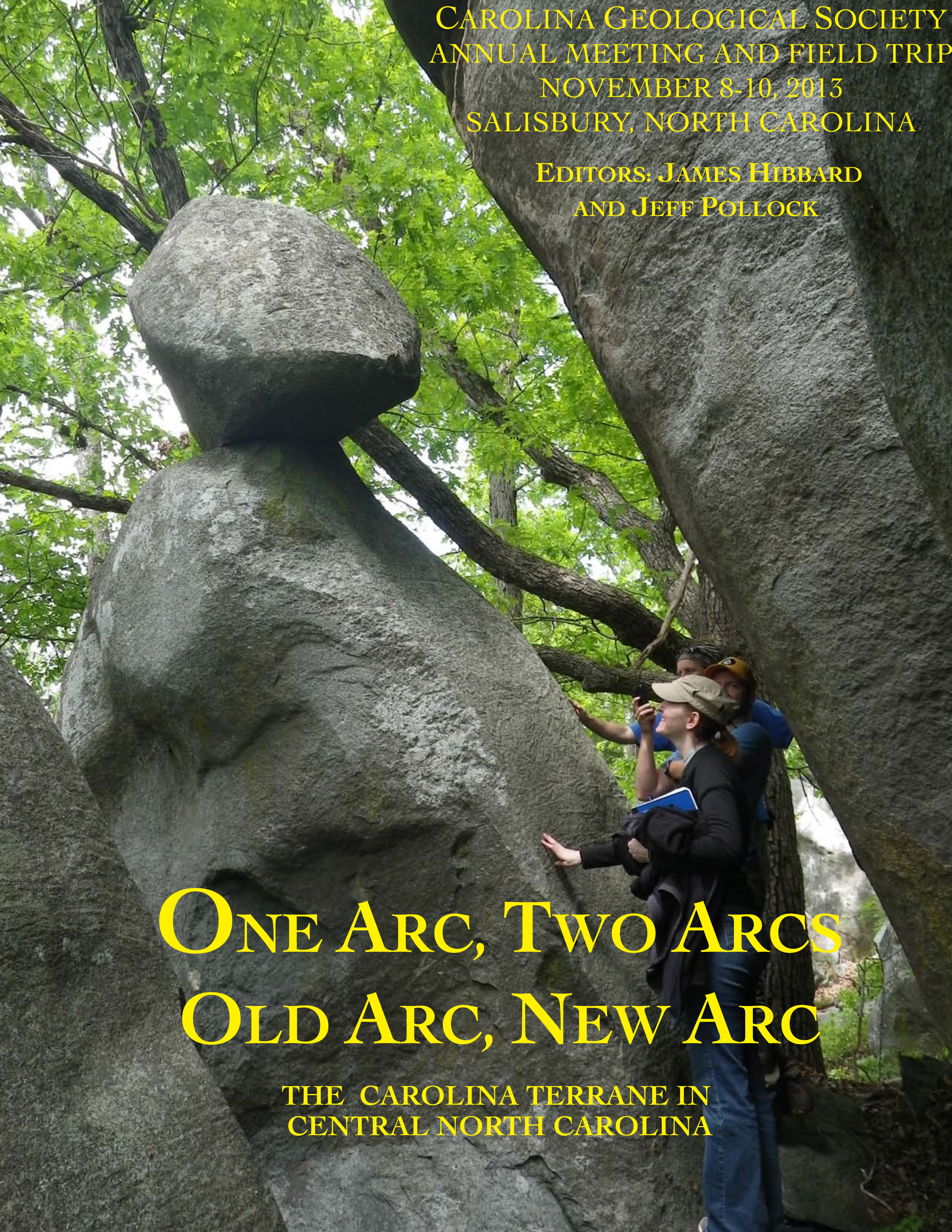

CAROLINA GEOLOGICAL SOCIETY
ANNUAL MEETING AND FIELD TRIP
NOVEMBER 8-10, 2013
SALISBURY, NORTH CAROLINA

EDITORS: JAMES HIBBARD
AND JEFF POLLOCK

ONE ARC, TWO ARCS
OLD ARC, NEW ARC

THE CAROLINA TERRANE IN CENTRAL NORTH CAROLINA

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EDITORS: James Hibbard and Jeff Pollock

TRIP LEADERS: James Hibbard, Jeff Pollock, Dennis LaPoint, Patricia Weaver, John DeDecker, Phil Bradley, Lee Phillips

LOGISTICAL SUPPORT: Phil Bradley, Tyler Clark, Robert Ganis

Carolina Geological Society
Annual Meeting, November 8-10, 2013
Salisbury, North Carolina

Carolina Geological Society

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ON THE COVERS

Front: Graduate students Laura Lukes, Dillon Nance, and John DeDecker between a rock and a hard place. Outcrops of Stony Mountain Gabbro on Ridges Mountain, Randolph County, North Carolina (see DeDecker et al., this volume).

Inside back cover: Sponsors of the 2013 Carolina Geological field trip.

Back: Stop map for the 2013 Carolina Geological Society field trip. Base map for stops by Phil Bradley incorporates regional LiDAR coverage (from NCDOT and NC Flood Plain Mapping) for central North Carolina with a portion of the Lithotectonic Map of the Appalachian Orogen (Hibbard et al., 2006).

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FOREWORD

The theme of the 2013 Carolina Geological Society Annual Meeting and Field Trip is 21st century advancements in our understanding of the Carolina terrane in central North Carolina. The Carolina terrane forms the 'heart' of Carolinia, one of the largest accreted crustal tracts within the Appalachian Orogen. At present, the Carolina terrane provides most of our knowledge of Carolinia mainly because its low grade metamorphic overprint and its relatively simple structural style render the terrane conducive to a variety of topical studies, e.g. stratigraphic, paleontologic, structural, geochronologic, geochemical, and paleomagnetic. Although rocks of the Carolina terrane in North Carolina have been the subject of many previous Carolina Geological Society trips (e.g. Stromquist and Conley, 1959; Conley, 1962; Bain et al., 1964; LeGrand and Bell, 1966; Gibson and Teeter, 1984; Harris and Glover, 1988; Bradley and Clark, 2006) it is particularly timely to revisit them now, in 2013, because controversies arising during the 1990's and early 2000's concerning the stratigraphy and tectonic history of the Carolina terrane have recently been addressed with new data sets. Also, during the past decade there have been new faunal discoveries within the terrane that may well shed further light on the nature, distribution, and evolution of soft-bodied organisms of the Ediacaran. In a broader forum, study of Carolinia and other Neoproterozoic blocks of the circum-Atlantic region is particularly topical as it sheds light on a critical time in Earth history marked by multiple glaciation events at equatorial latitudes, profound extremes in sea level, ocean chemistry and climate and changes in the distribution of land masses on Earth.

In addition to academic concerns, it is also timely for the society to return to the Carolina terrane in light of the elevated market value of gold. The Carolina terrane was host to the first authenticated gold discovery in the United States and historically has produced sufficient quantities of gold to warrant construction of a mint in Charlotte, NC in the 1800s. The present high market value of gold has led to significant renewed interest in understanding the origin and distribution of gold and other metallic deposits in the Carolina terrane. In addition, multiple other rock commodities are actively extracted from the Carolina terrane – e.g. ornamental stone, lightweight aggregate, and clay for bricks.

AN APPRECIATION TO THOSE WHO WENT BEFORE

The recent studies summarized in this guidebook are firmly rooted in the 'classical', 20th century, foundation studies undertaken by multiple academic, government, and industry geologists who came before us. In particular, the studies of Francis B. Laney, J. Robert Butler, Lynn Glover III and his cadre of graduate students from Virginia Tech - especially Charles Harris - James Conley, Don Secor, Victor Seiders, George Bain, Arvid Stromquist, Harold Sundelius, and Daniel Milton are of seminal importance to our modern understanding of the Carolina terrane in North Carolina (Laney, 1910, 1917; Butler and Ragland, 1969; Butler and Secor, 1991; Glover and Sinha, 1973; Harris, 1984; Harris and Glover, 1985, 1988; Conley, 1962; Conley and Bain, 1965; Bain, 1964; Milton, 1984; Secor et al., 1983; Seiders, 1978, 1981; Stromquist and Conley, 1959; Stromquist and Henderson, 1985; Stromquist and Sundelius, 1969, 1975; Stromquist et al., 1971). Of these geologists, J. Robert, 'Bob' Butler (photograph below), in particular, embodied the scientific method and in his understated, good-humored, and humble manner, he objectively let the rocks tell their story. At the time of his death in 1996, Bob was in the early stages of assembling a manuscript on the Flat Swamp Member of the Cid Formation (Stop 1.5), a key marker unit in the Carolina terrane of central North Carolina. In honor of his unfinished studies, we reproduce his last publication, a Geological Society of America abstract on the Flat Swamp caldera (Butler, 1995), in the scientific papers section of this guidebook.

J. Robert 'Bob' Butler at Hanging Rock State Park, NC, 1989.

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We thank the following companies for generous sponsorship of this Carolina Geological Society meeting, which has again, allowed for significantly reduced rates for students:

Haile Gold Mine Inc. a division of Romarco Minerals Inc.
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We are grateful to many people who have facilitated our access to view outcrops on private property, including the following:

- **Mr. Neal Choquette** of American Land Corp., Inc., for access to the Saratoga housing development, Mt. Pleasant, NC.
- **Mr. David Miller** of Hammill Construction, for access to the Immanuel Church quarries, Gold Hill, NC.
- **Mr. Guy Medlin** of Vulcan Materials, Inc. for continued access to the Vulcan Materials Gold Hill quarry, Gold Hill, NC, through many years of visits and for facilitating our lunch stop.
- **Ms. Vivian Hopkins** of the Historic Gold Hill and Mines Foundation, Inc., for helping us secure our lunch site at the Gold Hill Mines Historic Park, Gold Hill, NC.
- **Ms. Karen Baldwin** of Alcoa Power Generating, Inc for providing an activity permit for access to the High Rock powerhouse road.
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- **The Furr family** of Stony Mountain Vineyards for continued access to their property on Stony Mountain and for accommodating many geologists at the end of a long day with a wine-tasting.
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- **Mr. Larry Neal and Ms. Susan Smith** of the Reed Gold Mine Historic Site, for accommodating our large group on a Sunday.
- **Mike and Sharon Michaels** for access to the Yow Mill outcrop.

We also appreciate the contributions of student helpers Stephen Hughes (NCSU), Tray McLellan (UNC Pembroke) and Sean Pavia (NCSU).

2013 FIELD GUIDE TO STOPS

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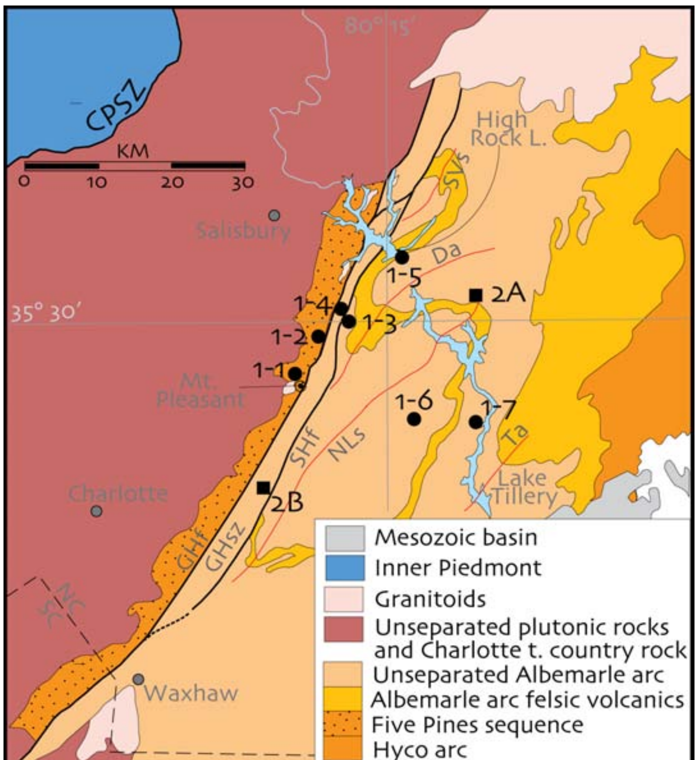
This one and a half day field trip will highlight field mapping and specialized studies that have been undertaken in the Carolina terrane of central North Carolina mainly during the first decade of the 21st century. This guide incorporates material from earlier field guides (e.g. Hibbard et al., 2008) and from the field reviews of former NCSU graduate students, including Sonja Boorman, Matt Brennan, Jill Oliver, Jeff Pollock and Issac Standard. Although one or two of the stops are well-worn classics, essential for any field trip, most of the localities are of more recent discovery and concern.

For those who have experienced field trips in the southern Appalachian Piedmont, you will realize that not all stops will be at photogenic textbook outcrops; the uninitiated will find that outside of quarry stops, our locales will be at relatively small, unassuming outcrops, that might be difficult for all members of a group such as ours to view at one time. However, the observations and deductions gleaned from these humble outcrops can have global ramifications.

The first day stops will represent a traverse across the the Gold Hill shear zone, a first order structure in the western portion of the Carolina terrane (back cover; Fig. 1); these stops will focus on the timing and significance of the shear zone. Lunch will be held at Gold Hill Mines Historic Park, within the shear zone. Here we will learn about the mining history of the region as well as a recent GPR pilot study carried out above the historic mine workings. The first two stops of the afternoon will feature units that are of stratigraphic importance in the Albemarle arc. Our last stop of the day will be in the Stony Mountain gabbro, an important unit for interpreting the tectonics of Carolinia and will be followed by a wine tasting.

On day two, attendees will choose between one of two all-morning stops (Back Cover). Stop 2A will highlight stratigraphic-sedimentary features and Ediacaran fauna of the Cid mudstone member at the Jacob's Creek quarry; Stop 2B will be a tour of the Reed Gold Mine, a North Carolina Historic Site, and site of the first authenticated discovery of gold in the United States. For a general background on the geology of the field trip area, the reader is referred to the overview paper (Hibbard et al., this volume).

As with most field guides, there are more stops described below than we can comfortably visit in the time allotted. The supplemental stops are included to both lend flexibility to the choice of stops in case of unforeseen circumstances (weather, time, etc.) and document important stops that we will not be able to visit on this particular trip. A substantial fraction of our field work along the Gold Hill fault took place during the drought of 2002, when lake levels in High Rock Lake dropped to as low as 24' below full pool level. Thus, many key outcrops along the lakeshore are accessible only when lake levels are significantly below normal. These important outcrops are written up here as supplemental stops, with full realization that after the wet summer of 2013, it's not likely that we will be able to visit them on this field trip. However, they will serve as a guide to those who want to revisit the area during times of low lake level. We estimate that High Rock Lake should be at least 10' below full pool level before the supplemental lakeshore outcrops described herein will be exposed and accessible (for information on lake levels, please consult either http://www.alcoa.com/yadkin/en/info_page/level_high_rock.asp or http://savehighrock lake.org/HRinfo1.asp. The supplemental stops are described following the intended stops for the day. Also note that because of the prevalence of GPS software in modern geology, for each stop we include the latitude/longitude and a thumbnail topo map, rather than a detailed road log. The total mileage from Stop 1.1 to 1.7 is approximately 51.7 miles (83.2 km).



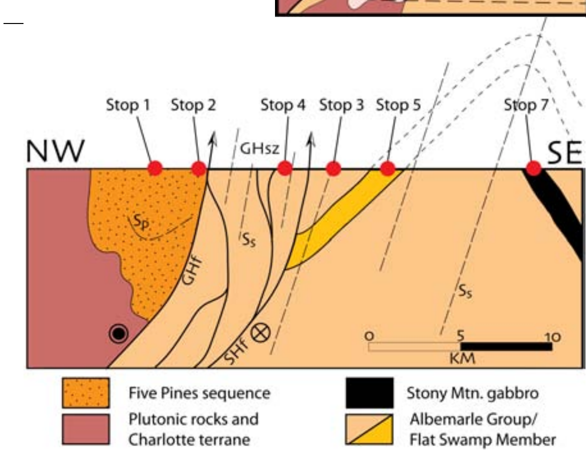
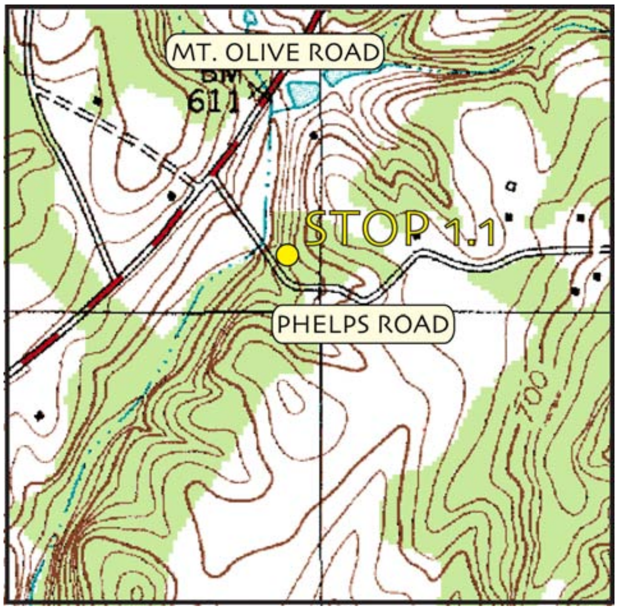


Figure 1. Geologic map and schematic structure section across the Gold Hill shear zone showing stop locations relative to regional structure. Da=Denton anticline, GHf=Gold Hill fault, GHsz=Gold Hill shear zone, NLs=New London syncline, S_s=slaty cleavage; S_p = phyllitic cleavage, SHf=Silver Hill fault, SVs=Silver Valley sycline, Ta=Troy anticline.

SATURDAY, NOVEMBER 9, 2013

STOP 1.1: HYCO ARC, FIVE PINES SEQUENCE CRYSTAL-LITHIC TUFF: PHELPS ROAD, MT. PLEASANT, NC (35° 26.577' N, 80°25.657' W). **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.



from the Mt. Pleasant 7.5' quadrangle

We will start our transect of the Gold Hill shear zone in the Five Pines sequence, which forms the hangingwall of the Gold Hill fault in many places in central North Carolina (Fig. 1, back cover). The felsic tuff at this stop also provides an age constraint on the Five Pines sequence. The Phelps Road outcrop is composed of massive, strongly foliated, quartz crystal - lithic dacitic tuff (Fig. 2). The rock contains a preponderance of large, plump, quartz crystals up to 5mm across, less obvious feldspar crystals, and lithic fragments set in a frosty gray aphanitic matrix. The sparse lithic fragments include lapilli of fine-grained felsic volcanic rock and flat clasts of chloritic, mafic rock. This tuff forms a distinct marker unit consisting of at least two identical felsic volcanic layers that can be traced discontinuously along strike for at least 12 km through

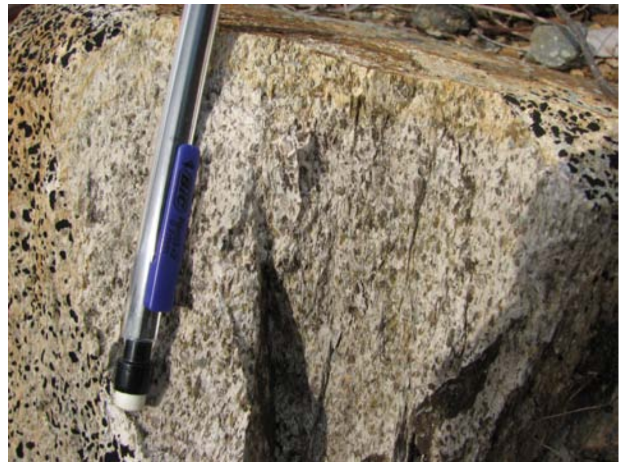


Figure 2. Dacitic quartz crystal-lithic tuff at Stop 1.2; black splotches on surface of outcrop are tar, splashed up from road repairs, grey splotches are mainly quartz crystals.

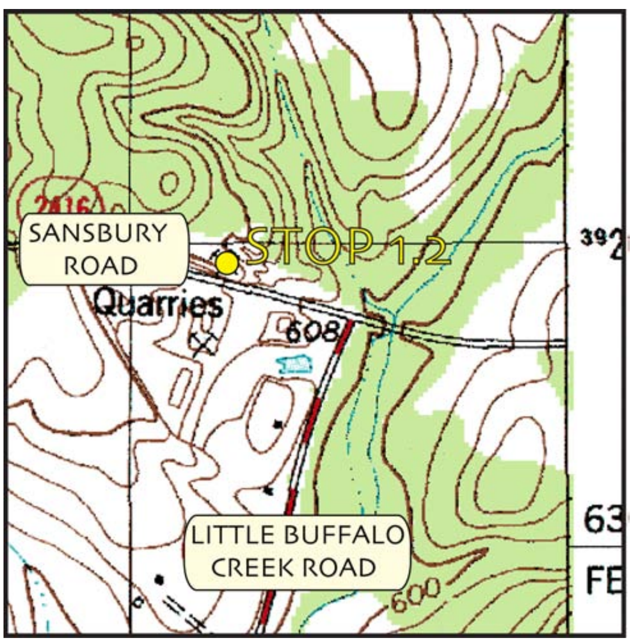
the area of Mt. Pleasant. It is interlayered with mafic and intermediate volcaniclastics in the structurally higher portion of the sequence.

A sample from this outcrop has yielded a U-Pb zircon TIMS age of 613$\pm$7 Ma (Hibbard et al., 2012), which is interpreted as the crystallization age for this rock and thus, provides a general age for the Five Pines sequence. In addition, this rock has yielded an ε_{Nd} value of + 4.6 with a model age of 0.8 Ga, indicating that it represents relatively juvenile crust. The lithology, age and Nd characteristics of this sample are typical of the Hyco arc at the NC-VA state boundary. Consequently, we correlate the Five Pines sequence with the Hyco arc.

Recognition of Hyco arc-equivalent rocks in the hangingwall of the Gold Hill shear zone indicates that the shear zone is not the boundary between the Carolina and Charlotte terranes, as has been commonly thought in the past. The terrane boundary must lie to the west of the Five Pines sequence and may well be obscured or obliterated by the large volume of plutonic rocks there.

Recognition of the Five Pines sequence as part of the Hyco arc also allows for determination of the stratigraphic throw on the Gold Hill fault and shear zone. Using minimum formational thicknesses for the region (Stromquist and Sundelius, 1969; Harris, 1984), emplacement of the Hyco arc onto the middle Albemarle arc equates to a minimum of 12.1 km of stratigraphic throw on the Gold Hill fault. Likewise, the Gold Hill shear zone places Hyco arc equivalent rocks on top of the Floyd Church Formation in the upper Albemarle arc, giving a minimum of 13.3 km of stratigraphic throw on the shear zone.

<u>STOP 1.2</u>: FIVE PINES PHYLLITE IN THE IMMEDIATE HANGINGWALL OF THE GOLD HILL FAULT, HYCO ARC (35° 28.682'N, 80° 22.847' W) IMMANUEL CHURCH QUARRY, SANSBURY RD., MT. PLEASANT, NC. **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.



from the Mt. Pleasant 7.5' quadrangle

Our next stop is at a quarry in tectonized Five Pines phyllite in the immediate hangingwall of the Gold Hill fault (Fig. 1) and structurally beneath the felsic volcanic at Stop 1. The quarry is owned by the Immanuel Lutheran Church and leased and operated by Hammill

Figure 3. Jeff Bowman inspects phyllite in the immediate hangingwall of the Gold Hill fault at Stop 1.2.

Construction Co. of Gold Hill, NC. The compact phyllite quarried here is used locally as aggregate. Here, the Gold Hill fault lies just to the east, between the quarry and Little Buffalo Creek.

The predominant rock type in the quarry is a silver-grey, phyllonite (Fig. 3). Close inspection of outcrops along stream-eroded channels down the west wall of the quarry locally reveal compositional laminae (variations in quartz, chlorite, white mica content) that are parallel to the phyllitic cleavage and that likely reflect original bedding. Some of the phyllite layers show cm-scale isoclinal folding and some of these folds are transposed along the plane of cleavage/layering; similar features are present at a microscopic scale (Lavallee, 2003). The phyllite commonly displays late stage kink bands. A concordant layer of medium-grained metabasalt approximately 1m thick by at least 100 m long trends subparallel to the top of the west wall of the quarry. Local bulbous forms in the basalt suggest that its protolith may have been pillow lava. The contact of the mafic rock with the phyllite is structurally disturbed but appears to be a modified stratigraphic contact. Similar metabasalt layers are found conformable with structurally higher Five Pines sequence strata. Large, meter-scale, quartz boulders that are common in the southeast corner of the quarry likely represent boudins of large quartz veins; they are pasted with phyllite and locally fine grained, dark gray to black irregular veins and smears of chlorite, interpreted to represent recyrstallized pseudotachylyte (Lavallee, 2003) (Fig. 4).

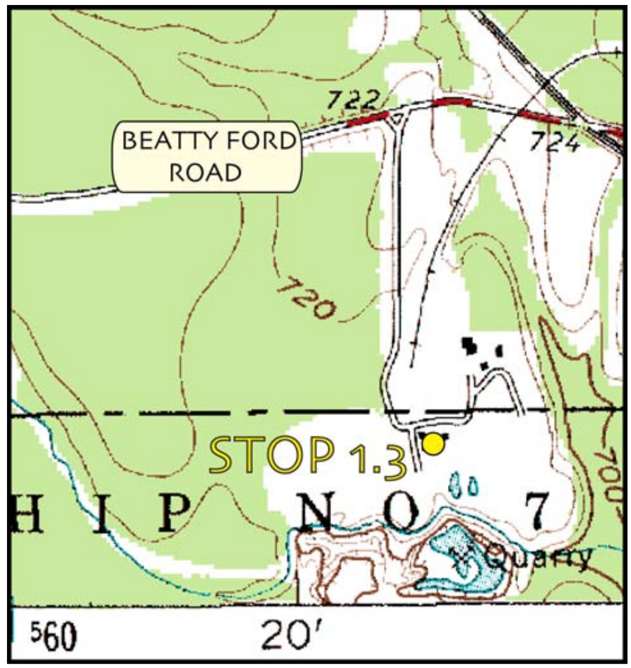
Figure 4. Black pseudotachylyte within the phyllite ‘rind’ of a quartz block at Stop 1.2.

An ^{40}Ar/ ^{39}Ar white mica age of of 374.37 $\pm$ 0.32 Ma has been obtained for the phyllite in the quarry (Hibbard et al., 2012). This age could indicate that either the immediate hangingwall of the Gold Hill fault here has been remobilized in the Late Devonian or that white mica in the sample is of mixed ages (Late Ordovician and Carboniferous?) and that the date could represent a 'hybrid' age. In support of the latter interpretation, two generations of muscovite have been reported from this rock (Lavallee, 2003).

<u>STOP 1.3:</u> SOUTHEAST-VERGENT STRUCTURE IN THE FOOTWALL OF THE GOLD HILL SHEAR ZONE, ALBEMARLE ARC (35°17.138’ N, 080°27.990’W) VULCAN MATERIALS CO. GOLD HILL QUARRY, 16745 OLD BEATTY FORD ROAD, GOLD HILL, NC. **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK, PHIL BRADLEY.

Our purpose in stopping here is to view the typical structural style of the Albemarle arc. The quarry is sited in the Floyd Church Formation, just west of the hinge of the Denton anticline (Fig. 1).

The Gold Hill quarry, originally opened by the Young Stone Company in the late 1950’s, produces crushed stone and ‘feed’ for a lightweight aggregate product. The lightweight aggregate is produced by the neighboring Carolina Stalite Corporation. The quarry was purchased by Vulcan Materials Co. in 1988.



from the Gold Hill 7.5’ quadrangle.

The Floyd Church Formation consists of well-bedded argillite, siltstone, and subordinate greywacke typically 10-60 cm thick. In addition, there are local layers of tuff and pebbly mudstone in the quarry. The Floyd Church Formation lies immediately above c. 547 Ma volcanics of the Flat Swamp Member of the Cid Formation and lies beneath the Yadkin Formation, which contains detrital zircons as young as 528 Ma (Pollock et al., 2010). Thus, the Floyd Church Formation likely ranges in age from latest Precambrian to earliest Cambrian (Terreneuvian).

The Gold Hill quarry is located in the immediate footwall of the Gold Hill shear zone,

Figure 5. Southeast-vergent (to the left) thrust faults and footwall syncline in Floyd Church strata at the Vulcan Materials Gold Hill quarry, south wall. S_0(yellow)=bedding, S_1(green)=axial planar cleavage, red=faults.

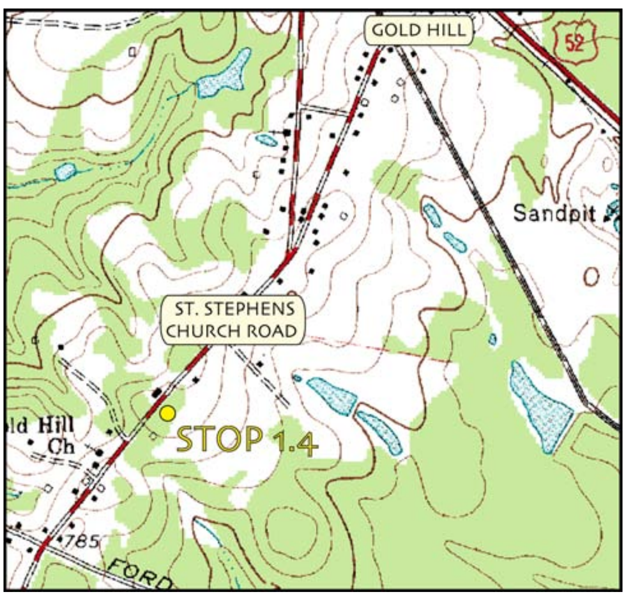
Figure 6. Gold Hill Vulcan quarry, March, 2013. Stop 1.3 and Fig. 5 located behind bench denoted by yellow arrow; upward extension of thrust fault shown in Fig. 5 outlined in red: solid, observed; dashed, approximate.

approximately 700 m structurally below the Silver Hill fault (Fig. 1). Floyd Church strata in the quarry are overprinted by folds, faults, and cleavage. Folds in the quarry are asymmetrical, with shorter, steeper limbs to the southeast; these structures likely represent second-order folds on the regional map-scale folds. Detailed sections constructed from drill data and observation of the quarry walls indicate that the folds are breached by southeast-vergent thrust faults (e.g. Linder and Barreiro, 1994). We will observe a southerly wall at the base of the 2013 quarry where a sinistral-oblique thrust fault zone with a footwall syncline is well exposed (Fig. 5); from the bottom of the pit, we can clearly see the fault extend upwards across at least three benches and up to the soil/talus horizon (Fig. 6).

Although indicators of both direction and sense of shear are scarce in the present outcrop, in 2005 we observed the fault zone to the northeast along strike, from where it has since been removed by quarrying operations. There, we noted NNW-trending, moderate plunging slickenlines within an approximately 6-8 cm thick cataclasite zone. On horizontal surfaces, the cataclasite displayed asymmetric sinistral

S-C like foliation. Collectively, these features are interpreted as indicating sinistral reverse motion along the fault. We have observed the same structural features along the Gold Hill fault; consequently, we interpret the structures here as roughly mimicking the regional structure of the Gold Hill shear zone. All of these structures have been attributed to the Late Ordovician Cherokee Orogeny and related to the accretion of Carolinia to Laurentia (Hibbard et al., 2012; see Hibbard et al., this volume).

STOP 1.4: GOLD HILL MINES HISTORIC PARK (35°30.669'N, 080° 20.675'W) ST. STEPHENS CHURCH ROAD, GOLD HILL, NC. **STOP LEADERS:** PHIL BRADLEY, LEE PHILLIPS, TRAY MCLELLAN.



from the Gold Hill 7.5' quadrangle.

At this stop we present preliminary findings from a Ground Penetrating Radar (GPR) survey to evaluate the use of GPR in locating abandoned mine workings and discuss the historical significance of the Gold Hill mining district. The GPR survey targeted the shaft and stoped areas associated with the Miller shaft (Fig. 8).

The Miller shaft and underground working are part of the Gold Hill Historic Park and are on land that was once part of the Gold Hill Mine and Gold Hill Copper Mining Company holdings. The Gold Hill Historic Park includes several shafts (including the Barnhardt and Randolph shafts), historic structures, historic mining equipment (Fig. 7), and extensive underground workings. A comprehensive review of the history of gold mining in North Carolina and Gold Hill can be found in Knapp and Glass (1999). A review of the economic geology aspects of the Gold Hill Mining District can be found in Laney (1910). Pardee and Park (1948) provide a summary of mining activities for the district.

Figure 7. Chilean mill preserved at the Gold Hill Mines Historic Park.

Miller and Barnhardt Shafts: Extensive underground workings are present beneath the Miller and Barnhardt shafts with horizontal drifts connecting the shafts (Fig. 9). The opening to the Miller shaft has been cleared and made easily accessible for viewing. An outcrop of altered sericite phyllite is visible at the bottom of the access stairs to the shaft. The foliation is oriented approximately 196/81 (right hand rule) and is generally parallel to the strike of the Gold Hill shear zone. The opening for the shaft appears to follow the trend of the foliation.

Figure 8. Map showing location of GPR transect lines and extent of stoping interpreted from GPR data. Miller shaft area - Gold Hill Historic Park, Gold Hill, NC.

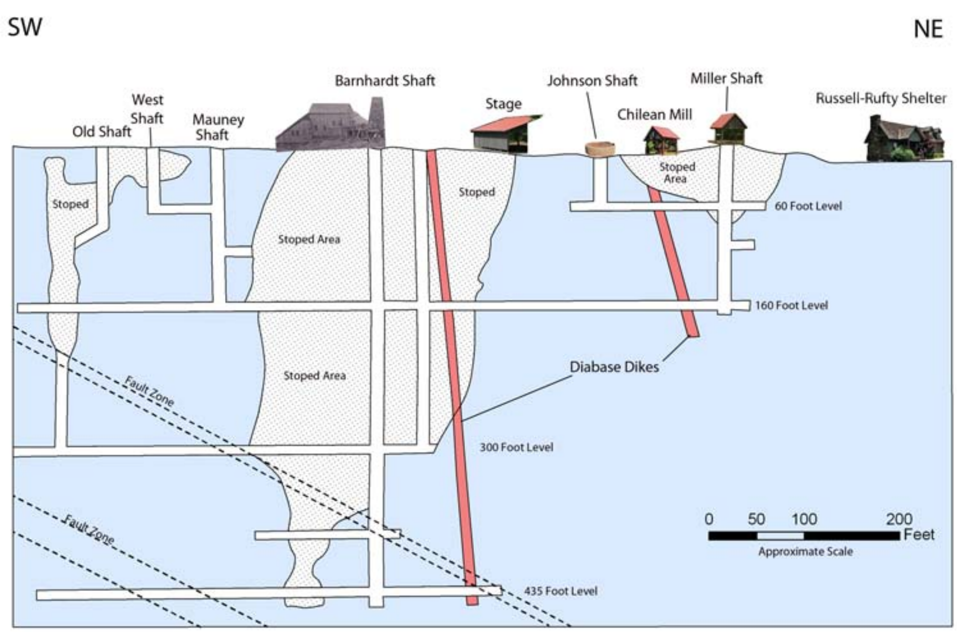


Figure 9. Sketch of cross section from southwest to northeast of the Barnhardt and Miller shaft areas. Sketch based on Plate XVII of Laney (1910) and Plate VIII of Nitze and Hanna (1896). Current and historic structures added for orientation purposes.

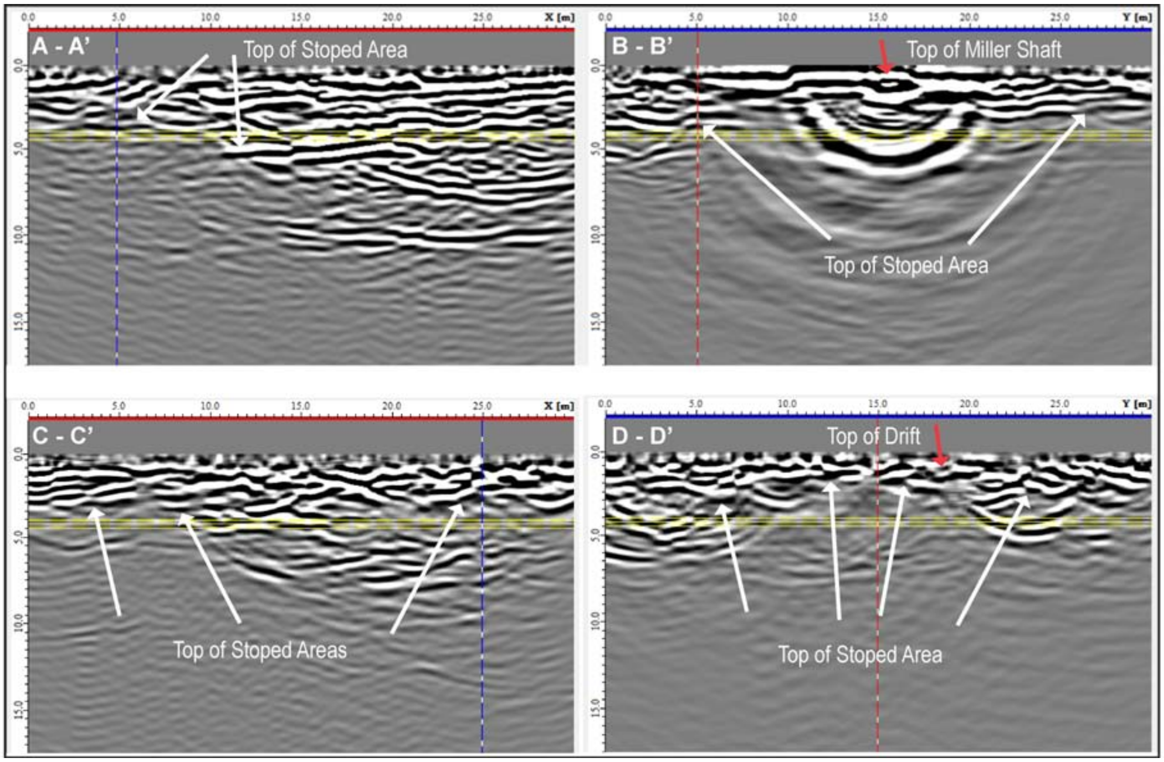


Figure 10. Representative cross sections of processed GPR data. Locations of transects indicated on Figure A.

Ground Penetrating Radar: North Carolina has a long history of gold and other metals mining within the central Piedmont. There are hundreds of abandoned prospects and old mines scattered throughout former mining districts – of which Gold Hill is a prime example. The locations of the Barnhardt and Miller shafts are well known, but the extent of the underground workings are not well known. The distribution of subsurface workings is known only from the historic contributions of sketches in Nitze and Hanna (1896) and Laney (1910). During the summer of 2013, we initiated a shallow subsurface evaluation of areas adjacent to the Miller Shaft to determine if a GPR unit could be used to more accurately locate disturbed areas.

The upper drift (~ 60 feet or 18 meters depth) and stoped areas (Fig. 10) within the vicinity of the Miller shaft are within range of imaging by use of ground penetrating radar (GPR). Several small depressions/collapse areas have been reported from the subsidence of land above the historic underground workings in the vicinity of the Miller shaft; most of which have been back filled as they occur.

The initial survey of the region was conducted using a MALÂ GPR unit over a 30 x 30 meter (3D) grid at intervals of 5 meters (Fig. 8). Each transect was walked twice, collecting data with 100 MHz and 250 MHz antennas. Data were processed using MALÂ 3D Vision software with the following parameters: velocity was set at 102 m/ms, as determined through migration; the FIR filter was applied with low pass at 5 and high pass at 15; time gain filter was applied beginning trace at 30, linear gain = 1000, and exponential gain at 35; and the aperture was set at 10.

The processed data reveal a maximum return depth of approximately 10 meters for the survey with the 250 MHz antenna. Despite potential deeper gains, survey with the 100

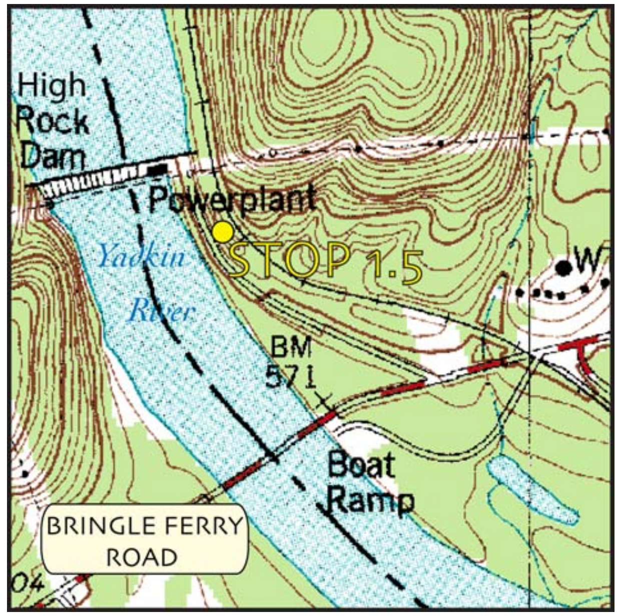
MHz antenna captured bedrock reflectors to a maximum depth of about 13 meters. The survey included passes across the platform above the Miller Shaft; which produced strong echoing of the signal (Fig. 10, B-B'). The known drift from the Miller Shaft served as a point of reference (e.g. Fig. 10, D-D') to establish the extent of the near-surface drift visible from the Miller Shaft opening. We interpret the survey data to reveal several near-surface disturbances possibly consistent with collapses and stoping.

Interpretations drawn from the initial GPR survey of the Miller shaft area are:

- The approximate location of near surface stoping for the area about the Miller shaft can be established by mapping disruptions in return of GPR signals (Fig. 10).
- It should be possible to map the distribution of near surface disturbances within the region with a higher degree of certainty using the GPR system. Additional surveys between the Miller and Johnson shafts should be performed.
- Even though features can be identified using the cart-mounted 250 MHz antenna, the 100 MHz antenna produces a better cross-section and is, therefore, a better choice for future surveys in this area.

STOP 1.5: FLAT SWAMP MEMBER OF THE CID FORMATION, ALBEMARLE ARC (35° 35.982'N 80°13.961'W) ALCOA POWER GENERATING INC., POWER- HOUSE ACCESS ROAD AT HIGH ROCK LAKE DAM, BRINGLE FERRY ROAD, DENTON, NC. **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.

A field trip in the Carolina terrane would not be complete without a stop in the Flat Swamp Member of the Cid Formation. The member forms a distinct, continuous, marker unit within the Albemarle arc (western, folded belt of felsic volcanics in Fig. 1) and in many places it is a topographic ridge-former (back cover). Although we have not mapped in the area of this stop, it affords a view of one of the larger, more easily accessible outcrops of the Flat Swamp Member; it is located on the NW limb of the Denton anticline.(Fig. 1).



from the High Rock 7.5' quadrangle.

The rock here is mainly massive fragmental dacite (?) with cm scale clasts (Fig. 11). The matrix and fragments appear to be relatively uniform in composition and the clasts locally exhibit a jigsaw puzzle-fit texture and curviplanar boundaries (Fig. 11). Collectively, these observations suggest that this rock may represent an altered hyaloclastite, generated by thermal stresses built up by rapid cooling of a lava (e.g. McPhie et al., 1993). Sedimentary lithic clasts are preserved locally at the north end of the outcrop/boulders.

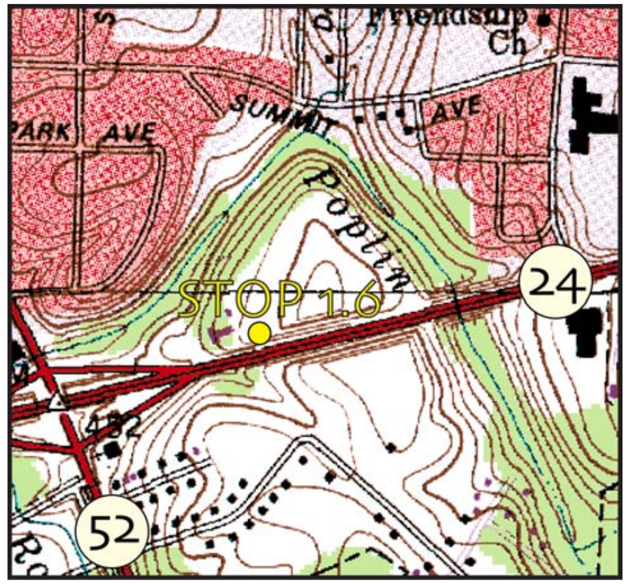
Butler (1995) interpreted the Flat Swamp Member to constitute deposits related to a submarine caldera complex (Butler, 1995; reprinted in this volume). He considered the rock at this stop to be part of his intracaldera facies.

