fault in the Cary terrane, at least three plutonic complexes, the Umstead, Beaverdam, and Buckhorn Dam metaintrusive suites, may represent magma chamber centers (Blake and others, 2001). Field relationships suggest that pyroclastic phenocrysts and lithic fragments in the Big Lake-Raven rock Schist are larger and more abundant proximal to Umstead intrusions in the Big Lake area of Umstead State Park in Cary, North Carolina, and diminish farther to the south near Raven Rock State Park on the Cape Fear River. Characteristic 'blue" quartz phenocrysts are common in the schist, especially where it structurally overlies the Reedy Creek Metagranodiorite, which also contains "blue"quartz phenocrysts.

One hypothesis to explain both the field relationships and the geochemical similarity of these metavolcanic and metaplutonic rocks is that the Reedy Creek pluton represents a subvolcanic magma for overlying felsic pyroclastic rocks, and may be intruding its own volcanic piles. Similar field and mineralogical relationships were originally suggested for hypabyssal volcanic rocks in northeastern Georgia that yield a 568 Ma U-Pb zircon date (Whitney and others, 1978, Butler and Secor, 1991). Based upon a 575 ± 12 Ma zircon $^{207}Pb/^{206}Pb$ crystallization age for the Big Lake-Raven Rock Schist (Goldberg, 1994), both of these volcanic-plutonic rock associations would be compatible with the Stage II magmatic event of Hibbard and others (2002).

In addition, felsic enclaves of the Big Lake Raven Rock Schist, or perhaps an older substrate, that crop out in the Beaverdam metaintrusive suite are in agreement with Hibbard and others (2002) assessment of these rocks as Stage II magmas. However, for a more accurate temporal interpretation for the Cary terrane and its lithodemic sequences, and their geochemical relationship to the rest of the northeastern Carolina terrane and other Carolina terrane sequences, further geochronology and isotopic data must be obtained and analyzed.

When evaluated as a suite, major and trace element concentrations and tholeiitic to calc-alkaline signatures are consistent with a similar island-arc origin for rocks of the northeastern Carolina and Cary terranes and other sequences of the Carolina terrane (Stoddard and others, 1996; Hibbard and others, 2002). Assigning the terranes to a subduction zone or back-arc basin environment has previously relied on the calc-alkaline trend and bimodal signature of the Carolina terrane (Seiders, 1978; Whitney and others, 1978; Black, 1980; Feiss, 1982; Rogers, 1982; Butler and Secor, 1991; Feiss and others, 1993; Kozuch, 1994; Shervais and others, 1996; Ingle, 1999). In addition, low TiO_2 values, generally less than 1% TiO_2, for all samples also imply a subduction origin for the northeastern Carolina and Cary terrane rocks, as well as the Carolina terrane sequences (Black, 1982; Rogers, 1982; Shervais, 1982; Kozuch, 1994; Ingle, 1999).

As a suite, trace element multielement discrimination diagrams for the northeastern Carolina and Cary terranes show that these rocks empirically mimic the subduction-related field anomalies originally reported from the Carolina terrane sequences (Kozuch, 1994; Dennis and Shervais, 1996; Shervais and others, 1996; Ingle, 1999). Such chemical trends are now widely ascribed to modern and ancient magmatic environments having known mature oceanic island-arc origins and incorporating subducted sediments (e.g. Arculus and Powell, 1986; Swinden and others, 1990; Jenner and others, 1991; Gamble and others, 1995; Wharton and others, 1995).

Together, these rocks display a number of geochemical characteristics that are attributed to subduction-related volcanism that are also reflected in field relationships observed in the northeastern Carolina and Cary terranes on both sides of the Deep River rift basin, and in the Virgilina, Albemarle, and South Carolina sequences. These geochemical characteristics include the continuous range of SiO_2 between 45-78 wt% when combined with the Harker and AFM diagram fractionation and calc-alcaline trends, depletion of compatible trace elements relative to MORB, and depletion of HFSE. REE and multielement discrimination diagram patterns for the northeastern Carolina and Cary terrane, as well as the main Carolina terrane sequences, display consistent variations in normalized HFSE, LILE, Th, and LREE concentration patterns that attest to their island-arc signature. All reported Carolina and Cary terrane rocks display enrichment of LREE/HREE and LILE relative to N-MORB, strongly depleted HFSEs for Nb (Ta) and Ti relative to LILE and N-MORB, positive Th-anomalies, and enriched LIL/ (Cs, Ba, Rb, Sr, LREE) abundances relative to N-MORB. Almost all northeastern Carolina and Cary terrane samples plot within the trace element fields of the Virgilina, Albemarle, and South Carolina sequences in the main Carolina terrane

However, subduction-related magmatism and contamination at active continental margins (Pearce, 1983) and magmatic incorporation of enriched lithospheric mantle or continental crustal contamination of more juvenile magmas (Wilson, 1989; Wever and Story, 1992) are also permissible methods to produce these trace element patterns, as well as the calc-alkaline differentiation trend on major element diagrams. Shervais and others (1996) suggest that the geochemical patterns of major and trace elements are consistant with the formation of an orogenic magma suite for a portion of the South Carolina sequence. These geochemical results also permit a common volcanic/magmatic arc link for the northeastern Carolina, Cary, and main Carolina terrane rocks, although the role of continental influence must be further investigated.

In support of the trace element concentration patterns, petrogenetic discrimination diagrams involving plots of Zr-Ti-Y, Th-Hf-Nb, Zr-Nb-Y, Ti versus V, Ta/Yb versus Th/Yb, and Nb/Th versus Y for metamafic rocks and Rb versus Y + Nb for metafelsic rocks also suggest an arc-related environment of formation for the terranes. However, on the Ti versus V diagram (Shervais, 1982), many of the northeastern Carolina and Cary terrane samples have back-arc basin/MORB signatures and involve some overlap into the field of alkaline compositions. Samples from main Carolina terrane sequences plot dominantly in the field of island arc tholeiite and display only minor overlap into the field of MORB/back-arc-basin.

Given our current understanding of Carolina Zone subduction polarity (Hatcher and Goldberg, 1991), perhaps there is a west-east spatial variation in island-arc development between the magmatic arc and the formation of a back-arc basin in the central and eastern Piedmont of North Carolina. Carpenter and others (1995) proposed that a gradation from dominantly metavolcanic to metasedimentary rocks in eastern Piedmont terranes signal the collapse of the Carolina Zone volcanic pile and possibly rift-related subsidence and mafic volcansism. This scenario would be compatible with conclusions drawn from the main Carolina terrane in North and South Carolina, where a pulse of intra-arc rifting (Feiss and others, 1993, Dennis and Shervais, 1991, 1996; Shervais and others, 1996) may have occurred during Stage II and III development of the Carolina Zone (Hibbard and others, 2002). This scenario is compatible with the hypothesis that sequences of the main Carolina terrane represent the suprastructure of this early Paleozoic island arc system, plotting with dominantly island-arc-tholeiite signatures, and calc-alkaline mafic rocks of the northeastern Carolina and Cary terranes plotting dominantly in the field of MORB or back-arc-basin basalt.

CONCLUSIONS

1. The easternmost central and eastern Piedmont Province of the southern Appalachian orogen provides abundant exposures of a diverse group of metamorphosed igneous rocks that record a relatively complex magmatic history. A suite of 181 samples from the northeastern Carolina terrane have been collected and geochemically analyzed. The easternmost Carolina terrane includes metavolcanic and metaplutonic rocks that Hibbard and others (2002) have defined as the Cary sequence. In an effort to simplify the nomenclature and to be consistent with eastern Piedmont terrane terminology used on the western flank of the Wake-Warren anticlinorium (Horton and others, 1994; Blake and others, 2001; Hibbard and others, 2002), the

easternmost Carolina terrane is now informally referred to here as the Cary terrane. The northeastern Carolina terrane in this study includes metavolcanic rocks of the Virgilina sequence and their metaplutonic equivalents. Protoliths for the northeastern Carolina and Cary terranes represent a diverse collection of metamorphosed basaltic, andesitic, dacitic, and more minor rhyolitic tuffs and flows, as well as subvolcanic and deep-seated gabbroic, dioritic and quartz dioritic, granodioritic, and granitic dikes, sills, and plutons based upon field, petrographic, and geochemical criteria resulting from NCGS STATEMAP efforts.

2. Major and trace element geochemical data indicate that samples from northeastern Carolina and Cary terranes represent a bimodal suite of magmatic rocks that produce a Daly Gap for intermediate compositions, mimicking the main Carolina terrane and a large portion of the Carolina Zone. Standard Harker SiO_2, AFM, and CaO-Na_2O-K_2O major element diagrams suggest that the samples follow a generally linear crystal fractionation trend, having tholeiitic to calc-alkaline compositions, and that intermediate and felsic rocks substantiate the eastern portion of the Carolina Zone as being a sodic, K-deficient region.

3. On trace element diagrams, the suite as a whole displays low to moderate negative REE slopes, depending upon whole-rock composition, and has enriched light rare earth element (LREE) La/Sm and generally flat heavy rare earth element (HREE) Gd/Lu. All sample LREE and HREE concentrations fall within the boundaries of the fields constructed from data for the Virgilina, Albemarle, and South Carolina sequences and the northwestern South Carolina Piedmont (Kozuch, 1994; Dennis and Shervais, 1996; Shervais and others, 1996; Ingle, 1999). These rocks produce patterns on trace element multielement discrimination diagrams that show generally comparable concentration variations among rocks in all mapped units. Mafic, intermediate, and felsic compositions are enriched in large ion lithophile elements (LILE; Cs, Ba, Rb, Th, K, and LREE) relative to high field strength elements (HFSE) and HREEs, and have higher concentrations of LILE relative to the LREE. All compositions of metaigneous rocks also display strongly depleted HFSE for Nb (Ta) and Ti, and fluctuations of Y that mimic the HREEs with respect to N-MORB compositions. All samples display subduction-related, island-arc geochemical signatures that appear to be consistent across the suite.

4. Geochemical signatures from the northeastern Carolina and Cary terranes appear to be consistent with published analysis from sequences in the main Carolina terrane in northeastern Georgia, central South and North Carolina, and Virginia. REE and trace element patterns as well as discrimination diagrams show significant overlap among the northeastern Carolina and Cary terranes and the volcanogenic sequences of the main Carolina terrane, thus establishing the Cary terrane through geochemical data as a structurally isolated portion of the Carolina terrane on the east side of the Durham Mesozoic basin. Together, the northeastern Carolina and Cary terranes represent Stage I and II events during the progressive development of the Carolina Zone.

5. Petrogenetic discrimination diagrams for the northeastern and Cary terranes involving plots of Zr-Ti-Y, Th-Hf-Nb, Zr-Nb-Y, Ti versus V, Ta/Yb versus Th/Yb, and Nb/Th versus Y for metamafic rocks and Rb versus Y + Nb for metafelsic rocks also suggest an arc-related environment of formation for the terranes. On the Ti versus V diagram, many of the northeastern Carolina and Cary terrane samples have back-arc basin/MORB signatures and involve some overlap into the field of alkaline compositions, while the main Carolina terrane sequences plot dominantly in the field of island arc tholeiite and display only minor overlap into the field of MORB/back-arc-basin. Petrogenetic discrimination diagrams suggest that this island-arc was built on dominantly oceanic substrate, but that some continental contamination and intra-arc or back-arc rifting may have been involved in the evolution of the northeastern Carolina and Cary terranes.

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GEOCHEMISTRY OF THE STONY MOUNTAIN GABBRO, NORTH CAROLINA: IMPLICATIONS FOR THE EARLY PALEOZOIC EVOLUTION OF CAROLINIA

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ABSTRACT

Carolinia comprises a collection of Neoproterozoic-early Paleozoic magmatic arc and sedimentary terranes that were amalgamated and accreted to Laurentia in the early to middle Paleozoic. In central North Carolina, mafic rocks of the Stony Mountain gabbro intrude sub-aqueous volcanic and sedimentary rocks and submarine epiclastic sedimentary rocks of the Albemarle Group. The age of the Stony Mountain gabbro is constrained to the Early Cambrian-Late Ordovician. Field relations indicate that the gabbro represents the final phase of magmatism following the eruption and deposition of the Neoproterozoic-earliest Cambrian Albemarle Group, yet the gabbro pre-dates regional metamorphism and tectonism related to the Late Ordovician accretion of Carolinia to Laurentia.

On a Hughes diagram, the Stony Mountain gabbro rocks display a moderate degree of scatter and plot near or in the igneous spectrum suggesting that the alkali elements have not been significantly altered by regional metamorphism. All rocks have sub-alkaline basaltic compositions, variable TiO_2, MgO and Ni/Cr values. Mg# values range from 80-50 and imply that the rocks span the range from primitive to more evolved. Primitive mantle-normalized rare earth element patterns are characterized by variable LREE enrichment with moderate sloping extended REE patterns. On tectonic discrimination diagrams the rocks have a geochemical signature typical of island-arc tholeiitic basalt. The degree of LREE enrichment, prominent negative Nb anomalies and Nb/Th ratios are all features of low-K to medium-K tholeiitic basalts in modern island-arc, subduction related lavas. The Stony Mountain gabbro is interpreted to reflect partial melting of depleted mantle that was contaminated by a subduction-related crustal component in the mantle wedge above a subduction zone.

Carolina has traditionally been correlated with the northern Appalachian peri-Gondwanan terrane of Avalonia on the basis of their overall similar Neoproterozoic lithological histories. The geochemical data, however, indicate the presence of Cambrian island-arc volcanism in Carolinia and argue against a correlation with Avalonia and suggest that Carolinia may be related to Ganderia.

INTRODUCTION

The Appalachian peri-Gondwanan realm (Hibbard *et al*., 2002) is an extensive tract of exotic Neoproterozoic-early Paleozoic crustal blocks that occur along the eastern edge of the orogen (Figure 1). It encompasses Carolinia in the southern Appalachians and Ganderia, Avalonia and the Meguma Zone of the northern Appalachians (Hibbard *et al*., in press). These crustal blocks are considered to have rifted from Gondwana in the Paleozoic during formation of the Rheic Ocean. Although it is generally accepted that these crustal blocks formed near or at the margin of Gondwana (Nance *et al*., 2002), several fundamental aspects of their early Paleozoic tectonic evolution are poorly known prior to their accretion to eastern Laurentia in the early to middle Paleozoic.

Carolinia comprises several late Neoproterozoic-Cambrian composite arc magmatic and sedimentary sequences that record a long and complex paleotectonic history. This study of the Stony Mountain gabbro is directed at unraveling part of the early Paleozoic evolution of Carolinia. The Stony Mountain gabbro (Ingram, 1999) represents the terminal phase of early Paleozoic magmatism in Carolinia and is affected by Late Ordovician tectonism related to the docking of Carolinia to Laurentia. However, the nature and paleotectonic setting of this magmatism has hitherto remained elusive. The Stony Mountain gabbro may represent within-plate magmatism

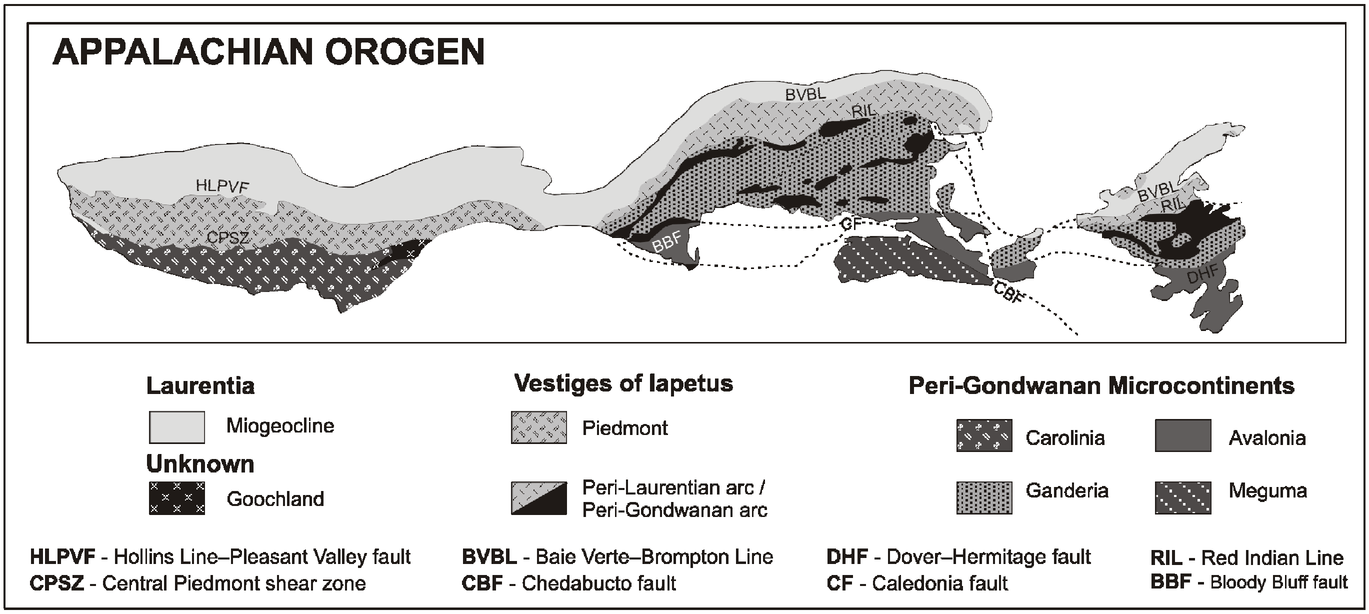

Figure 1. Major lithotectonic elements of the Appalachian Orogen.

that is the product of rifting of Carolinia from Gondwana, or alternatively, it may record a separate younger phase of arc-related magmatism.

In an effort to address these unresolved questions, we initiated a lithogeochemical study of the Stony Mountain gabbro. Geochemical data are presented to elucidate the nature of magmatism and tectonic setting of the Stony Mountain gabbro. These data are also useful in comparing the late-Neoproterozoic-early Paleozoic tectonic histories of Carolinia and other peri-Gondwanan crustal blocks of the Appalachian orogen.

GEOLOGICAL SETTING OF THE STONY MOUNTAIN GABBRO

Carolinia comprises a collection Neoproterozoic-early Paleozoic magmatic arc/sedimentary terranes that extend from central Virginia southwest to Alabama (Figure 2). In North Carolina, the tectonomagmatic and depositional history of Carolinia is best recorded in the Carolina terrane. The Carolina terrane comprises a tripartite succession of typically low-grade volcanic-plutonic and marine siliciclastic rocks formed in three distinct time intervals: (i) Pre-600 Ma rocks record a juvenile, felsic volcanic-dominated magmatic arc generated on an oceanic substrate; (ii) deposition of a magmatic-siliciclastic sequence occurred between 590-550 Ma; and (iii) post 550 Ma magmatic and depositional events are varied and include abundant felsic volcanism and associated epiclastic rocks, granitoid plutonism and intrusion of large mafic-ultramafic complexes.

In central North Carolina, the Carolina terrane is composed of lower-greenschist grade igneous and associated sedimentary rocks of the Virgilina sequence, Uwharrie Formation and Albemarle Group (Figure 3). The

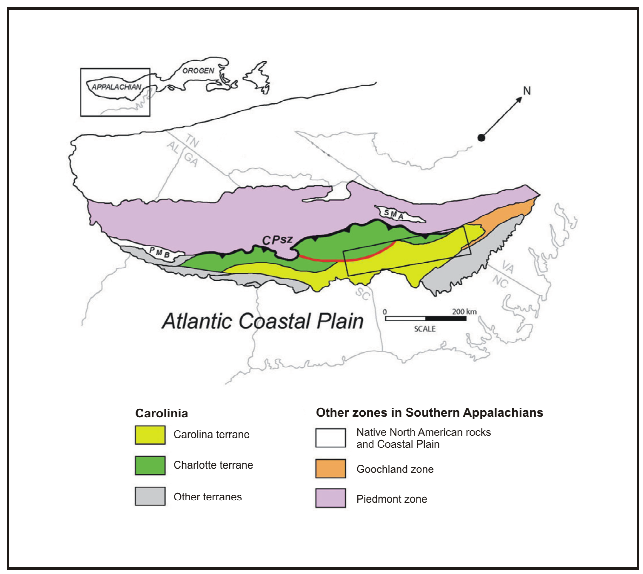

Figure 2. Location of Carolinia and its constituent geological terranes.

Neoproterozoic (633 to 612 Ma; Wortman *et al.*, 2000) Virgilina sequence is dominated by subaqueous volcanic rocks and turbidites that are unconformably overlain by the Uwharrie Formation, a collection of mainly subaqueous felsic volcaniclastic and sedimentary rocks that have yielded U-Pb zircon ages of 551 ± 8 Ma (Ingle-Jenkins *et al.*, 1999) and 554 ± 15 Ma (Ingle *et al.*, 2003). The Uwharrie Formation is overlain by the Albemarle Group, a sequence of submarine epiclastic sedimentary rocks with minor felsic and mafic volcanic rocks. Structurally, from lowest to highest, the group includes: 1) Tillery Formation, comprising thin-bedded fine-grained clastic sedimentary rocks with minor felsic and mafic volcanic rocks; 2) Cid

Formation, a sequence of fine-grained sedimentary rocks with substantially more felsic and mafic volcanic rocks than the Tillery Formation; 3) Floyd Church Formation, comprising medium-bedded fine-grained epiclastic rocks; and 4) Yadkin Formation, composed dominantly of greywacke derived from a mafic source (Hibbard *et al.*, 2002).

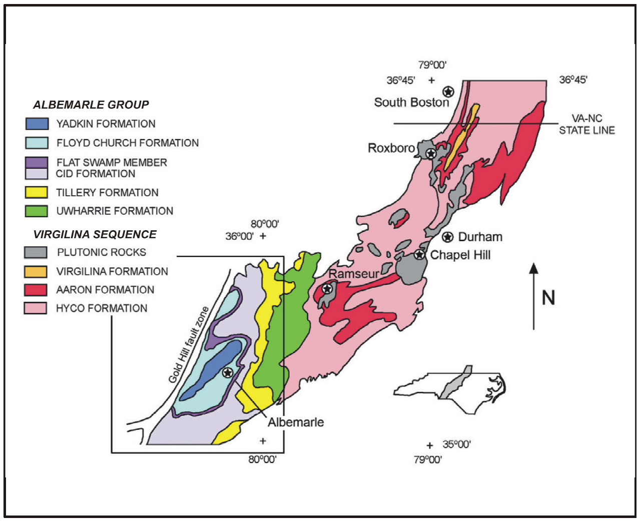

Figure 3. Geological setting of the Carolina terrane.

The age of the Albemarle Group is constrained by faunal and geochronological controls to the late Neoproterozoic-earliest Cambrian. The Metazoan trace fossils *Pteridinium* and *Aspidella* are reported from the Floyd Church Formation and Cid Formation, respectively (Weaver *et al*., 2006; Hibbard *et al*., 2006). Ingle *et al.* (2003) obtained a U-Pb zircon age of 554 ± 15 Ma for the Uwharrie Formation and a U-Pb zircon age of 540.6 ± 1.2 Ma for the Flat Swamp member of the Cid Formation; the member has also yielded zircon from rhyolite flows that have been dated by U-Pb TI-MS at 547 ± 2 Ma (Hibbard *et al*., 2006). The maximum age of the Yadkin Formation is constrained to the Early Cambrian from a detrital zircon dated by U-Pb TI-MS at 531 ± 2.5 Ma (Hibbard *et al*., this volume).

In central North Carolina (Figure 4), the Stony Mountain gabbro occurs as numerous irregular stocks of gabbro that are poorly exposed in outcrops along hilltops, ridges and lake shorelines. The contacts of most of the intrusions are not exposed; however, local intrusive contacts with the Tillery Formation and the outcrop pattern of the larger bodies suggests that the gabbro intrudes the Uwharrie Formation and all units of the Albemarle Group (Seiders, 1981). Geophysical data (Stromquist and Henderson, 1985) indicate that the gabbro intrusions in the limbs of large scale upright folds are present as northeast-striking and west dipping, sill-like bodies that vary in size from 1 metre to several hundred metres in thickness. The best exposures of these gabbro intrusions are located at the summit and along the surrounding ridges of Stony Mountain.

The gabbro is medium- to course-grained, consisting predominantly of plagioclase and pyroxene with secondary amphibole and biotite that has been affected by greenschist facies metamorphism. Plagioclase is present in the groundmass but is altered to sericite; colourless actinolite occurs in discrete patches where it replaces pyroxene grains. The centers of some of the amphibole crystals are altered to pleochroic colourless to pale green chlorite and epidote. Pyrite, quartz and opaque minerals are disseminated in minor amounts through the rock.

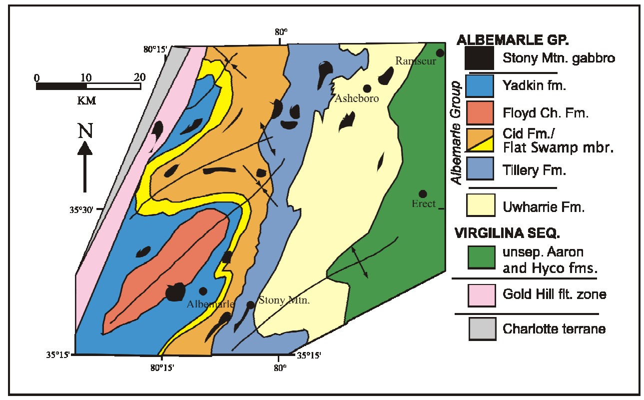

Figure 4. Geology of the Albemarle Group and Virgilina sequence.

The age of the Stony Mountain gabbro is constrained to the Early Cambrian-Late Ordovician. Intrusion took place after deposition of the early Paleozoic Yadkin Formation (maximum age ca. 532 Ma; Hibbard *et al*., this volume) but before a Late Ordovician (ca. 456 Ma) tectonothermal event responsible for upright folding and greenschist facies metamorphism in the Albemarle sequence (Offield *et al*., 1995).

LITHOGEOCHEMISTRY

Analytical techniques

Representative gabbro samples (n=23) from the Stony Mountain gabbro were submitted for whole-rock geochemical analysis. All samples have been metamorphosed to lower greenschist facies during regional metamorphism and where possible, samples with excessive alteration, veining, or weathering were discarded. Previous workers (Jenner, 1996) have demonstrated that the alkali-elements (Na, K, Ca), SiO_2 and the low field strength elements (LFSE: Rb, Ba, U, Cs, Sr) are mobile under these metamorphic conditions. Thorium, although by definition a LFSE, is however considered to be immobile during alteration and low-grade metamorphism. The rare earth elements (REE), high field strength elements (HFSE: P, Ti, Y, Zr, Nb, Hf, Ta), transition elements (Te-Sc, V, Cr, Co, Ni) and major element Al_2O_3 are considered to be immobile under low-grade alteration and metamorphic conditions. The exception however is Eu, which can be very mobile under most hydrothermal conditions.

Analyses of major-element oxides (recalculated to an anhydrous total of 100%) and selected trace elements

(Rb, Sr, Zr, Y, Nb, K, Ti) were performed on pressed powder pellets using X-Ray Fluorescence (XRF) spectrometry at the Department of Earth Sciences, Memorial University of Newfoundland. Analytical procedures, precision, accuracy and limits of detection are described by Longerich (1995). The REE and Th were determined by Na_2O_2 sinter dissolution, followed by solution and inductively-coupled plasma mass-spectrometry (ICP-MS) using the method of Longerich *et al*. (1990). The internal check of Zr and Hf analyzed by XRF and ICP-MS indicates that there were no dissolution problems with the Na_2O_2 sinter method. Precision in trace element analyses by XRF and ICP-MS, measured as percent relative standard deviation (%RSD), is observed as mainly excellent to good (0-7 %RSD); accuracy measured as percent relative difference (%RD) from IGRM standards is generally less than 8 %.

Alteration and element mobility

To assess the degree of silica and alkali-element mobility during hydrothermal alteration all samples are plotted on a total alkalies versus silica plot (Figure 5). The samples exhibit a large degree of scatter in SiO_2 that is most likely the result of silica mobility during hydrothermal alteration. Silica concentration generally decreases with hydrothermal alteration; in least altered rocks however, there is no correlation between SiO_2 content and indices of alteration (e.g. Ishikawa alteration index and Al_2O_3/Na_2O) suggesting that these rocks have largely retained their primary igneous SiO_2 contents.

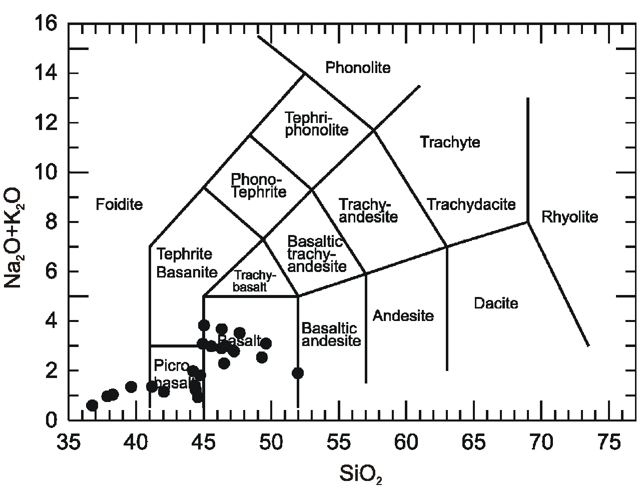

Figure 5. Total alkalies versus silica plot.

To asses the degree of spilitisation and K-metasomatism rocks are plotted (Figure 6) on a K_2O+Na_2O vs $K_2O/(K_2O+Na_2O)$ diagram of Hughes (1973). Most of the rocks lie within or near the igneous spectrum field suggesting that these easily mobilized elements have not been significantly altered by regional metamorphism. This alteration is also unlikely to have significantly fractionated the immobile trace elements. Previous studies (Coish, 1977; Coish *et al*., 1983; Alt and Emmermann, 1985) suggest that in rocks altered under low water/rock ratios, changes in the MgO/FeO ratio are considered to be small to negligible, thereby allowing this ratio to be used as an indication of primary igneous processes and differentiation index.

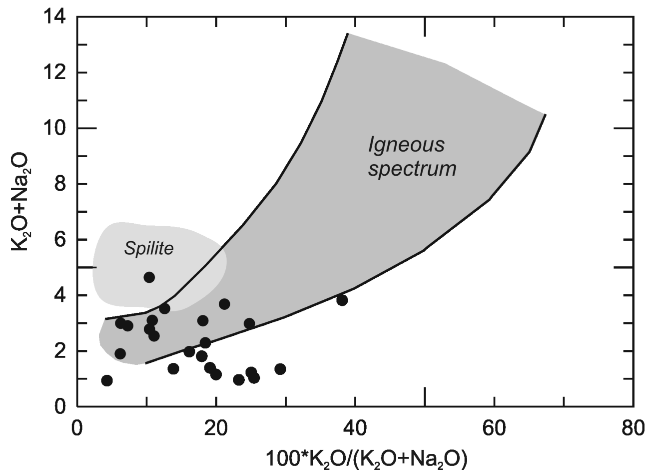

Figure 6. Modified Hughes (1973) plot illustrating Na and K changes during alteration of the Stony Mountain gabbro.

Geochemical characteristics

The rocks of the Stony Mountain gabbro have sub-alkaline basaltic compositions (Figure 7), contain between 0.2 to 1.5 per cent TiO_2 and have variable, but typically high MgO (8-20%), Ni (12-433 ppm) and Cr (16-1366 ppm) concentrations. They have major element compositions that range from high-Fe to high-Mg tholeiitic basalts (Figure 8). The Ni and Cr contents show a positive correlation with MgO, whereas the HFSE (i.e., Nb and Zr) increase with decreasing MgO. Mg# (Mg/(Mg+Fe)) range from 80-50 and imply that the rocks span the range from primitive to more evolved. The variation in Ni and Cr concentrations (Figure 9) is interpreted to be related to the degree of crystal fractionation. The rocks typically have Ni concentrations between 10 to 100 ppm, which is typical for island arc tholeiites with this MgO content (Gill, 1981). Many of the samples however, contain high Ni and MgO contents, and high Cr/Ni values (>3); features that are characteristics of boninites. On an AFM plot (Figure 10), the rocks show evidence for Fe enrichment; bivariant plots show that both V and Ti increase, whereas Cr decreases, with increasing degree of fractionation; all features characteristic of tholeiitic fractionation trends.

Rocks of the Stony Mountain gabbro are plotted on a series of discrimination diagrams using incompatible immobile trace elements to interpret the tectonic setting in which they formed. On the Ti vs. V plot (Figure 11 A) of Shervais (1982), all of the rocks plot in the normal island arc tholeiite (IAT) field and define a trend with chondritic Ti/V ratios (~15) with the least fractionated samples plotting at lower absolute abundances. On a ternary plot (Figure 11B) of Nb-Y-Zr (Meschede, 1986) most of the samples plot in the IAT field; the sample that that plots away from the Zr apex outside the volcanic arc basalt field and in the E-MORB field. Most samples plot (Figure 11 C) in the VAB field on a Nb-Hf-Th plot (Wood, 1980); however, they principally lie in the calc-alkaline not tholeiitic field. The major element and extended-REE data clearly demonstrate that these rocks are not calc-alkaline; this discrepancy is best explained by the relative depletion in Hf and Zr in these samples. To discriminate between arc and non-arc rocks the samples were plotted (Figure 11 D) on Swinden *et al.*'s (1989) plot of Nb/Th versus Y. The Stony Mountain samples have a clear arc geochemical signature and suggest derivation from a relatively refractory source.