Two radiometric age dates have been reported for the Flat Swamp Member. A felsic volcanic sample collected immediately west of this stop, on the western bank of the Yadkin River has yielded a U-Pb TIMS zircon age of 547 ± 2 Ma (Ediacaran) (Hibbard et al., 2009). A sample taken from a road cut approximately 5 km to the northeast along strike from this stop has produced a $^{207}Pb/^{206}Pb$ TIMS age from two multigrain zircon fractions of 540.6 ± 1.2 Ma (earliest Cambrian) (Ingle et al., 2003). However, this age may be slightly too young, due to the reverse discordance of part of their analyses (Hibbard et al., 2009). Consequently, we prefer the c. 547 Ma date and we consider the Flat Swamp Member to be Ediacaran, or latest Precambrian.

Figure 11. Massive fragmental dacite (?) at Stop 1.5. Note curviplanar borders on clasts

The Flat Swamp Member was thought to conformably overlie the Cid mudstone member (e.g. Milton, 1984); however, in the mid 1990's, USGS geologists reported fossils no older than Middle Ordovician from the Cid mudstone at Jacob's Creek quarry (Koeppen et al., 1995) (Stop 2A). This report, in conjunction with the more recent age dates on the Flat Swamp Member discussed above indicates that there should be a significant fault between the two members of the Cid Formation. However, our recent studies at Jacob's Creek Quarry (Brennan, 2009) and in the vicinity of this stop (Standard, 2003) refute the paleontological report (see Stop 2A).

STOP 1.6: FLOYD CHURCH FORMATION WITH ASH LAYERS AND TRACE FOSSILS (35.340931°N, 80.192065°W) RUSSELLS AUTOMOTIVE, 201 NC 27-24 BYPASS EAST, ALBEMARLE, NC. **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.



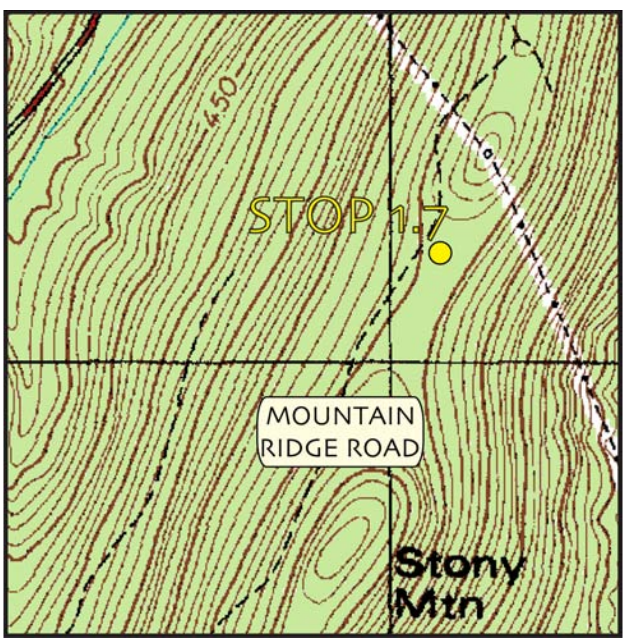
from the Albemarle 7.5' quadrangle.

At this stop, on the SE limb of the New London syncline, fresh mudstone of the Floyd Church Formation is interlayered with cm-scale clay seams (Fig. 12) of probable volcanic ash origin (Stromquist and Sundelius, 1969). Gibson (1989) shows this outcrop to be a trace-fossil bearing locality (presumably, though not explicitly stated to be, *Planolites*). Reasonably good bedding plane exposures will allow field trip participants the possibility of rediscovering trace fossils at this locality. The thicker volcanogenic clay layers show internal laminations suggestive of water-lain ash deposits. Brent Miller of Texas A&M Univeristy has recovered zircon grains from a 4cm-thick laminated clay layer; he reports that they are a combination of abraded detrital grains and acicular euhedral grains, presumably of volcanic origin. His single-grain analyses of the latter zircon type yield an as yet insufficiently resolved age of ca. 552 Ma. This age likely represents a detrital age as the

Figure 12. Floyd Church Formation strata with prominent seams of volcanic ash between beds; Stop 1.6 at Russell Auto.

Floyd Church Formation conformably overlies the c. 547 Ma Flat Swamp Member (see Stop 1.5).

STOP 1.7: STONY MOUNTAIN GABBRO (35°19'05.540"N, 80° 5'47.57"W) STONY MOUNTAIN VINEYARDS, 26370 MOUNTAIN RIDGE ROAD, ALBEMARLE, NC. **STOP LEADERS:** JEFF POLLOCK, JOHN DEDECKER, JIM HIBBARD



from the Morrow Mountain 7.5' quadrangle

At this stop we will examine mafic plutonic rocks that intrude volcanic and sedimentary sequences of the Albemarle arc and we will sample a variety of wines from the local vineyard. In the Stony Mountain area, the Stony Mountain gabbro (SMG)(Ingram, 1999) includes numerous irregular stocks of gabbro that are exposed in outcrops along the hilltops, ridges and shore of Lake Tillery. An intrusive contact between the gabbro and strata of the host Tillery Formation can be seen in a nearby exposure on Highway 24-27; however, the locality is dangerous, with little space for parking and heavy, often speeding, traffic. The largest body of gabbroic rocks of the Stony Mountain intrusive suite underlies Stony Mountain and it is an approximately 1.5 by 2.5 km, northeast-southwest trending body. The best exposures are located at the summit of Stony Mountain beneath the electricity pylons and throughout the parking area at Stony Mountain Vineyards, where several dozen large boulders that were removed during construction of the vineyard are present. North of the office building, clean, fresh boulders of the gabbro consist of massive pale-grey and white to pale-red weathering homogenous rock that is weakly deformed and mildly metamorphosed. On fresh surfaces it is a dark green to greenish-grey, medium- to coarse-grained, granular rock consisting of plagioclase, clinopyroxene, amphibole and minor biotite. Some of the boulders reveal leucocratic phases of the intrusion and one boulder reveals an unusual pattern of leucocratic dikelets (Fig. 13).

In thin-section the SMG contains predominantly subhedral to euhedral plagioclase (40-60%), clinopyroxene (15-25%) with lesser amounts of amphibole and biotite. Primary seriate to porphyritic igneous textures are well preserved, with metamorphism and secondary alteration resulting in plagioclase being saussuritized and completely altered to sericite/epidote, and the replacement of clinopyroxene by pleochroic colourless to pale green chlorite and actinolite. The cores of augite crystals are replaced by green-brown and

Figure 13. Unusual pattern of leucocratic dikelets developed in the Stony Mountain gabbro; in a boulder at the vineyard, Stop 1.7.

pleochroic hornblende. Hornblende also occurs as poikilitic crystals that enclose aggregates of alteration minerals and plagioclase crystals and is typically altered. Minor amounts of anhedral quartz occur interstitial to the plagioclase and mafic minerals. Pyrite and opaque minerals occur as accessory minerals in the groundmass.

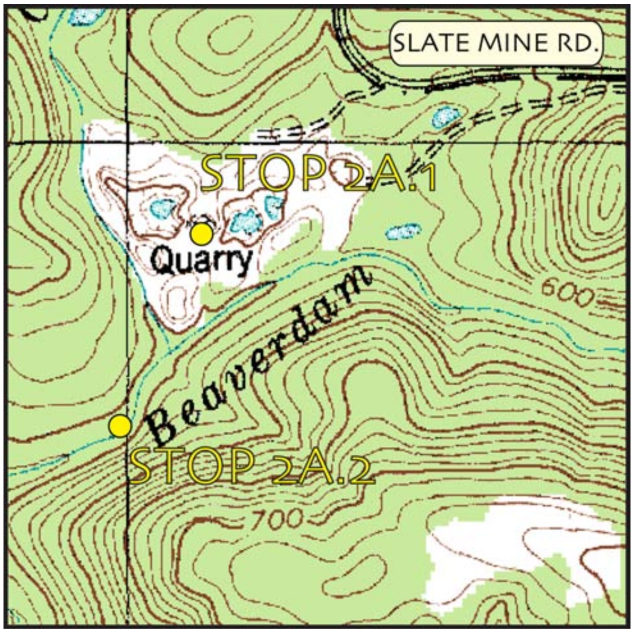
Lithogeochemical and radiogenic isotope analysis (Pollock and Hibbard, 2010) of the Stony Mountain gabbro indicates that the rocks have sub-alkaline basaltic compositions, with variable LREE enrichment with moderate sloping extended REE patterns. On tectonic discrimination diagrams the SMG has a geochemical 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 SMG is interpreted to record subduction zone magmatism in an island arc setting from hydrous partial melting of variable mixtures of lithospheric and asthenospheric mantle sources overprinted by a minor subducted-slab derived hydrous fluid component.

Stratigraphic relationships indicate that intrusion of the Stony Mountain gabbro occurred after deposition of the early Paleozoic Yadkin Formation (maximum age 528 Ma; Pollock et al., 2010) but before the Cherokee orogenic event (ca. 455 Ma) responsible for upright folding and greenschist facies metamorphism in the Albemarle arc that is interpreted to be related to accretion of Carolinia to eastern Laurentia (Hibbard, 2000; Hibbard et al., 2012). A gabbro sample collected from Ridges Mountain, just west of Asheboro, NC, yielded a $^{206}Pb/^{238}U$ date of 544.81 ± 0.55 Ma, and a $^{207}Pb/^{235}U$ date of 544.73 ± 0.95 Ma (DeDecker et al., this volume). A date of 545 ±1 Ma is interpreted to be the age of igneous crystallization. We note, however, that this date contradicts the stratigraphic relationship within the Albemarle arc and should be considered preliminary as the gabbro sampled for analysis yielded two single-fraction zircon crystals, only one of which is concordant.

By analogy with modern settings the rocks of the Stony Mountain gabbro are comparable to modern MORB-like to OIB-type enriched rocks from the western Pacific Ocean and are interpreted to have formed within an evolving early Paleozoic island arc–back arc rift-basin system. The Stony Mountain gabbro represents the terminal phase of Neoproterozoic–early Paleozoic magmatism in Carolinia and the presence of this arc-back arc rift system is broadly coeval with arc-back arc volcanism in other peri-Gondwanan blocks of the Appalachians and may well be related to the early Paleozoic opening of the Rheic Ocean.

<u>SUNDAY, NOVEMBER 10, 2013:</u>

<u>STOP 2A.1</u>: CID FORMATION: JACOB'S CREEK QUARRY (35. 52901° N, 80.10386°W) **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK, PATRICIA WEAVER.



from the Handy 7.5' quadrangle

Figure 14. View to the east of Jacob's Creek quarry,

Figure 15. Splitting operation at Jacob's Creek quarry.

The Jacob’s Creek Quarry (named after the Jacob’s Creek company, originally out of Charlotte; not a local creek) is a dimension stone quarry (Fig. 14), where flags of Cid Formation mudstone are extracted (Fig. 15). The smooth, natural bedding of the mudstone allows it to be used extensively in flooring, stair treads, patios, borders and windowsills. Many public school windowsills in North Carolina are made from this stone. Examples of where this stone can be seen include: Duke University's Fuquay School of Business, R. B. House Library at the University of North Carolina at Chapel Hill, Kings Mountain National Military Park (visitor center and exhibits), and the North Carolina Welcome Center on Interstate 85 at the NC-SC border.

Jacob's Creek quarry (Fig. 16) lies near the core of the New London syncline (Fig. 1). The quarry is underlain by the Cid mudstone member, which lies ~60 m stratigraphically below felsic volcanics of the Flat Swamp Member (Brennan, 2009), which have a precise U-Pb zircon age of 547 ± 2 Ma (Hibbard et al., 2009). In recent years, the Jacob’s Creek Quarry area has become one of the focal points in the debate over the age of the Albemarle Group. Interestingly, both Precambrian and Paleozoic fossils have been reported from the rocks within the quarry. Koeppen et. al. (1995) reported euconodonts (Late Cambrian and younger) from a loose block of clastic sedimentary rocks with carbonate interbeds situated near the quarry

Figure 16. February, 2013 image of Jacob's Creek quarry in the vicinity of the active quarry (pond in center of image). Slate Mine Rd. is the paved road in the upper right corner.

entrance. More recently, we found the Ediacaran fossil *Aspidella cf. A. terranovica* (Billings, 1872) on bedding surfaces from within the active quarry (Fig. 17) (Weaver et al., 2006; Hibbard et. al., 2006; Hibbard et al., 2009)(the best specimen recovered to date is housed at the North Carolina Museum of Natural History, Raleigh). *Aspidella* is mainly confined to the Neoproterozoic, although some elements are documented as extending into the Early Cambrian. The reports of both Neoproterozoic and Late Cambrian fossils from within Jacob's Creek quarry leaves us with bit of a stratigraphic quandary.

In this vein, our detrital zircon study indirectly supports a Neoproterozoic age for these strata. Pollock (2007; Pollock et al., 2010) sampled and analyzed 70 zircon grains from a greywacke bed at the east end of the quarry. The ages of the zircons are dominantly Neoproterozoic, with two peaks, one at c. 550 Ma and the other at c. 630 Ma. He also reports multiple older grains, ranging from c.

845 Ma - c. 2575 Ma. The youngest grain detected is c. 550 Ma, which provides only a maximum age constraint for strata in the quarry. However, younger formations in the Albemarle Group contain Paleozoic detrital grains (Pollock, 2007; Pollock et al., 2010). These observations thus suggest that the strata in the quarry are latest Neoproterozoic.

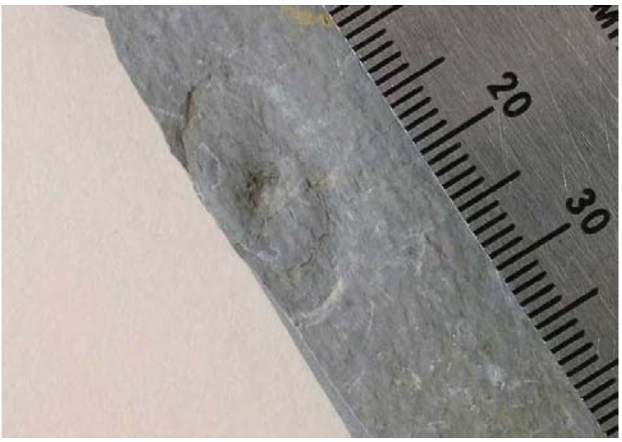


Figure 17. An example of *Aspidella sp.* recovered from the Jacob's Creek quarry. Photo by Chris Tacker, North Carolina Museum of Natural History.

The rocks in the quarry comprise thinly laminated to thickly bedded light to dark grey mudstone typical of the Cid Mudstone member. Brennan ((2009) interprets them as interbedded, mud-dominated T_{D-E} (Bouma, 1962) or T_3 (Stow and Shanmugam, 1980) turbidites and contourites. Thin bedded (30-70mm), normally graded, sand beds are also present; although, their origin is unknown. They have sharp basal and upper contacts and may result from bottom currents (Shanmugam, 2006) or they may be Bouma T_A divisions (Bouma, 1962). Near the top of the eastern quarry wall is a medium- to thickly bedded, siltstone to fine-grained sandstone layer with cross and hummocky cross stratification interpreted as a storm deposit. Other features in the mudstone beds include slump folds, concretions and flame structures. Discontinuous black hemipelagic layers, typically 10 mm thick, are present intermittently throughout the section and concretions, 7 - 20 cm long and up to 3 - 5 cm thick are commonly found within these layers. In several locations they have amalgamated and extend up to several meters laterally. Paleocurrent indicators from the storm bed together with the overturning direction of intrastratal folds and flame structures give a general sense of paleocurrent and slope facing direction towards the west (Brennan, 2009).

Dumas and Arnott (2006) suggest that hummocky cross-stratification optimally forms above (but near) storm wave base, which is rarely greater than 200m (Johnson and Baldwin, 1997). *Aspidella* was reported in the Mistaken Point and Trespassey Formations, west Conception Bay, Newfoundland, from contourite deposits layered between deep water (i.e. greater than 200m) Bouma T_{D-E} beds (Wood *et. al.* 2003).

In addition to *Aspidella*, stromatolite-like forms have been reported from loose blocks of Cid Mudstone on the quarry grounds (Fig. 18). Stromatolites are still used by many geologists as unequivocal indicators of very shallow-water conditions; however, there have been reports of stromatolites at water depths of up to 100m (Böhm and Brachert, 1993; Eriksson and Reczko, 1998). The depositional environment of the quarry rocks is difficult to determine from the evidence presented here alone; however, it is possible to suggest a shallow (<200m) environment based on the both the observations given above and the inferred depositional environments of the overlying Floyd Church and Yadkin Formations. Sedimentary structures present in the Floyd Church Formation include flaser, wavy and lenticular bedding which are common in intertidal areas. The stratigraphic and structural data collected to date from the Cid and Floyd Church Formations in vicinity of the quarry indicate a conformable, coarsening upwards sequence for the Albemarle Group (see next stop) (Brennan, 2009).

Figure 18. Stromatolite-like forms found in a large, loose block on the quarry premises near Stop 2.A.2

Structural features present in the quarry include a weak, but penetrative regional cleavage and kink bands at the eastern end of the quarry, near the top of the quarry wall.

STOP 2.A.2: CID FORMATION: CONTACT OF THE MUDSTONE MEMBER WITH THE FLAT SWAMP MEMBER STOP LEADERS: JIM HIBBARD, JEFF POLLOCK, PATRICIA WEAVER. See topo inset map for Stop 2A.1

This stop is at the contact between the mudstone and Flat Swamp members of the Cid Formation. Typical of many features of significance, the contact is almost entirely submerged beneath Beaverdam Creek. A stratigraphic section was measured during August 2007, but precise measurements were difficult to record due to water depth and turbidity. However, Matt Brennan was able to collect enough samples from the submerged outcrop to determine the nature of the contact and complete construction of the stratigraphic column (Brennan, 2009).

The measured section (Fig. 19) is approximately 70 feet thick with the bottom, Cid mudstone, exposed to the left when observed from the north bank of Beaverdam Creek. The top of the section is exposed to the right and consists of Flat Swamp epiclastics. In between is an intercalation of Cid mudstone /

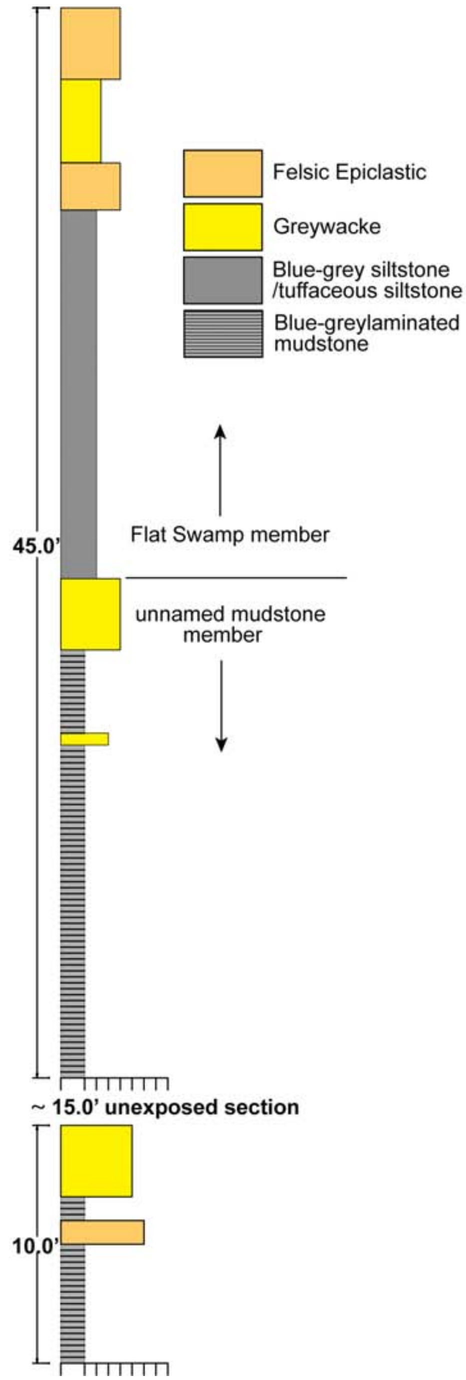
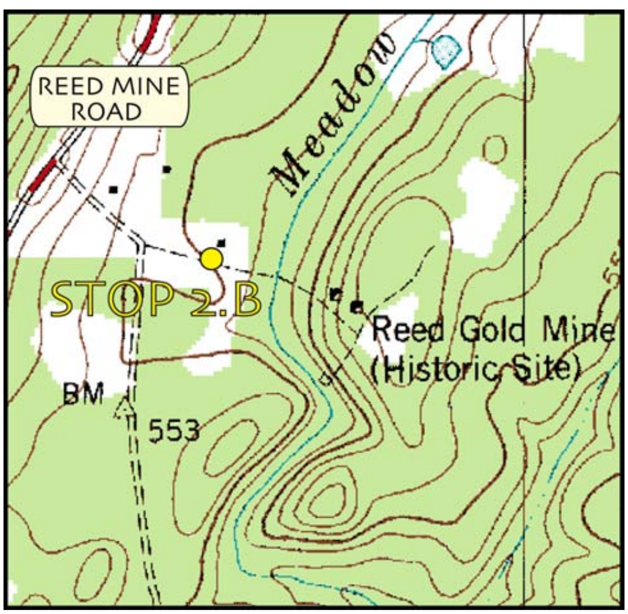


Figure 19. Stratigraphic Column of the gradational contact between the mudstone and Flat Swamp Members of the Cid Formation at Beaverdam Creek near the Jacob's Creek Quarry.

greywacke and Flat Swamp epiclastics and tuffaceous siltstone. Near the bottom of the section, overlying the mudstone and visible in the creek bank, is a thin bed of coarse-grained felsic epiclastics containing fragments of Cid mudstone (Fig. 20). The mudstone fragments are angular and range in size from 2 to 20 mm across. At the top of the section, a thin bed of Cid greywacke lies between two thin beds of felsic epiclastics. The entire section appears to represent a gradational rather than structural contact.

Figure 20. Clasts of Cid mudstone in felsic epiclastic rock.

<u>Stop 2B</u>: Reed Gold Mine State Historic Site, Gold Hill shear zone: (38.285633°N, 80.4665°W). **Stop leaders:** Dennis LaPoint, Phil Bradley



from the Locust 7.5' quadrangle.

The purpose of this stop is to highlight the significance of gold in the history of the Carolinas as well as to acknowledge the recent revival in gold exploration in central North Carolina. Renewed interest in gold in our state has been generated by its elevated market values over the last few of years. The Reed gold mine is one of the jewels of State's historic sites. The underground tour, stamp mill and museum are all outstanding stops from both a historic and geologic prespective.

History: The Reed Gold Mine is the site of the first authenticated discovery of gold in the United States and in the words of Nitze and Hannah (1896, p. 124), ". . . it was the first mine to give celebrity to the gold fields of the Appalachian range . . ." Various people encountered gold prior to 1799 in the eastern US, including the Indians, Spanish, gold in Guilford County in 1774, and Thomas Jefferson who reported a nugget in Virginia. However the the initial discovery at Little Meadow Creek in 1799 by Conrad Reed, the twelve-year-old son of John Reed, who retrieved a nugget estimated to weigh 17 lbs. from the creek (Knapp and Glass, 1999), led to the first gold rush in the nation (Knapp, 2001). In 1803, John Reed took three partners and they supplied a few slaves to work the creek. A slave named Peter found a 28 lb. nugget, the largest on record in the eastern United States.

By 1810, the US Mint had assayed 1,300 ounces of gold from Cabarrus County and Little Meadow Creek had produced over 150 pounds of nuggets which weighed over one pound (Knapp, 2001). Because of the gold rush that was developing, Yale educated geologist Denison Olmsted convinced the state government to fund geological field work starting in 1823. He hired a German mineralogist to conduct a study of the slate belt, a study completed by Elisha Mitchell. These studies, reports and maps, represent the nation's first state-funded geologic work (Knapp, 2001).

Until 1828, North Carolina was the sole producer of domestic gold in the country. During this period, the Reed property remained a placer operation. Nitze and Hannah (1896) noted that "The proportion of large nuggets has not been paralleled on this side of the continent."

Until 1825 mining was a low-technology alluvial operation done by farmers and slaves when not busy with crops. A farmer, Matthias Barringer, who lived 20 miles from the Reed property, encountered a vein of quartz in the hillside while searching along a creek. He found nearly pure gold in the 4 inch wide vein. The miners followed this vein for thirty feet and to a depth of 18 feet. Soon other quartz vein mines followed and Mecklenburg County became the leading gold county. By the 1830's North Carolina was experiencing a genuine gold rush and mining was only second to agriculture in value in the state(Knapp, 2001).

In 1831, the mining process at the Reed property advanced to an underground effort focused on unearthing auriferous quartz veins on the property. After John Reed passed away in 1845, the mine property went through multiple owners with sporadic mining operations. The last large nugget (23 lbs.) was found in 1896 and underground mining ended in 1912. The last private owners, the Kelly family, donated the mine site to the state of North Carolina in 1971 and it became a state historic site in 1976.

Geology: The Reed Gold Mine lies within the Gold Hill shear zone and near its eastern border, the Silver Hill fault (Fig. 21). Despite the past economic value of the mine, our understanding of the geology in the immediate

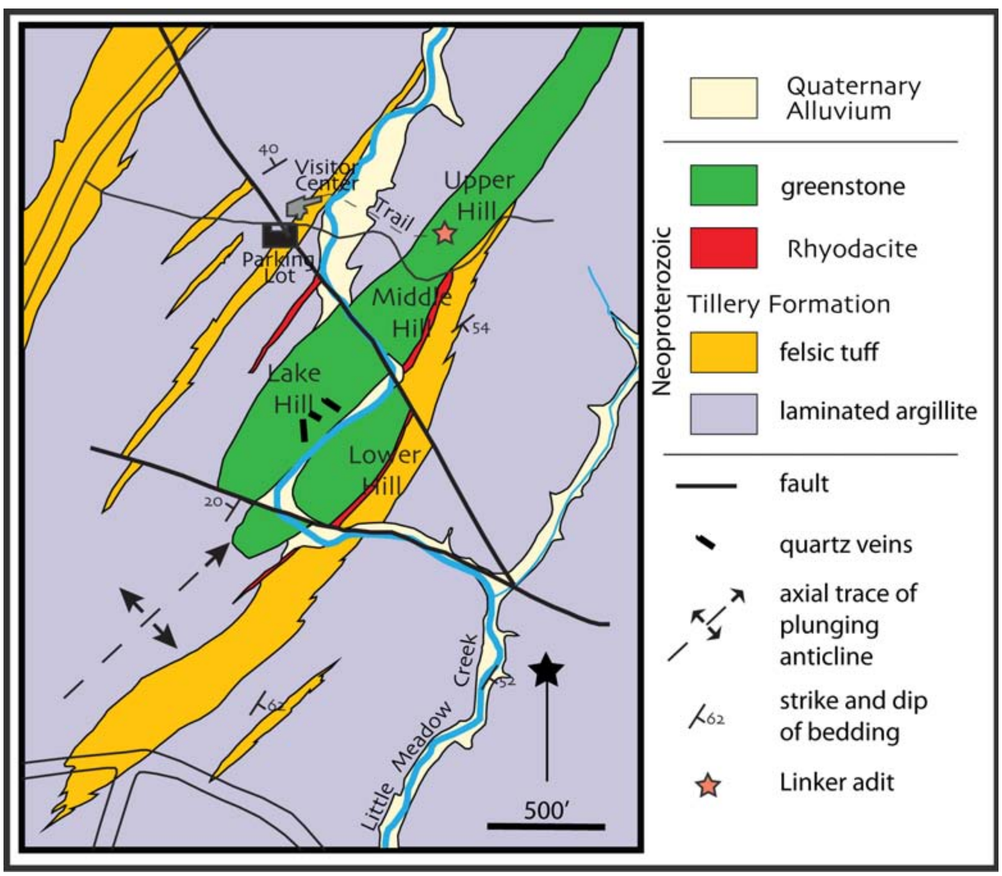


Figure 21. General geology of the Reed Gold Mine site (compiled from El Samani, 1978 and Sundelius and Stromquist, 1978).

mine area remains limited. Although it has been included in USGS regional mapping projects (e.g. Sundelius and Stromquist, 1978), the only systematic geological documentation of the immediate mine area was undertaken by El-Samani (1978) and Osman (1978).

Nitze and Hannah (1896) recognized that the gold mineralization at the Reed Mine is confined to quartz veins within a greenstone body. The greenstone underlies a northeast-trending ridge that includes the Upper, Middle, Lower, and Lake hills (Fig. 21). It has been interpreted to represent either a dike (Nitze and Hannah, 1896, El-Samani, 1978) or a sill (Pardee and Park, 1948) intrusive into the local host rocks. El Samani (1978) interpreted the greenstone as a metagabbro body.

The host rocks consist mainly of laminated argillite and felsic tuff with subordinate greywacke and rhyodacite (Fig. 21) (El-Samani, 1978). Although geologists concur that these host strata are part of the Albemarle Group within the Gold Hill shear zone, the rocks have been assigned to different formations by different workers. El-Samani (1978) considered them to represent Cid Formation strata whereas Sundelius and Stromquist designated them as part of the Tillery Formation; both formations are now thought to be latest Neoproterozoic (Hibbard et al., this volume). It is not clear if this issue is resolvable without significant effort, as stratigraphic assignment in the Gold Hill shear zone is tenuous due to stratigraphic and structural complexities (e.g. Hibbard et al., 2012).

All of the country rocks have been metamorphosed to lower greenschist facies and have been affected by a single regional cleavage that is axial planar to upright folds in the shear zone (El-Samani, 1978). One of these folds, the Reed Mine anticline, is defined by bedding dips and stratigraphic younging-direction reversal on the mine property (El-Samani, 1978); it lies directly along trend with the greenstone body (Fig. 21). This geometry prompted El-Samani (1978) to interpret the greenstone body as representing a post-deformational metagabbro dike that intruded along the axial surface of the anticline. However, there are problems with this interpretation. First, the greenstone is metamorphosed and it has been shown that the regional metamorphism accompanied the deformation responsible for the cleavage and folding (e.g. Hibbard et al., 2012); thus the greenstone is likely pre-deformational. Secondly, it would be fortuitous for a fold to form with the body localized along its axial surface. Instead, we suggest that the greenstone is likely either a sill, as indicated by Pardee and Park (1948) or concordant layer, that has been involved in the folding. The coincidence of the body directly along trend of the Reed Mine fold, and its wedge-shaped outcrop pattern are consistent with the outcrop pattern of a northeast plunging anticline (Fig. 21). In this scenario, the transverse quartz veins could have resulted from along-axis extension during folding and thus mineralization would be synchronous with the Late Ordovician regional deformation.

Gold Mineralization and Alteration: Quartz veins at the Reed mine vary from irregular stringers less than 1 inch thick to regular veins more than 6 feet thick. Underground mining and development in the mine have been confined, for the most part, to quartz veins or group of veins. Five major sets of gold-bearing veins have been recognized and mined on Upper Hill. The common trend of quartz veins is northeast with the most prominent veins striking N25°E and dipping to the southeast at 70 to 85 degrees. A less common set of quartz veins strikes northwest and dips northeast. The major veins range in strike from N10° to 38°E and the dip ranges from 47° to 85°SE. The veins contain, besides quartz, small amounts of calcite, epidote and chlorite. A large quartz body in Linker adit consists, of a composite of closely spaced quartz veins enclosing greenstone inclusions. This quartz vein is essentially barren of gold and sulfide mineralization (Osman, 1978).

Traces of the base-metal sulfides including pyrite, chalcopyrite, sphalerite and bornite are common in the quartz veins. Pyrite and chalcopyrite are disseminated in quartz and in the greenstone host rock. Pyrite is more abundant and tends to concentrate in aggregates along the contact between quartz veins and greenstone (Osman, 1978).

The alteration envelope associated with mineralization consists of calcite, epidote and chlorite and thus resembles the greenshist metamorphism of the region. The fluids and alteration, and gold mineralization are similar to other major gold camps in metamorphic environments and can be classified as orogenic gold deposits (LaPoint and Moye, this volume). Ore fluids are likely generated during metamorphism and the presence or absence of gold depends on the source material for the fluids. Fluid flow during tectonic events will migrate towards extensional sites where open space is generated and there are changes in temperature and pressure to deposit the quartz and gold.

The reason for the extraordinary size and quantity of large nuggets at the Reed site is not clear and has not been studied, in part because no nuggets are available for study. The nuggets probably form or grow in the weathering environment present during the formation of the saprolite and dissolution of quartz veins. Although gold is very immobile in the weathering environment, it can be mobilized during weathering of sulfides and the mobility is enhanced by organic acids or gold-organic complexes. During this process, the region needs to be stable to allow chemical weathering and precipitation of the large nuggets. It is postulated that gold is mobilized into the groundwater and is precipitated in Little Meadow Creek sediments. What exact conditions created the extrodinary size and quantity of large nuggets is not known.

At the stop: There are multiple activities to undertake at this stop; our group will follow the surface and underground tours described below (Figs. 22, 23). In addition the visitor center features exhibits on gold and the history of the Reed Mine and there is an orientation film about the gold mining industry in North Carolina.

Surface and Underground Tours: We will start at the visitor center and follow the tours that are abridged from literature available at the historic site and reprinted below (Figs. 22, 23). The trails cross lode and placer mining areas, leads us underground, and pass many historic sites. Weather permitting (water is not turned off for the season), we will view the stamp mill in operation and there will be time for gold panning in the panning area. In addition to the tours of the property described below, the Lower Hill Trail features various large rock samples from the southeastern U.S.

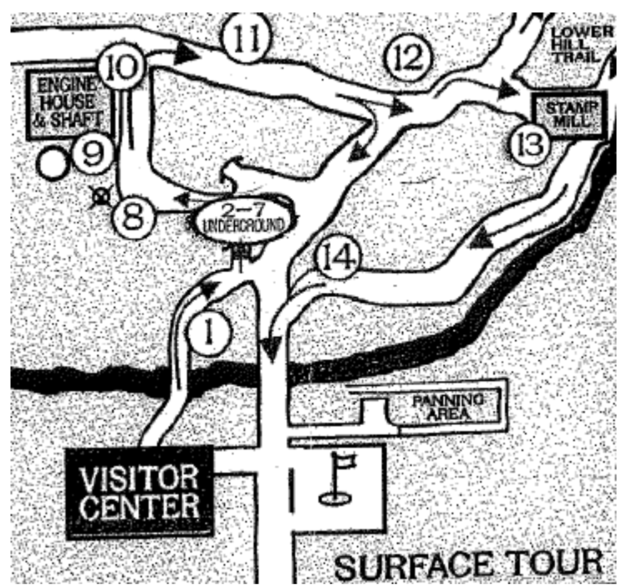


Figure 22. Schematic map of Reed Gold Mine Historic Site; numbers keyed to descriptions in text.

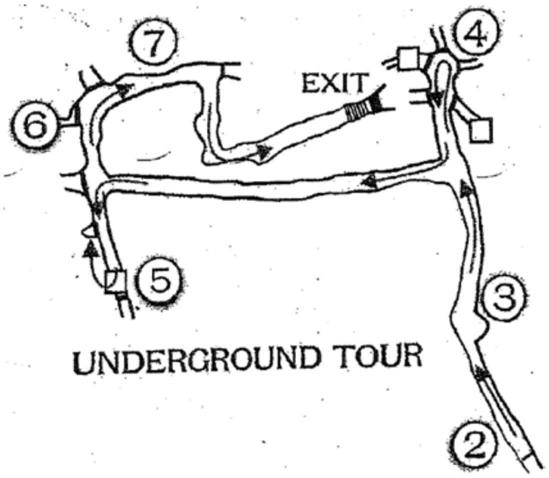


Figure 23. Underground tour stops 2-7 on Fig. 22.

1. <u>Bridge over Little Meadow Creek</u>: here in 1799, 12 year old Conrad Reed made the first documented discovery of gold in the United States.

2. <u>Entrance to the mine</u>: the Linker adit leads into the underground tour (Fig. 24).

Figure 24. View from inside Linker adit at station 3 looking towards the entrance.

3. <u>Stope and vein</u>: miners dug out a test sample of a quartz vein for assay. The original floor level can be seen in the dug out area; the floor on which you are standing was lowered so you can pass through without stooping over.

4. <u>Linker shaft room</u>: we are 50′ below the surface. This shaft was a conduit into and out of the mine; at the bottom of the shaft is a 'kibble' (Cornish for bucket) used to transport equipment, miners, and ore. Linker shaft was sunk directly on top of Vein 4, now a tunnel with round timbers above your head. It is thought that Vein 4 was one of the richest veins in the mine, based on the amount of work evident here.

In the cross cut that leads to stations 5-7, there are numerous quartz veins (Fig. 25) and at one locale in the cross cut, slickenlines are marked by a sign; slickenlines are better exposed and illuminated by the light near stop 7 (Fig. 26).

Figure 25. Quartz veins in greenstone in Linker adit at junction with the cross cut between stations 3 and 4.

5. <u>Morgan shaft</u>: this shaft is 50′ deep. The ore cart and tracks here are only for show, as Reed Mine tunnels were too narrow to accommodate them.

6. <u>Drill and Vein 5</u>: the area behind the barricade was Vein 5, which had little gold. The drills displayed here were not used at Reed Mine; instead miners used mainly hammer and chisel.

Figure 26. Slickenlines at interface between greenstone and quartz vein (removed), at light by station 7. The oblique orientation of these features on the vein margin is consistent with sinistral reverse motion in the Gold Hill shear zone.

7. Gallery room: this area of Vein 4 was called the gallery because of its 35′ high ceiling, which is only 15′ from the surface of the Upper Hill. The area behind the bars leads to Veins 1, 2, and 3 which are not open to visitors. Exit Underground Tour.

8. Morgan shaft headframe: headframe and kibble suspended over Morgan shaft.

9. Engine shaft: this shaft is the deepest on the property at 150′. The local water table is at 55′, thus water had to be pumped in order to work at the deeper levels.

10. Engine house: the chimney and foundation represent the remains of the engine house. A large boiler and steam engine powered machinery such as pumps, Chilean mills, arrastras, hoists, and wooden stamp mills. The boiler was originally installed in the long pit adjacent to the chimney.

11. Brunerville: the site of a small town with nearly 20 buildings erected by the Reed Gold and Copper Mining Company in 1853-1854.

12. Chilean mill stones: these stones were the 'business end' of Chilean mills, used to crush quartz in order to extract gold.

13. The Stamp mill: just west of the present building, Warren Kelly installed a 10-Stamp mill in 1898. The restored mill comes from the Coggins Mine and is the same style as the one installed at Reed (Fig. 27). Weather permitting (water is not turned off for the season), we will see this mill in operation.

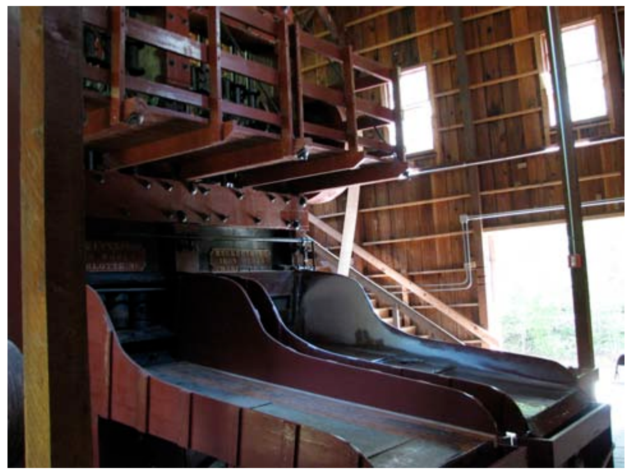


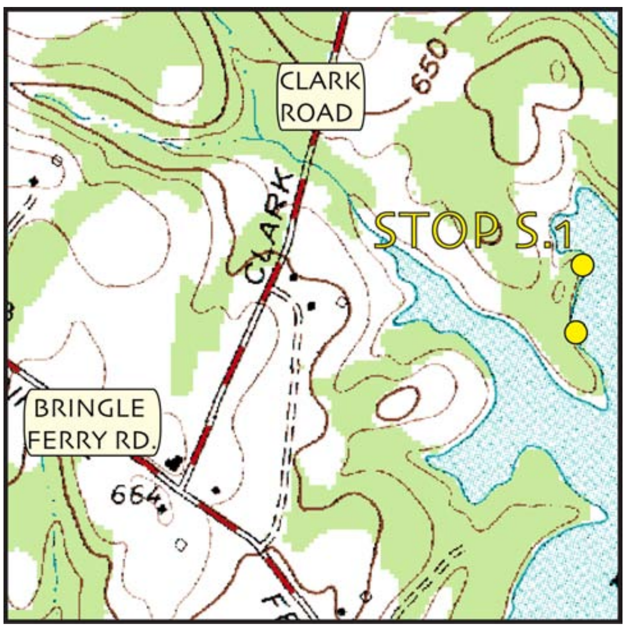
Figure 27. The stamp mill at Reed Gold Mine.

14. The Shinn nugget: this area is known as Dry Hollow. In 1896, Jacob Shinn unearthed the last large nugget (almost 23 lbs.) found at Reed Mine. A cast of the nugget is on display in the Visitor Center.

FIELD GUIDE TO SUPPLEMENTARY STOPS

STOP S.1: THE GOLD HILL FAULT (35° 37.039'N, 80°18.281'W). STOP LEADER: JIM HIBBARD

Lake level must be low to observe these outcrops. Please note that this stop is accessed via private property and permission must be obtained from Mr. Randy Connor at 2380 Clark Rd. A dirt track leads from the Connor residence east to the outcrop along the lake.



from the Gold Hill 7.5' quadrangle

A series of exposures along the shoreline here expose the Gold Hill fault. To the east of the fault lie low-grade metaclastic rocks of unseparated Albemarle Group whereas to the west of the fault lies mafic, chloritic phyllite of the Five Pines sequence. The fault is marked by chlorite and white mica schist with an intense foliation and many elongate quartz segregations that may represent boudins of quartz veins (Fig. 28). A subhorizontal mineral lineation is observed locally on the main foliation. At this locale, the fault fabric is affected by late folds; nonetheless, shear sense indicators on subhorizontal surfaces clearly record a sinistral component of motion throughout these exposures (Fig 28).

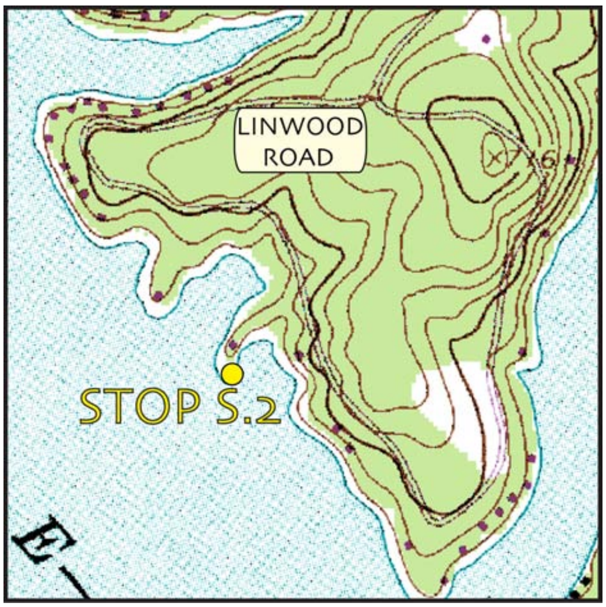
Figure 28. Asymmetric fabrics preserved along the Gold Hill fault at Stop S.1; Above: sinistral S-C fabric on subhorizontal surface in quartz-veined phyllite. Below: sinistral S-C fabric on subhorizontal surface in dark phyllite.

Unlike the regional fold set, the late fold axes are all steeply plunging to neutral and lack an associated axial planar foliation. The entire zone of intense deformation and juxtaposition of rock types is approximately a few meters wide. Unseparated Albemarle Group strata just southeast of the tip of the small peninsula display narrow (<10 cm thick) silvery, phyllitic shear zones and here the main

Cleavage is folded around steeply plunging late folds. This is one of the few places we have observed folding of the main foliation in the Albemarle Group.

STOP S.2: FOLDED PHYLLITE OF THE FIVE PINES SEQUENCE (35°38.903'N, 80°17 .570'W). **STOP LEADER:** JIM HIBBARD.

Lake level must be low to observe these outcrops. Please note that this stop is accessed via private property and permission must be obtained from the residents of 1910 Beckner Rd.



from the Southmont 7.5' quadrangle

The main purpose of this stop is to observe the structure of the Five Pines sequence. This spectacular outcrop consists of a variety of western sequence rock types that have undergone a foliation-forming event and subsequently were folded. The late folds are well exposed during times of low lake level (Fig. 29).

The Five Pines rock types found here at the point include rusty mafic sandstone, dark brown phyllite, silver-grey phyllite, green-gray phyllite, black (graphitic?) phyllite, and siliceous, blocky, black mudstone. To the west of the point, cm-scale cream-colored felsic interlayers are common among the phyllites.

The main structures observable in this outcrop include a penetrative, phyllitic cleavage with an associated lineation and shear sense indicators (mainly shear bands), and mesoscale folds that deform the cleavage and associated structures; to the west, vertical faults offset multiple layers and may postdate the folds. The lineation associated with the main foliation is a stretched grain (in sandstone) and mineral lineation (in phyllite) that varies in orientation with position on the folds. Likewise, shear sense indicators have also been folded, thus producing apparently opposing senses of shear on opposite limbs of the fold (Fig. 30); those viewed on subhorizontal surfaces on the east limbs record sinistral motion whereas those seen on subhorizontal surfaces on the west limbs appear to record dextral shear. The mesoscale folds affect all fabric elements and they are upright, gently southeast plunging (220/35), open folds with wavelengths of approximately 15 m. When plotted on an equal area net, the lineations define a partial small circle about the fold axes, suggesting that the folds formed by flexural slip (Ramsay, 1967). Upon unfolding of the fold limbs and rotating the axis back to horizontal, the unfolded lineations trend NW-SE and shear sense indicators consistently show tops to the southeast sinistral oblique motion for this hangingwall block of the Gold Hill fault. On the basis of their asymmetry, the mesoscale folds here appear to occupy the west limb of a regional, lower-order, antiform.

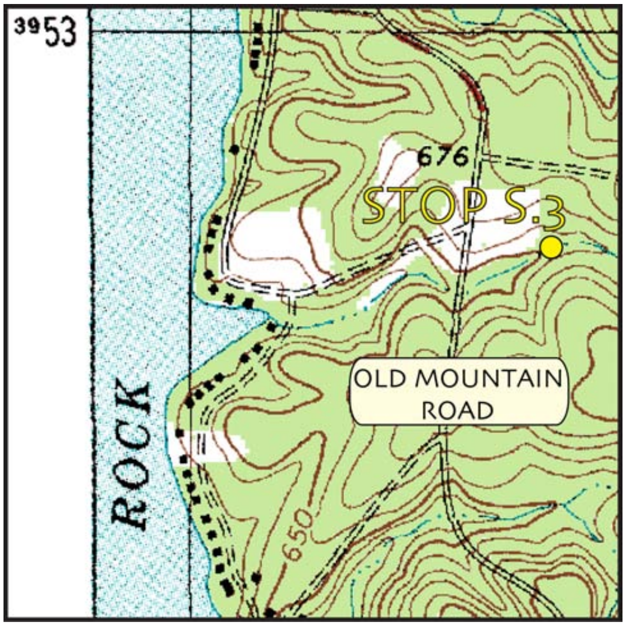
The mesoscale folds here have the same orientation and style as the regional folds in the Albemarle Group; on this basis, we correlate the two fold sets. If this correlation is valid, it implies that the phyllitic cleavage is older than the Late Ordovician fold set. Elsewhere in the Five Pines sequence, we have locally observed the phyllitic cleavage to be axial planar to tight folds; the attitudes of these few 'early' folds are disparate. The early phyllitic cleavage could record either a Neoproterozoic deformation event or it could represent an early phase of the Late Ordovician event. The sense of shear indicators preserved along the cleavage are compatible with the kinematics of the Late Ordovician event, so we tentatively suggest that cleavage formed early during that event.

Figure 29. Folded phyllite at Stop S.1; hammer handle approximately parallel to axial trace of fold.

Figure 30. Shear bands preserved in phyllite on opposite limbs of the late fold at Stop S.1. Left: shear bands with apparent dextral asymmetry on the west limb of a late fold. Right: shear bands with sinistral asymmetry on the east limb of the same fold. See text for explanation.

STOP S.3: VOLCANICLASTIC ROCKS IN THE GOLD HILL SHEAR ZONE (35°43.040'N, 80°14.440'W). **STOP LEADER:** JIM HIBBARD, ISSAC STANDARD.

Short traverse along an unnamed creek that crosses under Old Mountain Road; Please note that this stop is on private property and permission must be obtained from the owner, Dr. James Welborn, Lexington, NC.



from the Grist Mountain 7.5' quadrangle

Along the unnamed branch is a collection of exposures of typical mafic and felsic metavolcaniclastic rocks found in the GHfz. Most of the branch east of Old Mountain Road is underlain by chloritic phyllite and coarser mafic volcaniclastic rocks; we will go upstream as far as few felsic volcanic interlayers. All of these rocks prominently display the main foliation found in the fault zone and the down-dip lineation, common to this northern segment of the GHfz is common in outcrops along the branch; the subhorizontal lineation might also be found among these outcrops, but it is rare here. Shear sense indicators are sparse, but one outcrop of mafic fragmental rock, a few meters in the woods on the north

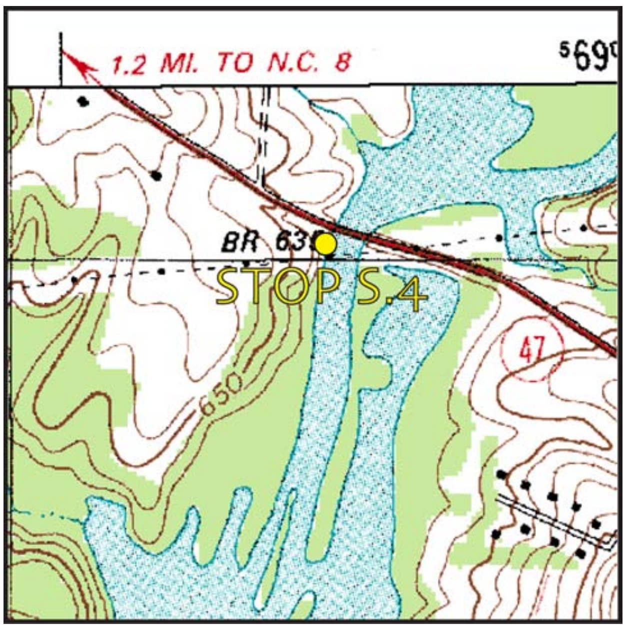

Figure 31. Typical volcaniclastic rocks along the unnamed creek at Stop S.3. Above: mafic volcaniclastics containing a hefty epidote-quartz clast that displays small wings indicating a sinistral component of motion along the foliation. Below: felsic crystal tuff that is interlayered with the mafic rocks at this stop.

side of the branch contains clasts that displays wings, on a subhorizontal surface; the wings indicate a sinistral component of motion (Fig 31). In addition, small, rootless, asymmetric folds of calc-silicate layers have been found in the mafic rocks; the few folds seen all indicate a sinistral component of motion.

A U-Pb zircon age (TIMS) of 542.0 + 8/-5.5 Ma has been obtained for the felsic quartz-feldspar crystal tuff at the farthest point of this traverse (Hibbard et al., 2012). This age was not available to Issac Standard when he was writing his masters thesis on this area

(Standard, 2003); these volcanic rocks are similar to the Five Pines sequence, with which he correlated them. The new age date confirms that the volcaniclastic rocks in the GHfz are time equivalent to, and likely correlative with, the Flat Swamp member of the Cid Formation, just to the east, in the Albemarle arc.

<u>Stop S.4</u>: Sinistral Shear in Hangingwall of the Gold Hill fault (35°44.855'N, 80°14.517'W). **Stop leader:** Jim Hibbard, Issac Standard.



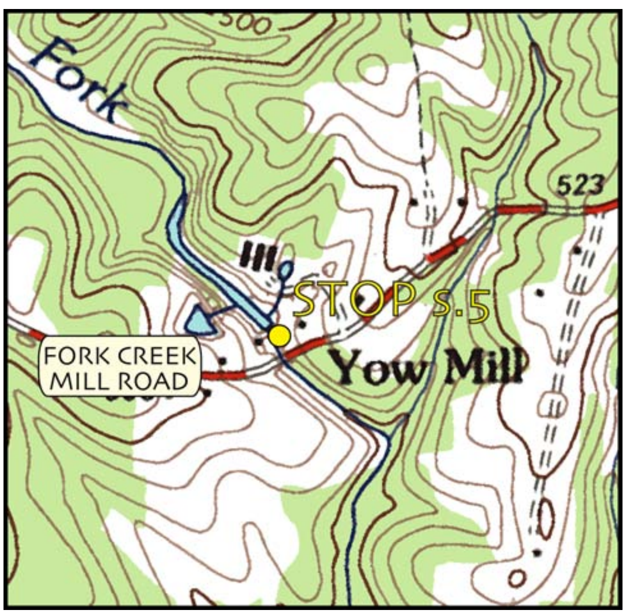
from the Grist Mountain 7.5' quadrangle

Lake level must be low to observe these outcrops. Rocks at this stop are distinct from any Albemarle arc rocks. Here, mainly mafic phyllite and schist with diorite and gabbro are exposed along the west bank of Abbotts Creek during times of low lake level. The Gold Hill fault is interpreted to lie within Abbotts Creek or its floodplain to the east of the creek, thus the outcrops lie in the immediate hangingwall of the fault. Rocks at this stop are similar to those of the Five Pines sequence in the Mt. Pleasant area. There, mainly mafic volcaniclastic rocks of the Five Pines sequence are intruded to the west by a granodioritic to gabbroic intrusive complex. We suggest that the phyllite and schist at this outcrop represent the intruded and tectonized equivalent of the Five Pines sequence and that the bodies of meta-intrusive rock here are equivalent to the intrusive complex in the Mt. Pleasant area. The most striking feature of this outcrop is the strong deformational overprint wherein gabbro /diorite layers form boudins with long axes parallel to the main foliation. The intrusive rocks also appear to be cataclasized. The main foliation is intense and penetrative, trending northeasterly and dipping steeply to the northwest; a subhorizontal mineral stretching lineation is associated with the main foliation. Shear sense indicators, such as S-C foliations, C' shear bands, and winged objects are common on subhorizontal surfaces here, and all of them indicate a sinistral component of motion (Fig. 32).

Figure 32. Mafic schist and phyllite on the west bank of Abbotts Creek at Stop S.4. Above: Note the clear sinistral asymmetry of the felsic layer. Below: well-developed sinistral C' shear bands in mafic schist.

On the west bank of the creek, just to the north of the bridge, are fresh outcrops (during times of low lake level) of fine to medium grained diorite, that we informally term the Abbotts Creek diorite. A diorite sample from these outcrops has yielded a U-Pb zircon age (TIMS) of 614 + 11/-3.3 Ma and a U-Pb titanite age of 603 ± 6 Ma. The older age is interpreted to be the crystallization age of the diorite, whereas the younger titanite age is thought to represent a slightly younger thermal pulse, perhaps related to other, as yet undated, intrusions in the complex. This diorite also has an ε_{Nd} value of 5.0 with a model age of 0.8 Ga, indicating that it represents relatively juvenile crust.

STOP S.5: ERECT MEMBER OF THE UWHARRIE FORMATION AT YOW MILL (35°33.135'N, 79° 43.434'W). **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.



from the Erect 7.5' quadrangle.

Although well to the east of other stops in this guide, this is an important outcrop from the standpoint of the age and stratigraphy of the Albemarle arc (Fig. 33). The outcrop is, to date, the most easily accessible example of an assemblage of volcanic-derived, locally quartz-rich, fine- to coarse-grained sandstone and pebbly sandstone that marks the base of the Uwharrie Formation in this area (Fig. 34). This sandstone member, termed the Erect Member, has been mapped consistently at the base of the Uwharrie Formation within the eastern portion of the Erect 7.5' quadrangle, where it strikes northeasterly and dips steeply to the northwest; available evidence indicates that it youngs consistently to the northwest. The member abruptly thickens and thins in the area, ranging from approximately 0.1 km up to 1.0 km thick. The sandstone is locally pebbly, with felsic volcanic clasts, and at one locale we noted cross bedding.

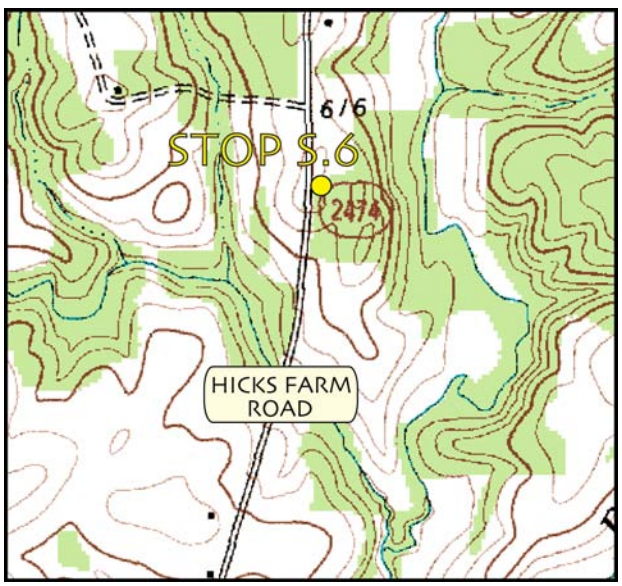
Figure 33. Outcrop of the Erect Member of the Uwharrie Formation at Yow Mill (Stop S.5); outcrop lies on right bank between the lower spillway (in sun) and higher spillway (in shade).

Approximately 1.1 km west of the mill on a west-northwest trending branch of Fork Creek, we collected a sample of the sandstone for detrital zircon analysis. Of 64 zircon grains analyzed, the youngest grain yielded a date of 545 ± 7 Ma (Pollock et al., 2010). This age is within analytical error of the 547 ± 2 Ma age of the Flat Swamp Member of the Cid Formation (Hibbard et al., 2009). We interpret these ages as indicating that the base of the Uwharrie Formation is likely diachronous and that part of the Uwharrie volcanics are correlative with the Flat Swamp

Figure 34. Fine grained, quartz-rich sandstone of the Erect Member at Yow Mill (Stop S.5).

Member of the Cid Formation (see Hibbard et al., this volume).

<u>STOP S.6</u>: AARON CONGLOMERATE, GOAT FARM, HICKS FARM ROAD, SILER CITY. (35°45.481'N, 79° 33.414'W). **STOP LEADERS:** JIM HIBBARD, JEFF POLLOCK.



from the Liberty 7.5' quadrangle.

This stop is close, if not the same as Stop 7 on the 1964 Carolina Geological Society trip led by George Bain (Bain, 1964). The outcrop lies in the northwest corner of an enclosed goat field, adjacent to Hicks Farm Road (Fig. 35).

Figure 35. Fin-like outcrop of Aaron conglomerate at Supplemental Stop S.6.

Permission of the property owners, who live at the end of the dirt drive on the north side of the goat field, is required.

In 1964, participants were instructed to ". . . pause here only long enough to verify the presence of conglomerate." Our interest here is in the detrital zircon data derived from this outcrop.

The outcrop is composed of interbedded matrix-supported pebbly conglomerate and greywacke that are interlayered on a scale of 10-20 cm (Fig. 36). The rounded clasts in the conglomerate are dominantly vein quartz and quartzite, although other clast types include reddish siliceous mudstone, black siliceous argillite, phyllite and fine-grained felsic volcanic rock.

The most prominent structure in the outcrop is a moderate slaty cleavage that is near vertical and strikes northeasterly. Bedding here is at a high angle to cleavage, suggesting that we are located near the core of a mesoscale fold.

Pollock et al. (2010) reported U-Pb detrital zircon dates for 60 grains from this outcrop. The youngest analysis yielded an age of 588 $\pm$ 11 Ma, indicating that the Aaron conglomerate is significantly younger, and likely not a part of the old, Hyco, arc (see Bowman et al., this volume).

Figure 36. Interbedded pebbly conglemerate and greywacke at Supplemental Stop S.6.

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2013 Scientific papers

ONE ARC, TWO ARCS, OLD ARC, NEW ARC: AN OVERVIEW OF THE CAROLINA TERRANE IN CENTRAL NORTH CAROLINA

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ABSTRACT
The Carolina terrane forms the heart of Carolinia, one of the largest accreted peri-Gondwanan crustal tracts within the Appalachian Orogen. The terrane consists of two major lithotectonic elements, the older Neoproterzoic Hyco magmatic arc, ca. 633-612 Ma, and the younger Neoproterozoic-early Paleozoic Albemarle magmatic arc, ca. 555-<528 Ma. Both formed in suprasubduction zone magmatic arc settings; the Hyco arc is interpreted to have formed mainly on an oceanic basement, whereas isotopic and geochronological data indicate that a more evolved crustal component was present beneath the Albemarle arc. The arc sequences are separated by an unconformity, and in places, a third lithotectonic unit consisting of clastic sedimentary rocks with subordinate volcanics, the Virgilina sequence, intervenes between them. The tectonic setting of the Virgilina rocks is unclear. The Carolina terrane appears to have departed from its peri-Gondwanan source area in the Early to Middle Cambrian; the Stony Mountain gabbro likely heralded this event and the Kings Mountain sequence may represent a sedimentary record of this rifting.

Two major tectonothermal events have overprinted rocks of the terrane. The Neoproterozoic Virgilina deformation, ca. 578-545 Ma, is heterogeneously developed in the Hyco arc and Virgilina sequence. This event appears to overlap in time with the stitching of the two largest components of Carolinia, the Carolina and Charlotte terranes at ca. 550 Ma. Eclogite metamorphism in the Charlotte terrane of South Carolina may be related to this event. The second event, the Cherokee orogeny, has penetratively overprinted rocks of the Carolina terrane with an axial planar cleavage to southeast vergent folds, locally associated with southeast vergent thrust faults. Multiple thermochronologic studies on micas defining cleavage indicate that this event started in the Late Ordovician and likely continued into the Early Silurian. The Cherokee orogeny most likely marks the accretion of Carolinia to Laurentia.

INTRODUCTION
The Carolina terrane forms the 'heart' of Carolinia, one of the largest accreted crustal tracts within the Appalachian Orogen (Fig. 1; Sidebar 1). At present, the Carolina terrane (Secor et al.,1983; Hibbard et al., 2002) (Fig. 1) provides most of our knowledge of Carolinia mainly because its low grade metamorphic overprint and its relatively simple structural style render the terrane conducive to a variety of topical studies, e.g. stratigraphic, paleontologic, structural, geochronologic, geochemical,

and paleomagnetic. It has been more than a decade since the geology of the terrane has been compiled and synthesized (Hibbard et al., 2002) and since that time, many new studies have been undertaken in the terrane. Consequently, it is timely, on the occasion of the 2013 Carolina Geological Society Field Trip, to summarize and synthesize the results of these 21st century studies in light of the classic 20th century studies that form the foundation of our knowledge of the Carolina terrane.

Many of the 21st century investigations into the geology of the Carolina terrane have been focused on controversies concerning its stratigraphy and tectonic history. These concerns have been addressed with new data sets produced mainly by personnel from North Carolina State University, Texas A&M University, Auburn University, and the North Carolina Museum of Natural History (Allen, 2005; Allen et al., 2005, 2008; Bowman, 2010; Brennan, 2009; Hames et al., 2003; Hibbard, 2000; Hibbard et al., 2002, 2006, 2007, 2009, 2012; Hibbard and Waldron, 2009; Ingram, 1998; Kurek, 2010; Lavalee, 2003; Miller et al., 2003; Pollock, 2007; Pollock and Hibbard, 2010; Pollock et al., 2009, 2010, 2012; Standard, 2003; Standard et al., 2002). These studies have

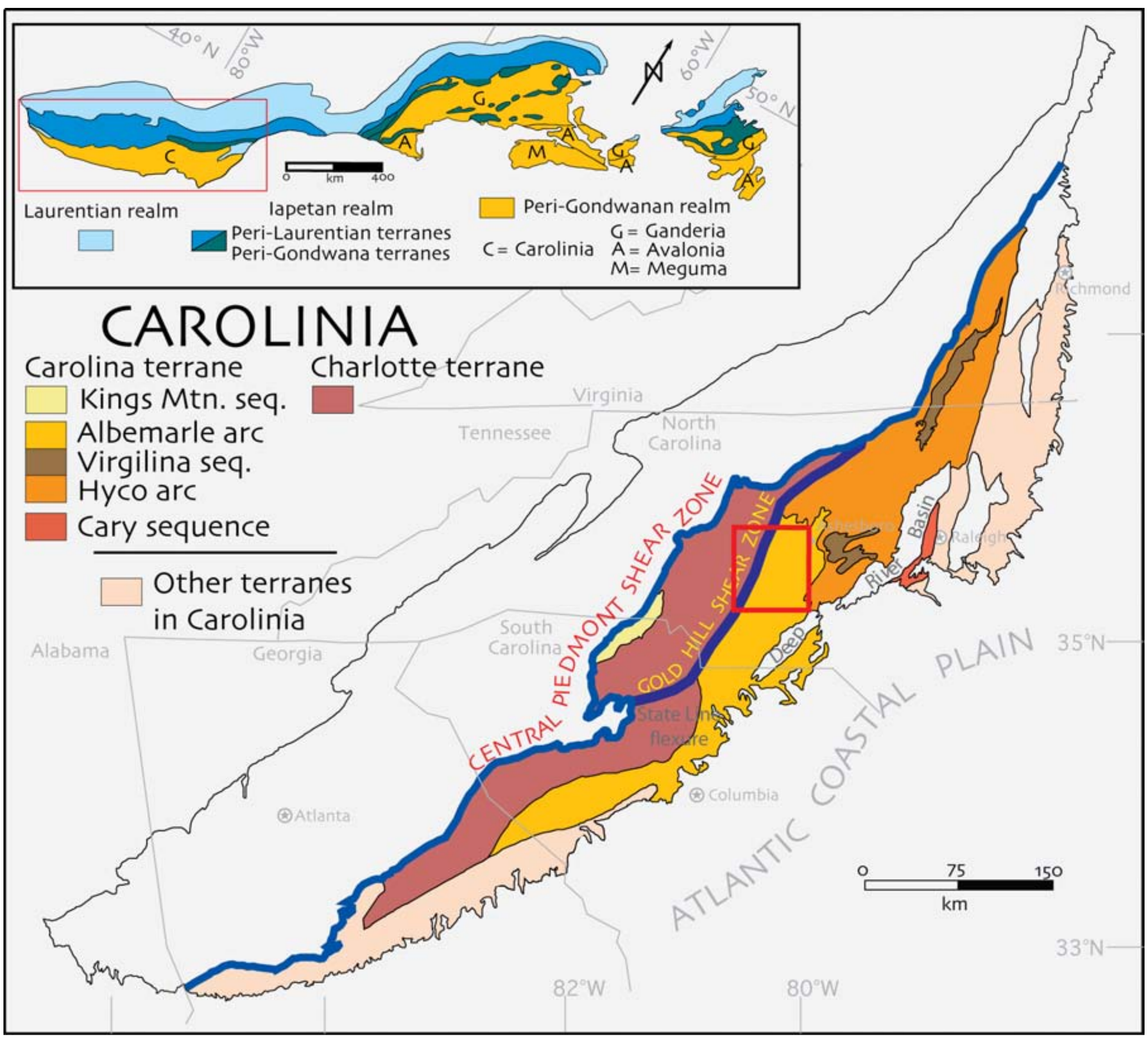

Figure 1. Distribution of the major lithotectonic elements in Carolinia; box indicates approximate area of the field trip. Inset: major elements of the Appalachian peri-Gondwanan realm (from Hibbard et al., 2006).

Sidebar 1

What's with all the names? Why not just 'Carolina slate belt'?

It is essential to clarify the nomenclature of regional geological classification in the southern Appalachians, and specifically, in our case, the rocks in central North Carolina. To paraphrase a former advisor 'If you don't know the meaning of the terms you use, no one will know what you're talking about!'

The common term '**Carolina slate belt**' was abandoned along with other belts of the southern Appalachians due to confusion in their defining features (Horton and Zullo, 1991); e.g., the belt system generally utilized a single feature, such as metamorphic grade or volume of plutonic rocks, to distinguish between belts. A more comprehensive means of classfiying regional packages of rocks was viewed as a more favorable approach (Horton and Zullo, 1991); consequently, 'terrane' classification, which utilizes multiple aspects to distinguish between crustal packages, has since predominated in the southern Appalachians. Thus, the **Carolina slate belt** and the Charlotte belt were subsumed by the **Carolina terrane** (Secor et al., 1983), which, itself, was later redefined; upon recognition that the the two former belts have distinct early histories, the western portion of Secor et al.'s (1983) Carolina terrane was assigned to the **Charlotte terrane**, while the term **Carolina terrane** was retained for only the more easterly of these rocks (Hibbard et al., 2002).

The term '**Carolina zone**' was introduced in order to group and refer to all of the peri-Gondwanan terranes of the southern Appalachians (Hibbard and Samson, 1995). The 'zone' apellation was abandoned in favor of the term '**Carolinia**', in order to gain consistency of nomenclature with peri-Gondwanan blocks of the northern Appalachians: specifically with Avalonia and Ganderia (Hibbard et al., 2007). It should be noted that Glover et al. (1997) first introduced the term '**Carolinia**' with a somewhat broader definition. Finally, all of the Appalachian peri-Gondwanan terranes have been grouped into the hierarchically broader '**Appalachian peri-Gondwanan realm**' (Hibbard et al., 2006).

anchored previously controversial stratigraphic sequences and they have substantially modified our understanding of the tectonic history of the Carolina terrane, including its provenance within Gondwana, the timing of its departure from Gondwana, the timing and nature of its accretion to Laurentia, and the nature of post-accretion tectonics. Also, during the past decade there have been new faunal discoveries within the terrane that may well shed further light on the nature, distribution, and evolution of soft-bodied organisms of the Ediacaran (Weaver et al., 2008; Hibbard et al., 2009; Tacker et al., 2010).

In a broader forum, Carolinia is one of several circum-Atlantic Neoproterozoic island arc systems that are preserved along the eastern edge of North America (Fig. 1) and at the western edge of Europe (e.g. Nance and Thompson, 1996). Study of these Neoproterozoic terranes and their paleogeography is particularly topical because the Neoproterozoic-early Paleozoic was characterized by dramatic changes in the global environment such as multiple glaciation events at equatorial latitudes, profound extremes in sea level, ocean chemistry and climate (e.g. Dalziel, 1997; Hoffman and Schrag, 2002), and changes in the distribution of land masses on Earth (e.g. Condie and Sloan, 1998). Collectively, these changes were associated with rapid evolution and a profound increase in biodiversity (Knoll, 1992; Narbonne and Gehling, 2003). The study of these island arc terranes, predicated on deciphering the geology of key units such as the Carolina terrane, ultimately will lead to a better understanding of this critical time in Earth history.

In addition to academic concerns, it is also timely to return to the geology of the Carolina terrane in light of the elevated market value of gold. The Carolina terrane was host to the first authenticated gold discovery in the United States and historically has produced sufficient quantities of gold to warrant construction of a mint in Charlotte, NC in the 1800s. The present high market value of gold, has led to significant renewed interest in understanding the origin and distribution of gold and other metallic deposits in the Carolina terrane.

The titles of the 2013 field trip and of this overview highlight the first-order architecture of the Carolina terrane as presently recognized – that of two major magmatic arcs, an older Hyco arc (c. 633-612 Ma) and a younger Albemarle arc (c. 555-530 Ma). This basic layout, first perceived by Harris and Glover (1985, 1988) forms the foundation for many of the recent findings summarized herein. Following a brief review of the regional setting of the Carolina terrane, this overview paper will first outline the major lithotectonic (Sidebar 2) components of the terrane in North Carolina, followed by a summary of the salient tectonic features that have been overprinted on these components; we close out our overview with a new model for terrane evolution that attempts to account for its first-order characteristics.

Sidebar 2

What are lithotectonic thingamajigees?

A **lithotectonic unit** is an assemblage of rocks that were either formed or deposited in a common tectonic setting during a finite time span (Hibbard, 2004). For example, the Hyco arc contains volcaniclastic rocks and magmatic rocks that formed during the c. 633-612 growth of a subduction-related magmatic arc in Carolinia. Lithotectonic units are scale dependent, contingent on both the time and scale of the tectonic process considered. The Hyco arc is part of the Carolina terrane, a lithotectonic element, in this case a crustal block that represents the amalgamation of at least two arcs; at a broader scale, the lithotectonic division of Carolinia represents an amalgamation of multiple different peri-Gondwanan arcs. In considering all of the peri-Gondwanan rocks of the Appalachians, the lithotectonic division is the Appalachian peri-Gondwanan realm.

Regional Context of the Carolina terrane

The Carolina terrane occupies a centrally located, axial, position within Carolinia and extends for more than 500 km along strike, from central Georgia to central Virginia (Fig. 1). The terrane generally follows the northeast-striking grain of the orogen, but in central South Carolina, it tracks a first-order oroclinal flexure wherein trends to the southwest of the flexure are roughly east-northeasterly, whereas those to the northeast of it are northeasterly; this feature has been termed the State Line flexure (Allen et al., 2008; Hibbard and Waldron, 2009)(Fig. 1). To the west the Carolina terrane is flanked by the extensive Charlotte terrane and the western Piedmont, whereas to the east it is bordered by a collection of piecemeal terranes with geologic histories that are generally not well constrained (Hibbard et al., 2002). The boundary between the Carolina and Charlotte terranes in North Carolina was formerly thought by many to be the Gold Hill shear zone; however, since the revelation that Carolina terrane rocks lie to the west of the shear zone, the location and nature of this boundary is open to reassessment (Hibbard et al., 2012; Dennis et al., 2012). In South Carolina the boundary between the two terranes is the Chappells shear zone (Secor and Snoke, 2002), and this tectonic zone appears to extend into Georgia. In Virginia, the Carolina terrane is in tectonic contact with rocks of the western Piedmont along the Alleghanian central Piedmont shear zone (Fig. 2)(Hibbard et al., 1998; Wortman et al., 1998). For its entire strike length, the contact between the Carolina terrane and more easterly terranes is a series of mainly late Paleozoic to Mesozoic faults.

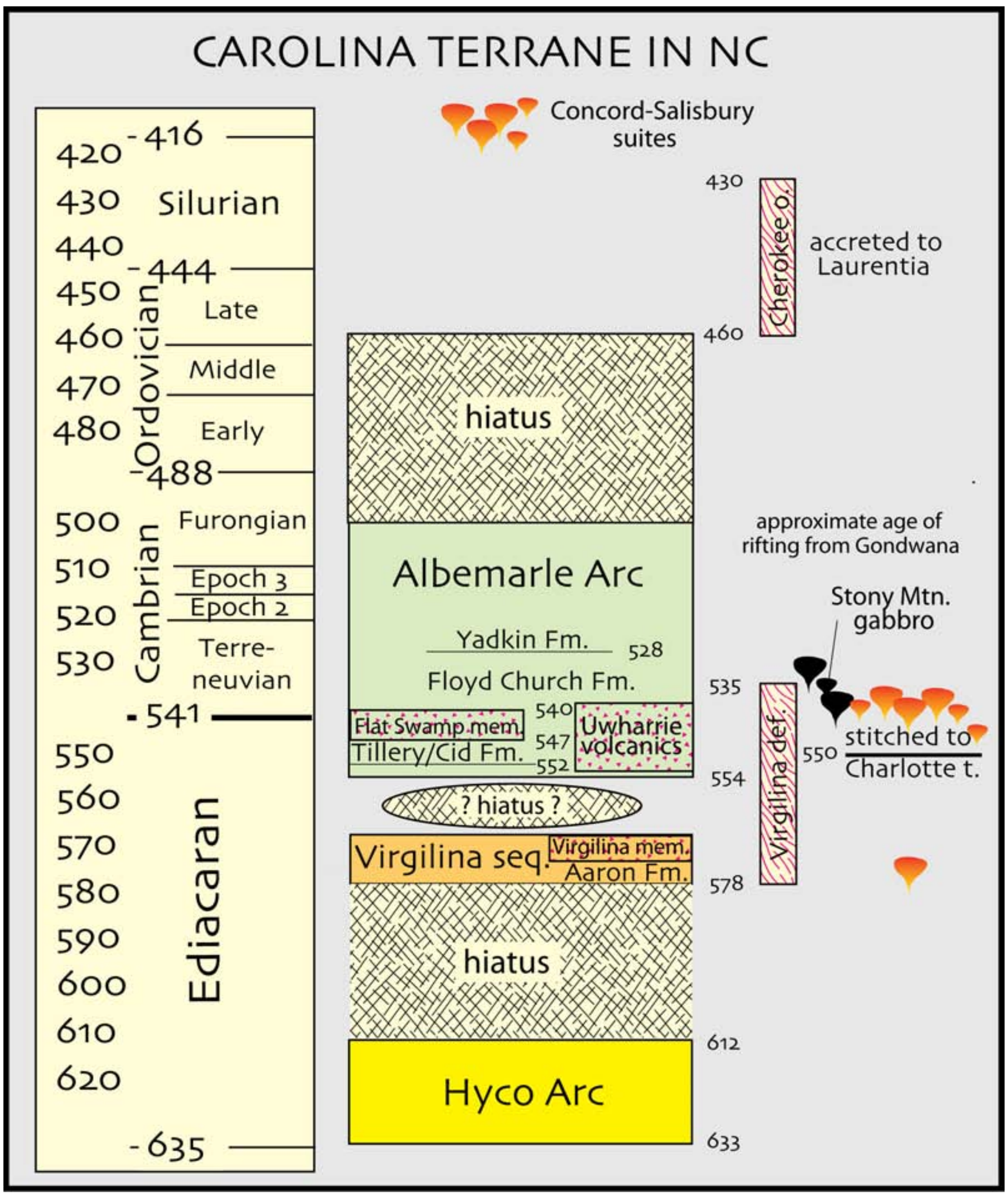

Figure 2. First-order components and events of the Carolina terrane in North Carolina.

Some of the early tectonic history of the Carolina terrane is thought to be related to interactions with the Charlotte terrane (e.g. Barker et al., 1998; Shervais et al., 2003); consequently we present a brief summary of the Charlotte terrane here.

There are few available data on rocks of the Charlotte terrane; it is dominated by plutonic rocks (King, 1955; Butler and Fullagar, 1978). In South Carolina, the metavolcanic and metasedimentary hosts to these plutons appear to be mainly pre- c. 570 Ma in age (e.g. Dennis and Shervais, 1991; Dennis, 1995; Dennis and Wright, 1997); geochemically, the metavolcanic rocks are calc-alkaline to tholeiitic and interpreted to have formed in a suprasubduction zone setting (Dennis and Shervais, 1991). Limited Nd isotopic studies in the terrane suggest that the older portions represent juvenile crust (Fullagar et al., 1997). The structure of the terrane is not well documented, but appears to be characterized by a steep schistosity that is axial planar to tight, upright folds with axial traces parallel to the strike of the terrane (Butler and Secor, 1991). $^{40}Ar/^{39}Ar$ ages on amphibole from the country rocks range from 425 to 430 Ma, suggesting that ductile deformation in the terrane is Silurian or older (Sutter et al., 1983). The Charlotte terrane contains a belt of retrograded eclogitic rocks immediately adjacent to its contact with the Carolina terrane in South Carolina (Shervais et al., 2003); the eclogites must be older than the c. 415 Ma Newberry granite, which intrudes them. In central South Carolina, structural and geochronological studies also indicate that the Charlotte and Carolina terranes were amalgamated along the Chappells fault that is stitched by the late Neoproterozoic (c. 550 Ma) Longtown metagranite (Barker et al., 1998).

The Carolina terrane in North Carolina

The Carolina terrane in North Carolina comprises three major lithotectonic elements, including two magmatic arc systems that are separated in time by a 'magmatic influenced' sequence of unknown origin (Fig. 2). These three elements span the time range from the early Ediacaran to the earliest Paleozoic. The older magmatic arc is here termed the Hyco arc, after the volcanogenic Hyco Formation of north central North Carolina (Laney, 1917, modified by Kreisa, 1980; Harris and Glover, 1988) and we call the younger arc the Albemarle arc, after the metavolcanic-metasedimentary Albemarle Group (sensu Milton, 1984). The lithotectonic element intervening between these two arcs is a sequence of metasedimentary rocks with subordinate magmatic rocks termed the Virgilina sequence (Bowman et al., this volume; modified from the Virgilina sequence of Hibbard et al., 2002). Two other lithotectonic elements have been associated with the Carolina terrane, including the Cary sequence, along the eastern side of the terrane and the Kings Mountain sequence on the west side of the Charlotte terrane, immediately adjacent to the central Piedmont shear zone. All of these lithotectonic elements have been heterogeneously overprinted by at least two fabric-forming events, including a Neoproterozoic event termed the Virgilina deformation (Glover and Sinha, 1973) and an early Paleozoic event, the Cherokee orogeny (Hibbard et al., 2010, 2012).

Lithotectonic Components of the Carolina terrane

The Old Arc: the Hyco arc

The older, Hyco arc forms approximately the northern portion of the Carolina terrane (Fig. 1) and it also occurs in a narrow outcrop belt immediately to the west of the

Gold Hill shear zone. It is composed mainly of the Hyco Formation (Laney, 1917; modified by Kreisa, 1980), which records dominantly felsic to intermediate magmatism during a c. 20 m.y. span starting at c. 633 Ma (Wortman et al., 2000; Bradley and Miller, 2011); it has a minimum thickness of 4900 m (Glover and Sinha, 1973). It was defined in the area of the Hyco River[1] in north central North Carolina (Laney, 1917; modified by Kreisa, 1980) and has been extended southward into central North Carolina by the studies of Green et al. (1982), Harris and Glover (1985, 1988), and Bradley et al. (2006, this volume). The narrow outcrop belt of Hyco arc rocks to the west of the Gold Hill fault have been informally referred to as the Five Pines sequence (Hibbard et al., 2012)(Stop 1-1).

The volcanics of the Hyco arc are dominantly sub-aqueous pyroclastics interpreted to have been deposited in shallow water with local subaerial volcanic centers (Glover and Sinha, 1973; Green et al., 1982; Harris and Glover, 1988; Bradley et al., 2006). Geochemically, these rocks have been characterized as tholeiitic to calc-alkaline and interpreted to have formed in a suprasubduction zone magmatic arc (e.g. Black, 1980; Bland and Blackburn, 1980; Rogers, 1982; Feiss, 1983).

Originally, the large proportion of felsic rocks relative to intermediate and mafic rocks and the presence of quartzite clasts in conglomerates overlying the formation led to the interpretation that basement to the Hyco arc was some form of continental crust (Glover and Sinha, 1973). However, it has been shown that conglomerates are on the order of 25 m.y. younger than the volcanics (see Virgilina sequence, below), not to mention that quartzitic sediments in felsic volcanic environments can be locally derived and do not necessarily represent continental basement detritus (Stanley and Cavaroc, 1980). In addition, the Nd isotopic hallmarks of the Hyco arc are highly positive ε_{Nd} values and model ages that are relatively close to crystallization ages of the rocks (Kozuch, 1994; Samson et al., 1995); also, the magmatic rocks in the Hyco arc lack evidence of inherited zircons (Samson et al., 1995; Ingle et al., 2003). Collectively, these observations strongly suggest that the Hyco arc is composed of juvenile, largely mantle-derived crust and likely represents a mature arc built upon an oceanic substrate (Samson et al., 1995; Mueller et al., 1996; Fullagar et al., 1997; Ingle et al., 2003).

The Virgilina sequence

The Virgilina sequence occurs in two major outcrop areas in the northern portion of the Carolina terrane, one at the North Carolina-Virginia state line and the other in central North Carolina (Fig. 1). Stratigraphically, it intervenes between the older and younger arcs of the terrane. Originally the sequence was defined as containing the Hyco Formation along with the overlying Aaron and Virgilina formations (Harris and Glover, 1988; Hibbard et al., 2002). The relationship between the Hyco arc and the Aaron Formation had been previously suggested to be an unconformity, although the time gap between the two units was interpreted to be insignificant (Newton, 1983; Harris and Glover, 1988). However, recent geochronological studies indicate that the dominantly metasedimentary Aaron Formation contains detrital zircons as young as c. 578 Ma (Samson et al., 2001) and c. 588 Ma (Pollock et al., 2010), thus indicating a gap of at least c. 24 m.y. between the youngest Hyco arc magmatic rocks (c. 612 Ma)(Wortman et al., 2000)

[1] This is the Anglicized shortening of 'Hicootomony River,' the early resident native's geographic term; 'Hicootomony' reportedly means turkey buzzard (Laney, 1917).

and depostion of the Aaron Formation (Bowman, 2010; Bowman et al., this volume). In addition, it has been shown that the Virgilina Formation (Laney, 1917, modified by Harris and Glover, 1988) forms a mappable member sandwiched within Aaron Formation metasedimentary rocks (Kreisa, 1980; Bowman, 2010; Bowman et al., this volume). Thus, the original Virgilina sequence has been redefined as containing only the Aaron Formation and its volcanic Virgilina member (Bowman et al., this volume).

The Aaron Formation consists of mildly metamorphosed epiclastic sedimentary rocks, conglomerate, argillite, tuffaceous mudstone, mafic tuff, mafic volcanic lapilli tuff, and possible mafic lavas, although felsic volcanics occur locally. The thickness of the unit ranges from ~ 1500 m in central North Carolina to ~ 4500 m in north central North Carolina (Harris and Glover, 1984). The most distinctive rock type in the unit is conglomerate that contains conspicuous pebbles and cobbles of vein quartz, quartz arenite, along with a variety of other clasts (see Supplemental Stop S-6). Sedimentological analysis of the Aaron Formation indicates that it was derived mainly from the underlying Hyco Formation and that it was deposited in a submarine fan to basinal plain setting (Harris, 1984). Detrital zircons from Aaron conglomerates have yielded zircon populations with an age peak at c. 620 Ma, and subsidiary peaks at c. 1.2 Ga, 1.65 Ga, and five grains between 1.9 and 2.16 Ga (Pollock et al., 2010). The presence of the older detrital populations implies a secondary basement source of detritus that is older than the underlying juvenile Hyco arc was available during Virgilina sequence deposition (Pollock et al., 2010).

Recently, a plutonic body has been identified that may be related to the Virgilina sequence. The East Farrington pluton, near Chapel Hill, NC has yielded a U-Pb zircon TIMS age of c. 579 Ma (Tadlock and Loewy, 2006). This age overlaps with the that of the youngest detrital zircons in the Aaron Formation, suggesting that deposition and magmatism may have been contemporaneous with each other. Relatively high ε_{Nd} values and model ages that are relatively close to crystallization ages of the rocks indicate a juvenile source for the pluton (Tadlock and Loewy, 2006). Rocks here included in the Virgilina sequence have been considered to form an intra-arc basin within the Hyco arc (Harris and Glover, 1988); however, recent geochronologic studies indicate that it is c. 25 m.y. younger than the arc (Samson et al., 2001; Pollock et al., 2010) consequently the tectonic setting of the sequence remains ambiguous. A comprehensive geochemical study of the magmatic rocks in the sequence may provide clarification.

The New Arc: the Albemarle arc

The younger arc, the Albemarle arc, extends from central North Carolina southward into South Carolina and Georgia (Fig. 1). In North Carolina, it is characterized by a thick felsic volcanic base, the Uwharrie Formation, conformably overlain by Neoproterozoic to Early Cambrian clastic sedimentary rocks with interspersed lenses, dikes, and stocks of felsic to mafic magmatic rocks of the Albemarle Group (e.g. Butler and Secor, 1991)(Fig. 3). The minimum collective thickness of units in the Albemarle arc of North Carolina is approximately 12,700 m (Stromquist and Sundelius, 1969; Bulter and Secor, 1991). Most geologists familiar with the area consider the group to include, in ascending stratigraphic order, the Tillery, Cid, Floyd Church, and Yadkin formations (Milton, 1984; Butler and Secor, 1991) and to span the Neoproterozoic to earliest Paleozoic. The top of the Cid Formation is marked by the Flat Swamp Member (Stromquist and Sundelius, 1969)(Stop 1-5), a distinct, latest Ediacaran to earliest Cambrian felsic volcanic dominated unit. In central North Carolina, the member forms a good marker unit within the Albemarle Group and generally supports topographic ridges (see lidar map, back cover).

Geochemically, magmatic rocks of the Albemarle arc have been characterized as tholeiitic to calc-alkaline and interpreted to have formed in a suprasubduction zone magmatic arc (e.g. Black, 1980; Bland and Blackburn, 1980; Rogers, 1982; Feiss, 1983; Ingram, 1999). Nd isotopic studies on rocks of the sequence document ε_{Nd} values in the range of -4 to +4 with early Neoproterozoic to middle Mesoproterozoic model ages (Mueller et al., 1996; Fullagar et al., 1997); furthermore inherited zircons in some extrusive rocks yield Mesoproterozoic ages (Mueller et al., 1996). Based on these data, it appears that the Albemarle sequence has a basement with some form of c. 1 Ga continental material (Mueller et al., 1996).