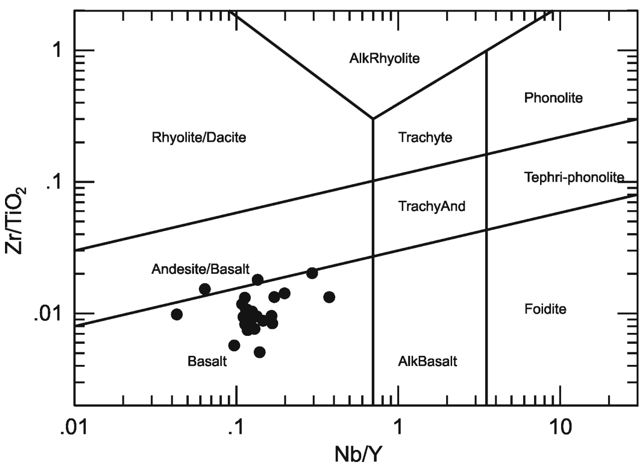

Figure 7. Lithology and subdivision into alkaline and sub-alkaline rocks using modified Winchester and Floyd (1977) Zr/TiO_2 vs Nb/Y plot of Pearce (1996).

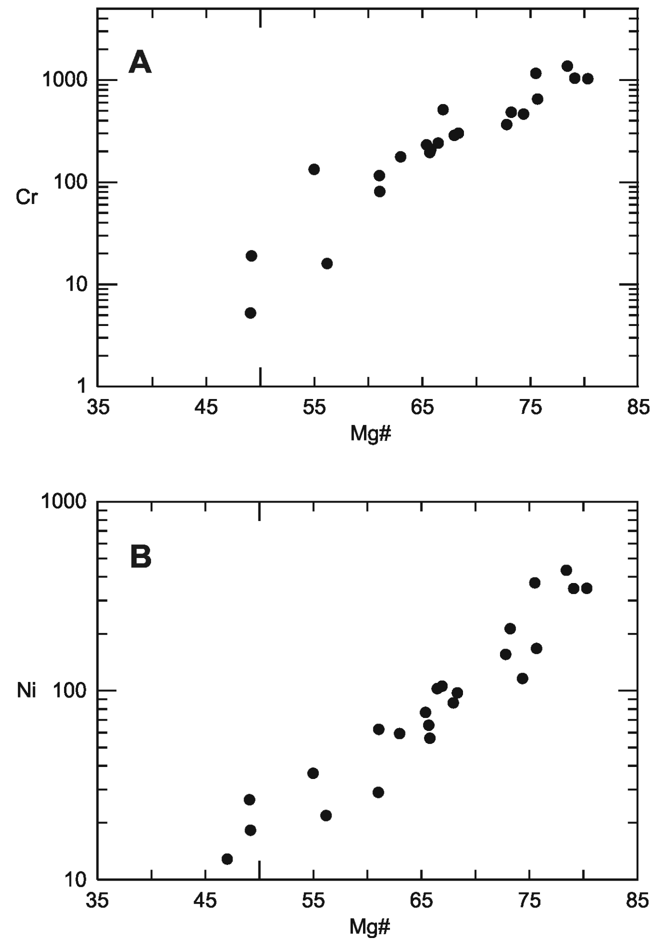

Figure 9. A) Log Cr vs Mg#; B) Log Ni vs Mg#.

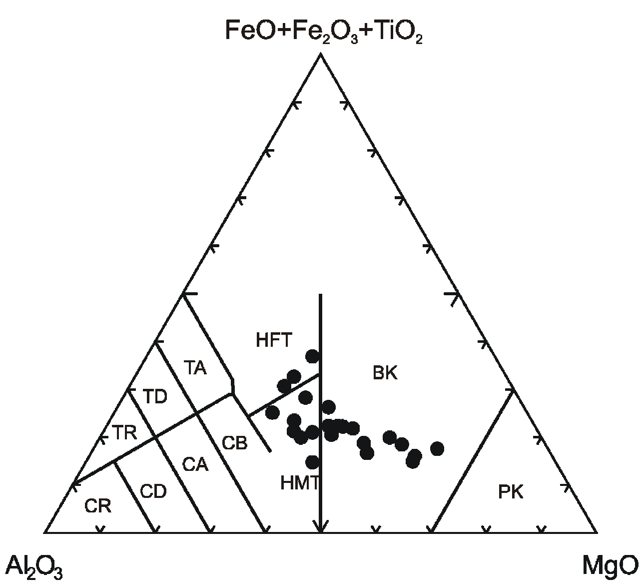

Figure 8. AFM ternary (cation percent) plot. HFT = high Fe tholeiite; HMT = high Mg tholeiite; BK = basaltic komatiite; PK = peridotitic komatiite; T = tholeiite; C = calc-alkaline, (A = andesite, B = basalt, D = dacite, R = Rhyolite).

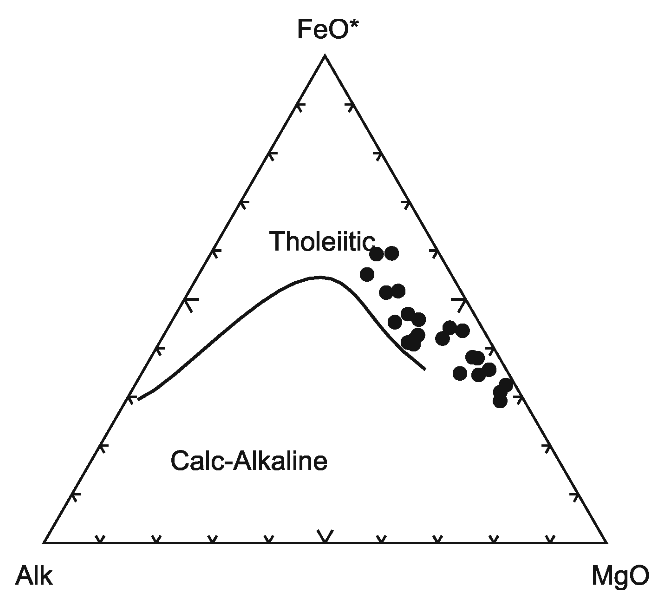

Figure 10. Definition of magma series using AFM diagram of alkalies ($Na_2O + K_2O$), Fe oxides ($FeO + Fe_2O_3$) and MgO.

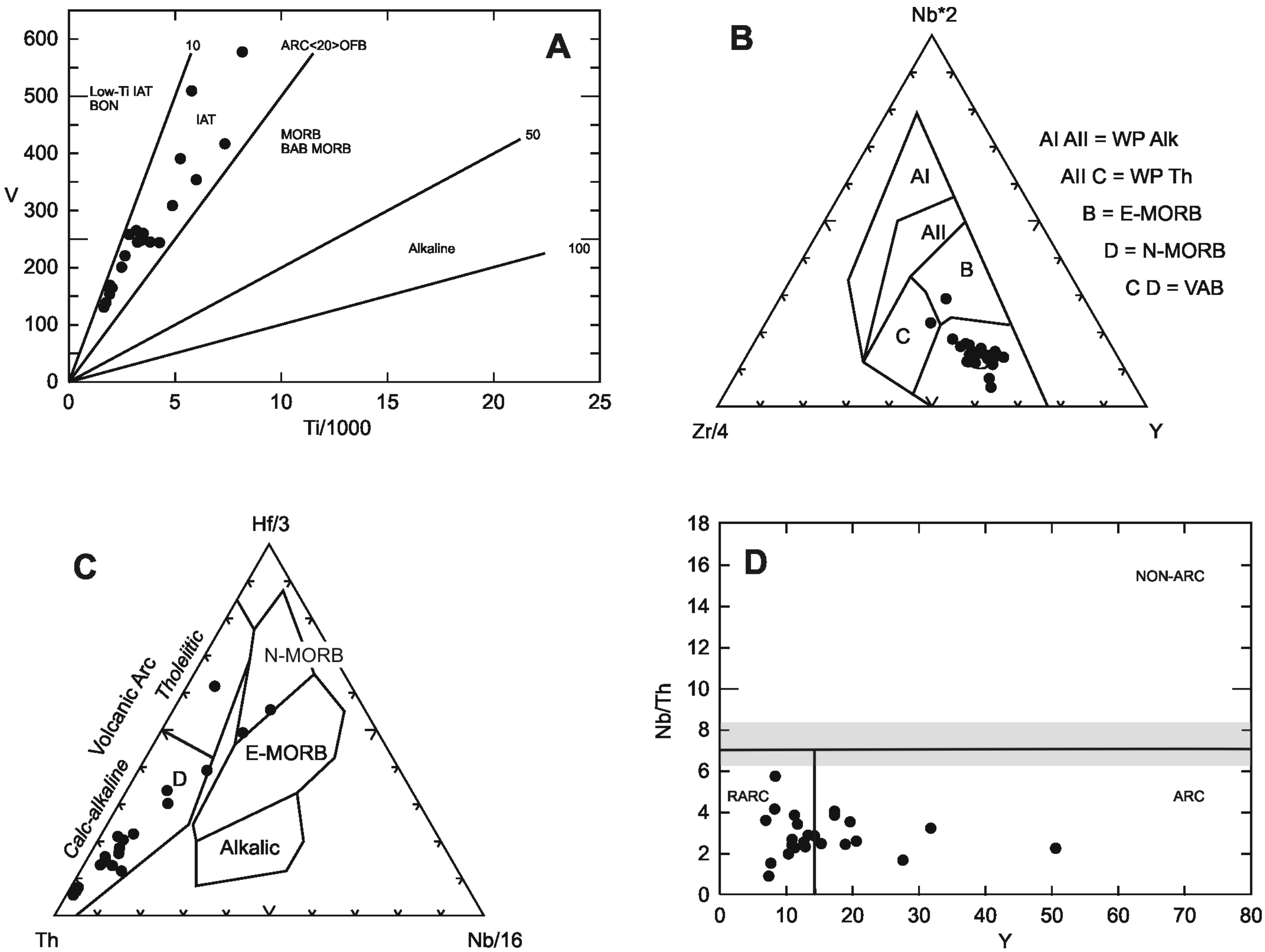

Figure 11. Tectonic discrimination diagrams. (A) Ti vs. V plot of Shervais (1982); (B) Nb-Zr-Y plot, with fields defined by Meschede (1986); (C) Zr-Nb-Th plot, with fields defined by Wood (1980); (D) Nb/Th vs Y diagram of Swinden *et al*. (1989) separating arc, non-arc and refractory arc magmatic rocks.

Although tectonic discrimination diagrams using highly incompatible immobile trace elements suggest an arc-related origin for the rocks of the Stony Mountain gabbro, ratios using the less incompatible elements (Zr, Ti, Y) indicate a non-arc origin in some of the samples (Figure 12). Plots involving Th, however, suggest an island arc-related setting (Figure 11 D). We propose that the ambiguity in the incompatible element ratios suggests a complex interaction of subducted crustal material and pristine mantle.

Primitive mantle extended REE patterns are presented in Figure 13 to illustrate the variety of REE patterns in the Stony Mountain intrusive suite. The data are characterised by an enrichment of the LFSE relative to the most incompatible HFSE and a depletion in Nb relative to La and Th, resulting in negative Nb anomalies. The data also show negative Zr relative to Sm and Nd, flat HREE patterns and differences in overall abundances relative to Mg#. The LREE ($[La/Yb]_n$ ~ 2.0-2.5) enrichment is also reflected in other ratios of more/less incompatible elements, namely Ti-V, Zr/Y and Nb/Zr that are to some extent higher than is typical of low-K tholeiites. The samples have essentially parallel patterns with the least primitive samples (lowest Mg#) having the higher element abundances, which is compatible with a suite generated by low-pressure fractional crystallization.

The average Nb/Ta values of the Stony Mountain gabbro are high while Ti/Sc ratios are low; both values are similar to rocks derived from the mantle or mantle-like sources (Taylor and McLennan, 1985; Barth *et al*., 2000). The HFSE, REE, Ni, Cr and Ti values, however, are typical of rocks derived from orogenic environments. We interpret the Stony Mountain gabbro to represent low to moderate degrees of multi-stage partial melting of depleted mantle peridotite which was metasomatized by a LFSE-enriched aqueous fluid or hydrous siliceous partial melt derived from subducted oceanic crust.

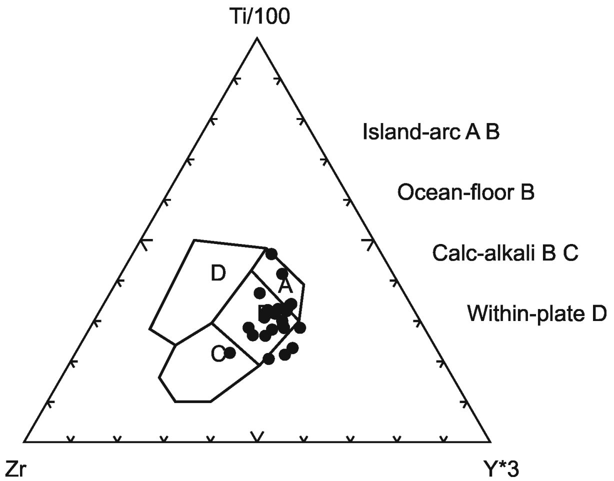

Figure 12. Ti-Zr-Y diagram of Pearce and Cann (1973).

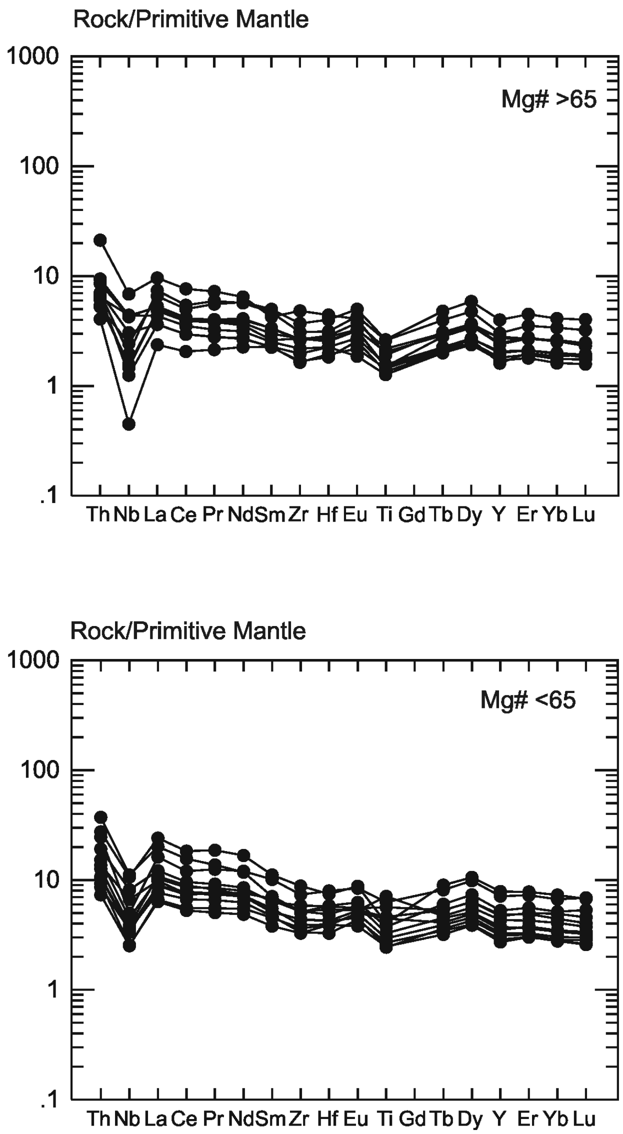

Figure 13. Primitive mantle normalized extended REE patterns showing the variation in trace element abundances at different Mg#. Primitive mantle normalizing values from Swinden *et al*. (1989).

DISCUSSION

The geochemical and geological features of the rocks of the Stony Mountain gabbro in central North Carolina are consistent with formation within a ~532 to 456 Ma island arc setting. The HFSE-depleted signatures coupled with negative Nb anomalies on primitive mantle extended REE diagrams are similar to those found in low-K to medium-K tholeiitic (Figure 14) rocks in modern island arc settings. Negative Nb anomalies are common features of rocks associated with subduction zones, due to the influx of LFSE into the mantle source regions from the subducted slab (Pearce and Peate, 1995). Ratios of fundamental HFSE in the Stony Mountain gabbro suggest the magmatism reflects low to moderate degrees of partial melting of depleted mantle contaminated by slab-derived crustal material in the mantle wedge.