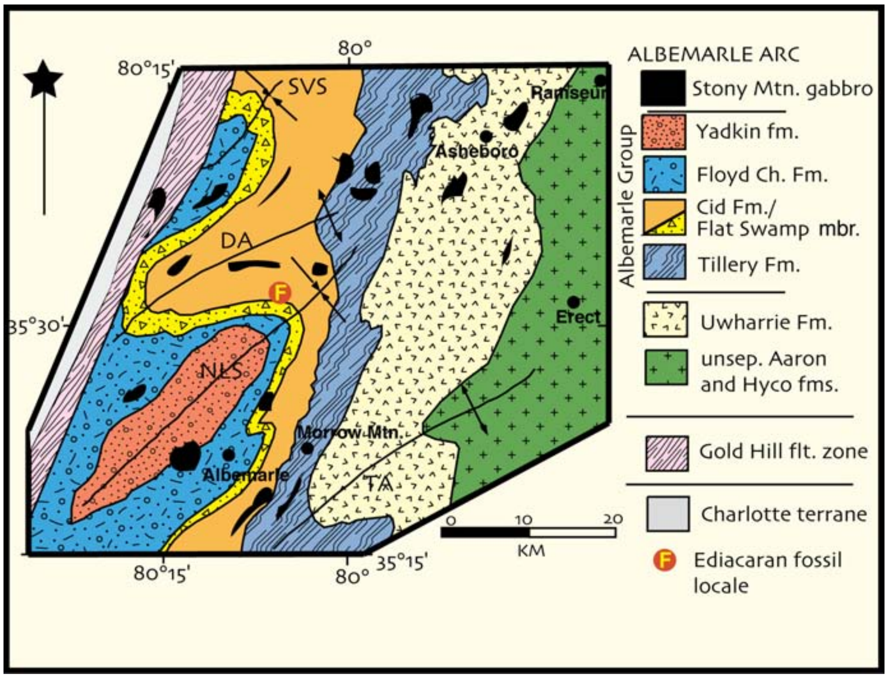

Figure 3. Geology of the Carolina terrane in central North Carolina. SVS=Silver Valley syncline, DA= Denton anticline, NLS=New London syncline, TA= Troy anticline.

The Stony Mountain gabbro (Ingram, 1999) forms the youngest unit within the Albemarle sequence (Stop 1-7); the gabbro has been shown as intruding all units within the Albemarle arc (Stromquist and Henderson, 1985). In addition, the gabbro is effected by deformation and metamorphism related to Late Ordovician accretion of Carolinia to Laurentia (see below). Thus, it is reasonable to hypothesize that the gabbro may well be a manifestation of the rifting of the Carolina terrane from Gondwana. This hypothesis is supported by recent geochemical studies that show the gabbro to be sub-alkaline magmatism that records subduction zone magmatism in a rifted island arc setting; consequently we interpret the gabbro to be related to the opening of the Rheic Ocean between Gondwana and Carolinia (Pollock and Hibbard, 2010). A new U-Pb zircon TIMS age on a gabbro body in the Tillery Formation suggests that rifting started as early as c. 545 Ma (DeDecker et al., this volume).

During the 1990's, the established stratigraphy of the Albemarle Group was brought into question by a report of Paleozoic fossils at different stratigraphic levels in the group (Koeppen et al., 1995). Specifically, one site was within a quarry in the Tillery Formation at Asheboro, North Carolina and the other was in the Cid Formation at the Jacob's Creek quarry, near the hinge of the New London syncline (Fig. 3). 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 (Koeppen et al., 1995). Considering that the Flat Swamp member of the Cid Formation has yielded U-Pb, zircon ages of c. 540 - 547 Ma (Ingle et al., 2003; Samson *in* Hibbard et al., 2006; B.V. Miller, pers. comm., 2010) and that the Floyd Church Formation contains the Ediacaran fossil *Pteridinium* (Gibson et al., 1984), thought to be confined to the Neoproterozoic, the reported Paleozoic fossils demanded a major revision of the stratigraphy of the Albemarle Group (Fig. 4)(Offield, 2000). This modification also required a new structural interpretation of the outcrop pattern of the Albemarle arc; Offield (2000) interpreted the contact between the Uwharrie and the Tillery formations, as well as the contact between the Flat Swamp member and the underlying Cid Formation, both formerly thought to be conformable, as representing major thrust faults (Fig. 4).

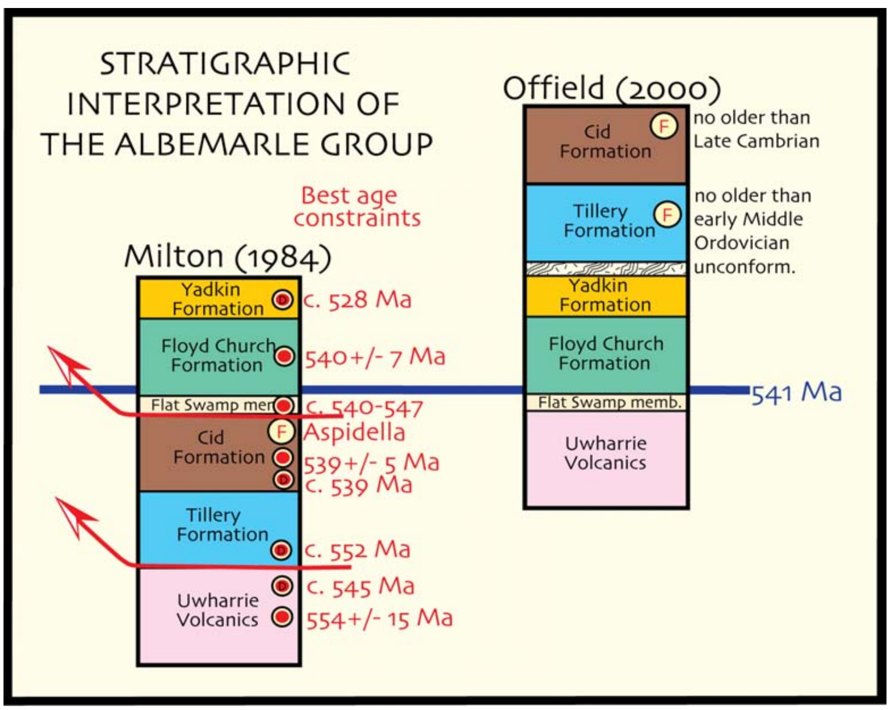

Figure 4. Stratigraphic interpretation of the Albemarle sequence. Left column (ignoring red arrows) depicts stratigraphy generally accepted by the 1990's (e.g. Milton, 1984; Butler and Secor, 1991) with data from recent studies added on the right side of the column; bulls-eye = new geochronological constraint (D denotes detrital zircon age), F = fossil constraint. Red arrows depict thrust faults required by stratigraphy proposed by the U.S. Geological Survey (Offield, 2000) as shown in column on right. Solid blue line represents the approximate location of the Precambrian-Cambrian boundary.

The conflict in the interpretations of the Carolina terrane stratigraphy motivated some of our recent studies in the heart of Carolinia (e.g. Ingram, 1999; Pollock, 2007; Brennan, 2009; Kurek, 2010). In the area where the Albemarle Group was first defined (Conley, 1962), Ingram (1999; Boorman et al., this volume) demonstrated that the Uwharrie

Formation is in gradational, conformable contact with the overlying Tillery Formation. In addition, she showed through field relationships and geochemistry that hypabyssal bodies of Morrow Mountain rhyodacite stratigraphically linked the Uwharrie Formation to the overlying Tillery and Cid formations. Both of these observations conflict with the USGS interpretation of the regional stratigraphy /structure (see Boorman et al., this volume).

Likewise, Brennan (2009) and Kurek (2010) also showed that the key contacts between the Flat Swamp member and the Cid formation, and the Uwharrie and Tillery formations, were conformable in the area of the two USGS fossil locales. We investigated the contact between Cid Formation mudstone and the Flat Swamp Member in the area of the Jacob's Creek quarry (Field Stop 2A) and found it to be conformable (Brennan, 2009; Hibbard et al., 2009). We also discovered Ediacaran fossils in the quarry; 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 earliest Cambrian, our discovery conflicts with the previous USGS report of fossils no older than Late Cambrian purportedly found on the premises. Collectively, these apparently 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 all the available data from our studies, we favor either of the first two interpretations (Hibbard et al., 2009). 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 studies indicate that the major modification of our understanding of the Carolina terrane proffered by Offield (2000), is unwarranted.

We also undertook new 1:24,000 scale field mapping in the area of the Asheboro quarry, the second site from which Paleozoic fossils were reported by the USGS. Mapping there has shown that the Uwharrie-Tillery formations contact is conformable (Kurek, 2010; Kurek et al., this volume). In addition, felsic dikes that cut the Tillery Formation in the quarry have been used to provide circumstantial evidence concerning the age of strata in the quarry (Kurek et al., this volume). The dikes cut the Tillery Formation, yet are deformed by the regional Late Ordovician Cherokee orogeny. Consequently, if the Tillery strata were no older than early Middle Ordovician, as indicated by the purported fossils, then the felsic dikes must be Middle Ordovician, a time that is void of magmatism throughout the Carolina terrane. In accordance with the conventional Albemarle Group stratigraphy, the felsic dikes are easily accounted for as magmatism related to either Morrow Mountain or Flat Swamp eruptive events.

Furthermore, Pollock (2007; Pollock et al., 2010) completed a detrital zircon study of

Carolinia that included four samples from the Albemarle arc. He sampled the Uwharrie, Tillery, Cid, and Yadkin formations and analyzed 271 zircon grains from these samples. Using the detrital zircon data to provide maximum ages of deposition for the units sampled in conjunction with both field relationships and existing U-Pb zircon ages from the sequence (Fig. 5) he concluded that the Albemarle sequence was deposited during a c. 25 m.y. interval spanning the late Neoproterozoic to Early Cambrian (Pollock, 2007; Pollock et al., 2010). Cogently, the maximum ages of deposition of the Albemarle Group formations became younger in an order consistent with the stratigraphy of the group as interpreted by Milton (1984); i.e. the maximum age of deposition of the Tillery Formation is older than that of the Cid Formation, which in turn, is older than that of the Yadkin Formation. Pollock's studies (Pollock, 2007; Pollock et al., 2010) also indicate that the Uwharrie Formation is laterally equivalent to the lower portion of the Albemarle Group (Fig. 5).

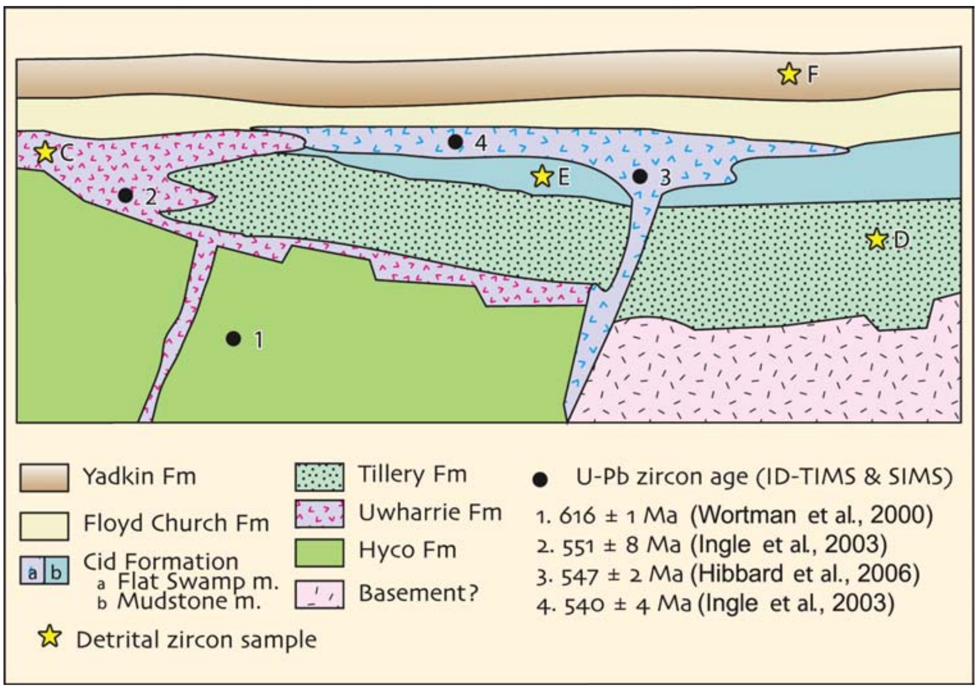

Figure 5. Schematic cross section through the Carolina terrane at the time of deposition based on detrital zircon data, field relationships, and U-Pb zircon ages given. Youngest detrital zircon ages constraining the maximum age of deposition of units sampled include for C, c. 545 Ma; for D, c. 552 Ma; for E, c. 540 Ma; for F, c. 528 Ma. From Pollock et al. (2010).

In summary, our new studies strongly confirm the conventional conceptualization of the stratigraphy of the Albemarle Group (Milton, 1984; Butler and Secor, 1991). The purported Paleozoic fossils must either be confined to very localized outliers on top of the mainly Neoproterozoic strata of the group or be erroneous, as a result of either sampling or processing errors.

In broader terms, the implication of confirming the Carolina terrane stratigraphy has orogen-scale repercussions. Specifically, the stratigraphic-structural history of Carolinia is not like that of the northern Appalachian Avalonia, a correlation that has permeated into our knowledge through traditional conceptualization; instead, it is more akin to that of the northern Appalachian peri-Gondwanan block of Ganderia, (Hibbard et al., 2007a, b; Pollock et al., 2012).

The Cary sequence

The Cary sequence occupies a narrow outcrop strip to the east of the Triassic Deep River Basin (Fig. 1) and it is not in direct contact with other components of the Carolina terrane. The sequence has been included in the terrane because of both its gross lithologic similarity to rocks of the terrane and its low metamorphic grade (Hibbard et al., 2002). It is dominated by dacitic crystal-lithic tuffs with subordinate phyllites and mafic rocks (Blake et al., 1999). Several felsic plutonic bodies are interpreted as local subvolcanic centers with intrusive facies interfingering with their subvolcanic equivalents (e.g. Farrar, 1985; Blake et al., 1999). A U-Pb zircon age of 575 $\pm$ 12 Ma has been determined for felsic metavolcanic rocks of the sequence (Goldberg, 1994). On its eastern side, the sequence is intruded by a felsic pluton that yielded a $^{207}Pb/^{206}Pb$ zircon age of ca. 560 Ma (Goldberg, 1994), consistent with the age of the metavolcanics of the sequence. The lithic content and age of volcanics in the Cary sequence suggest that it may be an equivalent of the redefined Virgilina sequence.

The Kings Mountain sequence

The Kings Mountain sequence (Horton, 2008; Dennis et al., 2012) lies on the west side of the Charlotte terrane, against the central Piedmont shear zone (Fig. 1); it is not in direct contact with other components of the Carolina terrane, but may well be part of the terrane on the basis of circumstantial evidence outlined below. The sequence is composed of the structurally lower, metavolcanic dominated Battleground Formation, which is structurally overlain by a distinctive epiclastic sequence with dolomitic marble, the Blacksburg Formation (Horton, 2008); the two units are separated by the Kings Creek shear zone, although displacement across the shear zone has been interpreted to be stratigraphically insignificant (Horton, 2008; Dennis et al., 2012). Detrital zircon studies of the sequence indicate that conglomerates in the Battleground Formation contain zircon grains as young as c. 503 Ma (late Middle Cambrian) and the detrital zircon population is dominated by Ediacaran (635-542 Ma) ages. Combined with the interpretation that the Kings Creek shear zone is stratigraphically insignificant, the detrital zircon data indicate that the Kings Mountain sequence is largely Middle Cambrian or younger. The preponderance of Ediacaran detrital zircon ages in the sequence has led Dennis et al. (2012) to suggest that the Kings Mountain sequence represents uplift and erosion of the Carolina terrane and forms a younger component of the terrane.

The detrital zircon study also indicates that progressively older sources were unroofed as deposition of the sequence proceeded (Dennis et al., 2012). In light of this pattern and of the rock types in the Battleground and Blacksburg formations, it has been suggested that the Kings Mountain sequence represents a rift sequence marking the Middle Cambrian severing of the Carolina terrane from Gondwana (Dennis et al., 2012).

Tectonic Events in the Carolina terrane

Compilation of available data indicates that there are four general periods of tectonothermal activity recorded in the the Carolina terrane of North Carolina, including 1. late Neoproterozoic to Early Cambrian Virgilina events, 2. Late Ordovician-Silurian Cherokee events, 3. Late Devonian-Early Mississippian events, and 4. Late Paleozoic Alleghanian events. In addition to these four events, Mesozoic rifting responsible for the modern Atlantic Ocean has also modified the structural geometry of the Carolinia. Only the earliest two events appear to have been significant fabric-forming events with regional affects in the Carolina terrane of North Carolina and they will be described here (Fig. 2). The younger events are mainly responsible for the reactivation of earlier structures in the Carolina terrane of North Carolina; they will be discussed in the field guide portion of this volume (e.g. Stop 1.2).

The Virgilina deformation

An Ediacaran deformational event in the Carolina terrane in the vicinity of the North Carolina-Virginia state line was first proposed by Glover and Sinha (1973). They termed this event the "Virgilina deformation", and identified it on the basis of a fault that disrupted a synclinorium in the Virgilina sequence, yet was truncated by a post-tectonic pluton (Fig. 2). The extent of the Virgilina event was expanded to central North Carolina by Harris and Glover (1988); they noted that rocks here assigned to the Hyco arc and Virgilina sequence were folded and faulted prior to the deposition of the Neoproterozoic Uwharrie Formation of the Albemarle arc. They interpreted the Albemarle arc to unconformably overlie the Hyco arc although this contact was not observed. In the area where the Virgilina deformation was originally defined, the post-tectonic pluton was documented as intruding foliated metavolcanics (Hibbard and Samson, 1995) and the youngest volcanic rock in the deformed Hyco arc yielded a U-Pb zircon age of 612 +5/-2 Ma while the post-tectonic pluton yielded a U-Pb zircon age of 546 $\pm$ 2 Ma (Wortman et al., 2001). Since that time, it has been shown that the Virgilina sequence conglomerates contain detrital zircon grains as young as c. 578 Ma (Samson et al., 2001). Thus, the Virgilina event in its type area appears to have involved upper crustal folding, foliation formation, and faulting between *c.* 578 and 544 Ma.

A late Neoproterozoic to earliest Cambrian, c. 580 – c. 535 Ma, event has also been documented in the western portion of the Charlotte terrane (Dennis and Wright, 1997). They also extended the effects of this event into rocks of the Carolina terrane of South Carolina where they recognzied that Middle Cambrian fossiliferous mudstone was deposited unconformably on Albemarle Group-equivalent clastic sedimentary rocks (Dennis and Wright, 1997; see also Secor and Snoke, 2002). Further evidence for a late Neoproterozoic event in the Carolina terrane has been documented in northeast South Carolina, where rocks here designated as part of the Carolina and Charlotte terranes were juxtaposed and deformed and metamorphosed between *c.* 557-535 Ma (Barker et al., 1998).

From the forgoing, it appears that an Ediacaran tectonothermal event(s) was imprinted upon portions of the Carolina and Charlotte terranes. In light of the time overlap between these tectonothermal features and the stitching of the Carolina and Charlotte terranes by the Longtown metagranite (Barker et al., 1998), it has been suggested that the Virgilina deformation resulted from the collision of the Carolina and Charlotte terranes (Hibbard et al., 2002), which may well be responsible for the localization of eclogite bodies in that part of the Charlotte terrane immediately adjacent to the Carolina terrane (Shervais et al., 2003).

The Cherokee orogeny

The term 'Cherokee orogeny' has recently been applied to Late Ordovician-Silurian tectonothermal events in Carolinia, which are especially well developed in the Carolina terrane of North Carolina (Hibbard et al., 2010, 2012)(Sidebar 3). It is the most regionally significant deformation and metamorphism in the terrane and it is recorded in rocks throughout the Carolinas; it is best documented in the area of central North Carolina (e.g. Hibbard et al., 2012). Effects of this event are also recorded in more westerly, Laurentian rocks (Hibbard, 2000; Hughes et al., 2013). In this section we will summarize the geometry and kinematics of Cherokee structures, their timing and nature, and their regional significance.

Sidebar 3

How is the Cherokee orogeny different from the Taconic orogeny?

In the northern Appalachians, the term 'Taconic orogeny' refers to early Paleozoic events related to the closure of a Taconic Seaway, which formed between Laurentia and magmatic arc(s) that formed on the Laurentian side of Iapetus (e.g. van Staal et al., 2007). That is, all the components involved in Taconic events are of native North American affinity. In contrast, the Cherokee orogeny involves early Paleozoic events that involved the interaction of a peri-Gondwanan component (Carolinia) with Laurentian elements and thus marks the closure of Iapetus; it is similar in timing and nature to the northern Appalachian Salinic orogeny that records the accretion of Ganderia to Laurentia (van Staal et al., 2008). The Taconic orogeny in the southern Appalachians is recorded by the Knox-Beekmantown unconformity in Laurentian rocks, the Blountian clastic sedimentary wedge, and c. 460-480 Ma metamorphism (including granulite and eclogite). The nature of the Taconic orogeny in the southern Appalachians is clouded by multiple tectonothermal overprints and possibly by burial of significant portions of the system beneath Alleghanian thrust sheets.

The Cherokee tectonothermal imprint on the Carolina terrane in central North Carolina is characterized by greenschist facies metamorphism accompanied by a steep, generally northwest-dipping, slaty cleavage that is axial planar to regional-scale folds that are generally overturned to the southeast; commonly, minor, southeast vergent thrust faults are associated with these structures (Stop 1-3). The intensity of structures generally increases within the Albemarle Group from east to west, with the most intense structures formed in a north-northeast-trending, steeply northwest-dipping, structural zone termed the Gold Hill shear zone (e.g. Gibson and Huntsman, 1984) (Figs. 1, 3); west from the zone, deformation effects gradually diminish. The shear zone is mainly confined to an outcrop belt up to 5 km wide that is contained between the Gold Hill fault on the west and the Silver Hill fault to the east; deformation related to the zone extends beyond these faults, particularly in the hangingwall above the Gold Hill fault (Stop 1-2). Contrary to previous reports (e.g. Stromquist and Sundelius, 1969; Offield, 2000), we did not encounter extensive areas of schists or recrystallized beds within the shear zone; phyllites and meter-scale shear zones are highly localized within the zone. The GHsz is geometrically linked to the regional-scale folds, as the folds form an en echelon array along the both sides of the shear zone, with individual fold axial traces oriented 25°-35° clockwise to the shear zone (Fig. 6); both the folds and cleavage appear to be truncated by the shear zone (Hibbard et al., 2012).

In terms of kinematics, in addition to the regional shortening recorded by the folds, faults, and foliation, two lines of evidence indicate that the bulk regional deformation also involved strike slip movement in central North Carolina: 1. subsidiary faults in the Albemarle Group display thrust separation along slickenlines that plunge steeply to the northwest of the dip of the faults and 2. regional folds on both sides of the GHsz are clockwise-oblique to the zone and locally dragged in a sinistral sense into the zone (Hibbard et al., 2012). These observations indicate that the regional deformation involved a sinistral component of motion. Within the GHsz, kinematic indicators such as asymmetric fabrics, winged clasts, and asymmetric folds are heterogeneously developed and concentrated mainly along, and proximal to, the Gold Hill fault. In-

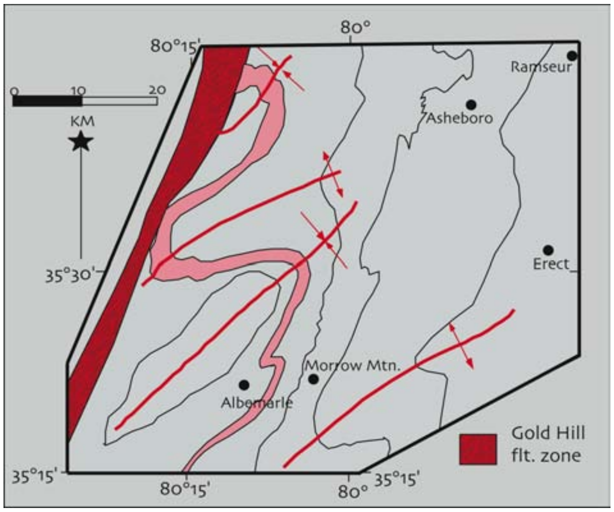

Figure 6. Geometric relationships between the Gold Hill shear zone and regional folds in central North Carolina. Flat Swamp member of the Cid Formation is highlighted in pink in order to accentuate the regional folds. Note that regional folds of similar orientation have been recognized on the west side of the GHsz (Hibbard et al., 2012).

variably, all kinematic indicators record either reverse, west over east motion, or sinistral motion (Laney, 1910; Hibbard et al., 2012). In summary, the regional bulk deformation and the GHsz form a geometrically and kinematically linked system that records southeast-directed sinistral transpression.

In contrast to the deformation in central North Carolina, structures in the vicinity of the GHsz near the South Carolina state line record dextral transpression (Schroeder et al., 1988; Allen et al., 2008). The transition in kinematics appears to occur on the north side of the State Line flexure; however, it has not been studied in detail, as yet. Interpretations of this kinematic contrast range from syn-accretion kinematic partitioning (Allen et al., 2008; Hibbard et al., 2012) to heterogeneous post-accretion tectonics overprinted on an originally sinistral reverse fault (Hibbard and Waldron, 2009; Hibbard et al., 2012).

There is insufficient evidence for the determination of either the net slip or horizontal slip on the GHsz; however we can obtain partial quantification of the dip-slip component of motion in terms of stratigraphic throw. In central North Carolina, the Gold Hill fault places c. 615 Ma Hyco arc rocks atop unseparated Albemarle arc rocks in the GHsz, which include volcanic rocks equivalent to the c. 547 Ma Flat Swamp member of the Cid Formation (Hibbard et al., 2012). Utilizing minimum formational thicknesses (Stromquist and Sundelius, 1969; Harris, 1984), these observations equate to a minimum of 12.1 km of stratigraphic throw on the Gold Hill fault. In a similar way, it can be shown that the GHsz has a minimum of 13.3 km of stratigraphic throw. In light of these kinematics and displacements, the GHsz is seen as a footwall duplex to the Gold Hill sinistral oblique thrust fault.

Multiple $^{40}Ar/^{39}Ar$ ages of c. 450 Ma on white mica associated with the axial planar cleavage indicates that cooling, and likely uplift and Cherokee deformation in the Carolinas is Late Ordovician (Noel et al., 1987; Offield et al., 1995; Ayuso et al., 1997; Hibbard et al., 2012). It has been argued that these argon ages record the timing of peak metamorphism in the Carolina terrane (Offield et al., 1995). There is also evidence that the Charlotte terrane was ductilely deformed and metamorphosed at this time or soon after, as amphibole $^{40}Ar/^{39}Ar$ ages of c.430-425 Ma have been obtained from amphibolites in the terrane. Thus, the Carolina terrane is structurally characterized by Late Ordovician-early Silurian regional sinistral transpression. There are also younger, Late Devonian and Mississippian $^{40}Ar/^{39}Ar$ mica ages recorded within the Carolina terrane, but in North Carolina these are confined to the immediate vicinity of the GHsz; they have been interpreted as periods of remobilization along the shear zone (Hibbard et al., 2012)(see Stop 1-2).

The Cherokeean GHsz regional sinistral transpressive system is responsible for the most widespread tectonism documented to date in the Carolina terrane and Carolinia; its generation requires a regional-scale mechanism. Further, manifestations of the Cherokee event span the southern orogen (Hibbard, 2000), including the c. 444 Ma Cherokee (or Tuscarora) unconformity on the Laurentian margin, c. 460-430 Ma suprasubduction zone magmatism in peri-Laurentian rocks, and c. 430 Ma metamorphic events in peri-Laurentian rocks (Aleinikoff et al., 2006; Wintsch et al., 2010). Cogently, the GHsz transpressive system was active at the same time as these events and at a time when paleomagnetic data place the Carolina terrane at the same paleolatitude as Laurentia (Vick et al., 1987; Noel et al., 1988). Logically, it follows from the foregoing observations that the Cherokee orogeny is considered to be the result of the accretion of Carolinia to Laurentia (Fig. 7).

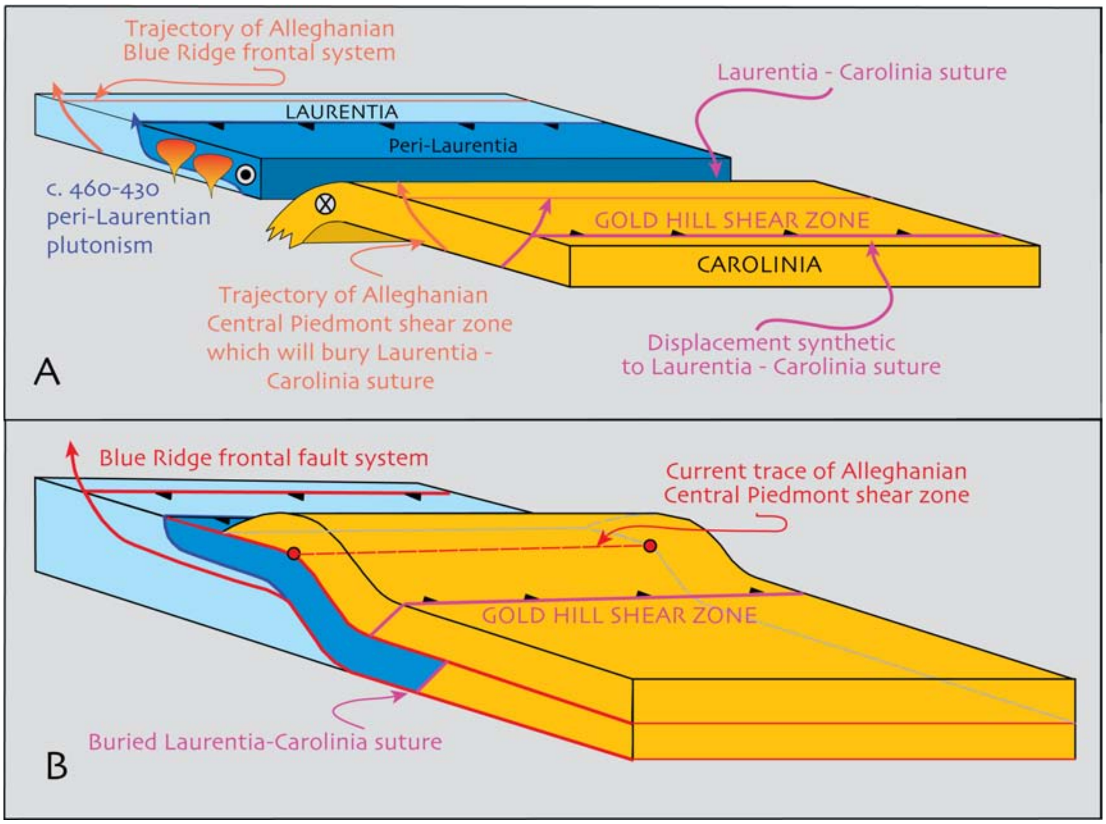

Figure 7. Schematic block diagram depicting the partial tectonic history of the Gold Hill shear zone. A: Late Ordovician docking of Carolinia to Laurentia and generation of the Gold Hill shear zone peripheral to the suture. B: Alleghanian burial of the Laurentian-Carolinia suture beneath the central Piedmont thrust sheet (Hibbard et al., 1998). From Hibbard et al., 2012.

Recognition of the nature and timing of the Cherokee orogeny has led to a reassessment of the crustal architeture of the southern Appalachians. The regional geometry of the Cherokee transpressive system is consistent with deep crustal reflectors imaged beneath interior portions of the orogen on the reprocessed and enhanced southern Appalachian COCORP seismic-reflection line (Cook and Vasudevan, 2006), which have been interpreted as marking the top of Carolinia in the subsurface (Hibbard et al., 2010)(Fig. 8).

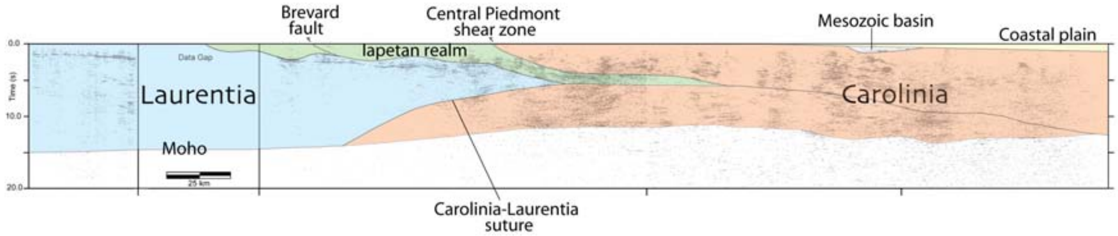

Figure 8. An interpretation of the reprocessed and enhanced southern Appalachian COCORP seismic-reflection line that is consistent with the regional structural geometry of Carolinia and the central Piedmont shear zone (also see Fig. 7); seismic data from Cook and Vasudevan (2006). From Hibbard et al., 2010.

A Tectonic model for the Carolina Terrane in North Carolina

Tectonic models are akin to cultural myths; myths are essentially an easy way by which we remember and relate important cultural or ethical information in a palatable way; likewise, tectonic models are a means by which geologists can more easily remember and relate significant geological relationships. In this concluding section, we summarize the important first-order geological relationships in the Carolina terrane of North Carolina and attempt to weave them into a plate tectonic model that is consistent with the available data and observations. Clearly, the data are insufficient to formulate a model that is continuous through time and so our model provides 'snapshots' of critical periods in the history of the Carolina terrane and we present these snapshots at both the scale of central North Carolina (Fig. 9) and lithospheric plate scale (Fig. 10). These models also serve other purposes; they highlight the outstanding problems in the region and they provide a target at which other researchers can focus their future research.

The oldest element in the Carolina terrane is the Hyco arc, a suprasubduction zone arc that was active for approximately 20 m.y. between c. 633-612 Ma (Figs. 9, 10). Isotopically, the arc is juvenile and the magmatic rocks lack inherited zircon; consequently we depict it as forming in the open ocean (Fig. 10). The polarity of subduction was likely from open ocean beneath the Hyco arc, rather than from the sea between the Hyco arc and more easterly Gondwanan elements, because there is no obvious evidence that collision of the Hyco arc with other Gondwanan components caused cessation of the Hyco arc. The apparent cessation of the Hyco arc at c. 612 Ma is curious, as the lack of a deformational event at that time strongly suggests that collision was not responsible for this lapse in magmatism. Multiple scenarios could account for termination of arc magmatism, including subduction of an oceanic plateau or some other buoyant feature on the downgoing plate, plate reorganization leading to development of a transform plate margin adjacent to the Hyco arc, and it is also possible that c. 612 Ma marks an apparent end of Hyco magmatism due to incomplete preservation of younger magmatism. More data are required to account for the apparent termination of Hyco magmatism.

The youngest detrital zircons in the Aaron Formation are between 588–578 Ma (Samson et al., 2001; Pollock et al., 2010), indicating that Virgilina sequence deposition must have started at least 25 m.y. after the apparent abandonment of the Hyco arc (Fig. 9). The Aaron conglomerates contain a diverse age poplulation of detrital zircons that date back to the Paleoproterozoic; thus, some form of Gondwanan basement that was absent during Hyco arc construction must be relatively proximal during Virgilina seqeuence deposition. The basement source for these older zircon grains could be from unspecified

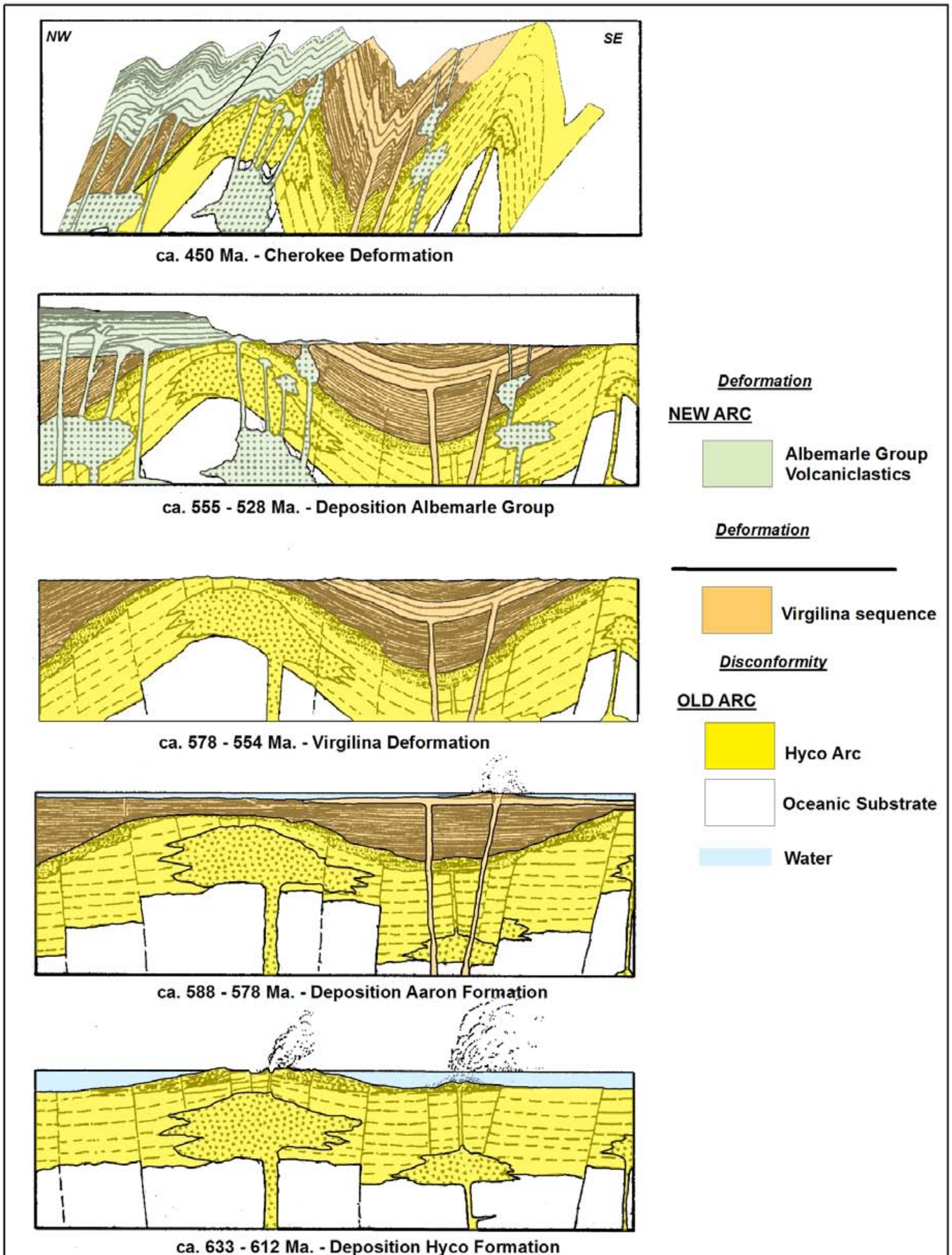

Figure 9. Schematic, regional-scale diagram of major events in the Carolina terrane of North Carolina between c. 635 – 450 Ma. Modified from Harris and Glover, 1985.

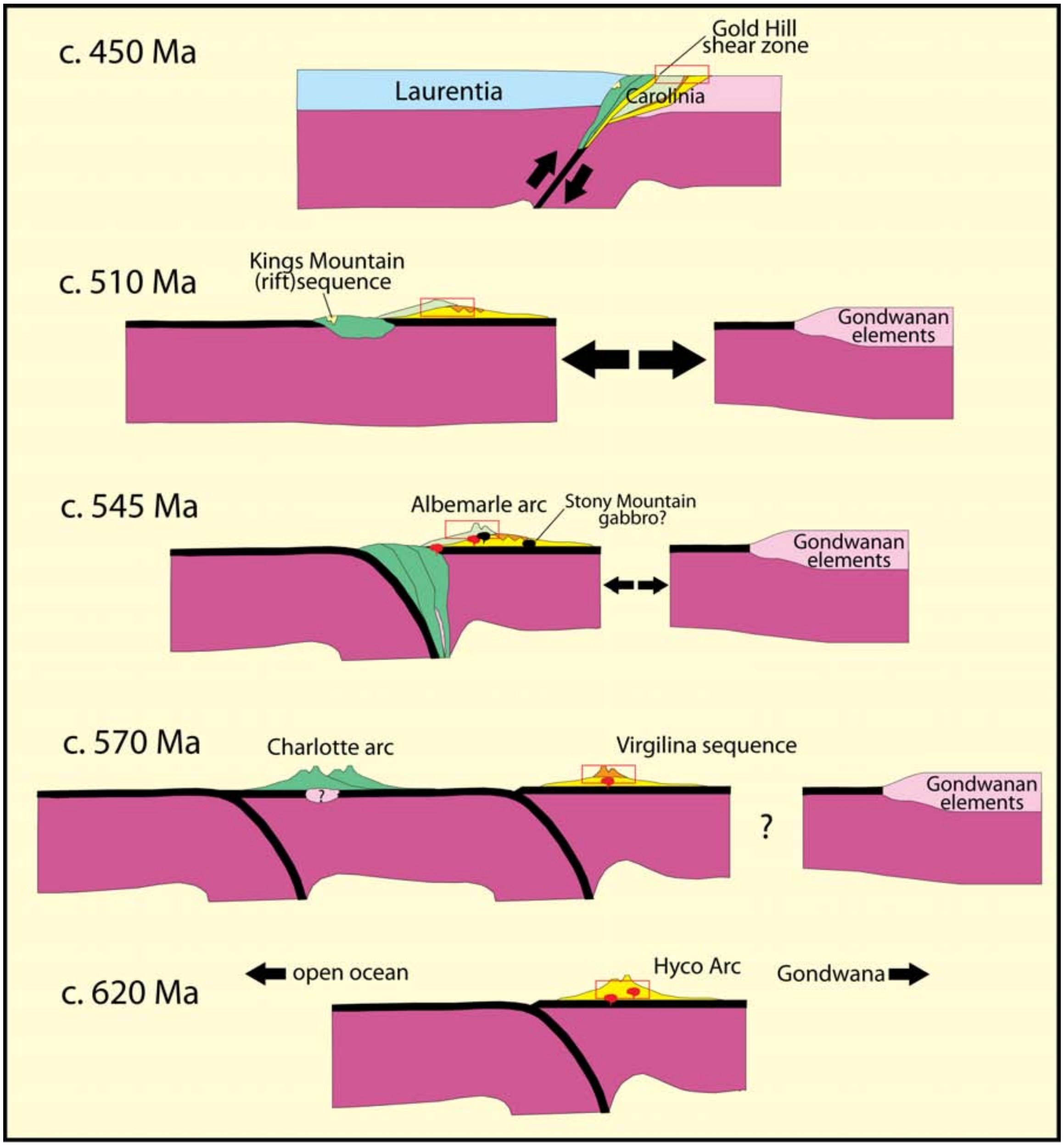

Figure 10. A possible schematic lithosphere-scale model for the Ediacaran-Ordovician plate tectonic evolution of the Carolina terrane. Red box in each time frame indicates approximate location of corresponding time frame in Figure 9.

Gondwanan elements that lay either to the east or laterally, along strike. Apparently during the hiatus between the Hyco arc and Virgilina deposition, the Hyco-Virgilina system was somehow brought into relative proximity to this source. It is also possible that the older detrital zircons are derived from the Charlotte arc, located either outboard or laterally along strike of the Hyco-Virgilina block. This scenario is discussed further in the following two paragraphs.

The tectonic setting of the Virgilina sequence is poorly constrained; it may represent renewed suprasubduction zone arc activity or it could represent an arc rift. The latter interpretation implies that an arc is active, therefore we depict the Virgilina sequence in a magmatic arc setting in Figure 10. We show subduction from the open ocean side beneath the arc to account for the Virgilina volcanics mainly because of two observations, 1) we need to juxtapose the Hyco-Virgilina arcs with the Charlotte arc by c. 550 Ma and 2) based on the modern distribution of these elements, the Charlotte arc likely lay outboard of the Hyco-Virgilina edifice. Alternatively, the Virgilina volcanics could have resulted from interactions between the Hyco arc block and oceanic, arc, and microcontinental fragments that lay to the east, towards Gondwana. At this point our model focuses on Charlotte-Virgilina interactions here and our model becomes biased due to the dearth of knowledge of these easterly terranes.