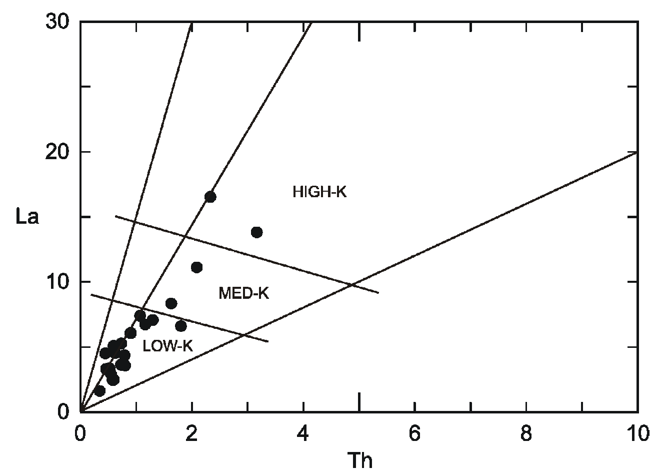

Figure 14. La vs Th discrimination diagram of low-, medium-, and high-K orogenic rocks (Gill, 1981).

The high MgO (>10), high Ni (>350 ppm), high Cr (> 1000 ppm) and low SiO_2 (<45%) in the samples with high Mg# (>70) suggest that these rocks are primary magma melts from the mantle that have not undergone significant high-level fractionation after segregation from their source. The increase in HFSE contents with progressive fractionation suggests a control by low pressure crystallization of olivine + plagioclase ± clinopyroxene phases. The low overall abundances of the HFSE are in all probability the result of remelting of an already depleted mantle lherzolite. Previous workers (Sun and McDonough, 1989) have demonstrated that the mantle and rocks derived from the mantle normally have Nb/Ta ratios of ca. 17.5, while the continental crust typically has lower Nb/Ta values of around 11 to 12. Rocks of the Stony Mountain gabbro generally have high Nb/Ta values (15.5-28.6) that imply derivation from mantle or mantle-like sources. This interpretation is also supported by Ti/Sc data. Mafic and mantle-derived rocks will have lower Ti/Sc values than felsic sources because Sc is more compatible than Ti. The rocks of the Stony Mountain gabbro have low

Ti/Sc values (59-255) that suggest derivation from mantle sources.

Evidence for a crustal input during emplacement, either through subducted slab metasomatism or crustal contamination, is provided by the characteristic island-arc related enrichment of LFSE which suggests that an incompatible element enriched fluid was added to the mantle prior to melting. The low Nb/Ta values (~13) also suggest input of a crustal or crustal-derived component that in all probability was a hydrous fluid or water-saturated silicate melt. Th/Nb–Zr systematics (Figure 15) also suggest a crustal influence, as all of the samples have high Th/Nb values at a given Zr content which is typical of magmas that have undergone crustal contamination. An equally possible alternative scenario for the Nb-Ta-Th behaviour is that the Stony Mountain gabbro formed from mantle-like mafic crustal sources in the basement to the island arc. Isotopic and geochronological studies indicate that Neoproterozoic rocks of the Albemarle Group were formed in a supra-subduction zone setting that was built upon a composite ca. 1 Ga basement; the evidence includes evolved geochemical and isotopic features exhibited by volcanic rocks with early Neoproterozoic to middle Mesoproterozoic model ages (Muller *et al*., 1996; Ingle-Jenkins *et al*., 1999) and the presence of Mesoproterozoic xenocrystic zircons in supracrustal rocks (Muller *et al*., 1996). Nd isotope data from the Stony Mountain gabbro are required to further elucidate either scenario.

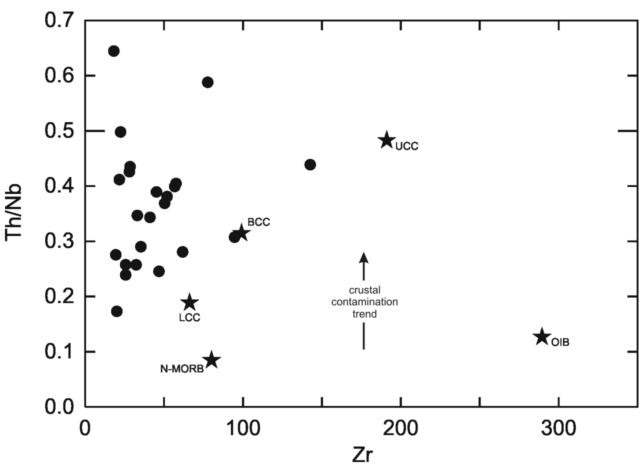

Figure 15. Th/Nb versus Zr plot of Piercey *et al*. (2002) showing the influence of crustal contamination on rocks of the Stony Mountain Gabbro. LCC, BCC, and UCC, lower, bulk, and upper continental crust, respectively from Taylor and McLennan (1985).

TECTONIC IMPLICATIONS FOR CAROLINIA

Our data require substantial revision of extant tectonic models for the early Paleozoic history of the Appalachian peri-Gondwanan realm. The recognition of rocks of island-arc affinity in the Stony Mountain gabbro suggests that subduction-related arc magmatism in Carolinia did not terminate with deposition of the late Neoproterozoic-earliest Cambrian volcanic sequences of the Carolina terrane, but continued with a younger episode of island arc magmatism that occurred in the Cambrian and potentially the Early to Middle Ordovician. The presence of an island arc in Carolinia during the early Paleozoic is critical for along strike correlation of peri-Gondwanan terranes in the Appalachians because Carolinia has traditionally been correlated with Avalonia. These comparisons have usually been based on the presence in both of Neoproterozoic felsic-dominated magmatic-sedimentary sequences, which have led many workers (Williams and Hatcher, 1983; Nance *et al*., 2002; Ingle *et al*., 2003) to consider these two first order crustal blocks as representing fragments of a single peri-Gondwanan microcontinent. However, on the basis of their detailed lithotectonic records, other workers (Samson, 1995; Hibbard *et al*., 2002; Hibbard *et al*., in press) suspect that Carolinia and Avalonia have distinct tectonic histories in the late Neoproterozoic-early Paleozoic and likely represent separate independent crustal blocks.

In Avalonia, arc magmatism ceased in the Neoproterozoic (ca. 565 Ma) with the transition from an arc to a San Andreas-type transform setting (Nance *et al*., 2002) followed by Early Cambrian development of a shale-dominated platformal sedimentary succession with laterally extensive lithostratigraphic units (Landing, 1996) that was tectonically undisturbed until the Late Silurian-Early Devonian. In contrast, our data from the Stony Mountain gabbro, plus that of Ingle *et al*. (2003), suggest that arc-related magmatism in Carolinia did not terminate in the late Neoproterozoic, but continued into the early Paleozoic and was deformed by the Late Ordovician-Silurian accretion of Carolinia to Laurentia. Both Carolinia and Avalonia also have significant faunal, paleomagnetic, isotopic, and tectonothermal contrasts (Hibbard *et al*., 2002; Hibbard *et al*., in press) suggesting that they represent paleogeographically distinct elements in the late Neoproterozoic-early Paleozoic.

Collectively, these data in Carolinia argue against the conventional correlation with Avalonia and suggest that the Carolinia may be more closely associated with Ganderia. The recognition of early Paleozoic arc-related magmatism in Carolinia correlates with Ganderia. The latter comprises a sequence of Cambrian-Lower Ordovician quartz arenite and shale that unconformably overlies Neoproterozoic volcanic-plutonic and Cambrian arc-related volcanic rocks (Rogers *et al*., 2006). Ganderia, like Carolinia was significantly deformed and metamorphosed during the Late Ordovician-Early Silurian accretion to Laurentia (van Staal *et al*., 1996, 1998). Although both Carolinia and Ganderia share common features in their first order geological and tectonic characteristics, it remains to be seen if they represent two independent peri-Gondwanan microcontinents or diverse tectonic regimes along different margins of a single crustal block.

ACKNOWLEDGMENTS

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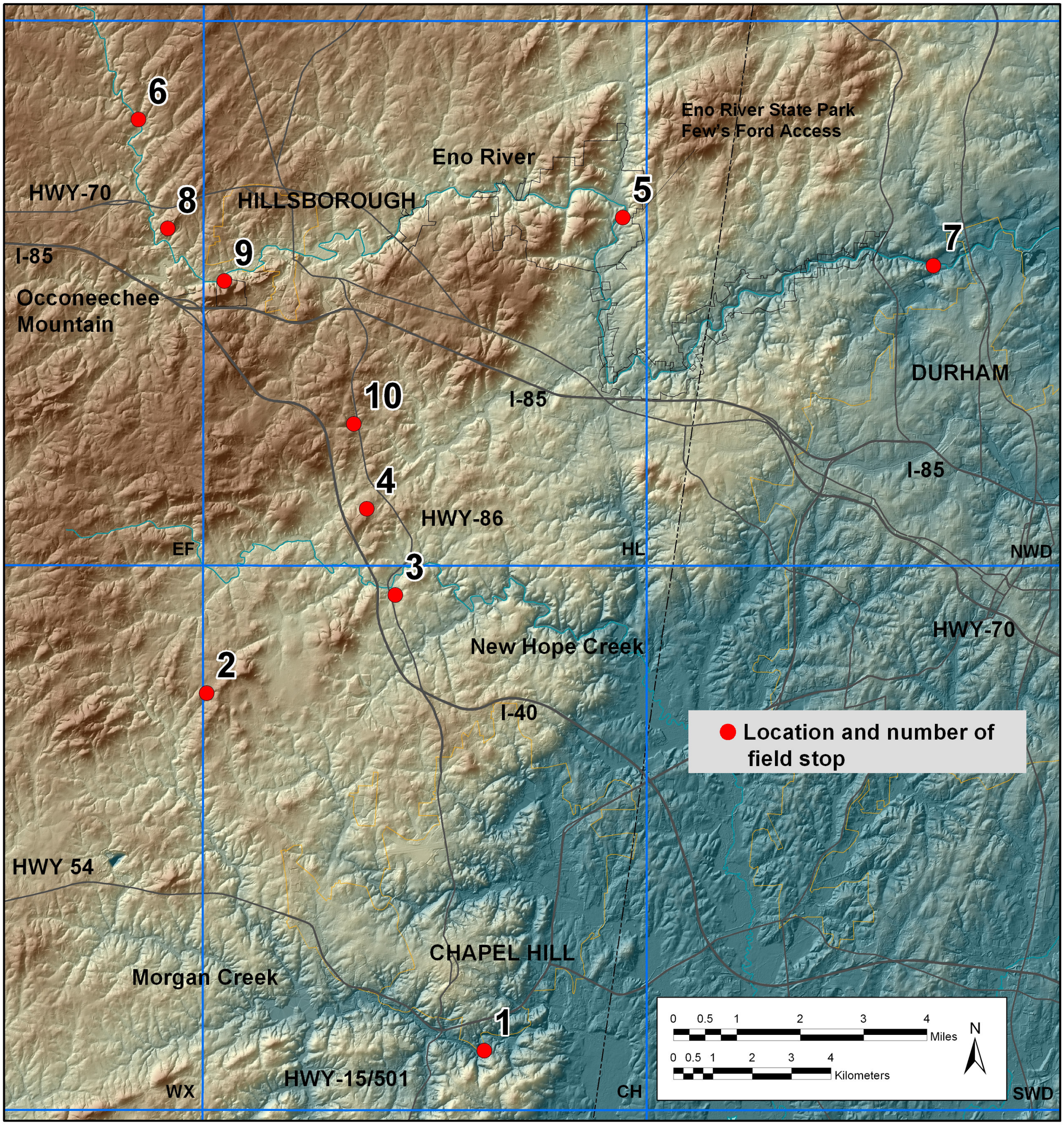

Figure 1. 2006 Carolina Geological Society field trip stops. Quadrangle names: WX – White Cross, CH – Chapel Hill, SWD – Southwest Durham, EF – Efland, HL – Hillsborough, NWD – Northwest Durham. Base map is from LiDAR hillshade data of Orange and Durham Counties.

Carolina Geological Society Field Trip
November 4-5, 2006

FIELD GUIDE

FIELD TRIP GUIDE TO THE GEOLOGY OF THE CHAPEL HILL, HILLSBOROUGH AND EFLAND 7.5-MINUTE QUADRANGLES: CAROLINA TERRANE, NORTH CAROLINA

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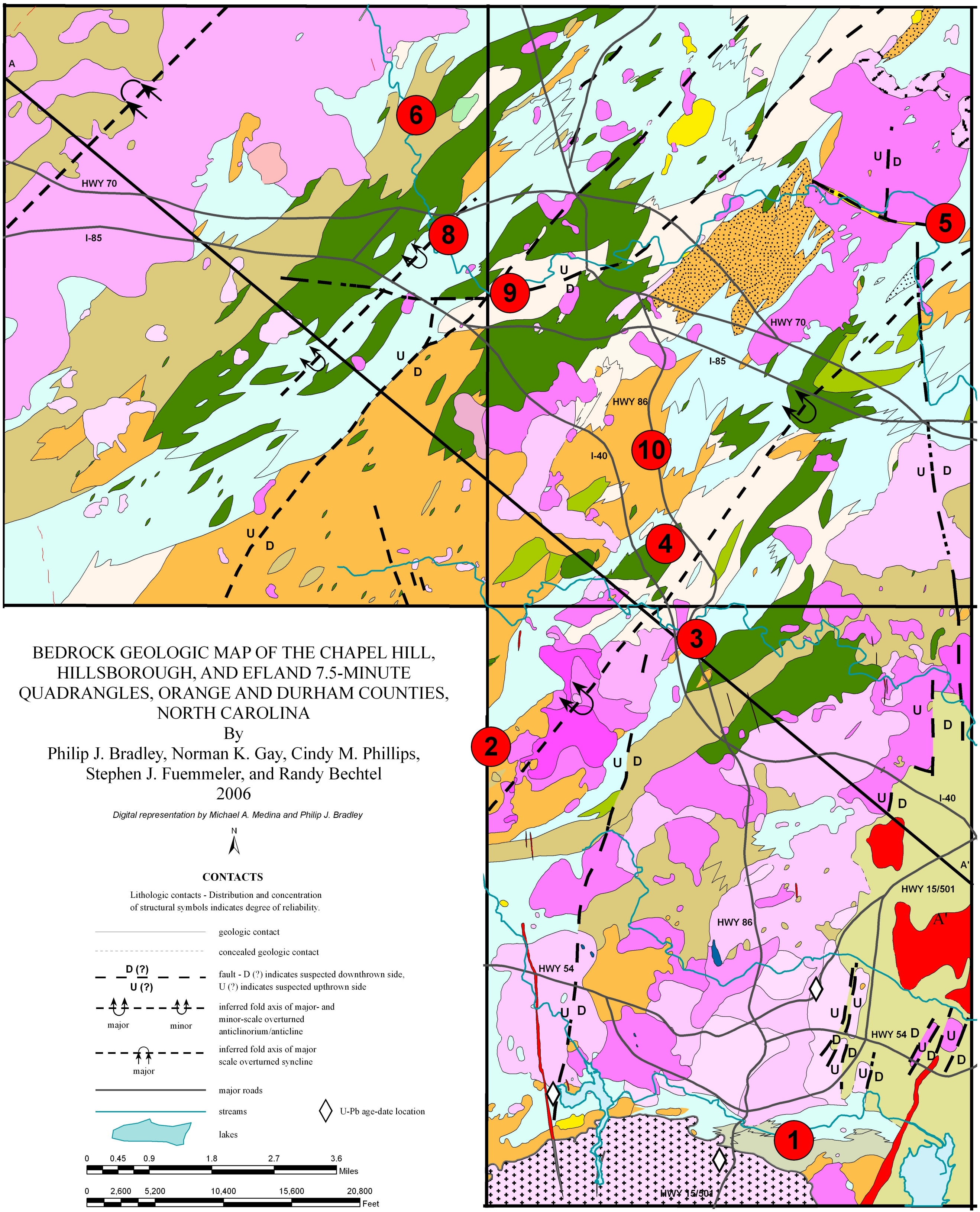
INTRODUCTION

The 2006 Carolina Geological Society Field Trip consists of 9 stops and one alternate stop. The objectives of the field trip are to examine primary pyroclastic and epiclastic rocks of the Chapel Hill, Hillsborough and Efland 7.5-minute quadrangles, North Carolina. The field trip transects a regional-scale anticlinorium (identified as the Hillsborough Anticlinorium) that exposes Late Proterozoic aged volcano-sedimentary and intrusive rocks of the Virgilina Sequence. A mixture of dominantly primary pyroclastic rocks and lavas of the Hyco formation are exposed in the core of the anticlinorium with epiclastic lithologies of the Aaron formation dominating the flanks of the anticlinorium. Intrusive rocks complexly intrude the volcano-sedimentary sequence. For details of the geology of this area, see Bradley et al. (this guidebook).