The Charlotte arc records active suprasubduction zone magmatism (Dennis and Wright, 1997) at approximately the same time as the Virgilina magmatism; in order to accommodate both arcs, we show subduction beneath each of them. We depict subduction as the consumption of open ocean beneath the Charlotte arc and the seaway between the two arcs beneath the Virgilina arc, although subduction could have involved consumption of the seaway at both sides. It is doubtful that subduction occurred beneath the Virgilina arc from the Gondwanan side, as this scenario would result in collision with easterly terranes, a collision for which it appears we lack evidence. The Charlotte arc is shown in Fig. 10 as being constructed on some form of Gondwanan crust. Although isotopic study of the Charlotte terrane to date indicate that it is juvenile with respect to its Nd isotopic signature, the number of samples analyzed to date are very limited (Fullagar et al., 1997). This bit of evolved crust beneath the Charlotte arc figures into the succeeding history below.

At present, available geochronological evidence does not allow for good time resolution of events between the Virgilina sequence and Albemarle arc. For example, it is not clear if subduction beneath the Virgilina arc was continuous during the time frame between the two elements or if there was a hiatus in activity (Fig. 2). We imply that subduction was continuous in Figure 10 mainly because reasonable explanations of a hiatus are elusive. Consequently, it appears that closure of the seaway between the Charlotte and Virgilina arcs led to collision and suturing of the Charlotte and Carolina terranes at by c. 550 Ma (Barker et al., 1998). The Virgilina deformation, constrained to the time span of c. 580-535 Ma, likely reflects the structural effects of this collision; likewise, the formation of eclogite along the east flank of the Charlotte terrane may well be the result of this event (Shervais et al., 2003).

The subsequent Albemarle arc, which was erupted atop the carcasses of the Hyco and Virgilina arcs, may have resulted from seaward stepping of the subduction zone and continued post-collision subduction beneath the combined Charlotte-Carolina terrane block. The possible introduction of more evolved crustal material within the Charlotte arc beneath the Albemarle arc could explain the change in Nd isotopic signatures from the juvenile Hyco arc to the more isotopically evolved Albemarle arc (for other possible explanations see e.g., Hibbard and Samson, 1995; Rogers and Coleman, 2010). This change in Nd isotopic signatures appears to be coeval with a change from lower $\partial^{18}O_{WR}$ values of the Hyco and Virgilina arcs to normal-high $\partial^{18}O_{WR}$ values in the younger ~545-540 Ma Albermarle arc (Potter et al., this volume). Soon after collision, it appears that the Charlotte-Carolina block underwent arc rifting as documented by c. 545-535 Ma zoned mafic-ultramafic complexes mainly in the Charlotte terrane (e.g. Dennis and Shervais, 1991, 1996, Dennis and Wright, 1997; Dennis pers. comm., 2013) and the Stony Mountain gabbro in the Carolina terrane (Pollock and Hibbard, 2010; DeDecker et al., this volume). Further to the Gondwanan side of the block, Albemarle arc magmatism was likely active at least until c. 528 Ma, the age of the youngest detrital zircon in the Yadkin Formation (Pollock et al., 2010). Also during this time frame of c. 550-510 Ma, it appears that the Carolina terrane entered the Iapetus Ocean, although how and when is not entirely clear.

Because the Stony Mountain gabbro 1. intrudes all components of the Albemarle arc, 2. is affected by later regional metamorphism and deformation associated with the accretion of Carolinia to Laurentia, and 3. geochemically reflects an arc-rift environment, the gabbro is interpreted as representing the rifting of the Albemarle arc from its peri-Gondwanan setting and the beginning of its migration across Iapetus to the margin of Laurentia. The c. 545 Ma age of the gabbro may represent the initiation of the suite and hence, rifting, although this interpretation is a topic of ongoing study (see DeDecker et al., this volume).

At present, it is unclear if the Kings Mountain early Late Cambrian rift sequence (Dennis et al., 2012) is the late interval of a protracted period of rifting from Gondwana. Alternatively, it could represent an arc-back arc rift system along the leading margin of Carolinia within the Iapetan realm; such a setting would be equivalent to that of the Late Cambrian, northern Appalachian, Penobscot arc (e.g. van Staal et al., 1998). The Kings Mountain sequence is shown in Figure 10 as lying along the westerly margin of this extensional system. As Carolinia migrated westward (modern coordinates) and Iapetus narrowed, it appears that it occuppied a lower plate setting, as no further magmatic activity took place in Carolinia during the early Paleozoic. The Cherokee orogeny at c. 460-430 Ma marks the accretion of Carolinia to Laurentia; the southeast vergence of Cherokee structures in Carolinia reinforces the idea that Carolinia was the lower plate during this collisional event.

Following accretion to Laurentia, the Carolina terrane underwent mild to moderate changes during ensuing Appalachian orogenesis and for the most part, maintained a relatively high position in the crust. It appears that the terrane migrated dextrally approximately 220 km during the time span between accretion by c. 430 Ma, and Alleghanian westward thrust transport at c. 330 Ma (Hibbard and Waldron, 2009). During Alleghanian shortening, the terrane was transported a minimum of 50 km to the northwest (Vines et al., 1998). In general, these events did not have a penetrative affect on the Carolina terrane in North Carolina, and only reveal themselves through local resetting of geochronometers, mainly along major structures (see Stop 1-2).

In conclusion, numerous geologists have dedicated untold hours of research to unraveling the geological evolution of the Carolina terrane in North Carolina. As demonstrated by our piecemeal tectonic summary model, unimagineable hours of investigation are yet required to seek answers to the innumerable gaps in our geological knowledge of the terrane.

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OVERVIEW OF EDIACARAN AGE FOSSILS FROM THE CAROLINA TERRANE: PAST, PRESENT AND FUTURE RESEARCH

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ABSTRACT

Specimens described as fossils from Ediacaran age sediments of the Carolina Terrane fall into three major categories: body fossils, trace fossils and pseudofossils. Body fossils represent either partial or whole organisms preserved in the sediments. Trace fossils are evidence of biological activity. Pseudofossils are specimens that were once thought to have biological origins, but later were determined to be geologic features. Determination of true fossils is often confounded by the fragmentary nature of most fossils, regional metamorphism, cleavage, volcanism, varied taphonomic processes, and by surficial features due to the presence of microbial mats. Historically, Carolina Terrane paleontological papers have focused on describing the fauna, as well as, age, paleoenvironmental, and paleobiogeographical determinations. Objectives of this paper are: to summarize the history of paleontological work in the Carolina Terrane, to present the current status of Carolina Terrane fossils and to encourage future work on this biota.

INTRODUCTION

Fossils from the Ediacaran Period (~635 to 542 million years ago) have been described from ~30 countries on five different continents (Narbonne, 2005) including fossils from the Carolina Terrane of North Carolina. Ediacaran age fossils are found from the Albemarle Group (Milton, 1984) sediments in Stanly and Davidson counties of North Carolina (Fig. 1). The Albemarle Group consists of a succession of four conformable formations, which includes, from oldest to youngest, the Tillery, Cid, Floyd Church, and Yadkin Formations (Milton, 1984; Butler and Secor, 1991; Hibbard et al., 2002; Hibbard et al., 2009). The Albemarle Group sits conformably above the top of the underlying Uwharrie Formation. General stratigraphy of Carolina Terrane formations, as well as lithology, radiometric age dates and a list of fossils are given in Figure 2.

In general, the Ediacaran fauna consists of body fossils, trace fossils and problematica. Most specimens described as fossils from the Carolina Terrane have undergone some form of taxonomic revision or reinterpretation. These revisions reflect the scientific knowledge of the time and the fragmentary nature of most of the specimens. Because of these factors, age, paleoenvironmental and paleobiogeographical determinations based on fossils have also undergone several revisions. What follows is a summary of what is currently known about Ediacaran age fossils from the Carolina Terrane.

BODY FOSSILS

As of this writing, *Pteridinium carolinaensis* (St. Jean, 1973), cf. ?*Swartpuntia* sp. Narbonne, Saylor and Grotzinger, 1997, *Sekwia excentrica* Hofmann, 1981, *Aspidella* cf. *A. terranovica* Billings, 1872, *Oldhamia recta* Seilacher, Buatois and Mángano, 2005, and a possible sac like organism are the only published

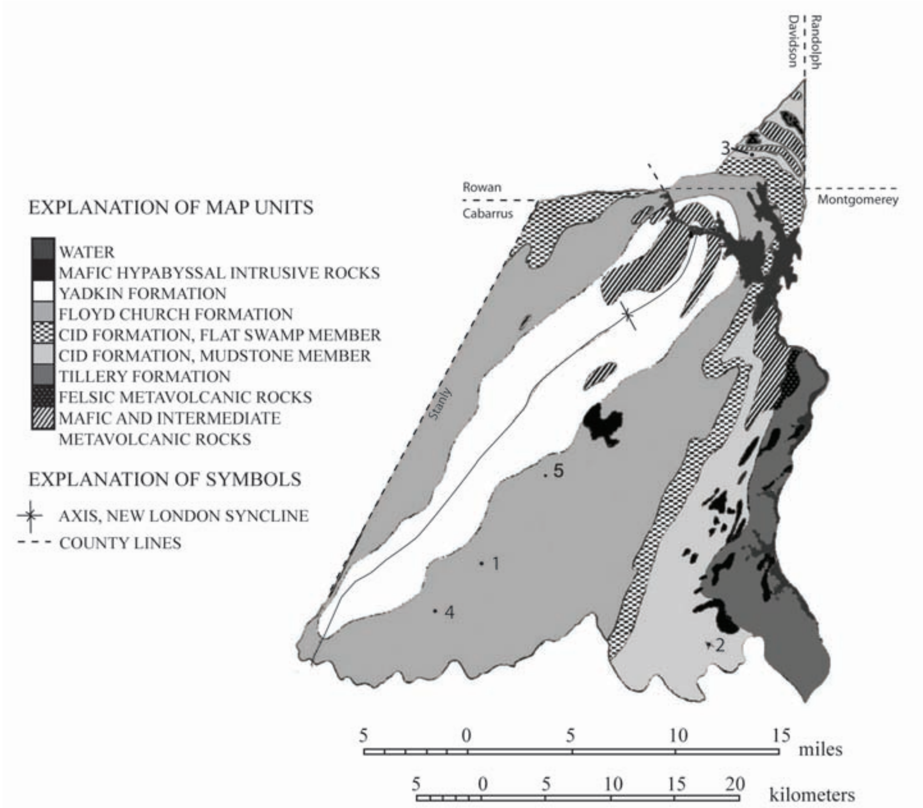

Figure 1. From Weaver et al. (2006b), generalized geologic map of south-central North Carolina (adapted from Goldsmith et al., 1988) showing some Ediacaran body fossil localities (St. Jean, 1973; Gibson and Teeter, 2001; Hibbard et al., 2006; Weaver et al., 2008): 1) Gleaning Mission Church, north of 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, 5) Abandoned quarry on private property, 0.5 km north of SR 1963, Stanly County.

body fossils recovered from Ediacaran age sediments of the Carolina Terrane. Cf. ?*Swartpuntia* sp., *Aspidella* cf. *A. terranovica* and a possible sac-like organism (originally described as ?Inaria (Weaver et al., 2006b), were recovered from the unnamed mudstone member of the Cid Formation (Fig. 3) (Weaver et al., 2006a; Weaver et al., 2006b; Hibbard et al., 2006; Weaver et al., 2008). *Pteridinium carolinaensis* was originally described as a the trilobite, ?*Paradoxides carolinaensis* (St. Jean, 1973), *Sekwia excentrica* and *Oldhamia recta*, originally described as a trace fossil (Seilacher et al., 2005), were recovered from the overlying Floyd Church Formation (Figs. 2, 4) (Gibson et al., 1984; Gibson and Teeter, 2001; McMenamin and Weaver, 2002; Weaver et al., 2006a; Weaver et al., 2006b, Tacker et al., 2010). To date no body fossils have been recovered from the Tillery or Yadkin Formations.

TRACE FOSSILS

Possible Ediacaran age trace fossils from the Carolina Terrane were first mentioned by Conley (1960). Gibson (1989), Tacker et al. (2010), and Martin and Weaver (2013, this volume) have also described and analyzed potential trace fossils (Fig. 2). To date, trace fossils have been described from the Tillery Formation (Gibson, 1989; Martin and Weaver, 2013, this volume), the Floyd Church Formation (Conley, 1960; Gibson, 1989; Martin and Weaver, 2013, this volume) and the overlying Cambrian age Yadkin Formation (Gibson 1989). However, in light of fundamental differences between Phanerozoic and Neoproteozoic paleoecology (Droser et al., 2006) and more recent work on organismal interactions with microbial mat features (e.g. Hagadorn and Bottjer, 1997; Noffke et al., 2001; Gehling and Droser, 2009), Ediacaran trace fossils from around the world, including those from North Carolina,

		Lithology	Radiometric ages	Fossils
Albemarle Group	Yadkin Graywacke	Graywackes and sparse andesitic volcanics (Stromquist and Sundelius, 1969). Sedimentary structures within the lower Yadkin Graywacke suggest shallow marine deposition (Gibson and Teeter, 1984), which appears to grade upward into non-marine facies (Gibson and Teeter, 2001).	540 +/- 7 Ma (Black, 1978, heterolithic tuff)	**Ichnofossils** *?Monocraterion* sp.#
	Floyd Church Formation	Epiclastic mudstone containing lenses of andesites and dacites (Milton, 1984).	567 +/- 32 Ma (Ingle et al. 2003)	**Ichnofossils** *Gordia arcuata?* *Helminthopsis* isp. *Neonerites biserialis** *N. uniserialis** *?Neonerites* sp.* *Planolites beverlyensis* *P. montanus* *?Planolites* sp. *?Tomaculum* sp.* *?Torrowangea* sp. Ichnogenera A & B of Gibson (1989) **Bodyfossils** *Pteridinium carolinaensis* *Sekwia excentrica* *Oldhamia recta*
	Cid Formation Flat Swamp Member	Sequence of felsic, mafic and rare intermediate volcanic rocks (Stromquist and Sundelius, 1969).	540.6 +/- 1.2 Ma (Ingle et al., 2003) 547 +/-2 Ma (Hibbard et al. 2006).	
	Cid Formation Unnamed Mudstone Member	Thinly bedded epiclastic mudstones (Milton, 1984) with thick beds of felsic volcaniclastics and lenses of both felsic and mafic lavas (Conley and Bain, 1965; Seiders, 1978).	542 +/- 14 Ma (Ingle et al. 2003)	**Bodyfossils** *Swartpuntia* sp. *Aspidella* sp. Indeterminate sac-like fossil Euconodonts (disputed report)
	Tillery Formation	~5,000 feet (~1,500m) of laminated to thinly bedded epiclastic mudstones with minor lenses of volcaniclastic rocks and felsic and mafic lavas (Milton, 1984). Lower part also includes cross-bedded sandstones and sub-aqueous debris flows (Gibson and Teeter, 1984). Upper part is more tuffaceous, with thin water-laid tuff layers, thinly laminated claystone and siltstone (Gibson and Teeter, 1984).	553+/- 20 Ma (Ingle et al. 2003)	**Ichnofossils** *?Monocraterion* sp.# *?Helminthopsis* isp. **Bodyfossils** Bryozoan zooecial & gastropod steinkerns (Koeppen et al., 1995)
	Uwharrie Formation	~20,000 feet (6,000 m) of felsic volcaniclastic rocks (Stromquist and Sundelius, 1969). Primarily felsic volcanics, including felsites, tuffs, bedded tuffs and epicastic conglomerates (Ingram, 1999).	554+/-15 Ma (Ingle et al. 2003).	**Pseudofossils** *Paleotrochis major* *Paleotrochis minor*
	Virgilina Sequence	Extensive succession of plutonic, volcanic and epiclastic rocks ranging from mafic to felsic in composition (Black, 1980; Rogers, 1982). Volcanics of this sequence are dominantly sub-aqueous pyroclastics interpreted as having been deposited in shallow water (Glover and Sinha, 1973; Green et al, 1982; Harris and Glover, 1988).	Bulk of sequence 633 (+2/-1.5) to 612.4 (+5.2/-1.7) Ma (Wortman et al. 2000). Extrusives 618+/-3 Ma, intrusives 605 +/- 7.4 Ma (Ingle et al. 2003).	**Ichnofossils?** *Vermiforma antiqua*

Figure 2. Generalized stratigraphic column showing formations contained within the Carolina Terrane, radiometric ages and fossil faunas. Dashed lines represent gradational boundaries between units. Wavy line indicates an unconformity. Trace fossil data from Gibson (1989) and Martin and Weaver (2013, this volume) asterisks indicate specimens that are being re-evaluated as possible body fossils, pound signs indicate specimens that are being re-evaluated as possible pseudo-fossils. Euconodont data from Koeppen et al. (1995), *Pteridinium carolinensis* data from Gibson and Teeter (2001), and *Aspidella* data from Hibbard et al. (2006), ?cf. Swartpuntia sp. data from Weaver et al. (2006a), indeterminate sac-like organism data from Weaver et al. (2008), *Oldhamia recta* data from Tacker et al. (2010).

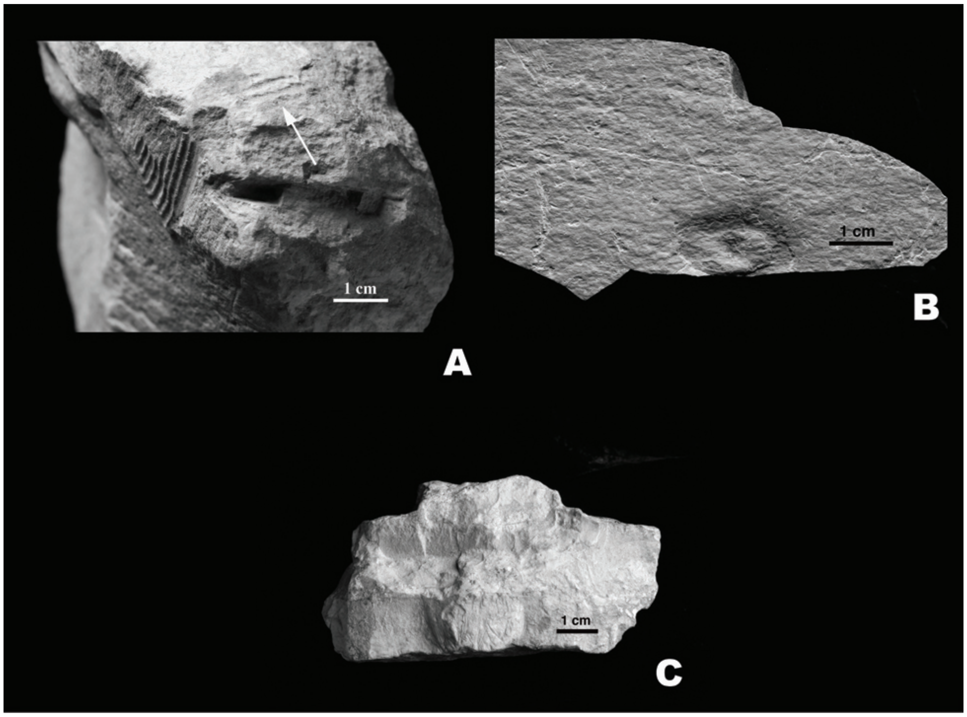

Figure 3. Ediacaran body fossils from the unnamed mudstone Member of the Cid Formation A) NCSM 9581, cf. ?*Swartpuntia* sp. Narbonne, Saylor and Grotzinger, 1997 (arrow points to a second vane ~ 90 degrees to the main vane) recovered from locality 2 of Figure 1. B) NCSM 9713 *Aspidella* cf. *A. terranovica* Billings, 1872 recovered from locality 3 of Figure 1. C) NCSM 9714 indeterminate sac-like organism recovered from locality 2 of Figure 1.

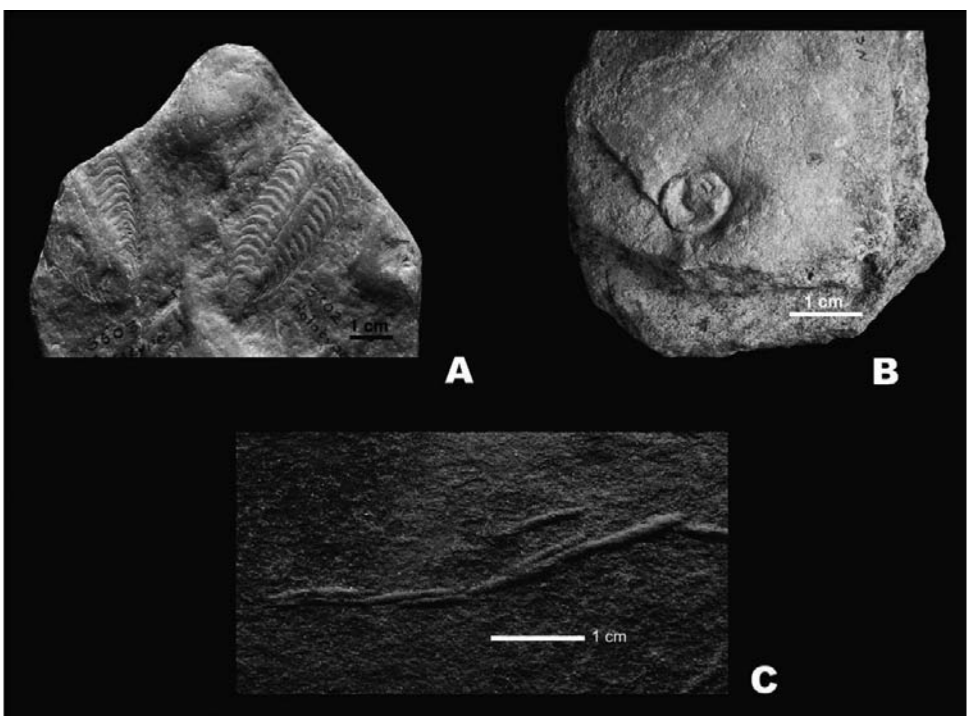

Figure 4. Ediacaran body fossils from the Floyd Church Formation. A) *Pteridinium carolinaensis* (St. Jean, 1973), entire block NCSM 4041, UNC holotype 3062, UNC paratype 3063 recovered from locality 4 of Figure 1 B) NCSM 9836 *Sekwia excentrica* Hofmann, 1981recovered from locality 1 of Figure 1. C) NCSM 4038 *Oldhamia recta* Seilacher, Buatois and Mángano, 2005 recovered from locality 5 of Figure 1.

are being reappraised (e.g. Jensen et al., 2006; Gehling and Droser, 2009; Tacker et al., 2010; Sappenfield et al., 2011).

Trace fossils, *Monocraterion* sp. and ?*Helminthopsis* isp. have been described from the Tillery Formation (Gibson, 1989; Martin and Weaver, 2013, this volume). Gibson (1989) described an indeterminate Ichnogenus C as sand filled burrow, elliptical in cross-section, from the mudstone member of the McManus Formation of Conley and Bain (1965) which, in the terminology of Milton (1984), should be equivalent to the unnamed mudstone member of the Cid Formation. However, based on the locality given by Gibson (1989) the quarry this specimen was found in is actually in the Floyd Church Formation. To date no trace fossils have been recovered from the Cid Formation. Other trace fossils described by Gibson (1984) from the Floyd Church Formation include *Gordia arcuata*? Książkiewicz, 1977, ?*Helminthopsis* sp. Gibson, 1989, *Neonerites biserialis* Seilacher, 1960, *Neonerites uniserialis* Seilacher, 1960, *Neonerites* sp. Seilacher 1960, *Planolites beverlyensis* (Billings, 1862), *Planolites montanus* Richter, 1937, ?*Tomaculum* Gibson, 1989 ?*Torrowangea* sp. Gibson, 1989, indeterminate ichnogenera A & B Gibson, 1989 and *Syringomorpha nilssoni*? (Torell 1868). The specimen of *Syringomorpha nilssoni*?, described by Gibson (1989), was subsequently synonomized into *Oldhamia recta* by Seilacher et al., (2005). More recently, Tacker et al. (2010) redefined *Oldhamia recta* as a body fossil. Gibson (1989) also lists ?*Monocraterion* sp. from the Yadkin Formation. Martin and Weaver (2013, this volume) are in the process of re-evaluating trace fossils that have been described from the Albemarle Group.

Problematica and conflicting reports

Published problematic fossils from the Carolina Terrane (Fig. 2) include a possible trace fossil *Vermiforma antiqua* Cloud, Wright and Glover III, 1976 from the Virgillina Sequence, *Paleotrochis major* (Emmons, 1856) and *Paleotrochis minor* (Emmons, 1856) from the Uwharrie Formation and reports of Cambrian and Ordovician age euconodonts, bryozoan zooecial and gastropod steinkerns from the Cid and Tillery Formations (Koeppen et al., 1995). *Vermiforma antiqua* was originally described, from Virgillina Sequence rocks, ~ 16 km northwest of Durham, NC, as a trace fossil consisting of J and U-shaped markings on bedding surface. Seilacher et al., (2000) reinterpreted these impressions as tool marks or tectographs.

Emmons (1856) described *Paleotrochis major* and *minor* from the Uwharrie Formation as a double cone, with grooved surface. Emmons (1856) regard these structures as a coral. Hall (1857) claimed *Paleotrochis* is "nothing but concretions" and Diller (1899) interpreted *Paleotrochis* as biconical spherulites in an acid volcanic rock. *Paleotrochis* is currently listed in the Treatise on Invertebrate Paleontology (Häntzschel, 1975) as a pseudofossil (suggestive of being fossils, but probably of inorganic origin).

Reports by Koeppen et al. (1995) of Cambrian age euconodonts from the Cid Formation and Ordovician age bryozoan zooecial and gastropod steinkerns from the Tillery Formation are difficult to reconcile with the data of others. These specimens would place the age of the Tillery as no older than Mid-Ordovician and the Cid as no older than late Cambrian. Koeppen et al. (1995) did not publish a descriptive paper or images of these fossils. These Paleozoic dates conflict with other radiometric and fossil ages for the Tillery and Cid formations (see Fig. 2) and resulted in a reorganized stratigraphy of the Albemarle Group by Offield (2000) opposing that of Milton (1984). Hibbard et al. (2009) used stratigraphic mapping, isotopic data and reports of Ediacaran age body fossils to challenge the reliability of the euconodont reports from the Jacob's Creek Quarry. Reports of Paleozoic fossils in the Albermarle Group rocks will remain controversial and unresolved until such time as they are fully described and imaged in the literature with confirmation of the lithology and stratigraphy There have been other problematic specimens recovered from Ediacaran age sediments of the Carolina Terrane, including reports of stromatolite-like forms from the unnamed mudstone Member of the Cid Formation (Hibbard et al., 2009). These stromatolite-like forms (Fig. 5), as well as, other potential fossils are currently being studied by researchers at various institutions. Some are most likely as yet unidentified partial body fossils. Others are likely to be preserved microbial mat features. Others are probably pseudofossils.

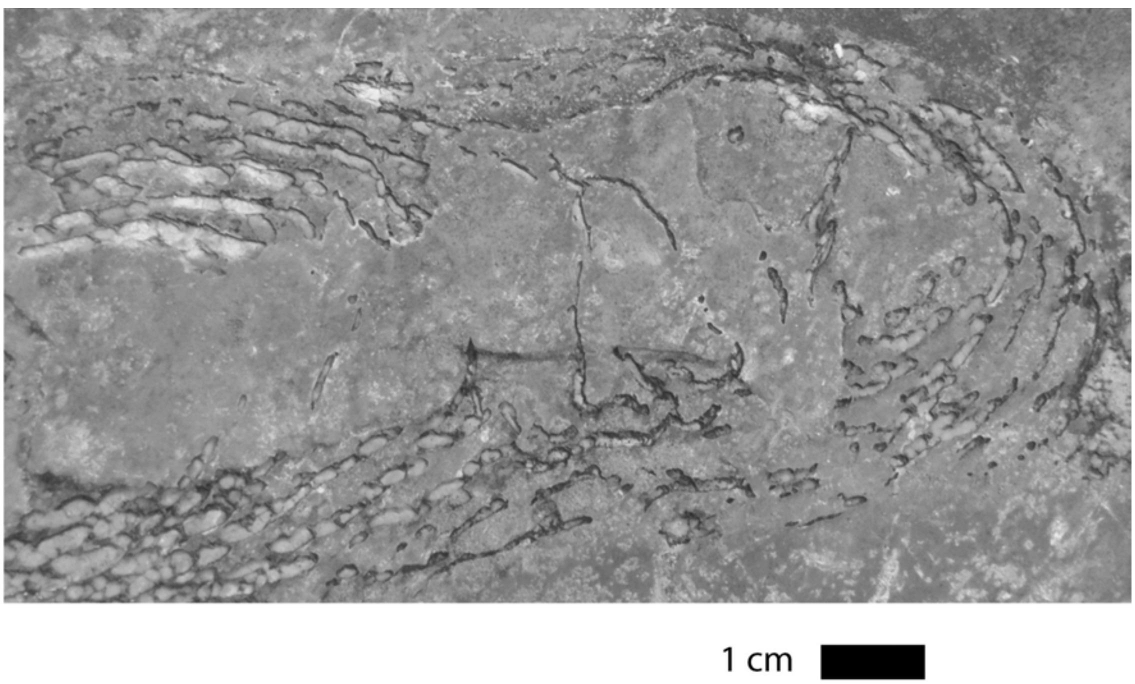

Figure 5. Stromatolite-like forms from locality 3 of Figure 1. Image courtesy of Dr. Michael Meyer.

SIGNIFICANCE

Ediacaran age fossils have been used to interpret age, paleoenvironments and paleobiogeography of the Carolina Terrane. The discovery of *Pteridinium* from the Floyd Church Formation was one of the first fossil indicators of a Precambrian age for the Ablemarle Group (Gibson et al., 1984). *Pteridinium carolinaensis'* initial identification as a trilobite was partially the result of the sheared morphology of the fossil as a result of metamorphism; how this metamorphism affects Carolina Terrane Ediacaran fossil morphology (and their identification) still requires further study (Meyer, 2010). Since the original report of *Pteridinium carolinaensis* , reports of other specimens of *Pteridinium carolinaensis*, as well as specimens of ?Cf. *Swartpuntia* sp., *Sekwia excentrica*, and *Aspidella* cf. *A. terranovica* (Gibson and Teeter, 2001; McMenamin and Weaver, 2002; Weaver et al., 2006 a,b; Hibbard et al., 2006; Weaver et al., 2008), as well as trace fossils described by Gibson (1989) and radiometric ages of Ingle et al. (2003), Hibbard et al. (2006) and Hibbard et al. (2009) all support an Ediacaran age for the majority of the Albemarle Group of the Carolina Terrane.

Gibson et al. (1984) and Gibson and Teeter (2001) used the lack of stalks on *Pteridinium* and the presence of trace fossils with in the McManus (= Floyd Church) Formation to interpret paleoenvironments. Gibson and Teeter (2001) concluded that *Pteridinium* specimens were transported from their living positions in high energy, shallow water environments and deposited as allochems into the deeper water, lower energy deposits of the McManus (= Floyd Church) Formation (Gibson et al., 1984). It is possible that specimens of *Pteridinium carolinaensis* lack stalks because they may have lived and grown within the sediment, as has been suggested for *Pteridinium simplex* and *Rangea schneiderhoehni* from Namibia (Grazhdankin and Seilacher, 2005). However, recent studies (Elliott et al, 2011, Meyer et al., *submitted*) have cast doubt on this hypothesis, and most *Pteridinium* specimens (from both species) are now believed to be transported before preservation (which may also be evidence for a pelagic life-stage (Meyer, personal communication)). The specimen of Cf. ?*Swartpuntia* sp. from the mudstone member of the Cid Formation (Weaver et al., 2008), as well as, *Aspidella* cf. *A. terranovica* and the sac-like organism (Weaver et al., 2006a,b) are interpreted as having been preserved by progressive burial, indicating a low energy environment. Unlike *Pteridinium*, *Swartpuntia* and *Aspidella* were exclusively benthic–epibenthic organisms that lived in, and utilized, the sediments that preserved them (Vickers-Rich et al., 2013).

Ediacaran age fossils from North Carolina have also added another piece of data to the continued debate over the paleogeographic origin of the Carolina Terrane. Though it is generally accepted that the Carolina Terrane is exotic with respect to Laurentia, its paleogeographic origins are still debated. One line of thinking is that the Carolina Terrane is one of the southern pieces of the disrupted Avalon Terrane (Williams and Hatcher, 1983; Hatcher et al., 1990). Association of the Carolina Terrane with the Avalon Terrane has been based on broad similarities in timing of magmatism, lithology, timing of docking with Laurentia, and faunas distinct from those of Laurentia (Secor et al., 1983; Gibson et al., 1984; Samson et al., 1990; Hibbard, 2000; McMenamin and Weaver, 2002, 2004; Ingle et al., 2003). However, when considered in detail, these two Terranes are quite different from each other. While a detailed discussion of the lithotectonic and isotopic differences between the Avalon and Carolina Terrane are beyond the scope of this paper, see Hibbard et al. (2002), Hibbard and van Staal (2004), Pollock and Hibbard (2006), Pollock (2007), and Hibbard et al. (2007) for more thorough discussions on the relationship between the Carolina and Avalon Terrranes.

Ediacaran age fossils have been used many times in discussions of paleogeographic reconstructions (McMenamin, 1982; Donovan, 1987; Waggoner, 1999; Hagadorn and Waggoner 2000). Studies by Waggoner (1999, 2003) Gehling (2001) and Grazhdankin (2004) divided the global Ediacaran fauna into three environmentally and age related assemblage types: Avalon, White Sea and Nama. Parsimony analysis by Weaver et al. (2006b) and further study (Weaver et al., 2008) show the Carolina Terrane Ediacaran fauna has a much greater affinity with the Nama Assemblage of Waggoner (2003) than it does with Waggoner's (2003) Avalon Assemblage. Whether this is a function of paleoenvironments, paleogeography or age is still in question (Grazhdankin, 2004). However, the Carolina Terrane Ediacaran fauna is distinctly different from that of the much older, deeper water Avalon Terrane Ediacaran fauna. These fossil data support lithotectonic and isotopic data that Carolina and Avalon were separate crustal blocks.

FUTURE WORK

Future study on the Ediacaran fauna from the Carolina Terrane continues and much more research is needed to elucidate how the Carolina Ediacaran fauna fits with the global Ediacaran fauna. More specimens, particularly more complete body fossils, are necessary for further taxonomic, morphological and paleogeographic studies. Carolina Terrane Ediacaran trace fossils need to be re-evaluated in light of differences between Phanerozoic and Neoproteozoic paleoecology and more recent work on organismal interactions with microbial mat features.

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Geochronologic and thermochronologic database of the Southern Appalachian orogen

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Abstract

Described here are the compilation, organization and coverage of a geochronologic and thermochronologic database for the southern Appalachian orogen containing 4165 records, from which 2220 sample locations are geo-referenced. After filtering data with age uncertainties greater than 3%, the U-Pb and $^{40}Ar/^{39}Ar$ components of the database are briefly evaluated to describe the geographic extent of data coverage and available constraints on the high-temperature Paleozoic tectonothermal events in the southern Appalachian orogen.

The location and tectonic affinity of U-Pb and $^{40}Ar/^{39}Ar$ age determinations from the southern Appalachians are closely related to the efforts of individual researchers and their collaborators, and thus clusters in the numbers of age determinations in both time and space reflect more the interests of a small number of researchers than representative populations of orogenic events. Nevertheless, age peaks do correspond broadly to the widely accepted and previously established times of southern Appalachian orogenic activities. Two exceptions to this trend are the poor resolution of ages related to the Silurian Cherokee orogeny and the late Devonian to early Mississippian Famennian (Neoacadian) orogeny. The latter event is indistinguishable from the onset of Alleghanian events in terms of its U-Pb and $^{40}Ar/^{39}Ar$ record. The database contains clusters of data at ca. 1200-950 Ma and ca. 740-515 Ma, which are related to the assembly and dispersal of the Rodinian supercontinent. Neoproterozoic arc-related processes in the outboard terranes of Carolinia give ages in the range ca. 650-520 Ma. The history of Appalachian mountain building events is recorded in ca. 500-430 Ma broadly Taconian ages, ca. 390-350 Ma ages that are classic Acadian, and Famennian (Neoacadian) and Alleghanian ages in the range ca. 340-260 Ma. Notably lacking in the SoAG database are age determinations from the southern Inner Piedmont, a vast tract of plutonic rocks and high-grade gneisses that may hold the key to better understanding the distinction between Devonian and Carboniferous tectonism in the southern Appalachians.
Until an internet-based interface can be constructed, the author will gladly share the latest version of the database upon request.

Introduction

In 1952, eminent Appalachian geologist and Yale University professor John Rodgers took on the task of compiling, "All available absolute age determinations made on radioactive minerals from the Appalachian region…" (Rodgers, 1952; pg. 411). His compilation consisted of sixty-four mineral and rock age determinations. After recalculating and evaluating the data, Rodgers (1952) concluded that these ages constrain four episodes of orogenesis at about 800, 600, 350, and 260 Ma. The first two episodes he recognized as restricted to Precambrian crystalline uplifts, the second and third groups of ages he associated with the Taconian and Acadian orogenies, respectively. The database at that time contained no ages that Rodgers considered

"Appalachian" (i.e., Alleghanian). In the intervening six decades the techniques, methodologies, and applications of radioisotope dating have evolved dramatically and radioisotope dating has grown to play a crucial role in furthering our understanding of the timing, style, conditions, and geographic extent of Appalachian tectonothermal events.

This paper reports on the current state of an ongoing effort to update Rodgers' (1952) database, at least for the southern segment of the Appalachian orogen, through compilation of a geo-referenced archive of all extant radioisotope dates – a southern Appalachian Geochronology (SoAG) database. Although the focus here is on evaluation of the U-Pb and $^{40}Ar/^{39}Ar$ components, ages determined by other methods are also included in the database. Compilation of this database can never be considered truly complete as new geochronologic and thermochronologic data are generated and published nearly every day. Furthermore, despite extensive efforts to find all published data, some amount of omission is likely.

The SoAG database can help researchers to evaluate the extent of data coverage, both temporally and spatially, highlight gaps in data coverage, determine where further refinement is necessary, and potentially point the way to fruitful lines of future research. The ultimate goal of this project is to allow researchers easy access to all relevant geochronologic and thermochronologic data, in a manner that can be readily quality-controlled, for the purpose of testing tectonic models of southern Appalachian orogenesis.

MOTIVATION, DEFINITION, AND SCOPE

The SoAG compilation project stems from the author's desire to evaluate the existing constraints on the timing and nature of southern Appalachian tectonic events as revealed through geochronology and high-temperature thermochronology. This is by no means the only, or even necessarily the best, way to evaluate the timing and extent of tectonic events. For instance, the age and location of sediment deposition (e.g., Becker et al., 2006; Ettensohn, 2004; Ver Straeten, 2010) and the age and character of the uplifted terrain supplying these sediments (e.g., Moecher et al., 2011), metamorphic pressure and temperature conditions (e.g., Page et al., 2003), formation and orientations of structures and metamorphic fabrics (e.g., Merschat et al., 2005; Waters-Tormey and Stewart, 2010), are among the important constraints on Appalachian tectonism. Nevertheless, there is a need for easy access to all available geochronologic and thermochronologic data in order to ensure that no relevant information is overlooked. Equally important is the need for a mechanism and set of criteria to evaluate extant data so that potentially inaccurate ages can be identified, scrutinized and if necessary purged from the literature, as wrong data are often worse than no data at all.

The SoAG database is organized as a flat-form Excel workbook (Fig. 1) and is accompanied by an EndNote library that includes PDF copies of primary and secondary data sources. The database structure allows for an emphasis on simplicity and completeness, transportability across computer platforms, is readily sorted and filtered, and is easily scrutinized for quality-control purposes. Future generations of the database will embrace more sophisticated data archiving technology, but simplicity and ease of use were deemed important for the initial construction of the database.

The scope of the SoAG database is limited to the lithotectonic and physiographic region of the southern Appalachians (Fig. 2). Hibbard et al. (2007) define the boundary between the northern and southern Appalachians as the break in structural trend around the New York promontory. Following their definition, the northern boundary of the SoAG compila-

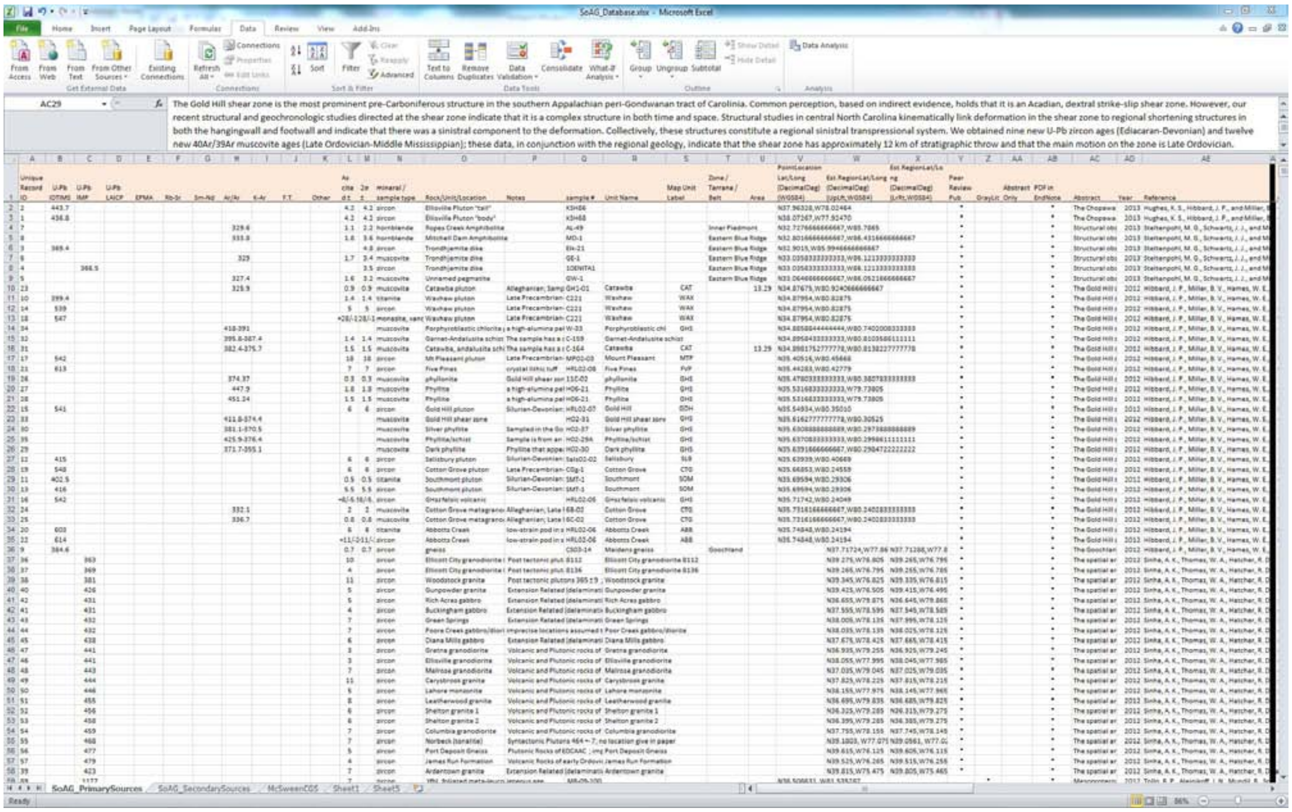

Figure 1. Spreadsheet layout of SoAG database. Each record (row) consists of data fields (columns): A) Unique Record Identifier, B-K) Reported rock or mineral age by analytical method (U-Pb isotope dilution, thermal-ionization mass spectrometry, U-Pb ion microprobe, U-Pb laser-ablation inductively coupled plasma mass spectrometry, electron microprobe micro-analysis, Rb-Sr, Sm-Nd, Ar/Ar, K-Ar, fission track, or other method, L-M) cited age uncertainty and 2-sigma age uncertainty, N) mineral or sample type, O) rock unit location notes, P) age interpretation notes, Q) sample number/name, R) unit name, S) map unit label, T) tectonic zone, terrane, or belt, U) area of map unit, V-X) point location or corners of best estimate area of location, Y-AA) source of data, peer-reviewed publication, gray literature, or conference abstract, AB) PDF of data source in EndNote, AC) text of abstract, AD) publication year, and AE) citation.

tion is set along the New York-Pennsylvania border and the Delaware River (Fig. 2). This represents the northernmost boundary of the NE-SW trending structures within the crystalline rocks of the southern Appalachian orogen. The eastern and southern boundaries are the Atlantic Coastal Plain onlap, although some data exist from drill holes through the coastal plain sediments. The western boundary is the Appalachian structural front. Within this geographic region U-Pb analyses by both isotope-dilution thermal ionization mass spectrometry (ID-TIMS) and ion microprobe (IMP), $^{40}Ar/^{39}Ar$, electron microprobe analysis (EMPA), Rb-Sr, Sm-Nd, $^{40}Ar/^{39}Ar$, K-Ar, fission-track (F.T.), and a few other radioisotope methods have been used on minerals and whole-rock samples to help understand the assembly and rifting of Rodina (Su et al., 1994; Tollo and Aleinikoff, 1996; Tollo et al., 2010; Tollo and Hutson, 1996), orogenic events exotic to Laurentia (Harris and Glover, 1988; Hibbard et al., 1995; Hibbard and Samson, 1995), three phases of Ordovician to Permian Appalachian orogenesis culminating in the assembly of Pangea (Hatcher, 2010), rifting of the Atlantic Ocean (Olsen et al., 1991), and subsequent cooling and uplift (Kunk et al., 2005; Spotila et al., 2004).

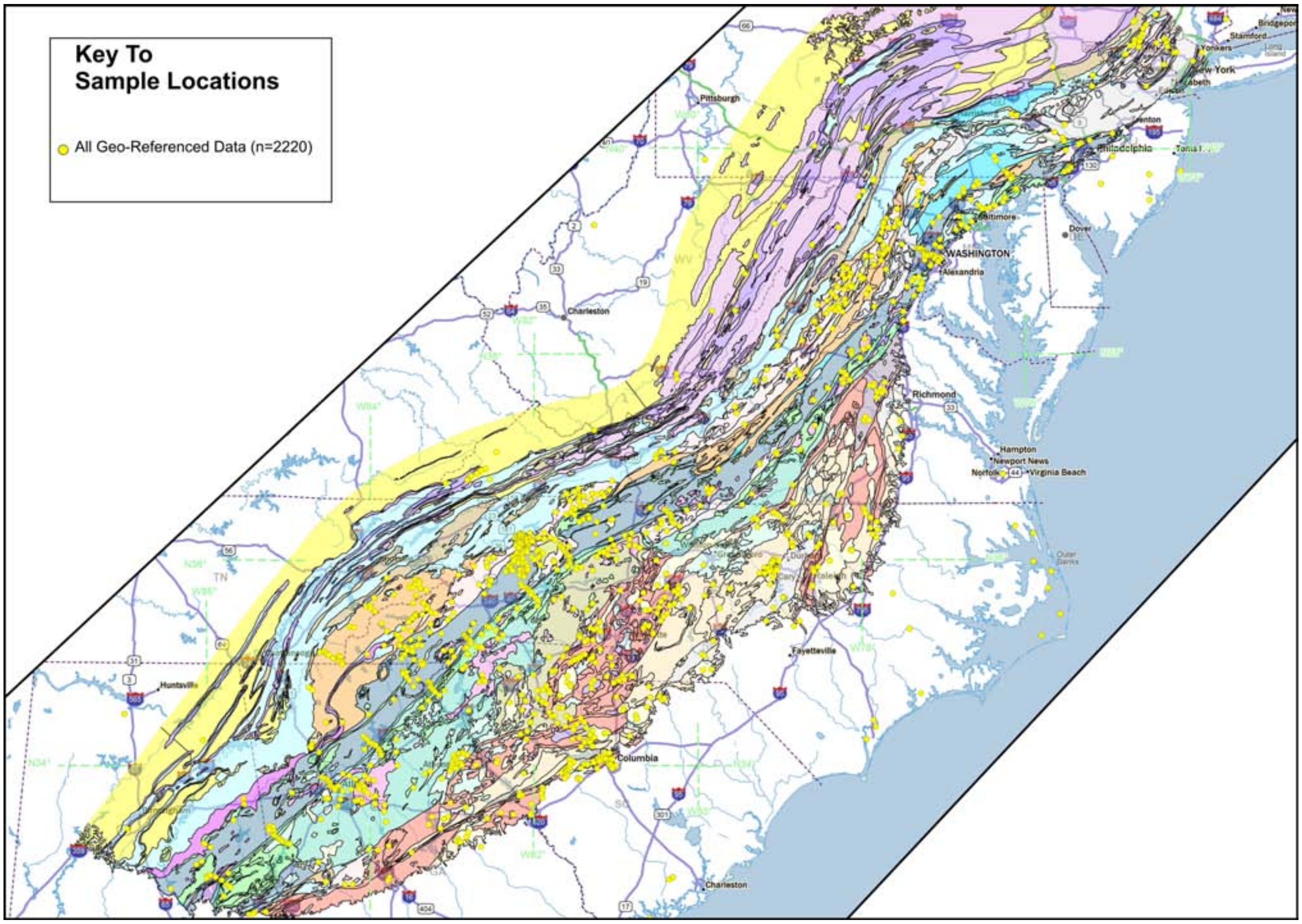

Figure 2. Locations of 2220 geo-referenced radioisotope age samples currently in the SoAG database. For this and subsequent maps, the software program Delorme XMap 8 was used for base map and GIS plotting. Lithotectonic reference map is from Hibbard et al. (2006).

The SoAG database does not currently include detrital zircon data. Future growth of the database includes plans to capture these types of data, perhaps as a subset of a global database currently under construction (Voice et al., 2013).

COMPILATION OF DATA

The SoAG database is a compilation of rock and mineral age interpretations acquired from primary-source documents. A list of potential primary source documents was generated mainly from internet and reference database searches of published scientific literature. The list was pruned of obviously irrelevant publications, then each remaining manuscript was obtained in either PDF or paper format and evaluated for new age data. Although extensive effort was expended to discover, document, and accurately compile all available data, omission of some data is likely and will be rectified as overlooked data sources are identified; the author welcomes submission of and suggestions for new or overlooked data sources and corrections of errors. Ages and their uncertainties are recorded from the original authors' best interpretation as published in the original paper, unless the ages were recalculated subsequently. An effort was made to determine whether uncertainties were reported at the 1- or 2-sigma level, but where unclear uncertainties were recorded simply "as cited". After compiling all new ages presented in a primary source, the document was searched for references to other ages – usually by conducting a text search for "Ma" and collecting the enclosing paragraph, from which was parsed ages and their references. Summary and overview papers (secondary sources) that make extensive use of primary geochronologic data were scanned in a similar manner to try to ensure capture of all relevant original data sources. The USGS National Geochronologic Database (Sloan et al., 2003) is a significant source of pre-1988 data. This database was downloaded, sorted by state and parsed into the appropriate SoAG fields. Ages with full supporting details published in theses or dissertations, in non-traditional sources, or in non-peer-reviewed literature are included in the database and designated as "gray literature". Ages reported in conference abstracts are included in the database for five years, after which they are expunged unless later published with full supporting details.

As of this writing, the SoAG database consists of 4165 records, however compilation efforts have focused on more recent work and thus not all older records are geo-referenced or fully populated with data. Marble (1936) provided the first radioisotope age in the database, a 580 Ma monazite age from Mars Hill determined by gravimetric analysis [recalculated to 600 Ma by Rodgers (1952)]. Figure 3 shows a frequency distribution of published ages by different methods for the intervening three-quarters of a century. Examination of the data used to generate Figure 3, indicates that the most significant advancements in terms of sheer numbers of dated rocks and minerals are due to the concerted efforts of individual researchers and their collaborators, and even individual projects. For example, 335 Rb-Sr results over the period 1969 to 1993 are due to the work of Dr. Paul Fullagar and his colleagues and students at University of North Carolina; Dr. David Dallmeyer and collaborators working in the University of Georgia lab produced 279 $^{40}Ar/^{39}Ar$ ages over a sixteen year period, and Dr. John Aleinkoff and his academic and USGS co-workers are credited with 432 U-Pb records in the database over the period 1995 to 2012. Dr. Stephen Kish's (1974) MSc thesis at Florida State University, his PhD at University of North Carolina, and just one of his numerous subsequent papers account for 127 K-Ar and Rb-Sr mineral and whole-rock ages. These four researchers and their coauthors are responsible for 53% of the geochronology in the southern Appalachians since 1968.

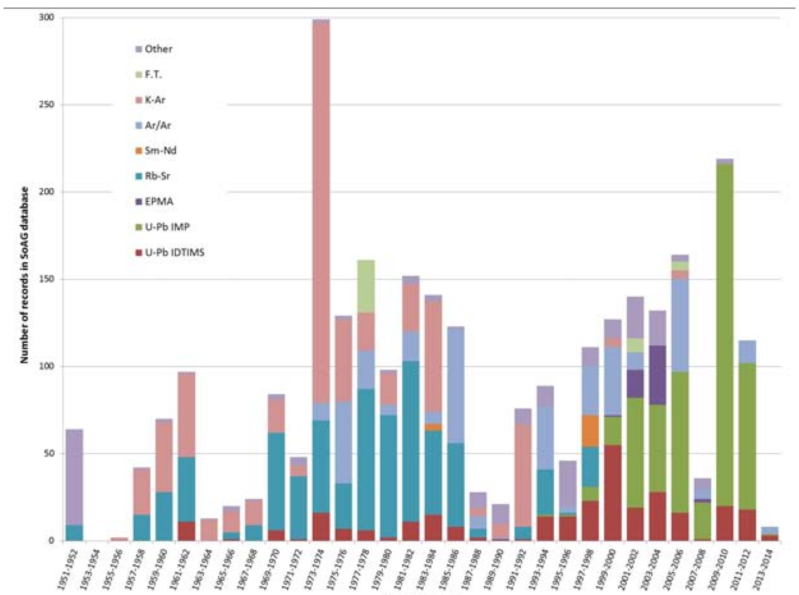

Figure 3. Numbers of mineral and rock age determinations (per two-year interval) in the southern Appalachians by various analytical methods since 1952.

GEOREFERENCING

Sample point locations (where necessary re-calculated to WGS84 datum) were acquired from the original source paper, online depository items, or in some cases theses and dissertations if samples could be matched with those of the primary source document. In cases where point locations were not available, digital scans or screen captures of map figures from the primary source document were georeferenced and locations recorded as boxes surrounding sample spots on the map. Thus, sample locations in the database are either in the form of a single latitude and longitude for point locations or the locations of the northwest and southeast corners of a box enveloping the best estimate of the region of the sample location.

At present, 2220 records in the SoAG database contain ages with georeferenced sample locations. The geographic distribution of all sample locations is shown in Figure 2. Like the numbers of dated rocks described above, the clustering of locations in the southern Appalachians also reflects, in large part, the efforts of individual research groups and their research foci. For instance, clearly evident are nine K-Ar dating traverses across the Brevard fault zone (Stonebreaker, 1973). Large clusters of data appear around the Potomac River west of Washington D.C., the Blue Ridge of northern Virginia, around the Grandfather Mountain window in North Carolina, and in the vicinity of Columbia, South Carolina. Noteworthy gaps in data coverage include large swaths of the southern Inner Piedmont and southern segment of Carolinia.

QUALITY CONTROL AND FILTERING

A first-pass filter for age precision set at 3% (cited uncertainty or 2-sigma, whichever is greater), essentially eliminates ages published prior to 1970, and significantly trims the number of, mainly Rb-Sr and K-Ar ages, published between 1970 and 1990 (Fig. 4). For Appalachian ages (470 to 260 Ma), ±3% corresponds to 28 to 16 million years of uncertainty within the 1- or 2-sigma confidence interval. Furthermore, it is often the case in modern analyses that more than about 4-5% uncertainty hints at the possibility of some sort of open-stem behavior, age-mixing or a technical complication causing excess scatter. Thus, ages with uncertainties greater than 3% are considered, for the purposes of most modern tectonic applications, unacceptably imprecise or at least in need of careful examination for potential sources of inaccuracy.

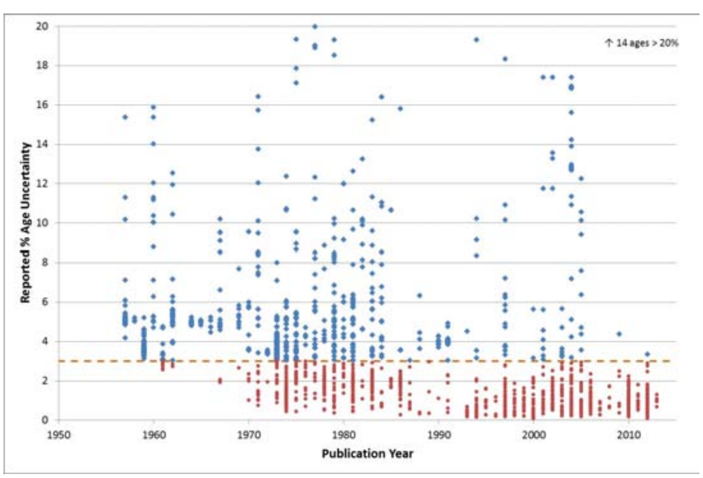

Figure 4. Age uncertainties in percent illustrating the effect of filtering data to better than 3% precision. The decline in the number of ages around 1990 is related to the transition from mainly Rb-Sr and K-Ar ages to mainly U-Pb and Ar/Ar ages (see also Figure 3).

The 3% first-pass filter leaves a database of 1286 ages consisting of pre-1990 (mainly Rb-Sr and K-Ar) ages and post-1990 (mainly U-Pb and $^{40}Ar/^{39}Ar$) ages (Figs. 3, 4). The geographic distribution of the 1074 georeferenced sample locations is shown in Figure 5. Additional filtering, mainly based on examination of the raw data behind individual age determinations, and the methods and criteria for doing so will be discussed in detail in an upcoming publication. For the purposes of this report, quality control filtering is set at 3% precision. Notably, and perhaps regrettably, culled from the database by this criterion are the dating traverses across the Brevard fault zone mentioned above. In addition, this exclusion criterion exacerbates the dearth of data from southern Inner Piedmont and Carolinia, where virtually all remaining ages are from large Devonian and Carboniferous-Permian plutonic bodies (Fig. 5).

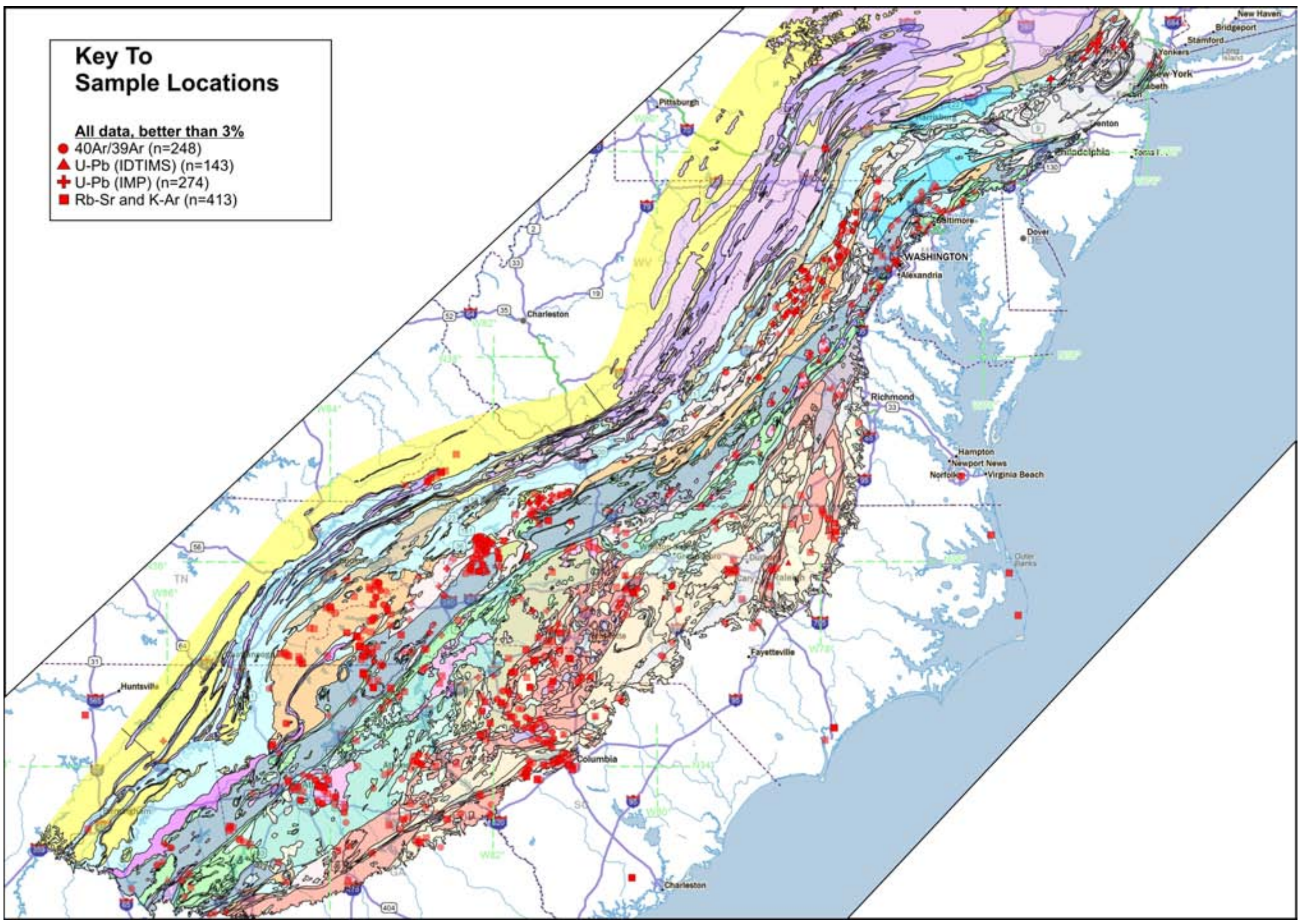

Figure 5. Geographic distribution of SoAG records with better than 3% age precision.

It is now known that some southern Appalachian Rb-Sr and K-Ar ages, whole-rock ages in particular, are susceptible to open-system behavior (Samson, 2001; Wortman et al., 2000). This is reflected in the decline in the number of these ages in the late 1980's and the 1990's upturn in the number of $^{40}Ar/^{39}Ar$ and U-Pb ages (Fig. 3). Although dominant in the 1970's and 1980's, Rb-Sr and K-Ar ages are virtually absent from the more recent southern Appalachian literature (Fig. 3). Some, pre-early 1990s Rb-Sr and K-Ar ages have proven accurate when reproduced by U-Pb methods; evaluation of the possibility for extracting accurate age information from the Rb-Sr and K-Ar components of the database will be discussed in an upcoming publication. It should be noted, however, that these older methods (gravimetric, K-Ar and Rb-Sr, large multi-grain zircon U-Pb analyses, etc.) were crucial in developing and testing earlier generations of tectonic models. These data and the ideas they fostered are an important, although now largely superseded, part of the history of southern Appalachian geology.

U-PB AND ^{40}AR/^{39}AR DATABASE

The 3% first-pass filter leaves largely intact most of the U-Pb and ^{40}Ar/^{39}Ar entries (n=1063; Fig. 6) published after 1990. Roughly half of these ages are from rocks related to the Mesoproterozoic assembly of Rodinia, the Neoproterozoic rifting of that supercontinent, and the Neoproterozoic history of Carolinia (Fig. 6). The geographic distribution of samples related to these three components of the pre-Appalachian history is shown in Figure 7.

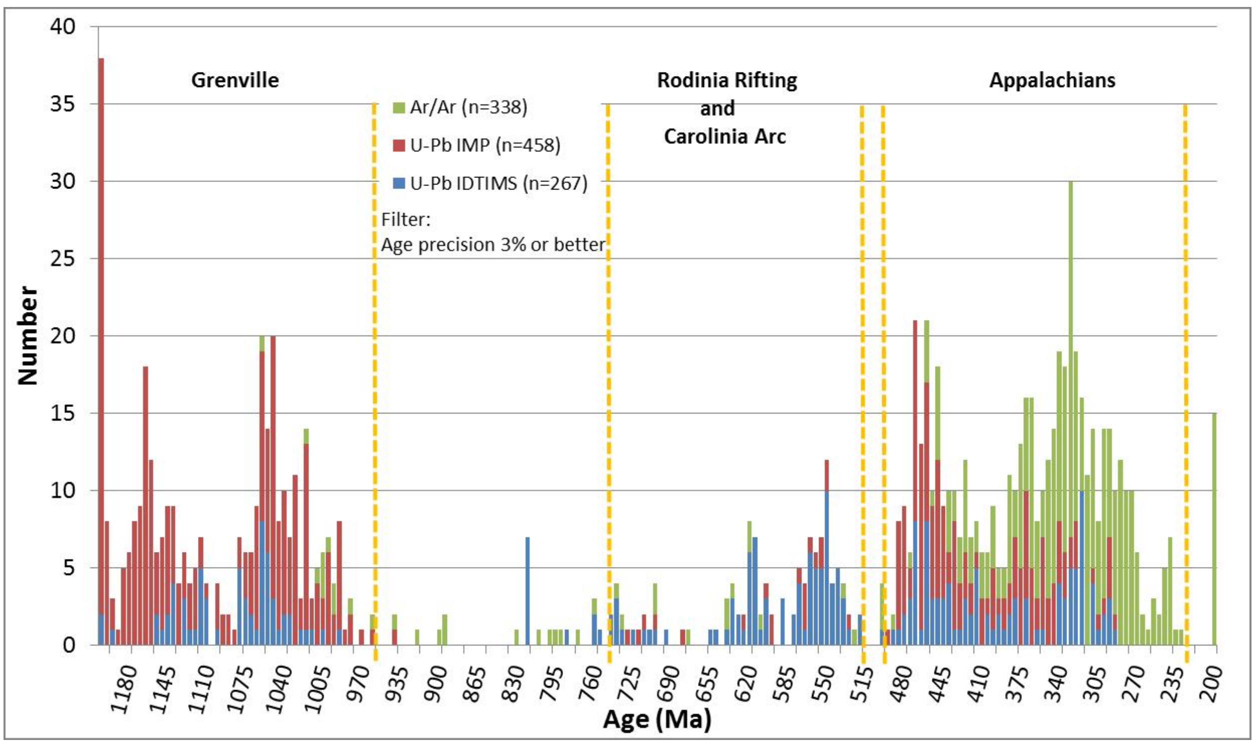

Figure 6. Age distribution of numbers of records in SoAG database with precision better than 3%.

The Appalachian history as recorded by U-Pb and ^{40}Ar/^{39}Ar ages consists of 540 records spanning the range of about 500-250 Ma (Fig. 8). Hatcher (2010) summarizes the Paleozoic history of Appalachian mountain building events in terms of three phases; the Ordovician Taconian orogeny, Devonian to Mississippian Acadian and Neoacadian orogenies, and the Pennsylvanian to Permian Alleghanian orogeny. A prominent Silurian event in the northern Appalachians (Dunning et al., 1990; Hibbard et al., 2010) may be tectonostratigraphically unrelated, but overlaps temporally with the southern Appalachian Cherokee orogeny (Hibbard et al., 2012).

The peak in the number of Ordovician ages in the SoAG database (not necessarily the peak of Taconian orogenesis) occurs at about 460 Ma and is well represented by U-Pb ages, but much less so by ^{40}Ar/^{39}Ar ages (Figs. 8, 9). As a result, there are few constraints on the timing of regional-scale cooling following Taconian tectonothermal events. Silurian ages

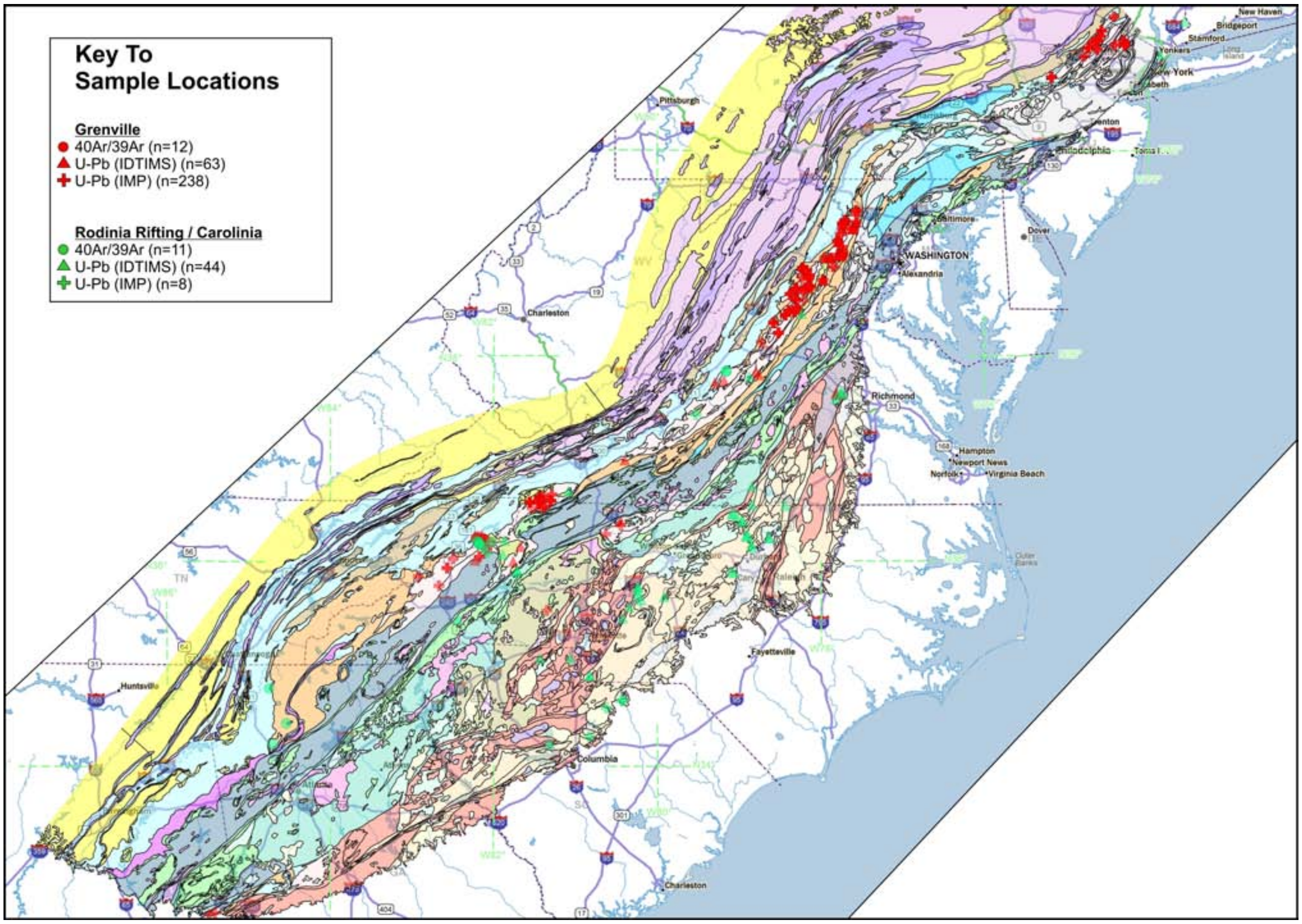

Figure 7. Geographic distribution of pre-Appalachian rock and mineral samples with ages 1200-950 Ma and 740-515 Ma (circles); these correspond broadly to the timing of the Grenville orogeny and Rodinia rifting events, respectively. Also plotted are Neoproterozoic ages related to the Gondwanan history of the Carolina zone (crosses).

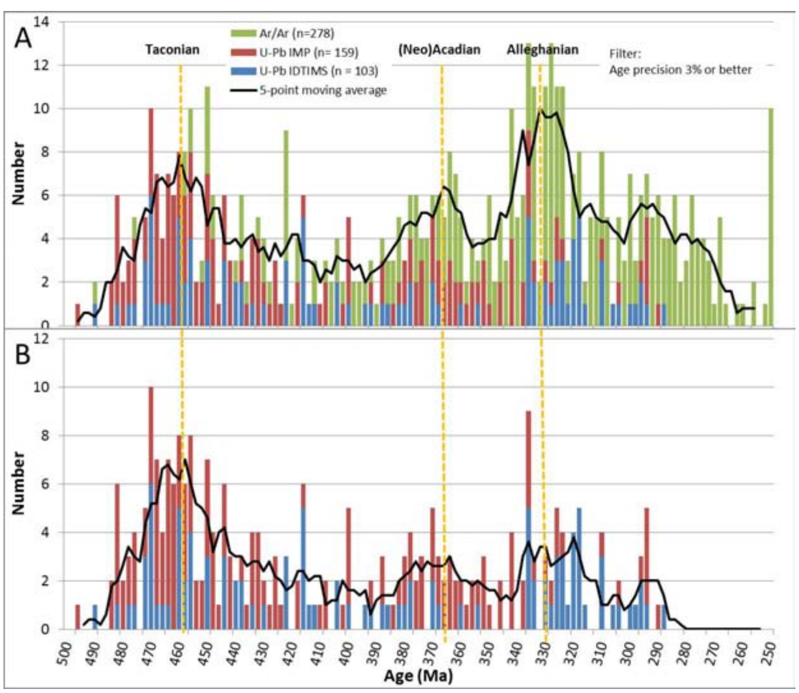

Figure 8. U-Pb and Ar/Ar data for all Appalachian records (500-250 Ma) in the SoAG database, filtered to 3% precision. A) The data define peaks in numbers of age determinations – which is not necessarily the same as the peaks in tectonothermal activity – in the Ordovician, late Devonian, and middle Carboniferous. Black line is 5-point moving average which serves to smooth the data. B) Same as (A), but U-Pb data only. Note that Ordovician ages are well represented in the U-Pb database, but less so for Devonian and Carboniferous ages.

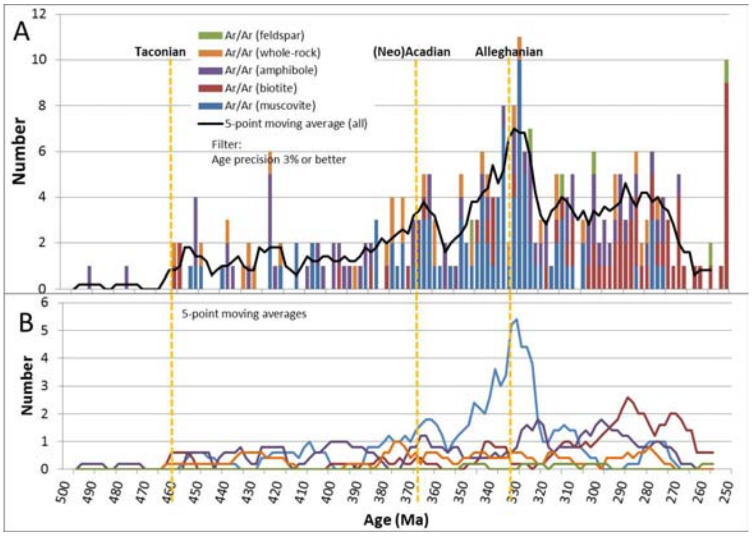

Figure 9. All Ar/Ar data in SoAG database, filtered to better than 3% precision. Positions of orange dashed lines are same as in Figure 7 based on the peaks of combined U-Pb and Ar/Ar. A) Histogram of all data sorted by sample type. Five-point moving average (black line) is used to smooth the data and better illustrate the peaks in the number of ages in database – which is not necessarily the same as the peaks in tectonothermal activity. B) Five-point moving average of each mineral or sample type. Note that, on the whole, biotite ages (red line) are shifted to much younger ages than the peak of muscovite ages (blue line). Ordovician ages are poorly represented; muscovite and amphibole ages record small Devonian peaks.

do not define a discrete peak in the U-Pb and $^{40}Ar/^{39}Ar$ database, but may be manifest as an elongation of the tail from the Ordovician peak (Fig. 8). Not surprisingly, rock samples that yielded Ordovician ages are concentrated along the western flank of the orogen (Fig. 10).

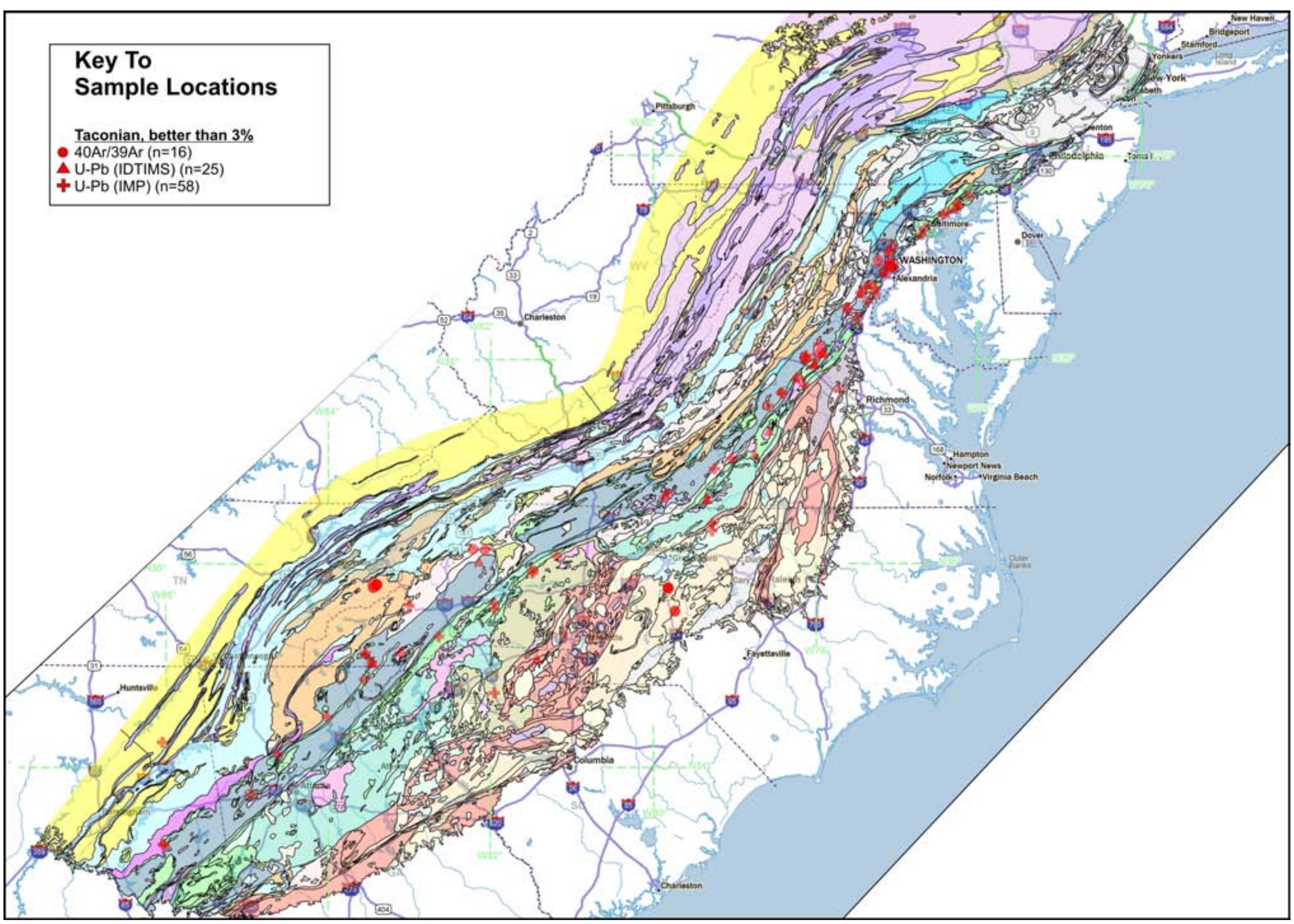

Figure 10. Geographic distribution of rock and mineral samples with ages 500-430 Ma, which corresponds broadly to the timing of Taconian orogenesis.

Stratigraphic evidence (e.g., Ettensohn, 2004) suggests up to four distinct pulses of sedimentation related to Devonian to early Mississippian tectonism in the southern Appalachians. Hibbard et al. (2010) considered the first two of these pulses, the middle to late Devonian phases, a response to classic Acadian tectonism in the New England sector of the Appalachians, and the latter two pulses were considered part of the orogen-wide, late Devonian to early Mississippian Famennian (or Neoacadian) orogeny, which they more closely link to Alleghanian events. The record of Devonian to early Carboniferous U-Pb and $^{40}Ar/^{39}Ar$ ages in the SoAG database shows a small but distinct peak between about 390-360 Ma and fails to resolve any gap between latest Devonian to earliest Carboniferous (Famennian/Neoacadian) and the middle Carboniferous peak of Alleghanian ages (Fig. 8). It is unclear why the high temperature geochronologic and thermochronologic record of the southern Appalachians is unable to resolve Famennian events from Alleghanian. Possible explanations include sampling bias due to the relatively few analyses and sparse data coverage (Fig. 11), blurring of the events by partial resetting during the Alleghanian, and the possibility that the high-temperature effects of these two events overlapped in time whereas their sedimentary manifestations were separated by a distinct unconformity. An obvious complication to resolving the timing of (Neo)Acadian events is the extremely sparse data coverage, particularly in the southern Inner Piedmont (Fig. 11), a vast tract of the middle crust that formed the high-grade core of the (Neo)Acadian orogeny (Hatcher, 2010; Merschat et al., 2012). One of the key lines of evidence for the timing of these events comes from metamorphic zircon rims on igneous and detrital zircon cores (Bream, 2002; 2003; Bream et al., 2001; Carrigan et al., 2001; Merschat, 2009; Merschat et al., 2010; 2012). These metamorphic zircon rim ages, however, are either not yet published or are presented as non-discrete age interpretations (e.g., age interpretation given as either an approximation or a range of ages), which cannot be parsed into the framework of the SoAG database.

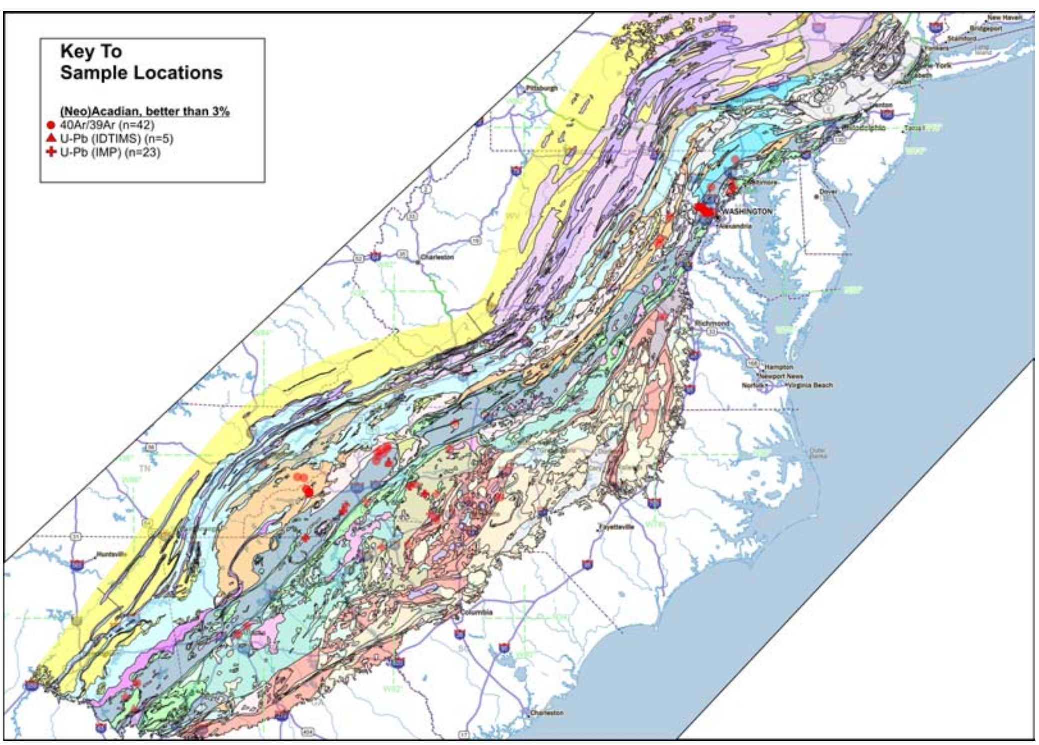

Figure 11. Geographic distribution of rock and mineral samples with ages 390-350 Ma, which corresponds broadly to the timing of Acadian and Neoacadian orogenesis.

The SoAG database contains 238 U-Pb and $^{40}Ar/^{39}Ar$ records in the range 340-260 Ma, which broadly corresponds to the timing of the Alleghanian orogeny (Figs. 8, 12). Alleghanian thermal events are well represented by $^{40}Ar/^{39}Ar$ cooling ages (Fig. 9). The peak of muscovite cooling ages slightly post-dates the peak defined by all ages (Fig. 8), by about 3-5 million years, not unexpected considering that these are cooling ages. More surprising is the concentration of biotite, and to a lesser extent amphibole, ages between about 300-260 Ma.

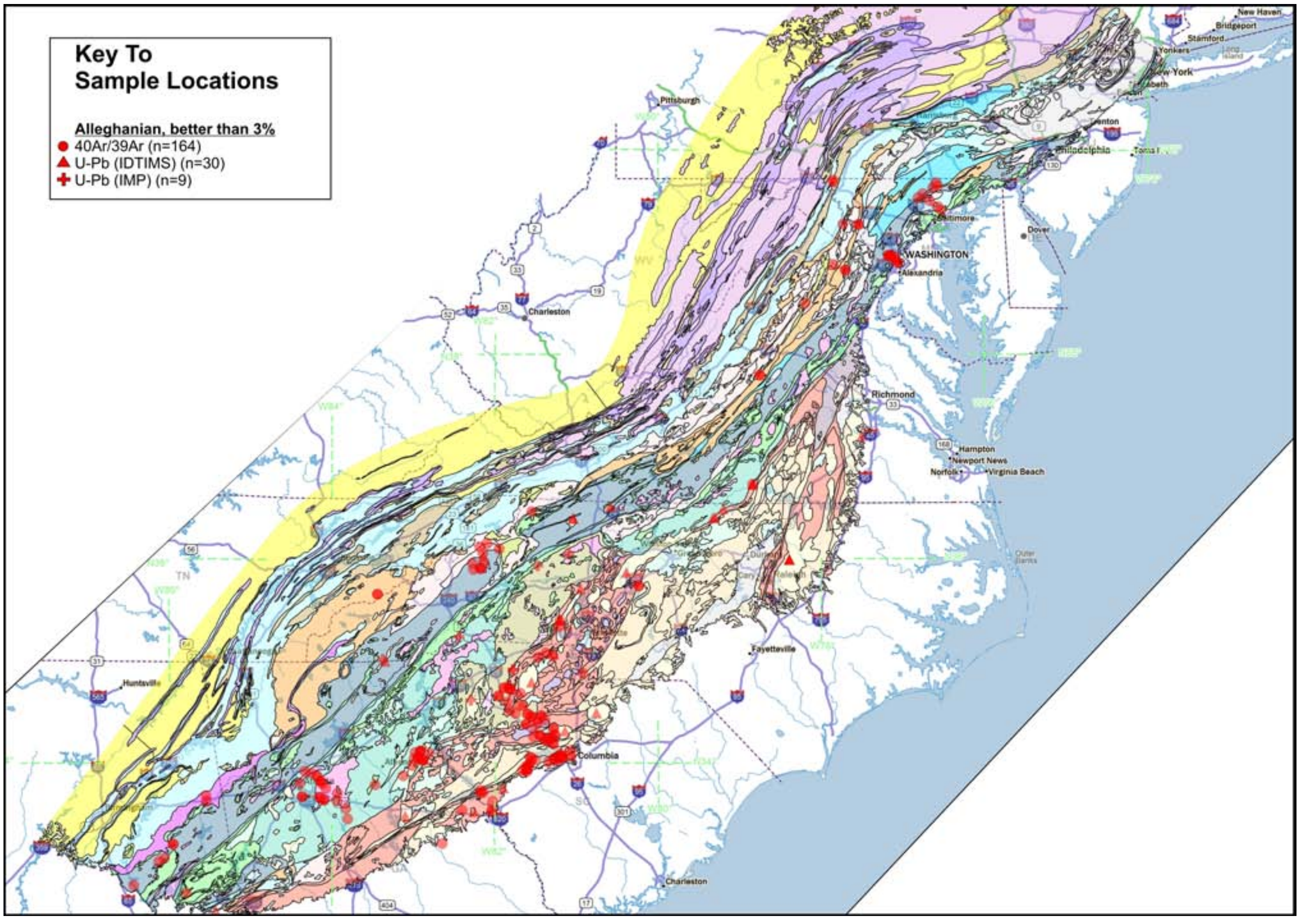

Figure 12. Geographic distribution of rock and mineral samples with ages 340-260 Ma, which corresponds broadly to the timing of Alleghanian orogenesis.