Few's Ford in Eno River State Park (Stop5) was first visited during the 1964 Carolina Geological Society Field Trip (Bain et al., 1964). The 1964 field trip also visited the Duke quarry located on the west side of the Eno River. This quarry, now identified as the "Old" Duke Quarry, was active in 1964 and is now abandoned. This field trip will visit the active ("New") Duke quarry (Stop 8) located on the east side of the Eno River. All stop locations are shown on the regional index map (fig. 1). A composite bedrock geologic map of the Chapel Hill, Hillsborough and Efland quadrangles (Bradley et al., 2004, Bradley and Gay, 2005 and Bradley et al., 2006) is provided as Figure 2 with field trip stop locations. Stop 7 is located on the Northwest Durham 7.5-minute Quadrangle and is not depicted on Figure 2. Figure 3a presents a cartoon drawing of a simplified schematic cross-section of the area with the generalized locations of the field trip stops indicated. Figure 3b presents a cartoon drawing of the simplified interpreted environment of deposition with field trip stops.

Note: The prefix "meta" is not included in the nomenclature of pre-Mesozoic rocks. All pre-Mesozoic rocks have been subjected to at least the chlorite zone of the greenschist metamorphic facies. Latitude and longitude are provided for each stop. The data was collected via a recreational grade GPS (Global Positioning Satellite) receiver using the WGS 84 map datum.

Two field trip stops are on State protected lands in Eno River State Park and Occoneechee State Natural Area. The use of hammers and the collection of rocks is not allowed at these locations. Additionally, many of the stops are on private land. Please respect the property owners land and ask permission to access the outcrops before entering onto private property.



BEDROCK GEOLOGIC MAP OF THE CHAPEL HILL, HILLSBOROUGH, AND EFLAND 7.5-MINUTE QUADRANGLES, ORANGE AND DURHAM COUNTIES, NORTH CAROLINA

By

Philip J. Bradley, Norman K. Gay, Cindy M. Phillips, Stephen J. Fuemmeler, and Randy Bechtel

2006

Digital representation by Michael A. Medina and Philip J. Bradley

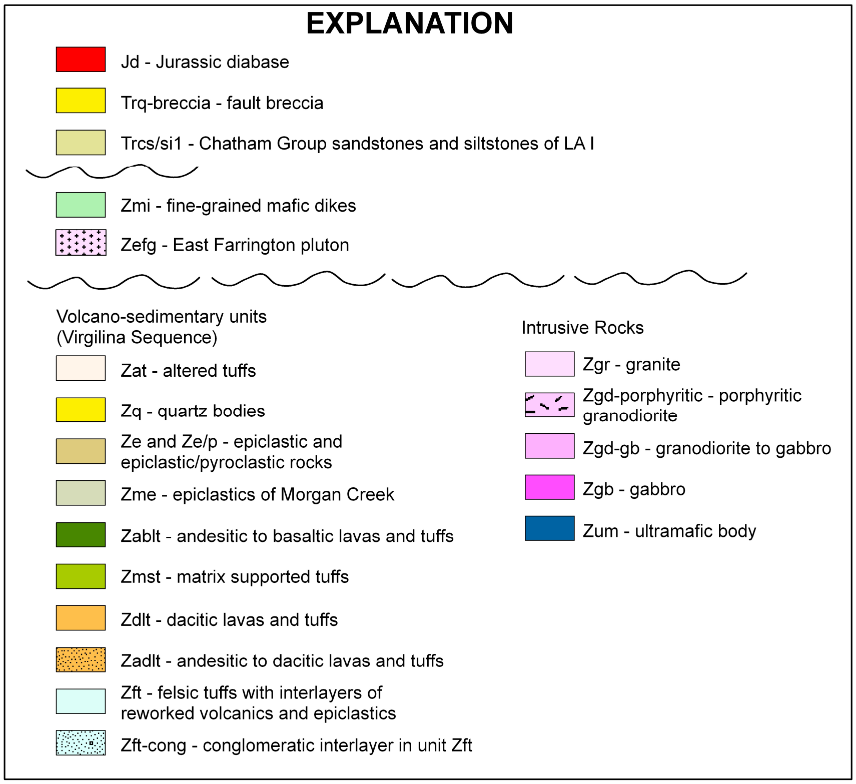


Figure 2. Field trip stops on composite bedrock geologic map of the Chapel Hill, Hillsborough and Efland 7.5 minute quadrangles, Orange and Durham Counties, North Carolina.

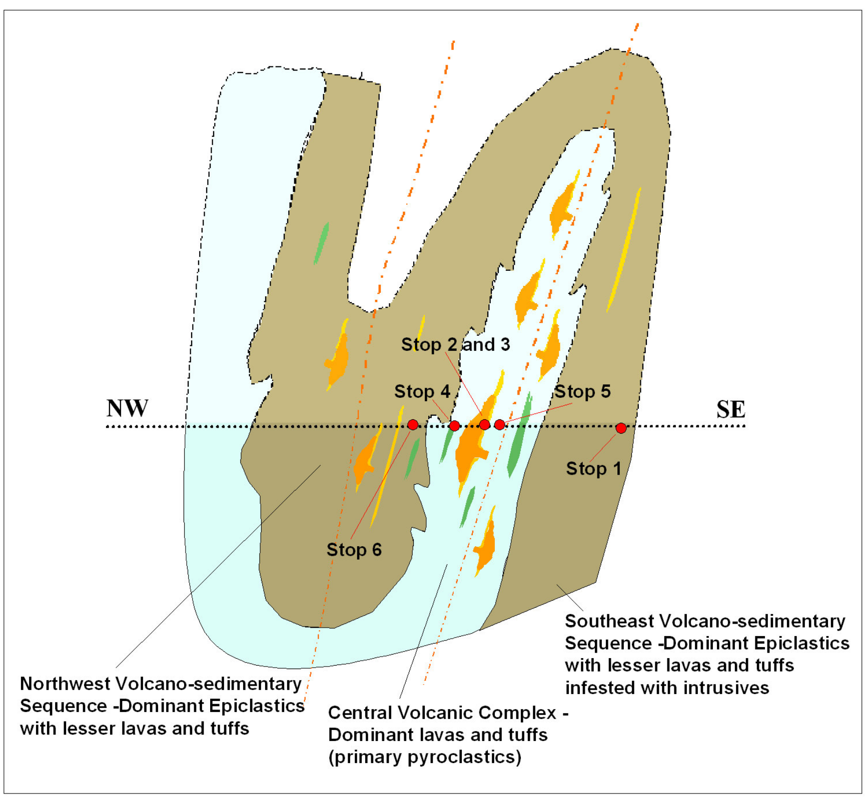
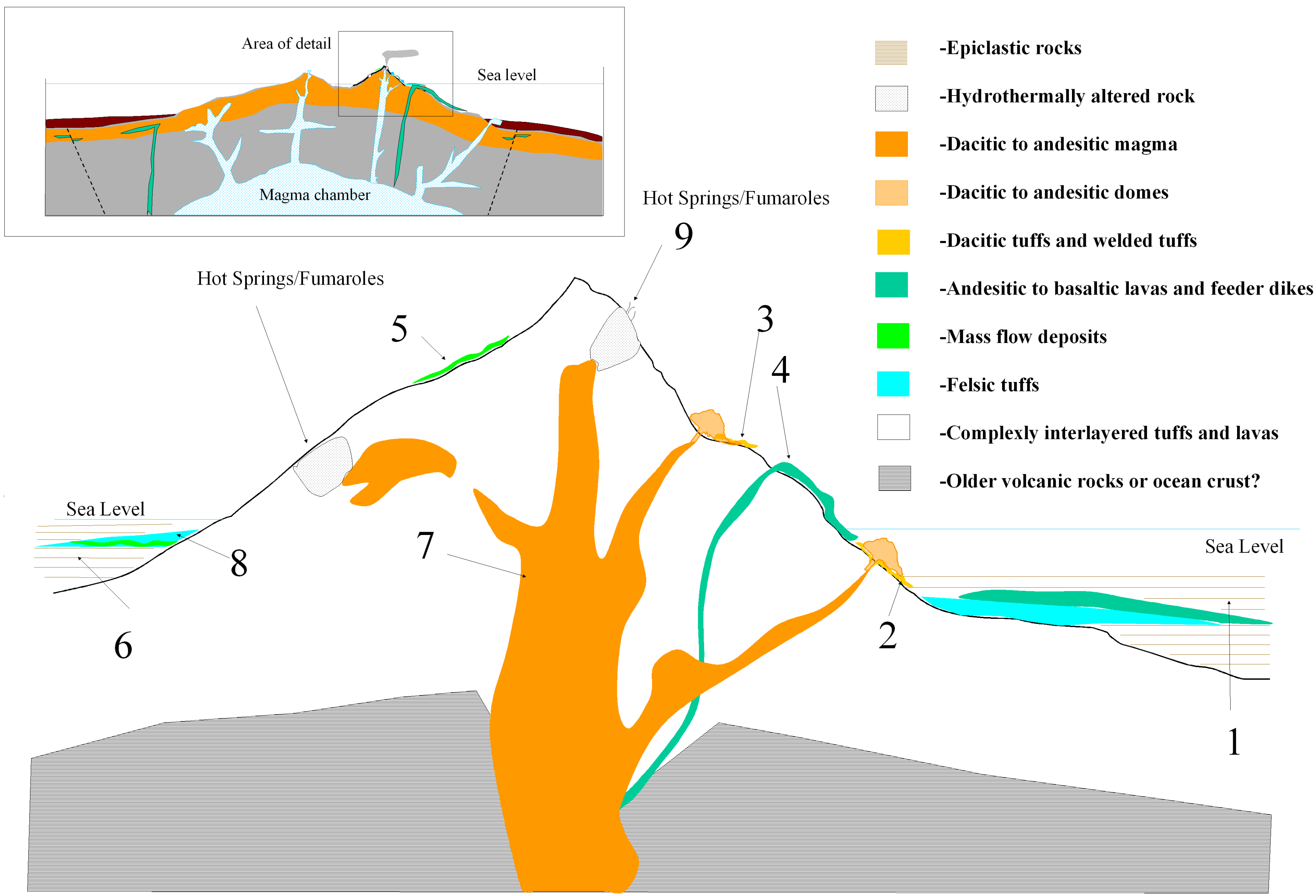


Figure 3a. Cartoon drawing of schematic cross-section of study area through the Hillsborough anticlinorium with relative field trip stop locations 1 through 6.



3b. Cartoon Drawing of Simplified Interpreted Environment of Deposition of Field Trip Stops

DAY 1:
SATURDAY, NOVEMBER 4, 2006

Stop 1: Thinly bedded siltstone exposed in Morgan Creek.
Lat. – 35.88868°, Long. – 79.04568°

Purpose: To examine an example of epiclastic rock of the southeast volcanosedimentary sequence and examine the structural trend of rocks (fig. 4).

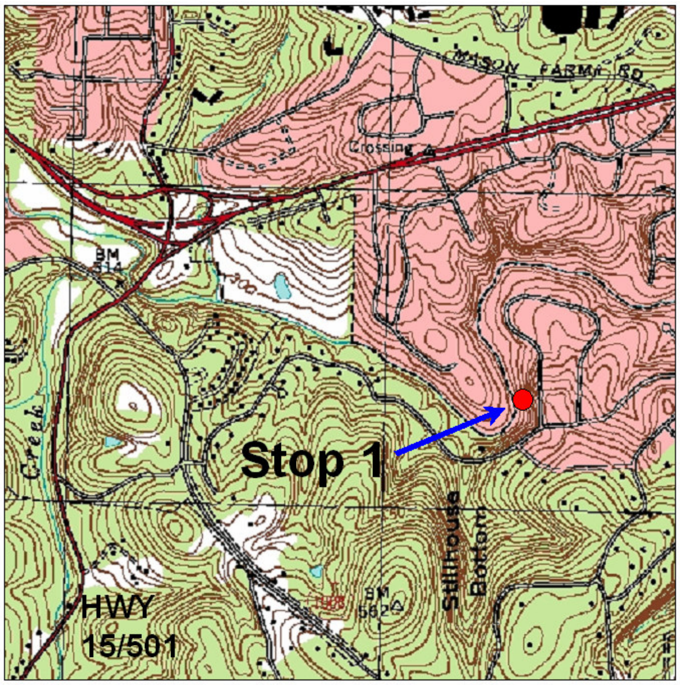


Figure 4. Location of Stop 1 in the Chapel Hill 7.5-minute quadrangle.

Lithologies: The outcrop consists of thinly bedded to very thinly bedded siltstones with lesser amounts of sandstone. Thin 1 to 2 cm thick layers of fine tuff are also present. Grain-size grading indicates that stratigraphic up is to the southeast assuming normally graded deposits. A fine-grained diorite dike ranging from 4-6 feet wide is exposed in the east wall of the outcrop area and can be traced west through the outcrop. The dike appears to cross-cut the metamorphic cleavage of the siltstones. Conglomeratic sandstones and conglomerates interlayered in this unit contain abundant clasts of primary volcanics including: porphyritic and flowbanded lavas; felsic tuffs; welded felsic tuffs as well as clasts of granodiorite and diorite. Clast lithologies are identical to the primary volcanic rocks exposed further to the north in the central volcanic complex in the Hillsborough area. To the west, this unit interfingers with primary pyroclastic rocks.

This outcrop is located within a north trending jog of Morgan Creek. Layering and cleavage are nearly perpendicular to the trend of the creek. Layering at this location and other outcrops along Morgan Creek are east-northeast trending (approximately N75E) with 45 to 50 degree dips toward the southeast. Cleavage is oriented generally parallel to the layering and dips between 70 to 80 degrees toward the southeast. Layering and cleavage orientations are typically more northeasterly trending in locations away from Morgan Creek.

Interpretation:

Environment of deposition – The thinly bedded nature of the siltstones suggest sedimentation below wave base. The presence of clasts of primary volcanic rocks in the more conglomeratic layers of this unit coupled with the presence of primary pyroclastic tuffs interfingered with this unit to the west along Morgan Creek suggest that this unit represents the penecontemporaneous erosion of a volcanic complex with active volcanism. The epiclastic rocks are correlative with the Aaron formation of Harris and Glover (1988). Harris (1984) interpreted that the Aaron formation was deposited in a retrogradational submarine-fan setting, below storm-wave base. He interpreted the environment of deposition as a deep marine basin marginal to or superimposed on a formerly active volcanic arc.

Structure - The bedding and cleavage orientations indicate that this location is on the southeast limb of an anticline. Morgan Creek exposes a relatively thin strip of volcano-sedimentary rocks sandwiched in between two plutonic bodies (Chapel Hill pluton to north and East Farrington pluton to south). The anomalous trend (ENE) of these rocks may be due to rotation during intrusion of the plutonic rocks located both to the north and south. Mesozoic faulting and subsequent fault block rotation may also account for the anomalous trend.

The cross-cutting dike at this location appears unfoliated and truncates the steeply dipping cleavage of the siltstone. Although undated, the dike may be related to the 578.7 +/- 5.5 Ma East Farrington pluton (Tadlock and Loewy, this guidebook). If this dike is related to the East Farrington pluton, the regional foliation developed prior to circa 579 Ma and is possibly related to the Virgilina deformation of Glover and Sinha (1973). Similarly, Hibbard and Samson (1995) interpret the regional foliation in the Virgilina sequence to be attributed to the Virgilina deformation in the Roxboro, North Carolina area.

Stop 2: Dacitic tuff and lithic tuff interlayered with thin layers of volcanic sandstone.
Lat. – 35.97098°, Long. – 79.12425°

Purpose: To examine an example of a primary pyroclastic lithology within the central volcanic complex and the structure of rock units.

Lithologies: This stop (fig. 5) contains outcrops of interlayed dacitic crystal tuff and lithic crystal tuffs and layers of volcanic sandstone. Crystal tuffs consist of abundant plagioclase crystal shards and lesser amphibole (hornblende) crystal shards in a fine-grained ash matrix (now recrystallized to a microcrystalline mosaic of quartz and feldspar). Clasts within the lithic tuff layers range from 1 mm up to 25 cm in diameter and are composed of plagioclase porphyritic dacite. Lithic crystal tuff is interlayered with fine-grained volcanic sandstone with cuspate load structures marking the contact with the tuffs. This location was described by Chiulli (1987) as part of a master's thesis under the direction of Bob Butler at UNC-Chapel Hill.