Forty-three of the Carboniferous U-Pb zircon or monazite ages are from Alleghanian granites. The geo-referenced lithotectonic base map of Hibbard et al. (2006) makes it easy to capture data on the surface area of these plutons for a rough evaluation of volume of plutonism (using present-day surface area as a proxy for volume) through time. To whatever extent it is valid to assume a relationship between present-day surface area and original volume of plutonism, the data do seem to suggest a peak in plutonism at around 325 Ma, with the largest plutonic complexes (Petersburg, Churchland, and Rollesville) forming at about this time or later (Fig. 13). Although the coincidence of these ages with the timing of Carboniferous glaciation (e.g., Fielding et al., 2008) cannot be ignored, the database at present seems inadequately resolved to draw any inferences about potential linkages – at least based on the high-temperature geochronologic and thermochronologic record – between southern Appalachian tectonics and Carboniferous climate change.

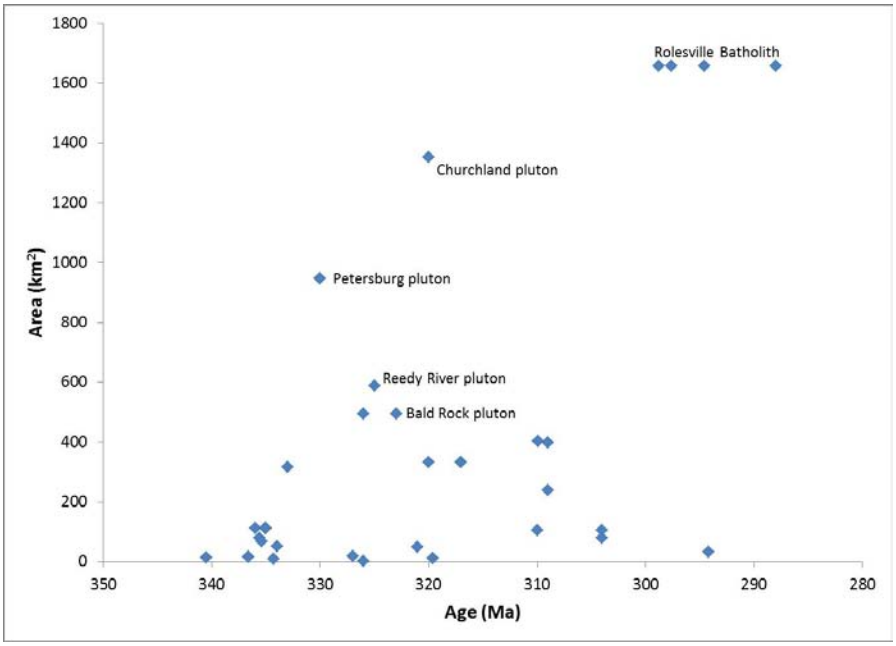

Figure 13. Area of Alleghanian granites vs. age. The five largest dated bodies are labeled.

SUMMARY AND CONCLUSIONS

Six decades after Rodgers (1952) first compilation of all available radioisotope ages from rocks of the Appalachians, both the number and precision of radioisotope ages have increased steadily. The southern Appalachian geochronology (SoAG) database represents an attempt to update Rodgers' age compilation and allows for evaluation of all existing age constraints for testing tectonic models of southern Appalachian orogenesis. The database shows peaks in the numbers of ages, which should not be misconstrued as the peak of orogenic events, that correspond to the assembly of Rodinia (ca. 1200-950 Ma), the rifting of that supercontinent (ca. 740-515 Ma), Neoproterozoic arc-related processes in Carolinia (ca. 650-520 Ma), and the Appalachian mountain building events of the Taconian (ca. 500-430 Ma), Acadian (ca. 390-350 Ma), and Alleghanian (ca. 340-260 Ma) orogenies. Evaluation of extant records fails to resolve a distinction between Famennian (Neoacadian) and Alleghanian thermal histories, but shows a clear separation between classic Acadian middle- to late Devonian ages and Famennian/Alleghanian late Devonian to middle Carboniferous ages.

The geographic distribution of ages in the SoAG database highlights important gaps in data coverage, most notably the southern Inner Piedmont. This region of high-grade gneisses and migmatites formed the high-grade core of the (Neo)Acadian orogen (Merschat et al., 2012) and would appear to be fertile ground for advancing our understanding of the timing of southern Appalachian tectonic events.

Future directions for database compilation efforts include expanding coverage to the entire Appalachian orogen, adding detrital zircon data, creating a web-based interface to search, filter, and display data. The web interface will also permit the research community to input data and edit the database. Until such an interface can be constructed, the author will gladly share the latest version of the database upon request.

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GOLD AND BASE METAL MINERALIZATION IN THE CAROLINA TERRANE OF CENTRAL NORTH CAROLINA

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INTRODUCTION

Gold and base metal mineralization is related to geologic setting (including styles of intrusive activity and tectonic events which tap sources of gold-rich hydrothermal fluids), structural and lithologic controls of fluid flow, and chemical and physical traps to capture metals in economic concentrations. The deposits themselves are also an important tool in understanding the geologic history of a region through analysis of their character and genesis, assisted by detailed studies required for exploration and development. Currently, the most cited classification of gold and associated base metal deposits generally divides them into epithermal, porphyry, and orogenic ore systems (Fig. 1). These models are related to the timing, mode of formation, and associations of mineralization within active tectonic regions (Fig. 2). The model types presented in Figure 1 should be considered end members of a spectrum of metal deposits as they relate to sedimentary, metamorphic, igneous and structural processes.

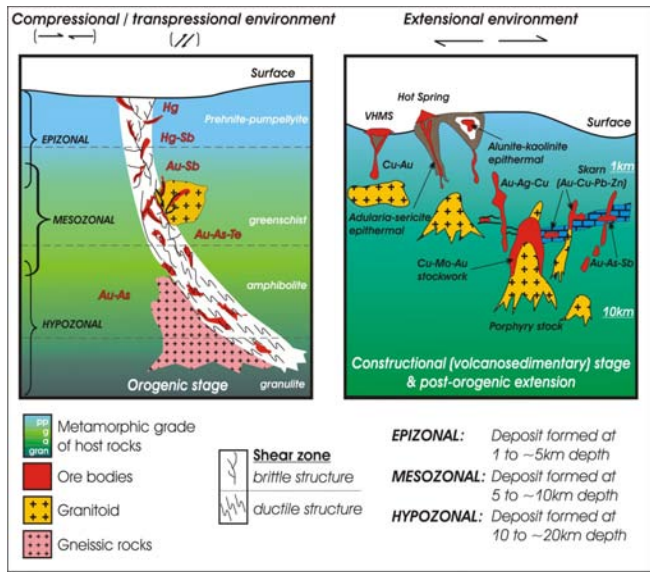

Figure 1. Generalized environments of gold deposition related to extensional and compressional geologic environments (Goldfarb, 2013).

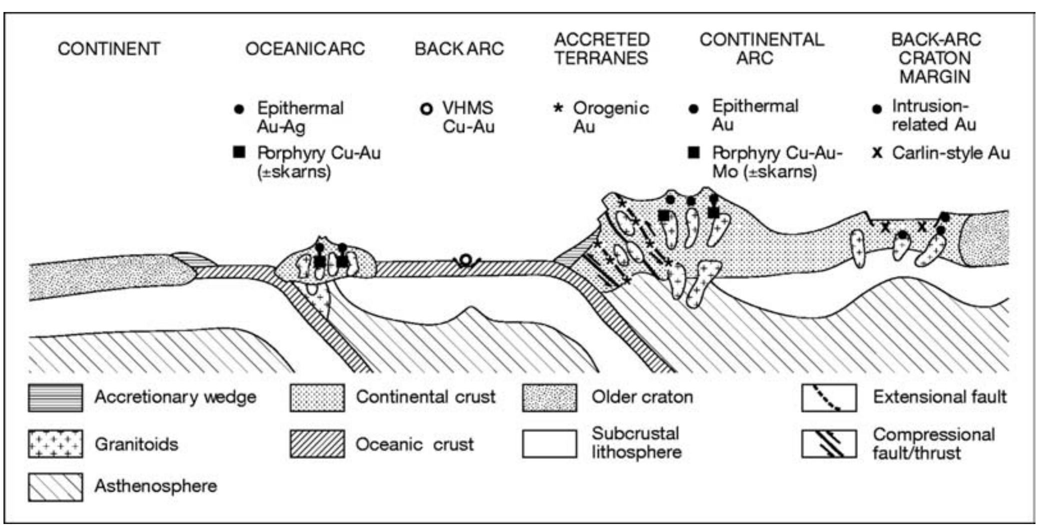

Figure 2. Tectonic setting of gold and base metal mineralization within extensional and convergent settings(Goldfarb, 2001).

Understanding the ore processes and models assist in categorizing ore deposits within their geologic framework and assist in exploration and encouraging stakeholder's interest. The Carolina Terrane is a diverse geologic region which can host multiple deposit types. For many known deposits, the only data is historic and predates current understanding of the geologic setting. As illustrated in Figure 1, current ore models are based on the concept that there are deposits associated with extensional tectonics (even within a compressional event) and those associated with compressional tectonics (even if early stage within an arc setting).

Orogenic gold deposits are a deposit type simple in concept, but difficult in detail. These deposits are related to lithospheric scale thermal processes and regions of high fluid flow formed during compressional tectonic events. Localized high-stain discontinuities, such as faults and shear zones, focus large-scale fluid flow and represent a primary exploration guide to associated ore deposits. Changing pressure-temperature conditions through multiple periods of fluid flow generated during faulting may interact with rheologically or compositionally favorable host rocks to form large deposits. Orogenic gold deposits are typically one of the most important type gold resources in mines throughout the world, primarily the greenstone belts in Precambrian shield areas.

Epithermal and associated porphyry-style intrusive related hydrothermal systems are associated with extensional events. They are related to high primary and secondary fluid flow associated with intrusive systems often found in areas of recent volcanic activity. They are formed at higher levels in the crust and therefore susceptible to erosion; however many Carolina Terrane mineral deposits have the textural and volcanic association of epithermal processes, but have a strong structural component too (LaPoint and others, 2012).

Recently, Hornsky and others (2012) link these models to a unifying theory related to accretionary terranes. They state that:

> "Accretionary orogens are the sites of long-lived convergent margin tectonics, both compressional and extensional. They are also the hosts to the majority of the world's important gold deposits. A very diverse range of deposit types occurs within accretionary orogens, commonly in close proximity in space and time to each other. These include porphyry and associated high-sulfidation Au-Cu-Ag deposits, classic low-sulfidation Au-Ag deposits, low-sulfidation Au deposits centred on alkalic intrusive complexes, Carlin-type Au deposits, Au-rich VHMS deposits, orogenic Au deposits, intrusion-related Au deposits and iron oxide Cu-Au deposits."
>
> "Various lines of evidence lead to the proposal that the underlying key generic factor controlling accretionary orogen gold metallogeny is regional-scale, long-term, pre- and syn-subduction heterogeneous fertilisation of the lithospheric mantle that becomes a source of mineralisation-associated arc magma or hydrothermal fluid components. This process provides a gold-enriched reservoir that can be accessed later in a diverse range of tectonomagmatic settings. Based on this concept, a unified model is proposed in which the formation of a major gold deposit of any type requires the conjunction in time and space of three essential factors: a fertile upper-mantle source region; a favourable transient remobilisation event; and favourable lithospheric-scale plumbing structure.

This framework provides the basis for a practical regional-scale targeting methodology that is applicable to data-poor regions. (Hornsky and others, 2012)."

Volcanogenetic massive sulfide (VMS) deposits form as minerals are deposited by hydrothermal fluids vented directly into the extensional marine environment (black and white smokers) or permeating shallow seafloor sediments. Their associated alteration and mineralization can form some of the world's richest base metal and gold deposits. Geologically, the exhalative units can provide marker horizons for stratigraphic and tectonic studies.

Historically, many gold deposits in the Carolina Terrane have been descriptively referred to as disseminated gold-pyrite deposits as opposed to the more classic quartz vein mines such as the Iola mine and the Reed gold mine (Day 2 of this field conference). The rock alteration is predominantly argillic, silicic and propylitic, similar to acid-sulphate systems of hot spring or epithermal gold systems, but also reflective of alteration in active deformation zones with high fluid flow. Based on historic production and results of recent exploration, they represent the most economically significant gold targets in the Carolina Terrane.

Quartz veins have been and remain the easiest target for prospectors and to explore the primary source of much of the early production in a variety of geologic environments. Most are not well described or explored and they are not discussed in detail in this paper. The Reed gold mine is discussed as Day two of the trip. The Iola mine was the highest grade gold producer in North Carolina (Fig. 3) and the veins seem related to structural zones and thus may fit the Orogenic gold model.

Metal deposits related to igneous intrusive events are discussed in two other papers in this guidebook (Moye and Rapprecht and others) and are also not discussed further in this paper.

The Carolina Terrane fits the definition by Hornsby and others (2012) of accretionary terrane with periods of both extensional and compressional events in a variety of tectonic settings. Recognizing and defining the importance of various geologic processes creates considerable debate by various geologists in the attempt to fit what they describe and interpret to the place into the perceived correct model. An example is intense cherty silification such as the Brewer Mine, South Carolina, which has been interpreted from exhalative chert to silicified rhyolite to silicification along structural zones depending on the understanding of the geologist. This variation in the interpretation continues to sparked considerable debate on the origin of many deposits (LaPoint and Maddry, 2012; Moye, 2012).

Ore deposits and their associated hydrothermal alteration products represent a significant insight into flow paths and the composition of igneous related, metamorphic or basinal fluids. They can provide key stratigraphic markers in the case of the exhalative units associated with volcanogenetic massive sulfide deposits (VMS) help to identify major crustal structures and intrusive timing and type. Ore deposit types are related to specific tectonic settings and provide insights into the geologic evolution of host lithologic associations and host terranes. (Fig. 2)

Exploration is business driven and therefore must be pragmatic. The geologist should focus on field relationships of mineralization in order to maximize the most likely drill targets that would lead to the discovery of a mineable ore body. Early stage projects in particular must sell the potential to Investors and management. It helps to demonstrate that metal deposits of the Carolina Terrane fit into the most economically viable deposit types. The region has excellent potential for new economic discoveries when and where economic and environmental conditions permit exploration and development. In the Carolinas, most known base and precious metal mineral deposits are significantly underexplored relative to modern exploration methods, geologic models and drilling. As with American's first gold rush in 1820's that developed the banking business in Charlotte, new mines can provide positive economic development with proper mine planning and reclamation and reuse of the land. Mines are great windows into understanding many Earth processes and they expose neat rocks.

ACKNOWLEDGMENTS

John Maddry reviewed this paper and offered excellent comments. Jen Spohn drafted Figure 3.

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS

One of the distinctive styles of mineralization present in the Albemarle Group of the Carolina Terrane in central North Carolina is volcanogenic massive sulfide deposits (VMS). Most known occurrences are clustered along the western side of the Carolina Terrane, and include deposits in the Cid and Gold Hill districts (Figs. 3 and 4).

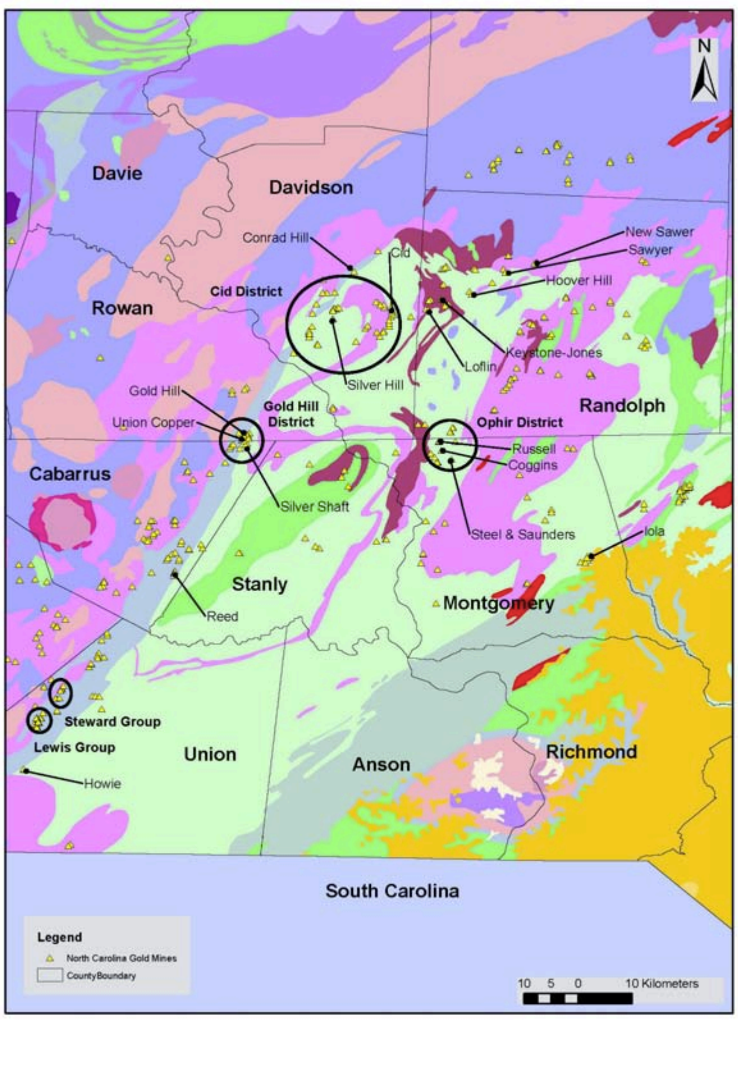

Figure 3. Gold and base metal deposits of the central Carolina Terrane (produced by Jen Spohn from the USGS Mineral Resource database online).

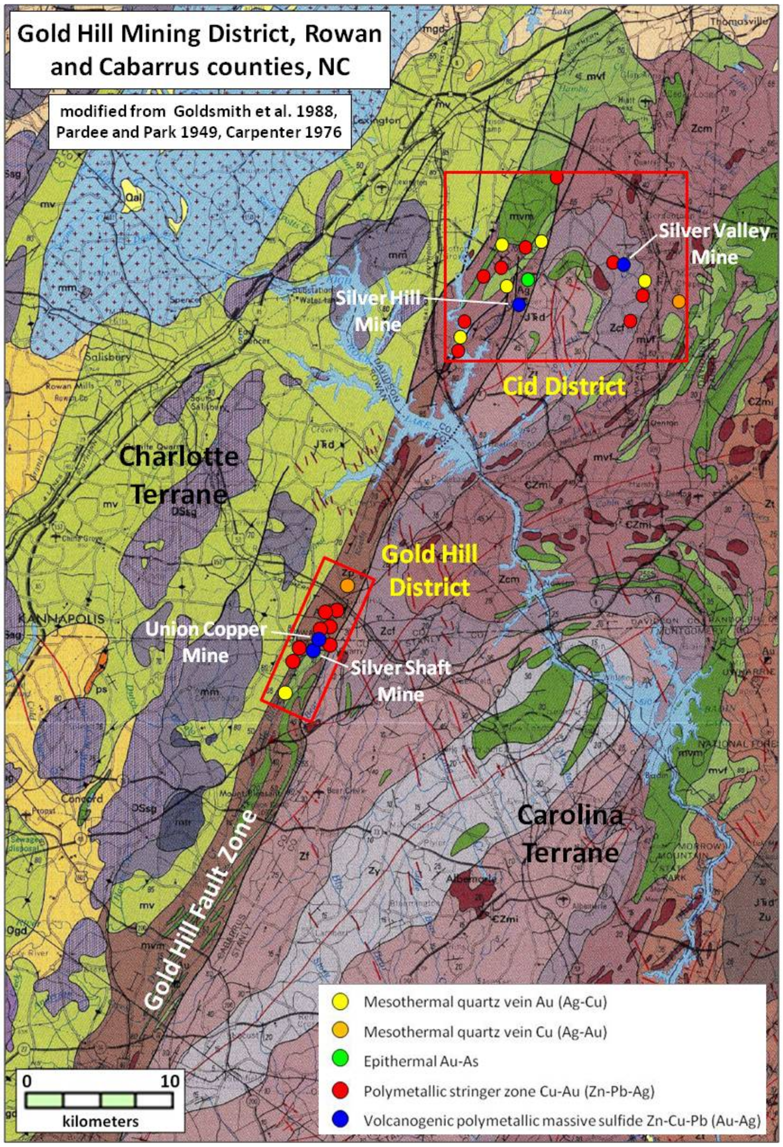

Figure 4. Metal Deposits of the Cid and Gold Hill VMS districts.

Feiss (1982) noted that these deposits are conformable with their host strata and often occur as complex, anastomosing lenses that pinch and swell along strike and down-dip. Primary sulfide minerals include pyrite, sphalerite, galena, and chalcopyrite; with accessory minerals that may include pyrrhotite, magnetite, pentlandite, tetrahedrite, arsenopyrite, and bismuthinite. Alteration gangue minerals include quartz, chlorite, talc, biotite, sericite, siderite, ankerite, and calcite. Deposits may become lozenge shaped with deformation, and may pitch steeply in the noses of meso-scale folds or within ductile shear zones (Feiss 1982). Ore and gangue minerals are typically strongly recrystallized with loss of primary textures, and local-scale remobilization as veins into discordant structures is common.

The VMS deposits of the Cid District in Davidson County appear to be hosted by the upper part of the Cid Formation and are spatially and probably genetically associated with the period of felsic-dominated bimodal magmatism that formed the Flat Swamp Member. Typical polymetallic massive sulfide deposits of the Cid District include Silver Hill and Silver Valley. The Union Copper-Silver

Shaft deposits of the Gold Hill District in Rowan and Cabarrus counties lie within the Gold Hill Fault Zone and their position within the stratigraphy of the Albemarle Group is less certain (Fig. 3).

Polymetallic deposits in the districts with an epigenetic character represent footwall alteration in the plumbing of VMS hydrothermal systems. These are often characterized by carbonate-chlorite and sericite alteration, silicification, and quartz veining, and are typically Cu-Au rich with sulfide phases dominated by pyrite and chalcopyrite. These deposits include the Conrad Hill, Cid, and Emmons deposits in the Cid District, and possibly the Cu-Au deposits of the Gold Hill Group of mines and the Whitney-Isenhour zone in the Gold Hill District.

Both the Silver Hill and Gold Hill districts have experienced multiple phases of exploration since the VMS model was developed in the 1960s; however, there has been relatively little drilling when compared to other VMS districts, in particular, the Maritimes of eastern Canada. This is largely due to a constant turn over in exploration programs and geologists, poor exposures, slow land acquisition, lack of supporting geologic, geophysical and geochemical data by government institutions, and loss of historic data and core in the absence of a government program of data retention.

Cid District

The Silver Hill mine, located 15 kilometers southeast of Lexington, NC, was discovered in 1838. The mine was worked continuously until 1850 when it encountered metallurgical problems. Over this time, the mine reached a depth of 600 feet (Nitze and Wilkens, 1897). The mine was reopened during the civil war as an alternate source of lead, and was worked until 1912 (Bell, Carpenter and Feiss, 1980). Since then, various attempts at reopening the mine have failed. The property has been explored by Tennessee Copper Company, New Jersey Zinc, Northfield Mines Inc., Phelps Dodge Corporation and Cyprus Mines.

The Silver Hill mine workings consist of three shafts, two vertical and one inclined, and multiple drifts. The workings follow two parallel veins striking NE and dipping 45-90 degrees west from the horizontal, each up to 15 feet wide. It is reported that the original workings reached a depth of 600 feet, where the combination of sulfides in the ore body became such that processing was not possible at the time. Records indicate that the ore from surface to 200 feet depth was mostly argentiferous galena, but ore from 200-600 feet depth became increasingly rich in pyrite, chalcopyrite and sphalerite, and became difficult to treat. Many concentrating processes were tried, but later analysis of the tailings indicated there was still poor metal recovery (Nitze and Wilkens, 1897).

After the closure of the mine, the most extensive development work at Silver Hill was carried out prior to WWII by Tennessee Copper Company. Sixteen diamond drill holes, oriented to the southeast, were drilled to test the extension of the northeast trending ore body and a small amount of underground work was carried out and some ore was partially developed and stockpiled on surface but never processed until a private company developed a small mill at Conrad hill in the 1980's and trucked the stockpile for processing.

Subsequent to the work by Tennessee Copper Company, New Jersey Zinc drilled 19 diamond drills holes. All drill holes were again drilled to the southeast, and for the most part duplicated the work of Tennessee Copper Company. Only two diamond drill holes are on record as being drilled by Northfield Mines Inc. and the timing of these with respect to the other exploration work is not clear. Reports indicate that Phelps Dodge Corporation also drilled 2 diamond drill holes, although no records have been found to indicate if this was the extent of the exploration program (Phifer, 1979). Results of the above outlined exploration of the Silver Hill Mine defined a block of ore between the 500 and 1400 foot levels that has an estimated grade of 13% Zn, 9% Pb, 1.25 oz/ton Ag and 0.3 oz/ton Au. This block of ore has reportedly been explored by several drifts and numerous diamond drill holes. It is also reported that there is additional ore of equal or better grade above the 500 foot level (Phifer, 1979). In 1973 Cyprus Mines carried out a soil sampling program, conducted an induced polarization and an electromagnetic geophysical survey and drilled three diamond drill holes. The soil program indicated a large zinc soil anomaly centered on the historical workings, and two smaller anomalies 300m due south of the main shaft (Lucas 2013).

In 2011 Revolution conducted diamond core drilling on the Silver Hill property. Eight drill holes were completed during this time for a total of 2,485 meters. Initial drilling targeted the historic mine workings and the inferred extension of the two main ore zones, based on the historical mine data available. The eight drill holes were drilled at various locations on the property. Drill holes were oriented at azimuths of 105-120 degrees with dips from -70 to -90 degrees. Drilling was met with varying success and failed to fully define the orientation or extent of the ore zone on the property. Exploration efforts, both historical and by Revolution, indicates that further drilling is required (Lucas, 2013).

The main lithological units at Silver Hill are mafic flows, volcanoclastic rocks and metasedimentary rocks. Quartz veining is prominent on the property, but distal from the main ore body. Locally the mafic flows and volcanoclastic rocks are highly sheared and can be difficult to differentiate. The metasedimentary rocks are mostly argillite with rare greywacke intervals. Alteration is confined to strong pervasive chlorite alteration in the argillites, and weak pervasive chlorite in the flows and volcanoclastic rocks. Proximal to the main ore zone there is some bleaching and silicification of the argillite, but dies out within meters from the ore zone. The ore body is reported to strike 200/45 on average, with the dip ranging from 45 to 90 degrees from horizontal. Mineralization at Silver Hill occurs in lenses of 40-50 percent sphalerite, galena, pyrite, and chalcopyrite, hosted in both argillites and tuffs. Mineralization is not confined to the massive sulfide units as there is a halo of disseminated sulfides for several meters around the main ore body. Locally the argillites will contain bands of pyrite, often containing anomalous gold (Bell, Carpenter and Feiss, 1980).

The Silver Valley Mine, also known as the Spring Valley Mine, is located in eastern Davidson County, NC. Mine operations began under the Silver Valley Mining Co. in the mid 1800's, and operated until 1893. There was some renewed interest in 1896 but nothing long term (Nitze and Wilkens, 1897). There are no records indicating that the mine underwent any sustained activity through most of the 1900's. In the 1980's Phelps Dodge and Texasgulf explored the property and region. In 1993, BHP leased the property and conducted a two year exploration program. The property was then purchased by Carolina Mineral Resources.

The 1893 shut down of the Silver Valley Mine was caused by the closing of the nearby smelter that had been processing the ore. The smelter closure was due to a lack of copper ore for fluxing. Many attempts were made to treat the ore, but none were successful (Nitze and Wilkens, 1897). During the height of operations, the mine reached a maximum depth of 120 feet, with the ore beginning at 60 feet. The mine infrastructure includes two shafts (one vertical and one inclined), multiple drifts and two surface pits. These workings were designed to chase the ore body that strikes NE and dips 45 to 90 degrees west from the horizontal. The ore consisted of sphalerite, galena, pyrite, chalcopyrite with some native gold and silver. Malachite, chalcocite and calcite are also locally present in the vein. The reported average grade that was sent to the smelter was 28% Zn, 12% Pb, 0.5% Cu, 21.0 oz/ton Ag, 0.06 oz/ton Au (Nitze and Wilkens, 1897). In 1896 activity on the property resumed and focused on gold in the creek south of the main mine site. A placer operation was set up with a washer, rifled sluices, amalgamating tables and a rocker, and was able to process 40-50 tons per day. Work was also done on an exposed auriferous quartz vein in the same creek. A 40 foot shaft was sunk on this vein. The vein was pyrite rich with some free gold (Nitze and Wilkens, 1897). In 1949, a minimum of seven diamond drill holes were completed by an unknown company. Evidence for this exploration work comes from drill casings that were located in the field by Revolution personnel. Between 1993 and 1994, BHP conducted an extensive exploration program on the Silver Valley Mine. During their tenure, 12 diamond drill holes were completed based on a ground magnetic geophysical survey and an IP geophysical survey. Results of the drill program were met with varying degrees of success. Both geophysical surveys outlined strong anomalies that were partially tested by the drill program (Lucas, 2013).

Diamond drilling on the Silver Valley property was carried out in 2011 by Revolution. Five drill holes were completed during this time for a total of 923 meters. Initial drilling targeted the historic mine workings and the inferred extension of the two main ore zones, based on the historical mine data available, and the work of BHP in 1993-1994. The five drill holes were drilled at various locations on the property. Drill holes were oriented at azimuths of 90-130 degrees with dips from -45 to -90 degrees (Lucas, 2013).

The main lithological units reported at Silver Valley are similar to Silver Hill and consist of dacitic volcanic rocks, tuffs, metasedimentary rocks and variations of each. The dacites range from phenocryst-rich to fragment-rich. The metasedimentary rocks are typically argillites with rare sandstone intervals. The tuffaceous rock intervals are fine grained with a distinct volcanic texture, and are spatially associated with the argillic units. Alteration on the property is strongest within the metasedimentary rocks, and is mainly silica-sericite. The dacitic rocks are weakly altered with chlorite and biotite. Mineralization at Silver Valley occurs in lenses of sphalerite, galena, pyrite, chalcopyrite, hosted in both argillites and tuffs. Malachite and chalcocite are locally present in quartz veins within the ore body. Pyrite is the most abundant of the sulfides on the property, occurring within the ore zone as well as along foliation planes in the adjacent units. The ore veins are described as being locally brecciated mylonitized and healed with sulfide minerals, sericite and silica (Bell, Carpenter and Feiss, 1980).

Gold Hill District

The Union Copper-Silver Shaft VMS deposits are part of the Gold Hill mining district (Fig. 4), a NNE-trending cluster of historic gold and base metal sulfide mines and prospects within an area measuring 29 x 13 kilometers (Laney 1910). The district lies across the Rowan-Cabarrus County line and is roughly centered on the town of Gold Hill. The shafts of the Union Copper Mine are aligned across the county boundary, and the Silver Shaft Mine is located about a half kilometer to the southwest in Cabarrus County.

The Union Copper Mine is located on the Rowan-Cabarrus county line, 2.3 kilometers southwest of the town of Gold Hill. The deposit was discovered in 1842 and the oxidized surface gossan initially mined for gold from a shallow open pit known as the Big Cut. Secondary enriched copper ores were encountered at a depth of 7.5 to 9 meters and the ore body named the "Big Cut copper vein" (Weed 1911). Five shafts were opened into the primary sulfide ores along a line trending 030°. The mine was most active from 1899 to 1906, ceasing operations in 1907. It produced 5,000,000 pounds of copper and 18,142 ounces of gold, with most of the gold (14,514 ounces) recovered from the oxidized zone. The deposit is hosted by a sequence of felsic to intermediate volcaniclastic rocks and massive to thin-bedded sedimentary units metamorphosed to the greenschist facies.

The precious and base metal deposits of the Gold Hill District lie within the Gold Hill fault zone, which is about 2.5 kilometers wide and trending 025° in this area (Fig. 4). The fault zone is a domain of heterogeneous ductile strain with a true thickness of about 2.2 kilometers and dips 70-75° northwest. The Gold Hill district is located on the western flank of the Denton Anticlinorium, about four kilometers northwest of the fold axis. Ductile strain on the Gold Hill Fault Zone post-dates formation of the Denton Anticlinorium and other large-scale en echelon folds in the Albemarle Sequence. These folds are consistent with sinistral strain; with axes and axial plane foliation oriented 25°-35° clockwise to the Gold Hill Fault Zone and truncated by the younger shear fabric (Hibbard et al. 2008).

Despite some degree of tectonic transposition, alteration and metal zonation studies by Unger (1982) suggest that the Union Copper deposit is largely intact and broadly preserves most elements of the original hydrothermal system architecture (Fig. 5). The geometry of the Union Copper ore body is very similar to that of the Silver Hill ore body in the Cid District to the north, and suggests similar tectonic modification of an existing VMS deposit.

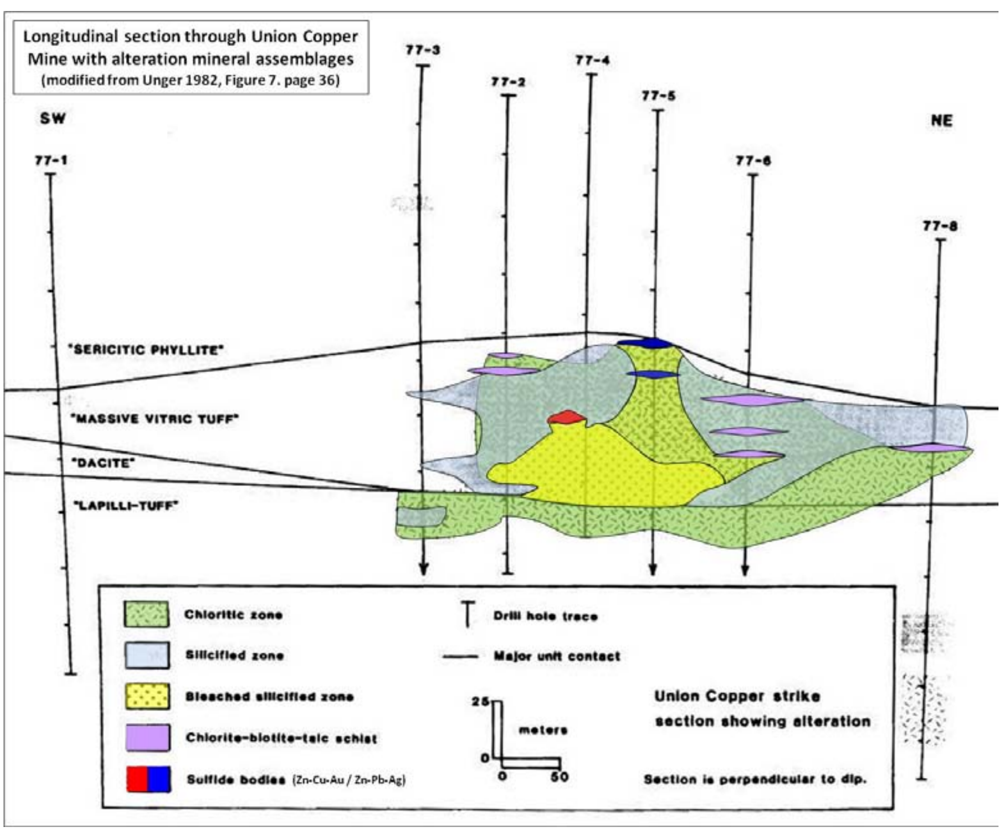

Figure 5. Longitudinal section through the Union Copper Mine with alteration (Unger, 1982).

Pervasive silicification is the most common form of alteration associated with the Union Copper deposit. It is strongly developed throughout the central and upper portions of the system, and is often broadly coincident with chlorite alteration peripheral to the central core. It is composed of 75-95 percent fine-grained to cherty silica with minor to trace sericite (Unger 1982). Chloritic alteration is less widespread than silicic alteration and characterized by 5 percent to over 50 percent chlorite (Unger 1982). Chlorite appears to extend throughout most of the system, but dominates the deep footwall and the periphery of the central silicic core. Although not recognized as a discrete alteration zone, potassic alteration is present as biotite and as plagioclase altered to K-feldspar, especially in the footwall where biotite is more abundant than chlorite in the matrix of the Lapilli Tuff Unit (Unger 1982).

The Union Copper deposit was drilled by the US Bureau of Mines in 1943 (Ballard and Clayton 1948). Eight diamond core holes totaling 762 meters tested the zone along 275 meters of strike. The Tennessee Copper Company (Cities Service) drilled 7 holes core holes totaling 1675 meters at Union Copper in the early 1960s, and Conoco Minerals drilled an additional eight diamond core holes with a total of 1860 meters in 1977. Seven Conoco drill holes largely tested the down-dip extension of the same zone tested by the US Bureau of Mines without discovering additional significant mineralization. Drilling encountered a generally lower-grade, strongly silicified mineralized zone 9-12 meters wide north and south of the old stopes, consisting of pyrite and sphalerite with accessory chalcopyrite and galena (Ballard and Clayton 1948). The ore body appears to be zoned from a Cu-rich central zone to a more Zn-rich periphery. Gold mineralization appears to be closely associated with higher Cu-values.

The Silver Shaft Mine is located on strike about 550 meters south-southwest of the Union Copper Mine in Cabarrus County. Joe's Bluff is a collapsed shaft or pit located 180 meters east of Silver Shaft. It is opened in silicic, pyritic volcaniclastic rocks, and appears to be correlative with a line of prospects footwall to the Union Copper deposit. There is no record of production at Silver Shaft, but it was probably worked during the late 1800s to early 1900s.

Phelps Dodge evaluated the Silver Shaft deposit in 1980-1981. The area was mapped at a scale of 1:100, extensive soil geochemical sampling and ground geophysical surveys were completed (magnetic, HLEM, SP, IP-Resistivity), and seven diamond core holes totaling 1345.1 meters were drilled (Fig. 6). The best drill hole result was 7.3 meters averaging 8.88 opt Ag and 1.113 percent Zn. However, ore-grade mineralization appears to be highly localized and was not intersected along strike or at depth. The Silver Shaft mineralization was unresponsive to geophysical methods and no coherent soil geochemical anomaly could be established. The geochemical and geophysical response of the mineralization may have been masked by the widespread occurrence of up to 2-5 percent to locally 10-15 percent disseminated and laminar pyrite and pyrrhotite and widespread minor disseminated sphalerite, galena, and chalcopyrite throughout much of the host sequence.

Three local lithologic sequences were identified on the basis of detailed surface mapping and drill hole core logs, and form a continuous homoclinal sequence over 600 meters thick (Figs. 7 and 8). The same sequence is described by Unger (1982) at the Union Copper Mine. These sequences are:

- Upper Volcanic Sequence
- Siltstone Sequence (host to mineralization)
- Lower Volcanic Sequence

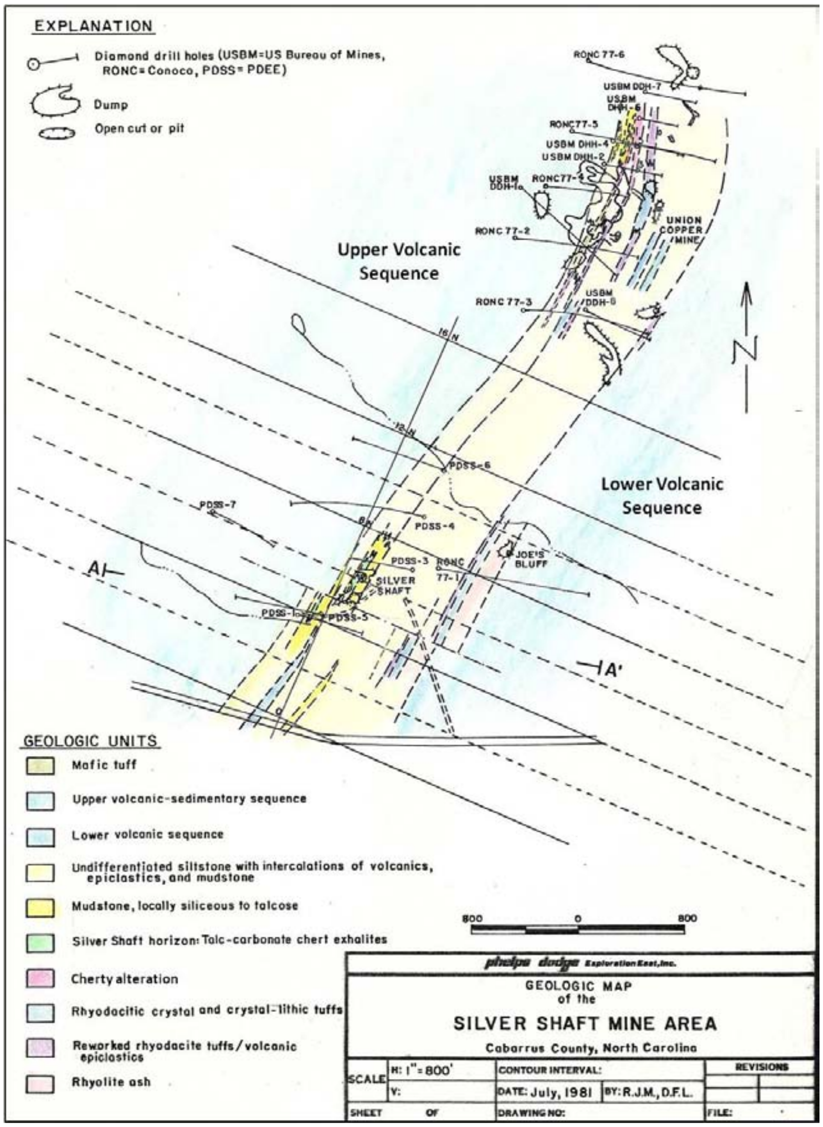

Figure 6. Geologic map of the Union Copper-Silver Shaft area.

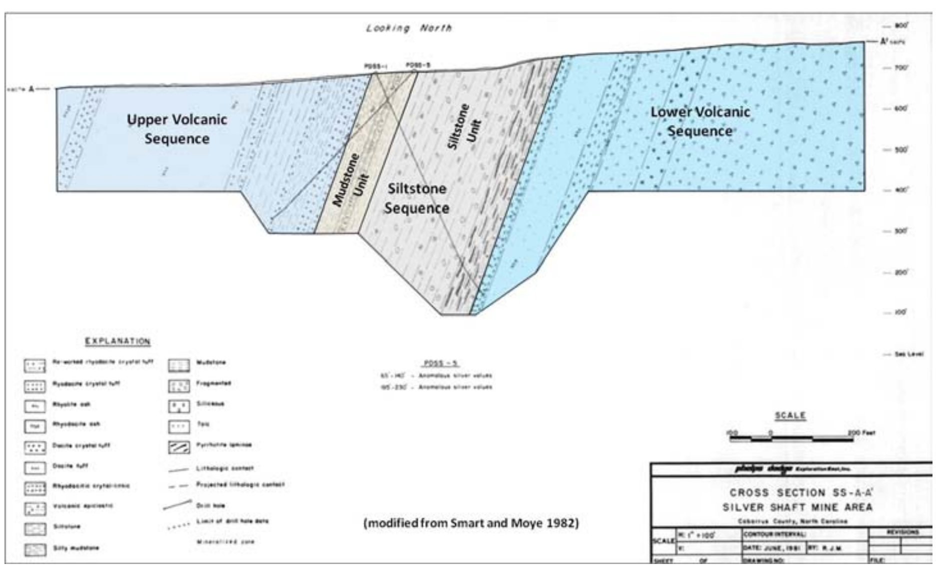

Figure 7. Silver Shaft core drill hole cross-section A-A'.