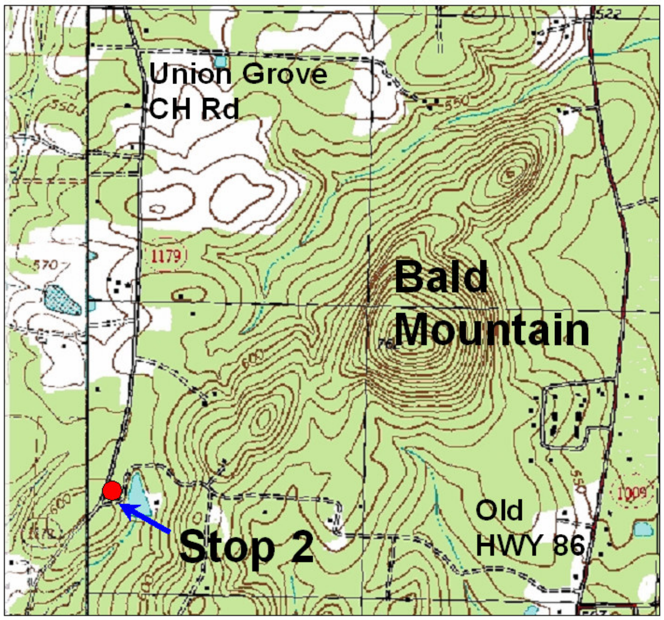


Figure 5. Location of Stop 2 in the Chapel Hill and portion of White Cross 7.5-minute quadrangles.

Interpretation:
Environment of deposition – These outcrops are interpreted as pyroclastic debris ejected from a dacitic dome or dome complex and proximally deposited in water. The cuspate load structures may indicate episodic deposition of volcanic ejecta in thick (<1 to 3 m) massive beds. This outcrop is part of a unit of interlayered dacitic tuffs, lavas and shallow intrusive bodies that extends for over 6,000 feet to the northwest and includes Bald Mountain. Bald Mountain, located approximately 3,000 feet along strike to the northeast in the Blackwood Division of Duke Forest, is a resistant knob with an elevation of approximately 760 feet making it the highest point within the Chapel Hill quadrangle. Bald Mountain is composed of plagioclase + quartz porphyritic dacite and flow banded dacite and tuffs. The rocks that compose Bald Mountain are interpreted as a dacitic dome or composite dome complex and may have been the source for the pyroclastic debris at this stop.

Structure - The cuspate load structures indicate that stratigraphic up is to the northwest. This outcrop occurs on the northwest limb of an anticlinal structure within the central volcanic complex.

Stop 3: Outcrop of welded crystal tuff located at cross roads of Blackwood.
Lat. – 35.99331° Long. – 79.07096°

Purpose: To examine an example of a primary pyroclastic lithology within the central volcanic complex.

Figure 6. Location of Stop 3 in the Chapel Hill 7.5-minute quadrangle.

Lithology: This stop (fig. 6) is a good example the felsic tuffs of the Blackwood area (Zft-b) unit. The outcrop consists of resistant fins of welded tuffs and lesser amounts of welded lithic tuffs. Plagioclase and quartz crystal shards compose approximately 15-20% of the rock. Clasts range from 2 mm up to 3 cm. The rock exhibits a distinct planar fabric defined by aligned clasts and thin fiamme-like lenticular shaped clasts that are interpreted as flattened pumice or relict glass shards. Weathered-out lithic fragments and fiamme-shaped clasts (1-10 mm long) give the surface of rock perpendicular to the cleavage a pock-marked appearance and defines the primary welding/compaction foliation. The welding/compaction foliation trends approximately N30 to 45E and dips approximately 85 to 88 degrees to the northwest. A metamorphic cleavage is also present with a strike generally parallel to welding/compaction and a dip of approximately 80 to 85 degrees to the southeast. In thin-section, embayed quartz grains and sericitized feldspar crystals are present in a fine-grained relict ash matrix. A strong compaction/welding foliation is evident by the deflection of aligned matrix material near the edges of larger crystals (fig. 7). A small outcrop of phyllite is exposed along the railroad tracks near this stop.

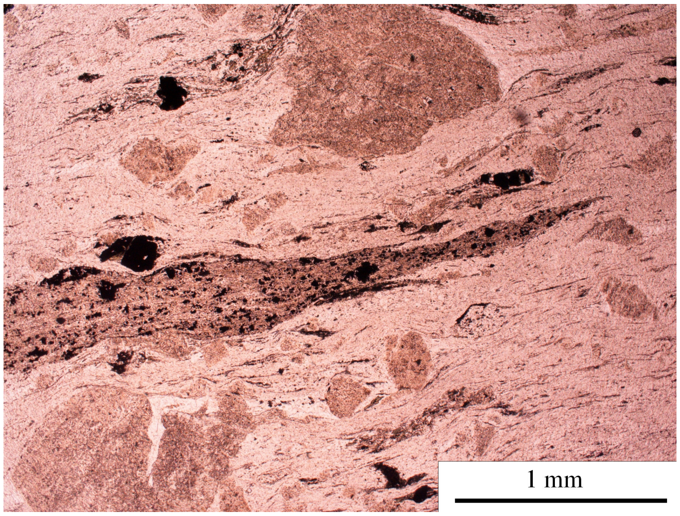


Figure 7. Thin section of welded tuff from Stop 3 showing fiamme-shaped lithic clast and strong welding/compaction foliation. Plane polarized light with 25x magnification.

The welded tuffs of this unit are generally indistinguishable from welded tuffs intermingled with dacitic lavas of the Zdlt unit. These rocks and others like them were designated as a distinct unit due to the absence of abundant interlayered lavas and absence of larger size lithic clasts. The unit is commonly in close proximity with Zdlt map units.

Whole rock geochemistry data of a sample from a nearby outcrop (sample CH-6) within this unit indicates a rhyodacitic composition (fig. 8). A sample of plagioclase + quartz porphyritic dacite (CH-1260) collected from Bald Mountain plots close to sample CH-6 and may imply a genetic relationship. The majority of fine-grained felsic extrusive rocks analyzed for whole rock geochemistry plot within the dacite field of the IUGS QAP ternary plot. Sample CH-6 may have been partially altered causing it to have an apparent rhyodacitic composition.

Interpretation: The welding/compaction foliation is interpreted to be a primary feature of the rock. For welding to occur, the magmatic heat of the ash deposit must be high enough to sufficiently sinter together the tephra clasts. Deposition in water results in rapid quenching and is unlikely to allow for welding. Therefore, this unit is interpreted to have been deposited in a subaerial environment associated with more distal portions of dacitic (rhyodacitic) domes. The source domes were sufficiently distal to not contribute large-sized clasts. Red colored lavas and welded tuffs suggestive of a subaerial environment are commonly present with the dacitic dome deposits with in the central volcanic complex. The abundance of welded tuff units may be due in part to their resistance to erosion and preferential preservation in the geologic record.

Arsenic content of rock: As part of an ongoing collaborative study into the source and distribution of naturally-occurring arsenic in Orange County with researchers from Duke University, Orange County, and NCDENR Aquifer Protection Section, the North Carolina Geological Survey analyzed the arsenic content of rock samples from multiple locations in the study area. Analyses via X-ray fluorescence indicated the presence of arsenic at a concentration greater than the detection limit of 3 parts per million (ppm) in 21 of the 27 samples analyzed. Detected concentrations ranged 3 to 42 ppm. In addition, groundwater collected from private potable wells throughout Orange County detected concentrations of dissolved arsenic ranging from 1 part per billion (ppb) up to 23 ppb. The whole rock data appear to indicate that arsenic is ubiquitous in the volcano-sedimentary rocks in the low ppm concentrations. The understanding of the mechanism of the liberation of arsenic into the groundwater and the apparent sporadic occurrence in groundwater samples is not well understood.

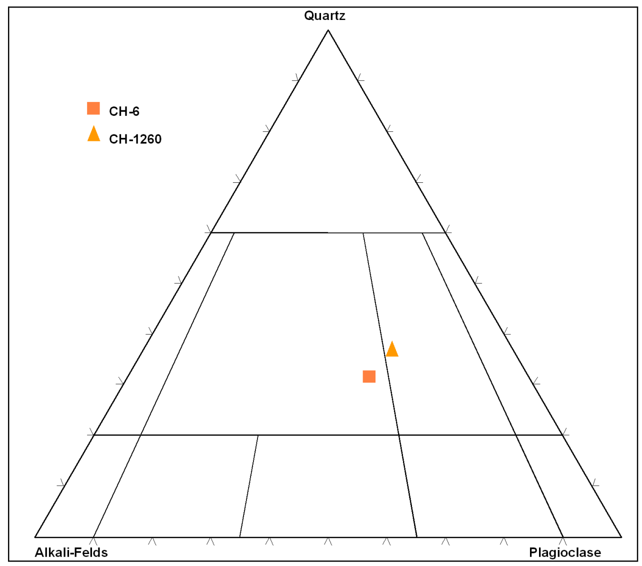


Figure 8. QAP whole rock analyses plot. Sample CH-6 is a welded tuff similar to stop 3 (NCGS sample CH-6). Sample CH-1260 was collected from the top of Bald Mountain (NCGS sample CH-1260) in the Chapel Hill quadrangle.

Preliminary statistical analyses performed by researchers at Duke University in the Children's Environmental Health Initiative program of the Nichols School for the Environment appear to indicate that the detection of arsenic in individual wells is more likely when the well is closer to the transition zones between the central volcanic complex and the adjacent northwest and southeast volcano-sedimentary sequences. These transition zones may have created favorable alteration horizons that increase the likelihood of arsenic detection similar to the gold and base-metal mineralization horizons of Feiss et al. (1993). Additionally, the proximity of a well to an intrusive body, mafic lava or dacitic dome complex may also increase the likelihood of the detection of groundwater arsenic.

Stop 4: Outcrops of amygdaloidal basalt located on New Hope Trace Road.
Lat. – 36.01245° Long. – 79.07928°

Purpose: To examine outcrops of amygdaloidal basalt exposed along the eastern frontage of New Hope Trace Road. Andesitic to basaltic lavas and associated pyroclastic rocks are common in the Hillsborough area.

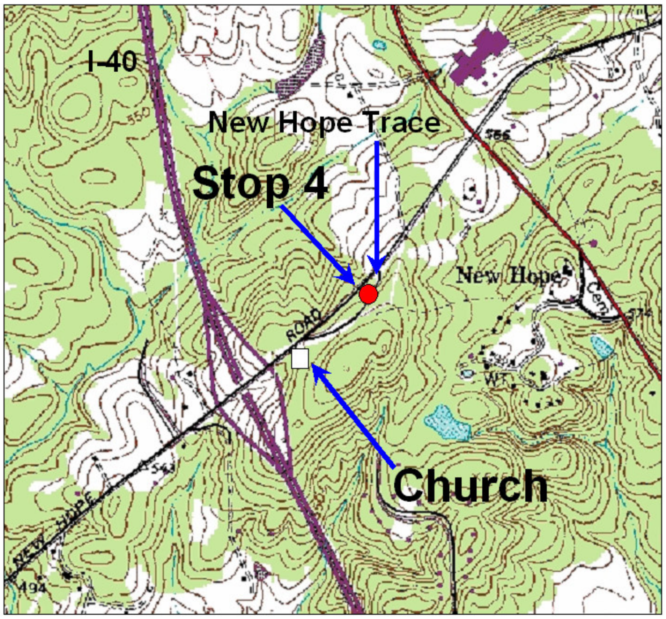


Figure 9. Location of Stop 4 in the Hillsborough 7.5-minute quadrangle.

Lithology: This outcrop area (fig. 9) is part of an approximately 0.5 by 1.5 mile, northeast-trending body of basalt and associated interlayered tuffs (Zablt). Two outcrop areas are present along the frontage of Trace Road along private property. The outcrops are fine-grained greenstone with abundant amygdules. Black, 1 to 4 mm, round-shaped masses of fibrous actinolite are also present in some locations. Relict mineral grain outlines of these masses exhibit a prismatic shape suggesting that the grains are relict augite phenocrysts. Major minerals of the basalts are epidote, chlorite, plagioclase, quartz, and opaques. Plagioclase grains typically exhibit heavy sericite and epidote alteration.

Butler (1964) collected and conducted a chemical analysis on a sample (OC-28C) from the immediate vicinity of this stop. Wilson and Allen (1968) and Allen and Wilson (1968) interpreted the rounded weathering patterns of outcrops and spheroidally shaped structures in some of the mafic lavas as possible pillow structures.

Interpretation: Several similar maps-scale bodies are present within the central volcanic complex with lesser amounts of map-scale bodies located in the northwest and southeast volcano-sedimentary sequences. The basaltic units are interpreted as lava flows intercalated with dacitic pyroclastic units and volcano-sedimentary units. Sparse occurrences of plagioclase porphyritic basalts within map-scale bodies are interpreted as hypabyssal intrusions or dikes that may have feed the lava flows.

Lunch stop

Few's Ford picnic shelter

Stop 5: Few's Ford Access Area – Eno River State Park. Outcrops of tuff breccia interpreted to be lahar deposits.
Lat. – 36.07996° Long. – 79.00643°

Purpose: To examine an outcrop of tuff-breccia (fig. 10) interpreted as a lahar deposit and discuss effects of Mesozoic faulting in area.

This stop consists of extensive outcrops along the Eno River in the Few's Ford Access Area of Eno River State Park. ***The use of hammers and the collection of rock samples is prohibited!***

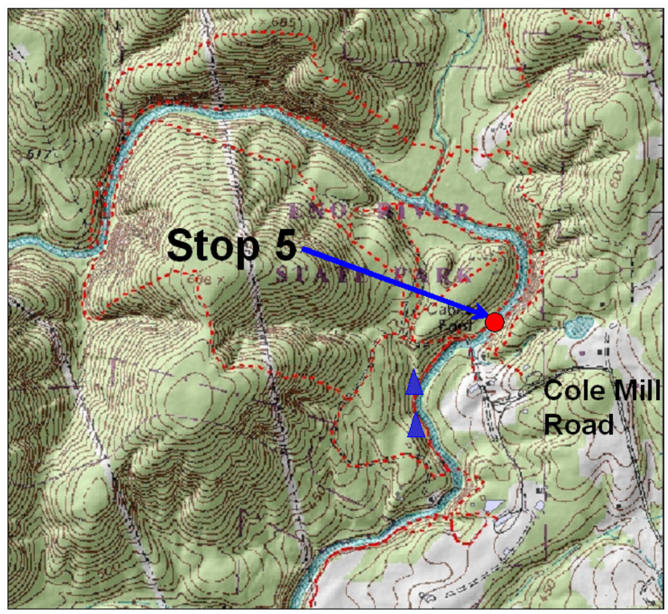


Figure 10. Location of Stop 5 in the Few's Ford access area of Eno River State Park in the Hillsborough 7.5-minute quadrangle. Triangles indicate approximate outcrop locations of reddish-colored andesitic lavas.

Lithology: Outcrops at Few's Ford and the former mill area are included in the matrix supported tuffs unit (Zmst). The outcrops within the Eno River consist of green to dark green, matrix supported, polymictic, very poorly sorted, tuff-breccia (fig. 11). Clasts are angular to subrounded and range in size from a few millimeters up to 1 meter. Clasts types include flow-banded lavas, tuffs and altered tuffs, porphyritic intrusive rocks and fine- to medium-grained intrusive rocks. Some clasts display appreciable rounding suggesting possible reworking in a stream. These outcrops were interpreted as lahar deposits by Allen and Wilson (1968) and

Rochester (1978). A lahar is a type of debris flow characterized by a slurry of volcanic-derived debris and water. Lahars are typical of subaerial volcanic terranes and are deposited within existing stream valleys on the slopes of volcanic edifices or at the base of steep volcanic slopes. Lahars contain juvenile angular volcanic debris from locations near the vent and also entrain more mature subrounded to rounded stream gravels and boulders.

Figure 11. Photograph of outcrop of tuff breccia exposed at Few's Ford, Eno River State Park (Stop 5).

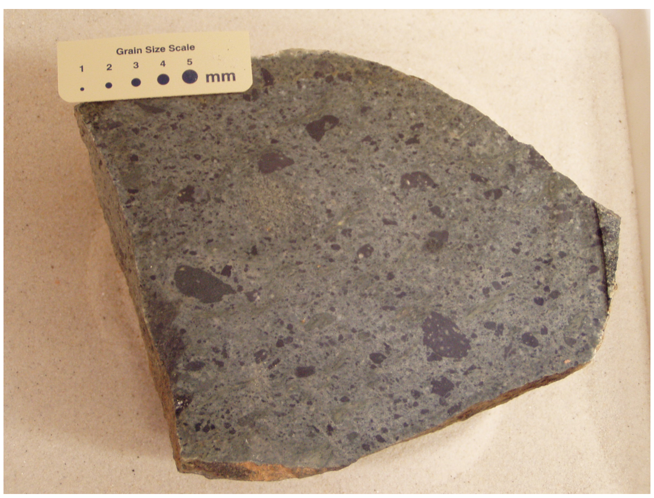


Figure 12. Sawn slab of green lithic tuff from Few's Ford area.

A mafic dike ranging from 3 to 4 feet wide crosscuts the tuff breccia and can be traced for several feet. The tuff breccia is interlayered with green-colored lithic tuffs (fig 12) commonly containing clasts of black plagioclase porphyritic dacite. Additionally, slightly reddish-tinged, dark gray to black plagioclase porphyritic lavas of andesitic composition (fig. 13) are also present and can be viewed along a foot path on the west side of the river to the south of the Few's mill and dam area.

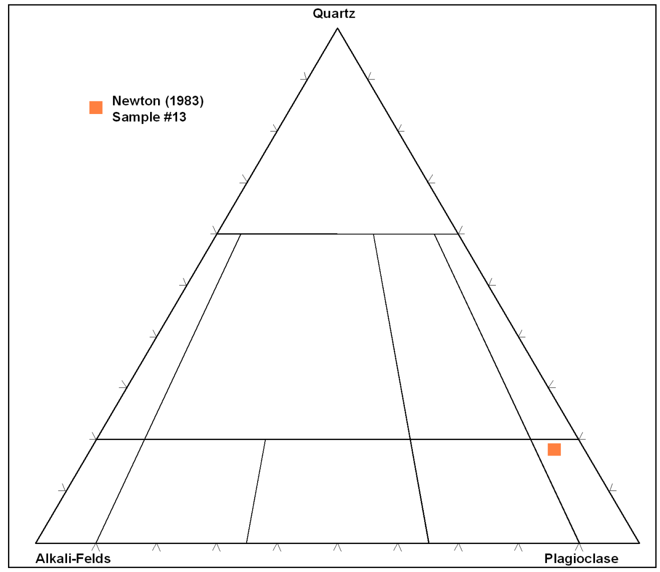


Figure 13. Whole rock analysis from a sample of dark gray to black plagioclase porphyritic lava collected and analyzed by Newton (1983) from the Few's Ford area. (Sample #13 of Newton, 1983).

Interpretation and Discussion:

Environment of Deposition - The felsic tuffs of the Few's Ford area are interpreted to have been deposited relatively proximal to a vent of dacitic to andesitic composition as suggested by the clasts of plagioclase porphyritic dacite and the intercalated outcrops of reddish-tinged andesitic lavas. The presence of lahar deposits coupled with the reddish-tinged lavas may suggest that this area was a subaerial paleovalley that was infilled with lahar flows, lavas, and lithic tuff.

Brittle overprint of Carolina terrane rocks - Immediately upstream of the Few's Ford and Mill area, the Eno River abruptly bends toward the south at a high angle. This high-angle bend coincides with the Eno crossing over and flowing into a prominent set of north-south oriented lineaments extending over 7 miles toward the south into the Durham Basin (fig.1). The same prominent north-south lineament extends toward the north for at least 4 miles and is occupied by Buckquarter Creek for a portion of its trend.

Detailed geologic mapping along the trace of the most prominent lineament has indicated the following:

1) The lineament coincides with an apparent offset of a granite/granodiorite pluton in the southeast corner of the Hillsborough quadrangle;
2) Outcrops of brittly-deformed foliated granite and granodiorite;
3) Brecciated and silicified felsic tuff within the lineament zone;
4) Small scale brittle faults and fault gouge; and

5) The lineament terminates in the Durham Triassic basin in the vicinity of Kerley Road and New Hope Creek.

Based on the above observations, the north-south segment of the Eno River is interpreted to coincide with the trace of a brittle fault that is likely Mesozoic in age. Detailed topographic data indicates the presence of abundant north-south, northwest-southeast and northeast-southwest trending lineaments that may suggest widespread brittle faulting. Many of the northwest-southeast trending lineaments are coincident with identified diabase dikes.

Detailed mapping to the west of the Few's Ford and Mill area has identified a quartz breccia zone that is oriented east-west for a portion of its trend and approximately N60W – S60E. The quartz breccia zone ranges in width from a few feet to several hundred feet and extends for over 1.5 miles through a diorite/granodiorite body. The quartz breccia zone may be related to Mesozoic-aged faulting.

The Location of ford and mill sites and brittle faulting:

Of interesting note is that Few's Ford is on trend with the quartz breccia zone that appears to terminate approximately 800 feet west of where Few's ford crosses the Eno River. Faulting may have continued toward the east but without appreciable quartz precipitation forming a less resistant zone of brittle deformed rock or gouge zone. Erosion of the fault zone may have formed landscape conditions suitable for a ford. Additionally, possible headward erosion of this theoretical fault scarp may be responsible for the presence of the rapids immediately upstream of the ford. The presence of the rapids and resistant outcrop presented a favorable location to construct the mill dam in a location were there was already a natural hydraulic head of several feet.

Holden's Mill, located 1.3 miles upstream from Few's Mill, is located immediately downstream of an abrupt (probably fracture controlled) bend to the north of the Eno River. This location also coincides with another north-south oriented lineament. The original offset of rock units and headward erosion may have provided the ideal conditions for mill sighting. A cursory review of lineaments and other mill location within the Piedmont section of the Eno River appear to indicate a possible correlation of mill sites and lineaments.

Stop 6: Epiclastics on northwest limb of Hillsborough anticlinorium at Faucette's Mill.
Lat. - 36.06893° Long. - 78.91887°

Purpose: To examine epiclastic rocks correlated with the Aaron formation and interpreted to be located on the northwest limb of Hillsborough anticlinorium. Faucette's Mill is located on private property. Permission to visit the site must me gained in advance. According to the Eno River Calendar of 1978 (Eno River Association), Faucette's Mill may be the oldest mill on the upper Eno River. A mill was at this location before 1758. Richard Faucette operated the mill here in the early 1770's. The mill ceased operation in 1918.

Figure 14. Location of Stop 6 in the Efland 7.5-minute quadrangle.

Lithology: Outcrops located at Faucette's Mill (fig 14) are included in the epiclastic unit (Ze) and are part of a northeast-southwest trending unit of interlayered siltstones, sandstones and conglomerates up to 1.7 miles wide that extends for over 8 miles toward the southwest and continues outside of the subject area.

The outcrops are located west and northwest of the mill house along the Eno River. West of the mill house the outcrops include greenish gray to dark gray, moderately sorted, coarse- to very coarse-grained, subarkose to sublitharenite volcanic sandstone. Curved, laminated and slightly wavy bedding can be seen. Northwest of the mill house at the head of the mill sluiceway, the sandstones are mostly pebbly sandstone with interbedded cross-bedded fine-grain sandstone and thin beds of pebble conglomerate. Bedding trends N 215 to 226 E and dips 80 to 88 degrees to the northwest.

In thin section, the quartz grains are subangular to well rounded, with simple undulatory extinction; feldspars are mostly plagioclase with traces of sanadine and are angular to subangular. Rock fragments are typically altered to epidote and are subrounded. The matrix is sericite.

In other locations within this unit, many sedimentary structures were observed, including numerous cut and fill structures where curved-bottomed sandstone beds are cut into bedded and massive siltstones and curved-bottomed conglomerate beds cut into sandstones. Bedding in the area is usually parallel and continuous, thickly laminated to thinly bedded. Siltstones are usually silicified, micaceous, and very thinly laminated, with very low angle, parallel and continuous bedding. Sandstones are massive to well bedded to cross-bedded. Conglomerates are moderately poorly sorted; clasts are subrounded quartz pebbles up to 35 mm in diameter and rounded volcanic rock clasts. The clasts are massive and randomly oriented to strongly imbricated. The sedimentary structures indicate stratigraphic up is consistently to the northwest.

Interpretation: These epiclastic rocks are interpreted to be located on the northwest limb of the Hillsborough anticlinorium and are correlated with the Aaron formation.

Stop 7: Sennett Hole: West Point on the Eno Park – Example of shallow intrusive body.
Lat. – 36.06893° Long. – 78.91887°

Purpose: To examine an example of a shallow intrusive body. The stop is located in West Point on the Eno Park in the historical location of Sennett Hole.

Lithology: This stop (fig. 15) consists of an extensive outcrop area of granodiorite porphyry along the Eno River. The identification of this rock as a granodiorite porphyry instead of a dacite porphyry is a matter of perspective. Rock identified as dacite porphyry or porphyritic dacite have aphanitic groundmasses with no discernible groundmass minerals with a 7x to 10x magnifier.

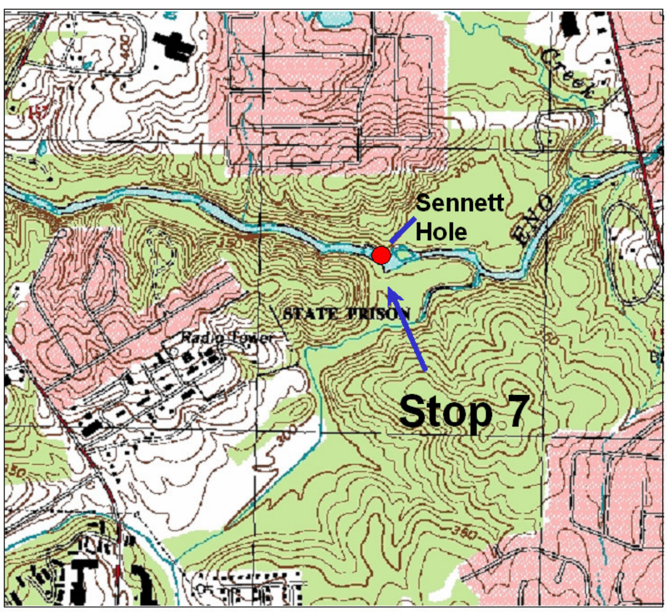


Figure 15. Location of Stop 7 in the Northwest Durham 7.5-minute quadrangle.

In hand sample, the granodiorite porphyry consists of conspicuous white-colored plagioclase feldspar and lesser amounts of pinkish-hue (orthoclase?) feldspar phenocrysts ranging from 1 mm up to 10 mm diameter. The pinkish-hue feldspar phenocrysts are generally larger in size (5-10 mm) than the plagioclase. In the pinkish-hued phenocrysts, the pink color appears to be more intense in the cores and typically grades to white at the rims. Feldspar phenocrysts are often broken giving the rock a protoclastic texture. Amphibole (variety hornblende?) occurs as small (up to 1 mm diameter) phenocrysts and as inclusions in plagioclase phenocrysts. The groundmass is green and fine-grained (<1 mm diameter). Green colored fine-grained epidote-quartz veins, ranging from a few millimeters up to several centimeters wide, are common in the granodiorite porphyry. A small portion of the outcrop contains a zone of fragments of granodiorite porphyry suspended in a fine-grained matrix (fig. 16). Outcrops of lithic tuff and interlayed dacitic lavas are present to the immediate west of the granodiorite porphyry. A portion of the outcrop visible in a large rock in the middle of the river contains a zone of medium-grained granodiorite within the granodiorite porphyry.

In thin section, the pinkish-hue feldspar phenocrysts do not exhibit twinning and are more heavily sericitized than plagioclase. Lack of twinning and heavy sericitization causes identification of the type of feldspar to be difficult. Amphiboles are altered to chlorite and epidote masses. The groundmass is composed of a mosaic of plagioclase, quartz and relict amphibole grains up to 1 mm diameter.

Many fine-grained mafic dikes intrude the granodiorite porphyry at Sennett Hole. Such dikes, consisting of chlorite, epidote and relict phenocrysts of pyroxene, are common in the study area.

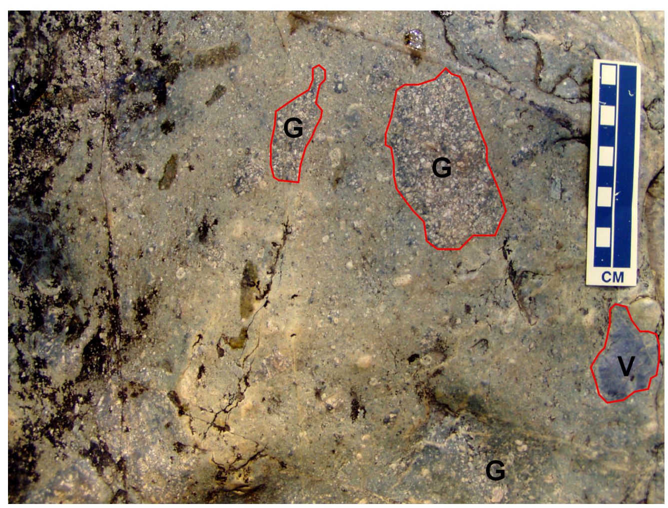


Figure 16. Photograph of outcrop surface at Sennett Hole with clasts of granodiorite porphyry and volcanic rock in fine-grained intrusive textured groundmass. Outcrops like these are interpreted as vent breccias by Wright (1974). "G" indicates clast of granodiorite porphyry and "V" indicates clast of fine-grained volcanic rock.

Discussion: The granodiorite porphyry of Sennett Hole was mapped as part of Unit B of Wright (1974). A small portion of the outcrop displays fragments of granodiorite porphyry suspended in a fine-grained matrix. Wright interpreted these features as vent breccias. He described the vent breccias as containing a large percentage of comminuted (pulverized) granodiorite, dacite porphyry and volcanic rock commonly marked by a zone of hydrothermal alteration (fig. 16). The vent breccias mark the locations of the conduits where portions of the magma body were extrusive to the surface. Wright identified fragments of granodiorite similar to those associated with the vent breccias within overlying pyroclastic units. Wright also identified vent breccias in two additional locations along the Eno River.

McConnell and Glover (1982) correlate the intrusive rocks of the Sennett Hole area with the Flat River Complex. The presence of vent breccias linked to pyroclastic units, protoclastic texture in marginal zones of the Flat River Complex and emplacement pressure data from mineral analyses collectively suggest crystallization of the Flat River Complex at a shallow depth of less than 1 km and that it was surface breaking (McConnell and Glover, 1982).

DAY 2:
SUNDAY, NOVEMBER 5, 2006

Stop 8: Duke Quarry.
Lat. – 36.07892° Long. – 79.13393°

Purpose: To examine excellent exposures of phyllitic and lithic tuffs in the active Duke Quarry.

Safety warning: There is abundant loose material on top of the quarry walls. Do not climb on top benches while people are below. Be careful of your footing at all times.

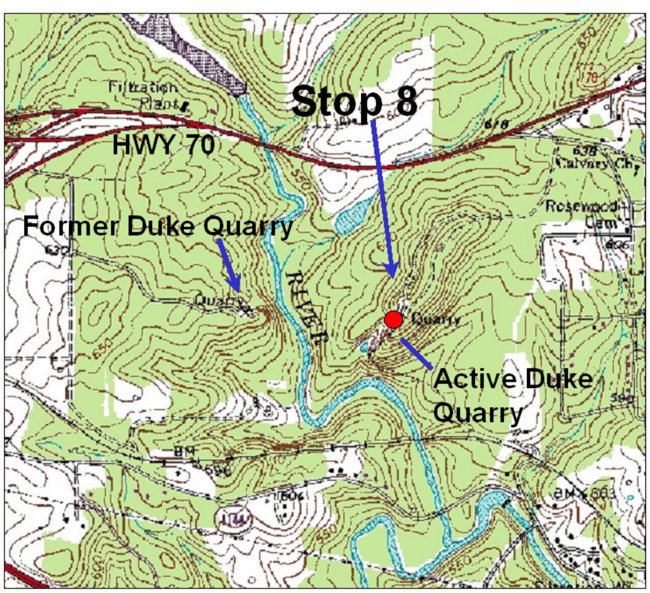


Figure 17. Location of Stop 8 in the Efland 7.5-minute quadrangle.

The active Duke quarry (fig. 17) is located on property owned by Duke University. It was opened in 1965 to obtain building stone for use in construction of campus buildings. Prior to 1965, Duke University quarried building stone from an older quarry located approximately 2000 feet to the west of the current quarry on the west side of the Eno River. The older quarry land was purchased in 1925 by Duke University and the stone was quarried for use in construction projects on the west campus of the University (Allen and Wilson, 1968).

Lithology:

Rocks exposed at the Duke Quarry are mainly interlayed phyllitic tuffs, lithic tuffs and tuffaceous sandstones. Layering ranges from the centimeter- to the meter-scale and strikes approximately N35 to 45E and dips approximately 70 to 85 degrees to the northwest. Grain-size grading indicates that layering is likely overturned to the southeast assuming normally graded deposits. A well-developed foliation is parallel to layering. Locally, lithic clasts are oriented in a general down dip orientation and define a clast lineation on the foliation surface with north-northwest trends and plunging approximately 72 degrees to the northwest. Lithic clasts are apparently elongate within the foliation plane (fig. 18). Quarrying of building stone is made easier by the presence of joints sets that cleave the rock at an angle to layering and foliation creating rhombus shaped rock slabs.

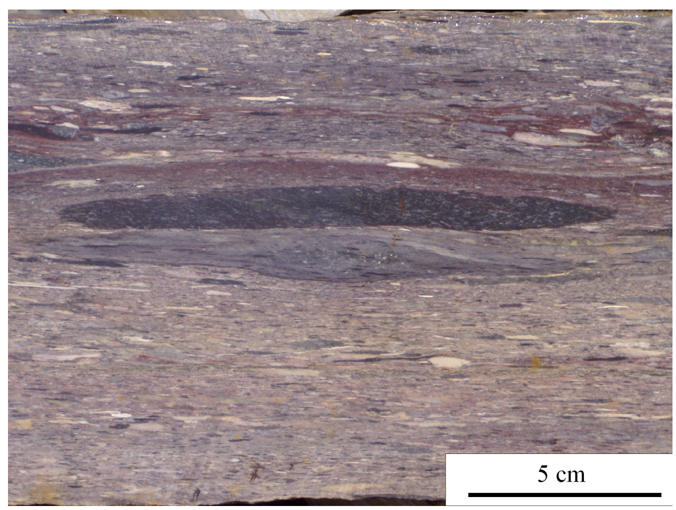


Figure 18. Sawn slab of lithic tuff from active Duke Quarry. Slab is cut parallel to clast lineation and perpendicular to foliation.

The abandoned Duke quarry was visited during the 1964 CGS Field Trip with Bob Butler as the stop leader (Bain, 1964). The lithology of the abandoned Duke quarry is generally identical to the active quarry. Butler described that a portion of the phyllitic rocks exposed in the abandoned Duke quarry were derived from lithic tuff and tuff breccias. Informal strain analyses described by Butler indicated that some of the clasts have been strongly deformed and were present as thin lenses in slabs cut perpendicular to the cleavage (similar to fig. 18). The ratio of maximum length of the lenses (measured in the plane of cleavage) to thickness (measured perpendicular to the cleavage) was reported to be as much as 8:1. Other layers are less strongly deformed and with ratios reported as 2:1 or less.

Chloritoid:

Furbish (1967) reported on the occurrence of chloritoid in the Duke Quarries. Furbish reported that chloritoid occurs in three general modes: 1) Chloritoid occurs in random orientations in small "patches" that constitute only a small portion of the overall rock mass. These small "patches" are present in rocks with no fractures and are generally restricted to non-phyllitic rock types. 2) Chloritoid occurs in random orientations, with no apparent association with foliations, but is concentrated near fractures or fracture systems in rocks with fractures. This mode constitutes the bulk of chloritoid occurrence. 3) Chloritoid occurs as vein fillings in fractures and cleavage planes of the more phyllitic rocks.

Furbish interpreted that the presence of chloritoid was related to the appropriate initial local chemical composition and that chloritoid growth was enhanced near fractures or cleavage planes due to the presence of pathways for chloritoid constituent migration to locations of chloritoid formation. Chloritoid was interpreted to have formed during, but late in the metamorphic history of the phyllitic rocks in the chlorite zone of the greenschist facies.

Discussion:

The rocks exposed at the Duke quarries are sequences of felsic volcanics with interlayered reworked volcanics that are not spatially associated with a nearby volcanic vent like a dacitic dome. The graded bedding suggests deposition in a marine setting. Apparently deformed clasts are elongate in the foliation plane. No folds, strongly asymmetric clasts or other kinematic indicators were found to indicate ductile shearing of the units. As such, the apparent flattening/stretching observed in the quarry is likely from volume loss due to intense pressure solution during foliation formation and not from ductile shearing.

The rocks of the quarry display a well-developed foliation more intense than typical felsic tuffs in the study area. Relatively higher stain rocks, which include well-foliated altered tuffs and locally foliated intrusive rocks, are present in discontinuous and sometimes bifurcating zones through out the study area. The nature and origin of the relatively higher-strain rocks within these zones is not well understood.

Allen and Wilson (1968) reported the presence of tuffaceous sandstone exhibiting normally-graded bedding with truncated cross beds in the abandoned Duke Quarry indicating a stratigraphic up direction toward the northwest (see photo 1, plate 4 Allen and Wilson, 1968, p.16-17). Based on the overturned graded bedding in the active Duke quarry and the stratigraphic indicators in the abandoned quarry, the quarries are interpreted to be located on opposite limbs of an overturned anticline. Note: Allen and Wilson (1968) interpreted the presence of an overturned syncline between the quarries. However, the location of the quarries were apparently inadvertently switched in Allen and Wilson (1968) causing the correctly interpreted stratigraphic up indicators to yield an interpretation of a syncline.

Stop 9: Occoneechee Mountain Area – Eno River State Natural Area. Slope Stability and hydrothermally altered rock.
Lat. – 36.06549° Long. – 79.11897°

Purpose: To examine geologic features of a recent slope failure (see Wooten and Latham, this guidebook) and examine rocks with sericitic and argillic alteration products from hydrothermal alteration of andesitic to dacitic tuffs.

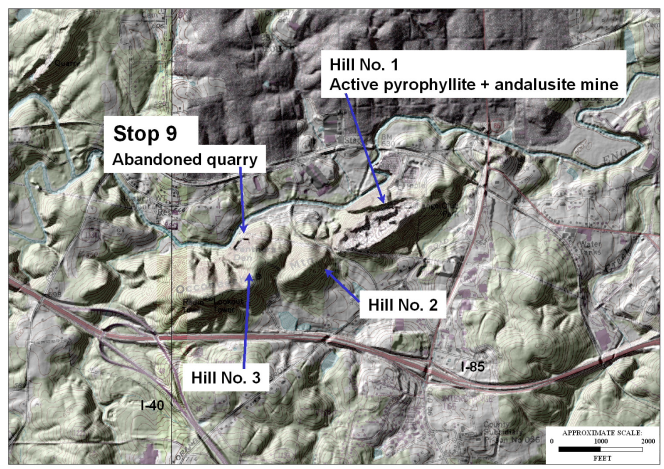


Figure 19. Location map of Stop 9 in the Hillsborough 7.5-minute quadrangle. Base map is from LiDAR hillshade data for Orange County draped with the Hillsborough and Efland 7.5-minute quadrangles.

This stop consists of an abandoned quarry (fig. 19) on the northwest face of Occoneechee Mountain. The abandoned quarry is part of Occoneechee Mountain State Natural Area and is administered by Eno River State Park. ***The collection of rock samples is prohibited!*** Occoneechee Mountain is composed of three hills designated from northeast to southwest as Hill No. 1, Hill No. 2, and Hill No.3. The abandoned quarry is located on the northwest side of Hill No. 3. The apex of Hill No. 3 is the highest point in Orange County at approximately 867 feet above sea level. The quarry was reportedly opened before the Civil War and used for fill material for construction of nearby railroad tracks and for general fill material in the Hillsborough area. Active quarrying ceased sometime around 1908. In 1906 the quarry was operating under the name of the Southern Broken Stone Company (Eno River Calendar for 1995, Eno River Association). An active pyrophyllite + andalusite quarry, in operation since the 1960's, is present on Hill No. 1.

Lithology:

Occoneechee Mountain is generally composed of a central spine of dense siliceous rock grading into a sericite phyllite/schist to the northwest. The quarry contains mainly sericite phyllite/schist with lesser amounts of massive pyrophyllite and siliceous rock. Radiating pyrophyllite is present as fracture fill. Andalusite, topaz, ilmenite, and kaolinite are also present. Dark brown to red colored fracture coatings of goethite exhibit an iridescent spectrum of color in some float blocks within the quarry debris.

Three foliations are observed in the sericite phyllite/schist rock within the quarry. The main foliation (S1) is northeast trending (approximately N50 to 60E) with dips ranging from 55 to 70 degrees. S1 is parallel to the regional foliation and the trend of area map units. S2 is also NE trending, generally parallel to S1 with a shallower dip of approximately 35 to 45 degrees to the northwest. S3 is a poorly formed, discontinuous foliation that appears to overprint S1 and S2. S3 dips approximately 15 to 35 degrees toward the northwest. Shear bands are present in the abandoned quarry indicating reverse motion with tops to the southeast (fig. 20). The quarries are on trend with zones of intensely foliated phyllites and foliated intrusive rocks.

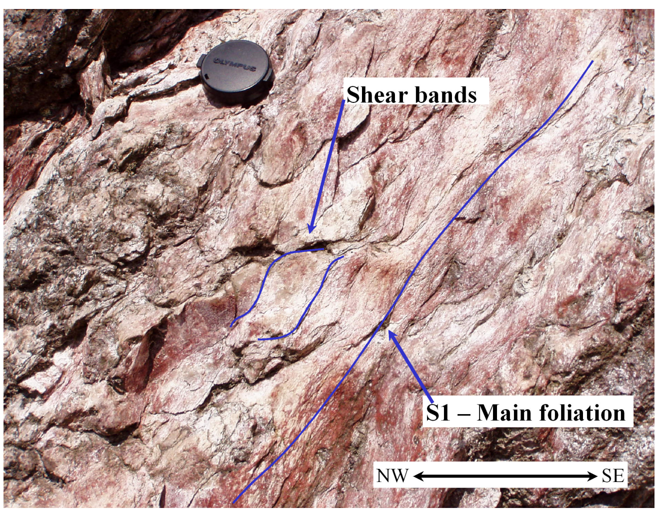


Figure 20. Photograph of outcrop of foliated silicified rock with shear bands in the abandoned Occoneechee Mountain quarry. Shear bands indicate reverse motion with tops to the southeast.

Pyrophyllite protolith and genesis

The Hillsborough pyrophyllite deposit is located less than 3,000 feet to the east from the abandoned quarry. Spence (1975) and McDaniel (1976) developed a hot spring-fumarole alteration model in a study of the pyrophyllite deposits at Glendon, NC. A hot spring-fumarole alteration model is applicable to the Hillsborough deposit.

Sykes (1976) and Sykes and Moody (1978) performed detailed field and petrologic investigations on the Hillsborough pyrophyllite deposit. Sykes and Moody (1978) interpreted that the parent material of the deposit was andesitic and dacitic volcanic rocks that were leached by hydrothermal processes before regional metamorphism. Hydrothermal activity provided the parent material (likely fluorine-bearing kaolinite deposits) for the pyrophyllite. The kaolinite deposit was metamorphosed producing andalusite and topaz rock. Later introduction of silica-rich fluids interacted with the andalusite and topaz rock to produce the pyrophyllite. The andalusite-topaz rock and pyrophyllite zones likely represent argillic alteration. The sericite phyllites/schists likely represent sericitic alteration with silicification as the main process to produce the quartz rock that defines the spine of Occoneechee Mountain (Table 1).

Oxygen Isotope data

Feiss et al. (1993), as part of an investigation into favorable horizons for gold and base-metal mineralized deposits, reported on whole-rock oxygen isotope analyses from various locations throughout the Carolina terrane including the Hyco formation. Pyrophyllite samples from the Hillsborough deposit (located in the Hyco formation) were analyzed for their oxygen isotope composition. The oxygen isotope data indicated that the hydrothermal fluids involved in the formation of the Hillsborough pyrophyllite deposits involved meteoric water that are typical of subaerial hydrothermal systems. A subaerial environment of deposition for at least some of the rocks in the Hillsborough area agrees with the abundant presence of welded tuffs and red colored felsic lavas.

Cane Creek Fault:

Detailed mapping in the Efland quadrangle indicates the presence of a fault within the trace of a regional scale lineament coincident with Cane Creek (See Bradley et al., and figure 11 therein of this volume for a more detailed discussion of the Cane Creek fault). Informally named the Cane Creek fault, this fault is interpreted to extend to the northeast where it is defined by a zone of hydrothermally altered rock (which includes the Hillsborough pyrophyllite deposit) and bodies of foliated diorite. The interpreted main trace of the Cane Creek fault is located approximately 1,000 ft northwest of the abandoned quarry on Occoneechee Mountain and 3,000 ft northwest of the active pyrophyllite mine on the northern end of Occoneechee Mountain (south of the Town of Hillsborough). The quarries are interpreted to be located in a splay of the Cane Creek fault that trends toward the northeast. The trace of the splay is defined by foliated intrusive rocks, chlorite phyllites in a basaltic unit (Zablt) and strongly foliated hydrothermally altered rock. The splay is also on trend with the Murray pyrophyllite prospect in the Caldwell quadrangle to the north of Hillsborough.

Shear bands in the abandoned quarry indicate a reverse sense of motion with tops to the southeast (fig. 20). The motion on the Cane Creek fault is therefore tentatively assigned a reverse motion with the upthrown block on the west.

Table 1.

Sykes and Moody (1978) mineral paragenesis	**Speculative relationship to regional geology based on recent geochronologic data and new field mapping.**
Hydrothermal alteration of protolith	Circa 620 to 630 ma *
1) Greenschist facies regional prograde metamorphism produced the andalusite-topaz-quartz rock;	Virgilina deformation (Ca 612 to 586 ma)**
2) Partial to complete silicification of the andalusite-topaz rocks occurred with secondary formation of andalusite;	Virgilina deformation
3) A deformational event fractured and deformed the andalusite-topaz-quartz rock and produced the foliation in the schist and quartz rock;	Virgilina deformation
4) Sericite, pyrophyllite, and quartz formed fracture fillings in the andalusite-topaz-quartz rocks and as veinlets in the quartz rock and schist parallel to foliation;	Virgilina deformation?
5) Retrograde metamorphism formed kaolinite as an alteration product of andalusite and development of a second foliation, and	Deformation associated with Cane Creek fault?
6) Kaolinite was deposited as fracture fillings from low-grade metamorphism and weathering	Middle Paleozoic (Ca 450 ma) or younger deformational event?

* Age dates for protolith from age of extrusive volcanics in Chapel Hill and Virgilina areas (Wortman et al, 2000)
**Virgilina deformation ages from Wortman et al., 2000.

Deformation along the Cane Creek fault may be wider in less competent lithologies such as pyrophyllite and sericite phyllites and may account for the deformation in the Occoneechee abandoned quarry and active mine. Kink bands, multiple generations of fractures in the active pyrophyllite mine (Sykes and Moody, 1978) and shear bands in the abandoned quarry indicate a long and probably complicated movement history on the Cane Creek fault or perhaps a system of intersecting faults of varying ages.

Stop 10 (Optional Stop): Outcrop and boulders of pumiceous lithic tuffs.
Lat. – 36.03331° Long. – 79.08168°

Purpose: To examine boulders and outcrop of well preserved flattened pumiceous lithic clasts in lithic tuffs.

Lithology: At this stop (fig. 21), boulder piles strewn throughout the woods contain boulders of lithic tuff with fiamme-shaped lithic clasts up to 15 cm long that are strongly flattened in the plane of compaction. Lithic clasts are black, plagioclase porphyritic dacite pumice and contain abundant (approximately 0.2mm diameter) vesicles. In thin section the vesicles are infilled with quartz and calcite. Primary compaction foliation and metamorphic cleavage are visible in a nearby outcrop of welded tuff. The orientation of the compaction foliation is approximately 255/54NW and the cleavage is oriented approximately 233/85NW.

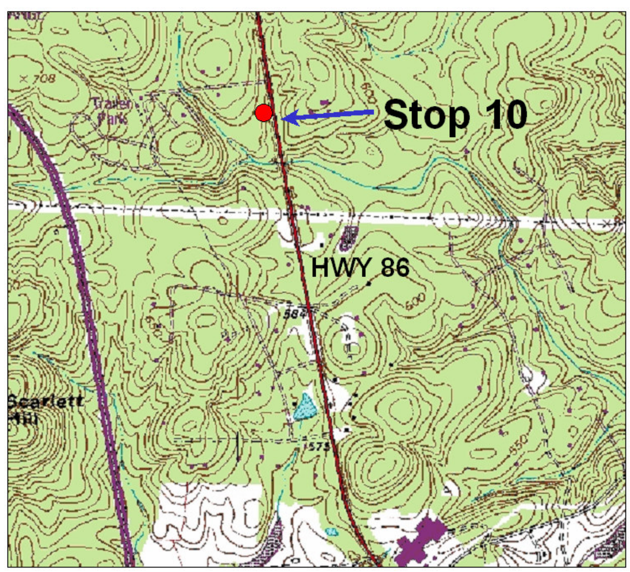


Figure 21. Location of optional Stop 10 in the Hillsborough 7.5-minute quadrangle.

Interpretation:

Environment of deposition - The pumiceous lithic clasts suggest deposition by a subaerial pyroclastic flow proximal to a dacitic composition vent. This outcrop is assigned to the dacitic lavas and tuffs (Zdlt) map unit and is variably interlayed with other welded tuffs and dacitic lavas interpreted to have been part of a dome complex.

Structure – Primary compaction foliation and fracture cleavage orientation relationships indicate that the stratigraphic up direction is likely toward the northwest, which is consistent with the outcrops location being on the northwest limb of a large anticline structure.

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