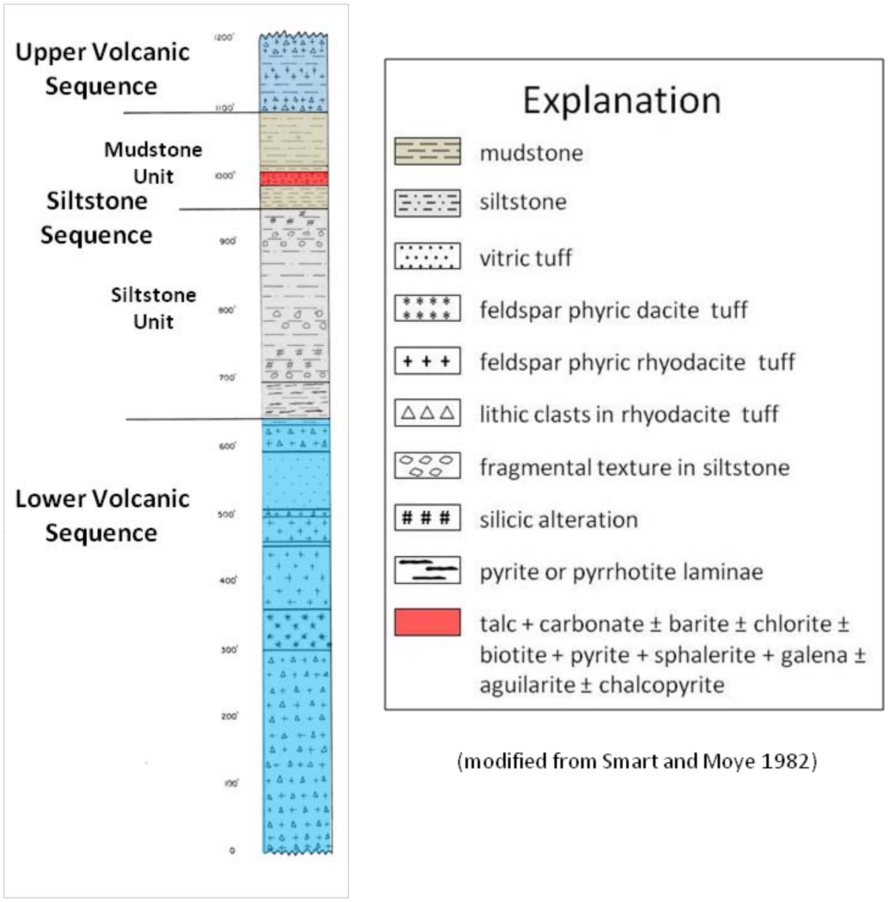

Figure 8. Idealized stratigraphic column for Silver Shaft-Joe's Bluff area, Gold Hill district, Carolina terrane, central North Carolina.

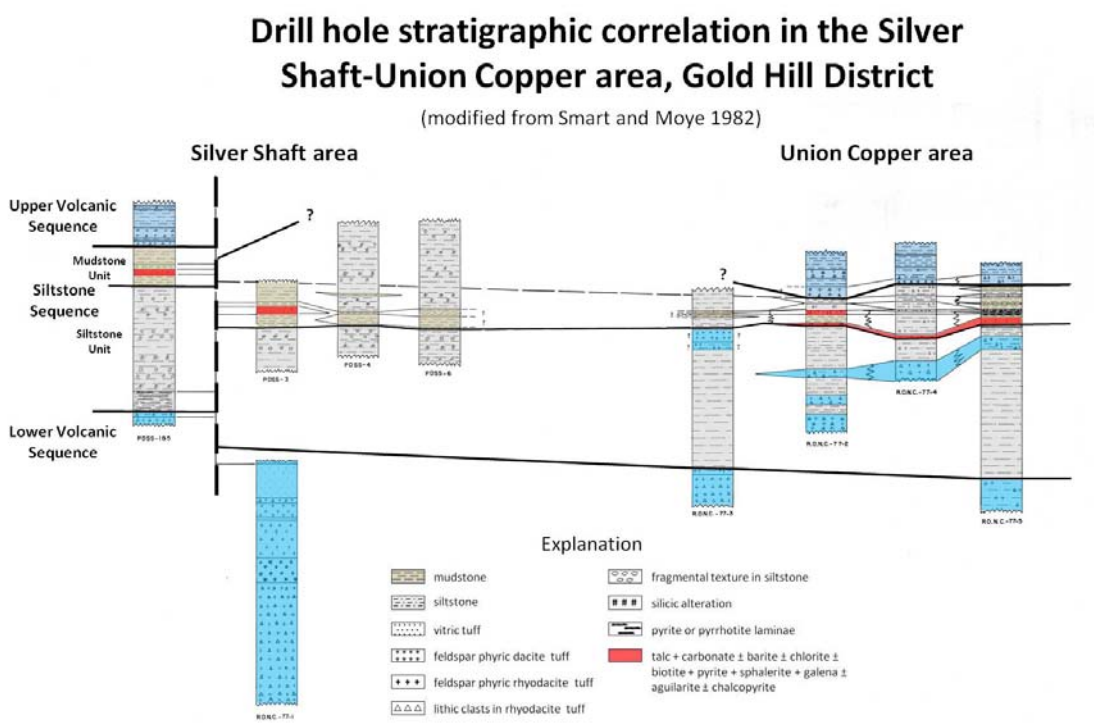

Figure 9. Stratigraphic correlation in the Union Copper-Silver Shaft area.

Stratigraphic units extend without significant deflection or major fault offset for over a kilometer from the Silver Shaft area northward through the Union Copper Mine area, and appear continuously conformable, upright, and west-facing (Figure 9). Stratigraphy in the Silver Shaft area strikes 025°, dips 70°NW, and is right side up, while cleavage strikes about 030°-045° and dips 75°-80°NW. Foliation is strongly developed in finer-grained units, and weakly expressed in coarser-grained, more massive rocks.

At Silver Shaft, the Lower Volcanic Sequence is over 250 meters thick, and composed of usually thick, texturally variable units of feldspar-rich dacitic to rhyodacitic crystal and crystal-lithic volcaniclastic rocks that outcrop to the east of Joe's Bluff. The maximum size of lithic clasts in these rocks is about 2-3 centimeters. The rocks are locally silicified and contain fine-grained disseminated pyrite that ranges from less than 1 percent to 3-5 percent, to locally 10-15 percent. In addition, reddish-brown sphalerite occurs as a trace to locally 3 percent disseminated grains scattered heterogeneously throughout the sequence. Dissmeninated chalcopyrite is locally present to 10 percent over narrow intervals in the lower part of the sequence, and trace galena is present locally in the upper part. There is an abrupt change from pyrite to pyrrhotite as the dominated disseminated Fe-sulfid phase in the upper 15 meters of the sequence.

The Lower Volcanic Sequence appears to fine upward conformably into the Siltstone Sequence which hosts the Union Copper Mine and Silver Shaft mineralization. This sequence is about 137 meters thick at Silver Shaft and further diviced into the lower Siltstone Unit (93 meters) and the upper Mudstone Unit (44 meters). The entire sequence generally fines upwards (west) and shows extensive evidence of hydrothermal activity in the form of silicification, chloritization, intense Mg-metasomatism (talc) and sulfides. This sequence appears to vary significantly in thickness and contains interbeds of coarser-grained felsic volcaniclastic rocks in the Union Copper Mine area. Thinly bedded mudstone units are localized and discontinuous in the upper portion of the sequence.

The base of the Siltstone Unit at Silver Shaft consists of about 15 m of distinctive laminated volcaniclastic or epiclastic siltstones with 1-5 percent pyrrhotite as disseminated grains and thin (1-2 mm) lenses and laminae. These locally increase to 15 percent with laminae up to a cm thick. This interval has a strong magnetic response in geophysical surveys. The rest of the unit is composed of massive to poorly-bedded to streaky-textured siltstone interbedded with 30 cm to 4.5 m thick intervals of silty mudstone.

The siltstone is generally siliceous and locally grades into partial to pervasive cherty silicification. The sequence locally contains varying amounts of disseminated fine-grained chlorite. Both pyrite and pyrrhotite occur as trace to 5 percent disseminated grains, lenses, and irregular laminae. Fragmental textures are commonly observed, generally characterized by elongate, often flattened fragments of dark siltstone in a lighter, more siliceous matrix. Portions of the sequence are chaotic mixtures of siltstone fragments, chert fragments, and occasional epiclastic volcanic rock fragments and feldspar crystals in a silty to siliceous matrix. A variety of origins for the breccias are possible.

The Siltstone Unit at Silver Shaft is gradational into the overlying Mudstone unit. This 44 m thick sequence is further divided into a lower 19 m thick mineralized mudstone and upper 25 m thick barren silty mudstone. The mineralized Mudstone unit is characteristically poorly-bedded to well-bedded and contains locally abundant pyrite (10-15 percent) as disseminated grains, lenses, and thin laminae. The mudstones become increasingly talcose upwards and streaky, irregular laminae of pyrite, pale yellow-brown sphalerite, and minor galena appear just below the ore horizon. The ore zone lies about 11 meters above the base of the Mudstone Unit. Significant concentrations of Zn-Pb-Ag mineralization appear to be coincident with these lenses of thinly-bedded mudstone. The Mudstone Unit appears to be grouped with the Massive Vitric Tuff unit of Unger (1982) at the Union Copper Mine. This unit contains both the Union Copper hanging wall Zn-Pb-Ag rich zones and the Silver Shaft Zn-Pb-Ag ore body.

The Siltstone Sequence terminates abruptly at a rhyodacitic crystal-lithic volcaniclastic unit at the base of the Upper Volcanic Sequence. The sequence is probably over 250 meters thick and characterized by crystal and crystal-lithic dacitic to rhyodacitic volcaniclastic units alternating with volcanic epiclastic sediments including siltstone, mudstone, and sandstone. Lithologies suggest a sporadic renewal of volcanic activity following a period of quiescence. Trace to 5 percent pyrite and pyrrhotite are present as disseminations and thin, irregular laminae, along with local trace red-brown sphalerite.

The Silver Shaft ore body appears to be highly localized and elongated down-dip, similar to the geometry of the Union Copper main zone. Drilling outlined a possible estimated resource measuring about 60 meters strike, 120 meters dip, and 7 meters thick with about 190,000 tons of ore averaging 8-9 opt Ag and 1-2 percent Zn (Smart and Moye 1982).

Base metal sulfides (sphalerite, chalcopyrite, and galena) are heterogeneously distributed throughout the defined stratigraphic section in the Union Copper-Silver Shaft area. Base metal sulfides occur in three associations:

- as massive to semi-massive stratabound lenses
- as accessory minerals and aggregates in quartz veins
- as trace to minor disseminated grains throughout the section

Massive to semi-massive accumulations of base metal sulfides occur only within the Siltstone Sequence, and include the main Zn-Cu-Au ore body at the Union Copper Mine, the Zn-Pb-Ag lenses in the hanging wall at Union Copper, and the ore body at the Silver Shaft Mine. These occurrences may be syngenetic exhalative horizons where hydrothermal fluids have vented onto the ocean floor, or replacement mineralization at shallow depths below the sea floor. Semi-massive mineralization at Union Copper is locally gradational laterally into chlorite-biotite-talc-sulfide schist (Unger 1982), suggesting a stratigraphically controlled alteration or replacement origin.

Quartz ± carbonate ± sulfide veins form a stockwork (high density) to stringer (low density) zone surrounding the Union Copper main ore body, most strongly developed in the footwall (Unger 1982). Similar veins are present in the footwall of the Silver Shaft deposit, and both suggest formation from hydrothermal fluids within or peripheral to major fluid pathways footwall to the massive sulfide lenses. The formation of veins suggests brittle fracture, potentially hydraulic, of coherent rocks, possibly cemented during an earlier phase of alteration.

Disseminated base metal sulfides are scattered heterogeneously throughout the Lower Volcanic Sequence and Siltstone Sequence, and sphalerite is noted locally in the Upper Volcanic Sequence. Total disseminated base metal sulfide content is typically a trace to 2 percent by volume. Sphalerite, galena, or chalcopyrite may be locally dominant, but sphalerite is most common and chalcopyrite least abundant. Sphalerite is typically reddish-brown in the Lower Volcanic Sequence, the lower part of the Siltstone Sequence, and the Upper Volcanic Sequence. Pale yellow sphalerite appears only in the Mudstone Unit of the upper Siltstone Sequence, footwall to, and within the Silver Shaft ore body.

The Union Copper and Silver Shaft ore bodies of the Gold Hill District are typical VMS deposits, products of a hydrothermal system that was active synchronously with deposition of a portion of the host felsic volcaniclastic stratigraphy. The hydrothermal system may have vented to the seafloor intermittently during deposition of the middle to upper portions of the Siltstone Sequence, forming the Union Copper and Silver Shaft massive to semi-massive polymetallic sulfide lenses. The hydrothermal system cooled and weakened but continued to operate during initial deposition of the Upper Volcanic Sequence.

The large area of intense alteration and mineralization centered at the Union Copper Mine represents a focused hydrothermal discharge across the stratigraphic section. The hydrothermal system operated over at least a kilometer of strike and across 300 meters of stratigraphic section. The heterogeneous but almost ubiquitous occurrence of both cherty silicic alteration and disseminated trace to minor pyrite and/or pyrrhotite suggest authigenic formation in water saturated sediments from discharging hydrothermal fluids. The extensive distribution of both alteration types throughout the Lower Volcanic Sequence and Siltstone Sequence may suggest other centers of focused hydrothermal mineralization as yet undiscovered.

The character and thickness of the felsic crystal-lithic tuff of the Lower Volcanic Sequence in the Union Copper-Silver Shaft area are not consistent with volcanic units described in the Tillery Formation, the Floyd Church Formation, or the Mudstone Member of the Cid Formation (Conley 1962, Stromquist and Sundelius 1969). These units are most consistent with lithologies of the Flat Swamp Member of the Cid Formation, in agreement with the interpretations of Ledger (1978) and Unger (1982). The Siltstone Sequence, host for the Union Copper and Silver Shaft ore bodies, is consistent with the transition zones described by Stromquist and Sundelius (1969) at the top and base of the Flat Swamp Member.

The Flat Swamp Member also appears to be the host for the Silver Hill and Silver Valley VMS deposits in the Cid District to the north. If correct, this interpretation suggests that, with the exception of the Scarlett Mine in north Asheboro, all known polymetallic VMS deposits in the Albemarle Sequence are associated with the Flat Swamp Member of the Cid Formation, and also limited to the thickest sections of this formation in the northwestern portion of the Albemarle Group outcrop area.

Preservation of intact Flat Swamp Member stratigraphy within the Gold Hill Fault Zone in the Gold Hill District is consistent with observations concerning the character and distribution of ductile strain within the fault zone (Standard 2003, Hibbard et al. 2008, and Hibbard et al. 2012). It appears likely that preservation of the stratigraphic section within any given section of the Gold Hill Fault Zone is dependent on the degree of decoupling from the intact stratigraphic section in the footwall of the Silver Hill Fault. Stratigraphy is more likely to be intact over large areas in the lower portion of the Gold Hill Fault Zone, although potentially overturned or repeated by mesoscale folds and second order reverse faults. Preservation of intact stratigraphic sections is probably reduced with proximity to the Gold Hill Fault and metallic deposits may assume characteristics related to structural controls and possible remobilization of mineralization.

The generally intact hydrothermal architecture of the VMS deposits suggests that alteration assemblages and even massive sulfide mineralization have not been preferentially deformed during ductile deformation within the Gold Hill Fault Zone, nor have they acted as loci for initiation or portioning of strain. The partitioning of strain appears to be largely determined by lithology and rheological contrasts, with fine-grained volcaniclastic and sedimentary epiclastic units more strongly deformed relative to more massive, coarser-grained sequences.

DISSEMINATED GOLD-PYRITE DEPOSITS

The Ophir District, Randolph and Montgomery Counties

At least 10 historic mines and prospects cluster within an area of about 5 x 8 km centered about four kilometers west of the town of Ophir in northern Montgomery and southwest Randolph County, North Carolina (Fig. 10). Gold and silver were the only economic production from the district, with only trace base and other metals present. Significant gold producers in the district include the Russell, Coggins, and Steel and Saunders Mines. Mineralization in the area is typically low total sulfide, pyrite-dominant, and hosted by strongly sheared and silicic to sericite-pyrite altered, thinly-bedded shale and siltstone of the Tillery Formation. Historically mined ore bodies show distinct local structural control and discontinuity along strike and dip.

The Russell and Coggins Mines are the largest, best described, and most studied of the gold deposits in the district. Based on modern drilling and sampling of the Russell Mine area, Piedmont Minerals suggested a resource of 4 Mt at an average grade of 0.051 opt gold for a total of 209,380 ounces Au, with an additional Inferred resource of 3.2 Mt at 0.038 opt, for a total of 331,100 ounces Au (Maddry and others. 1992). The width, extent and Au-grade of mineralization in the district suggest significant potential for deposits that could be economically mined, either individually or collectively.

Exploration by at least seven companies in the Ophir District since 1939 is documented by Maddry and others (1992). Other companies have examined the mines in the area, but not acquired land positions. A total of 35 diamond core holes and 14 reverse circulation drill holes totaling over 10.8 kilometers aggregate length have been completed in the area, largely in and around the Russell Mine.

Haile Gold Mine Inc. drilled 5 core holes around the Russell Mine Big Cut in 1939, but with poor recovery. ASARCO completed two core holes through the Little Lead and Big Cut zones in 1969. The best result was 23 meters of 0.07 opt in the Big Cut ore zone. Cyprus Exploration did extensive work at the Russell Mine in 1974 and 1976, with soil and rock chip sampling, detailed geologic mapping, and 1341 meters of trenching. They also drilled 3 core holes at the Big Cut and two at the Coggin Hill Mine. Results included 37 meters averaging 0.066 opt Au in the Russell Big Cut ore zone. GRC Exploration Company conducted geophysical and geochemical surveys of the area in 1979, and drilled 4 core holes collared southwest of the Big Cut that intersected the main ore body. A single core hole sited northeast of the Coggins Mine intersected weak Au mineralization over a 7.6 meter interval at a depth of about 140 meters. Gold Fields Mining Corporation conducted soil and rock chip sampling around the Russell Mine in 1983.

Tenneco Minerals Company conducted a comprehensive evaluation of the area in 1984, including detailed geologic mapping at 1:1000 scale over a 78 km^2 area. Stream sediment silt and panned concentrate sampling vectored to known gold workings and rhyolite domes. Extensive soil sampling was conducted, and

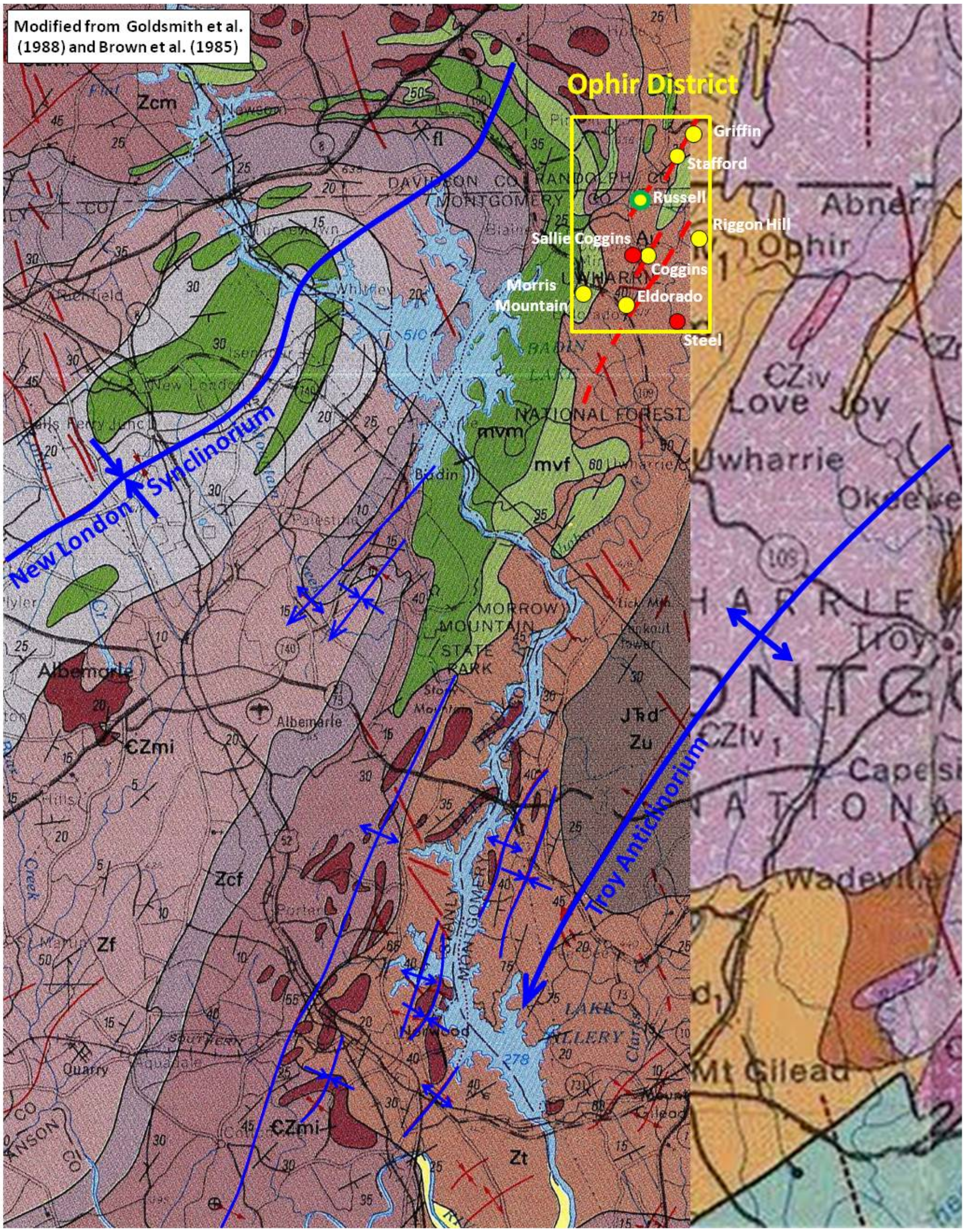

Figure 10. Location and district geologic setting of the Ophir District

accessible mine workings mapped and sampled. A total of 1100 meters of exploration trenches were excavated and sampled across the Little, Big Cut, Palmer and Walker zones. Airborne EM and magnetic surveys of the area were unsuccessful in defining the mineralized zones. Tenneco drilled a total of 7 core holes in the Russell Mine, Big Cut, Coggin Hill, and Parmer zones, and 4 holes in the Griffin and Stafford prospect area to the north. One shallow rotary hole was also drilled at the Griffin Prospect. The drilling successfully tested the main Russell lode and discovered the lower lode, with results that included 49 meters averaging 0.044 opt Au in the main zone and 23 meters of 0.111 opt Au in the lower zone. Broad intervals of lower Au-grade mineralization were also intersected in the Big Cut, Little Lead and Palmer zones. Only narrow intervals of anomalous gold mineralization are reported from the Griffin-Stafford area.

Piedmont Mining Company Incorporated conducted exploration in the area from mid-1989 through 1993. Ground geophysical surveys included magnetic, SP, VLF and VLF-resistivity. Detailed geologic mapping was completed around all known mineralized zones, and four trenches totaling 239 meters were excavated across the Coggins Mine zone. A total of 11 core holes and 14 RC holes were drilled in the Russell Mine area, largely to test the main and lower Big Cut zones. Results included 100 meters averaging 0.045 opt Au in the Big Cut main zone and 98 meters of 0.109 opt Au in the Big Cut lower zone.

Piedmont Minerals sold the mineral rights to the Russell Mine area to Mineral Mining Corporation who in turn sold the rights to The Land Trust for Central North Carolina in 2006 thus effectively ending any further exploration or mine development. At recent gold prices, it would be one of the most promising gold projects in North Carolina along with exploration at the Keystone Jones and Sawyer-New Sawyer mines. The long list of exploration companies also illustrates the revolving door of exploration companies in the southeast with low sustainability of the exploration programs. Typically corporate decisions involving funding southeastern projects or cycles of lower gold prices are the reason for ending exploration and not the potential of the project.

At the Russell Mine, ore bodies are typically described as having indefinite boundaries determined largely through sampling and assay, although zones of stringer quartz veins or lenses may be present. Alteration is typically strongly silicic in ore zones, gradational into surrounding quartz-sericite-pyrite and quartz-sericite-chlorite-pyrite phyllite. Sulfide content is typically 3-5 weight percent and mineralogy is dominated by pyrite, with subordinate chalcopyrite, galena, and sphalerite in some deposits. Minor arsenopyrite and molybdenite are reported at the Russell Mine (Klein et al. 2007). Pyrite occurs as fine grains disseminated over broad intervals, locally concentrated in bedding-parallel laminae, as small semi-massive to massive lenses, and in quartz veins and stringers parallel to cleavage.

Mineralized zones are typically 3-21 meters wide, invariably described as located within shear zones. Where adequate information is available, alteration and mineralization are described as conformable with a penetrative cleavage, often at a high angle to bedding in the host metasedimentary rocks (Pardee and Park 1948, Klein and others 2007). Bedding is often strongly folded at small scales, dismembered, and transposed into the cleavage (Klein and others 2007). Quartz stringers, veins and lenses may be present and conformable with the fabric. Zones of intense penetrative cleavage development, shearing, and hydrothermal alteration are localized and contrast strongly with the enclosing weakly deformed, unaltered metasedimentary sequence. Shear zones and mineralized lodes typically strike 025° to 045° and dip 70-80°NW. The host Tillery metasedimentary rocks strike about 045° and dip gently to moderately northwest.

Klein and others (2007) conclude that six mineralized structures are distributed over a 500 meter wide zone at the Russell Mine; all are characterized by intense cleavage development and strong small-scale folding, faulting, and transposition in asymmetric, southeastverging, doubly plunging, meso-scale anticlines (Fig. 11). Maddry and others (1992) describe two additional parallel mineralized structures farther southeast, one at the contact of Tillery metasedimentary rocks with breccia units associated with the rhyolite cryptodome. This brings the width of the known area of mineralization in the Russell-Coggins area to about 1200 meters. Mineralized zones strike about 045° parallel to the dominant cleavage. Cleavage and reverse faults are typically axial planar to the meso-scale asymmetric folds. The dominant structure at the Big Cut of the Russell Mine is a doubly-plunging anticline striking 045° (Klein et al. 2007), with the lower limb and ore body truncated against a reverse fault.

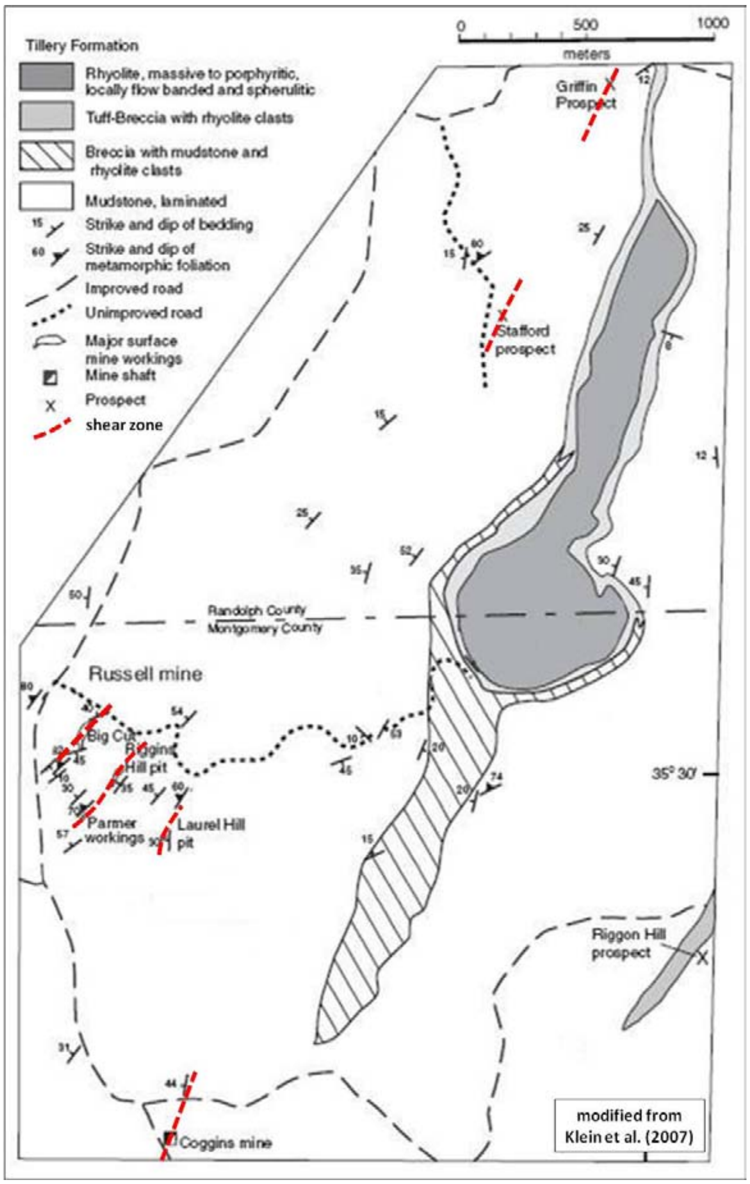

Figure 11. Geologic map of a portion of the Ophir District (Klein and others, 2007).

A 0.6 × 2 km rhyolite dome or crypto-dome, located about 1.1 km northeast of the Russell Mine (Fig. 11), is conformable within the Tillery Formation and appears to have been emplaced synchronous with sedimentation (Klein et al. 2007). The rhyolite is sparsely feldspar-biotite-almandine phyric and flow banded to locally spherulitic, and enclosed by units of tuff breccia with rhyolite clasts and breccia with mudstone and rhyolite clasts (Klein et al. 2007) that extend for 1.5 km southwest parallel to the dominant fabric. A series of larger rhyolite bodies are present to the west and south, including the Morrow Mountain complex, emplaced into both the Tillery and Cid formations.

On a regional basis, gold mineralization in the Ophir District appears to be located within a 5-6 km wide zone of NNE-trending second to third-order, asymmetric, SE-verging folds developed on the common limb of the Troy Anticlinorium and the New London Synclinorium (Fig. 12). These folds resulted from compression of the Albemarle Group between the Charlotte Terrane to the northwest and a block to the southeast composed of the Uwharrie Formation and Virgilina Sequence-Hyco Arc basement. The axes of the New London Synclinorium and Denton Anticlinorium appear to be deflected into parallelism with this zone approaching the Uwharrie Formation contact. This compression may post-date initial formation of the regional first-order folds that dominate the Albemarle Group in central North Carolina, and may be synchronous with large offset sinistral-reverse displacement on the Gold Hill Fault Zone, constrained to the late Ordovician (Hibbard et al., 2012). The orientation of the parasitic folds, the southeast limb of the New London Syncline, and the western contact of the Uwharrie Formation are parallel to the Gold Hill Fault Zone to the northwest.

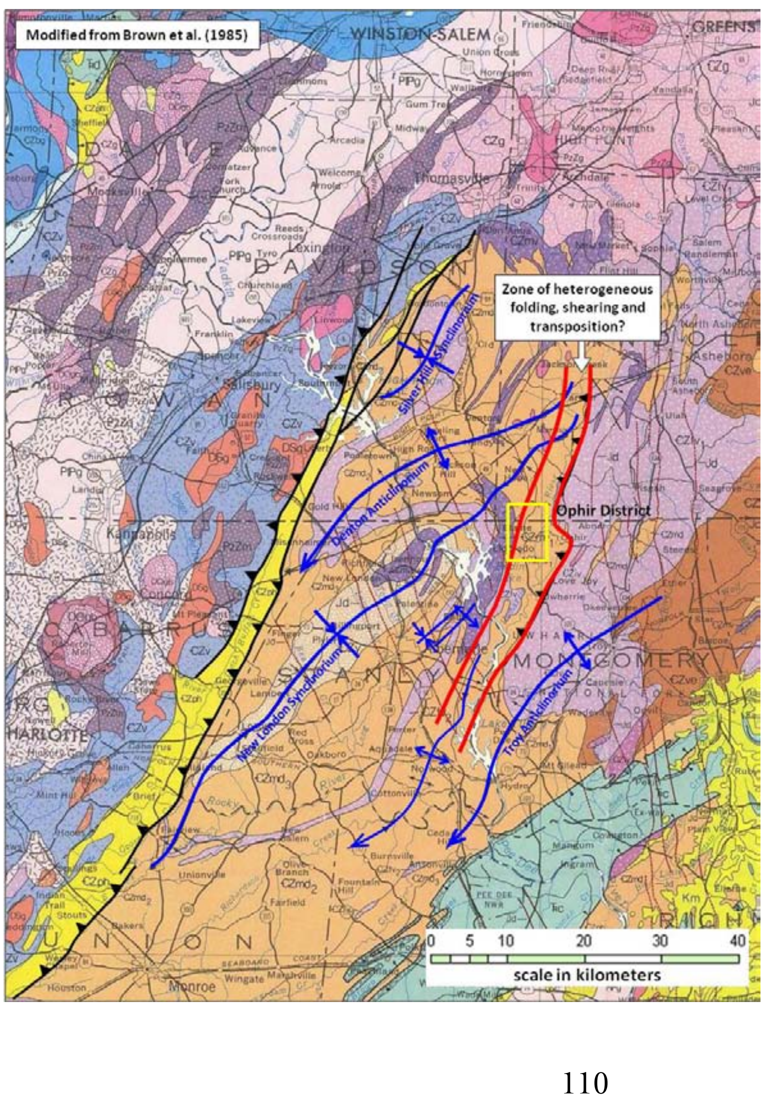

Figure 12. Possible zone of heterogeneous fractal-scale folding, shearing and transposition along the east side of the Albemarle Group in central North Carolina.

This deformation zone lies largely within the Tillery Formation, and is most strongly developed in northwest Montgomery and southwest Randolph County, but does not appear to extend northward into the Asheboro area. The deformation zone appears to be strongly compressed and the mapped width of the Tillery Formation narrowed in the Ophir District area, coincident with an apparent north and west step-over between linear segments of the Tillery-Uwharrie contact (Fig. 13). Many meso-scale asymmetric folds in this area may have failed as reverse fault shears.

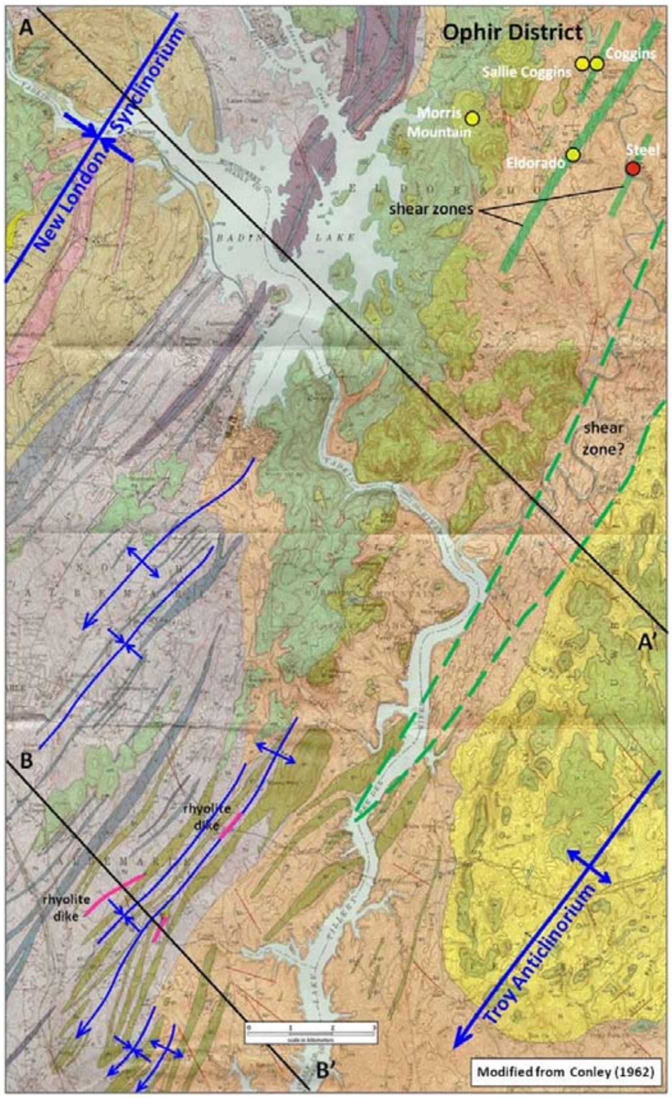

Figure 13. Suggested structural controls on mineralization in the Ophir district.

The Ophir District represents a problematical style of gold mineralization in the Carolina Terrane of central North Carolina. The character and origin of these ore deposits have been contentious, generally divided between epigenetic (Pardee and Park 1948) and structurally modified volcanogenic-syngenetic (Worthington and Kiff 1970, Klein and others 2007) models. The most recent model is that proposed by Klein and others (2007). They cite evidence of mineralization that is syngenetic or epigenetic. They suggest a "gold-rich, base-metal poor, volcanogenic massive sulfide deposit in which gold was remobilized, in part, during Ordovician metamorphism" into shear zones along the axes of asymmetric NE-trending, SE-verging meso-scale folds. This model is lateral secretion (*sensu stricto*), with ore zone components sourced from lower-grade, syngenetic exhalative sulfide mineralization in adjacent host rocks. A small rhyolite intrusive-extrusive center located a little over a kilometer to the northeast is proposed as a possible genetic association.

Klein and others (2007) also suggest the Ophir District gold deposits are located within a zone of heterogeneous northeast-trending, steeply northwest-dipping, southeast-directed reverse ductile strain characterized by possibly *en echelon* asymmetric folding at several scales, a locally intense axial planar cleavage, and discontinuous *en echelon* or anastomosing shear zones and reverse faults. Gold mineralization is associated with low sulfide, pyrite-dominated silicic to sericite alteration and appears to be localized along the reverse shears axial to asymmetric anticlines.

Initial alteration in the Russell and Coggins deposits probably occurred at relatively low strain during meso-scale folding, and consists of localized sericite alteration, sulfidation and pyrite formation, often parallel to bedding. Bedding and both disseminated and bedding parallel pyrite laminae are progressively deformed and transposed into a spaced to penetrative axial planar cleavage at higher strain. This fabric provided deeply penetrating brittle-ductile pathways for Au-bearing fluids, accompanied by in locally intense silicic alteration and Au-Ag-As mineralization with minor accessory base metals and local trace molybdenite. Some anticlines experienced post-mineralization failure as reverse faults, which may truncate and offset mineralization.

Metasediments of the Tillery Formation are a host rock that facilitates hydrothermal alteration and mineralization over zones tens of meters wide, rather than the narrow structures commonly present in more competent lithologies, such as felsic and mafic volcanic units where thin, high grade quartz veins may host gold mineralization. The availability of iron in the form of detrital, diagenetic or metamorphic Fe-Ti oxides and chlorite may have been a factor in suitability for sulfidation reactions. A reevaluation of detailed magnetic geophysical data could potentially distinguish intervals of higher Fe-content, as well as areas of possible magnetite destruction through sulfidation. Additionally, areas of strong sericitic alteration are potentially more K-enriched, and possibly distinguished in detailed low-altitude airborne or ground radiometric surveys.

A unique structural feature of the Ophir District is the west and north step-over in the otherwise linear Tillery-Uwharrie Formation contact, located immediately to the east (Fig. 13). This step-over zone and the apparent abrupt narrowing of the deformation zone in this area may have been a factor in focusing mineralizing hydrothermal fluids to this specific area. The west and north left-stepping *en echelon* pattern in second-order folds along the deformation zone, the step-over in the Tillery-Uwharrie contact, and possibly in the distribution of mineralized structures across the Ophir District, is the same kinematic pattern seen in the Lewis Mine Group and other clusters of gold deposits along the Gold Hill Fault Zone to the west. This may support the theory that gold mineralization and host structures in the Ophir District may have formed synchronous with Cambro-Ordovician overthrusting of the Carolina Terrane by the Charlotte Terrane along the Gold Hill Fault Zone.

The influence of early epithermal fluids in the Ophir district remains unclear. Host structures for mineralization do not parallel stratigraphy, and ore shoots are indicated to be discontinuous and possibly *en echelon* along strike and down dip. Drilling programs should follow structure rather than stratigraphy and not assume lateral or vertical continuity. Detailed geologic mapping and 3-D modeling of drill results may be effective in identifying step-over and en echelon continuity of deformation zones that host mineralization, but it is unlikely that all structures will carry significant mineralization,

The Stewart Mines Group, Union County, North Carolina

This group of 14 historic gold mines occurs along a 12 km long zone located at the western edge of Union County within the Gold Hill Fault Zone (Fig. 14).

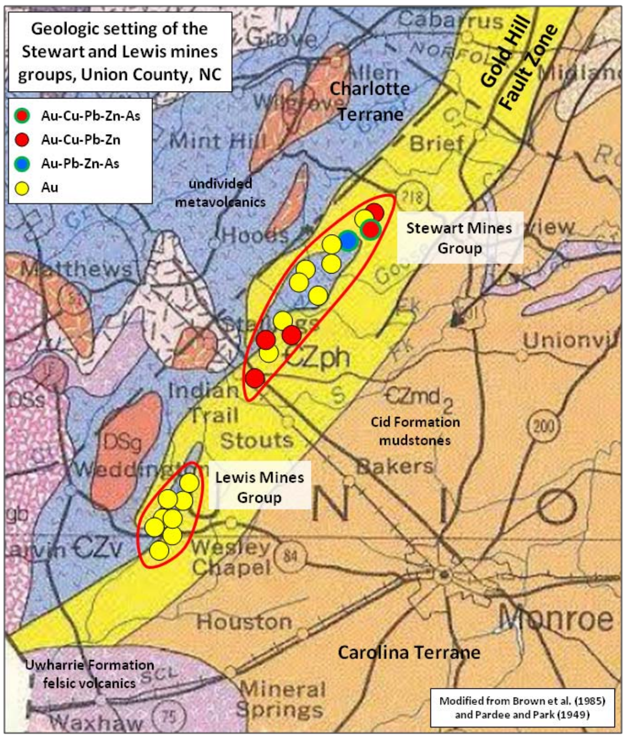

Figure 14. Location and geologic setting of the Stewart and Lewis mines groups.

The host rocks are described as chloritic to sericitic schists, and probably largely fine-grained metasedimentary rocks strongly foliated within the Gold Hill Fault Zone. The mines appear to be developed along quartz vein sets disposed almost symmetrically around a NE-trending domain of undivided mafic metavolcanic rocks about 7.5 km long and 2 km wide, conformable with the tectonic fabric of the Gold Hill Fault Zone. Rheological contrast with the fine-grained, phyllosilicate-rich phyllites that dominate the surrounding rocks may have strongly partitioned strain and fluid flow within and peripheral to this domain (Fig. 15). Similar controls are suggested for the Lewis Mine Group to the southwest.

Little detailed information is available, but the mineralization appears to be largely hosted by cleavage-parallel, variably silicified chloritic to sericitic schists, quartz veins, and quartz stringer zones. Base metal sulfide occurrences in these deposits contrast strongly with the Howie Mine and the Lewis Mine Group to the southwest. Many of the Stewart Group quartz veins carry appreciable base metal sulfides (chalcopyrite, galena, and sphalerite) and two, the Lemmonds and the Stewart, also carry accessory arsenopyrite. Base metal sulfides are only locally reported from the Lewis Mine Group, and no arsenopyrite.

Quartz veins and stringers are typically located in shear zones that appear to parallel the tectonic fabric, with chlorite ± sericite alteration of mafic host rocks and silicification and sericite alteration of phyllitic metasedimentary rocks. Despite the numerous veins present, the absence of widespread, intense and pervasive sulfide-bearing alteration suggests strongly localized fluid flow along narrow structural pathways.

The US Bureau of Mines drilled three core holes at the Moore and Stewart mines of the Stewart Group in 1952. This drilling was part of an investigation of the base metal mining potential of gold-bearing quartz vein deposits in this area of the Carolina Terrane (Peyton 1957). Generally narrow zones of silicic-sericitic alteration were intersected at the Stewart, Moore (Blue Shaft), and Bright Light mines, and no significant intervals of base metal mineralization were reported. The core was only selectively assayed for base metals and there were no assays for Au or Ag. The results of the USBM drilling at the Moore and Stewart Mines appear inconsistent with historical reports of the abundance of

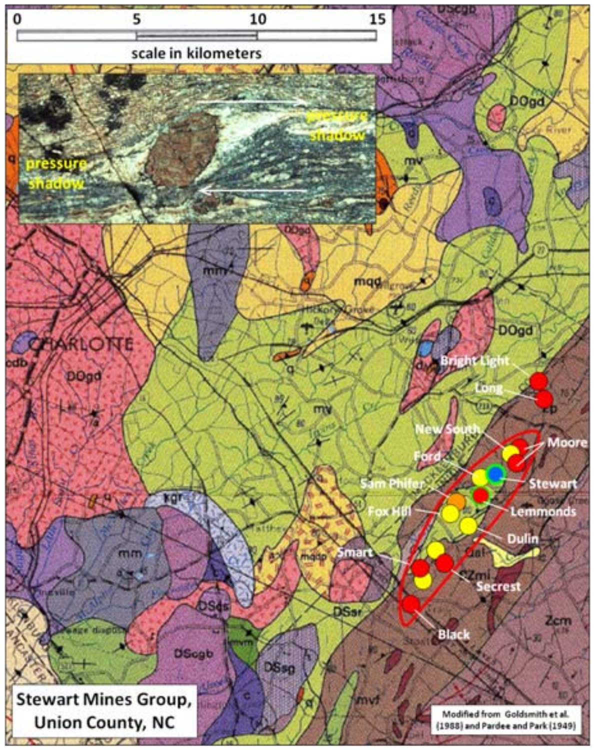

Figure 15. Location and geologic setting of the Stewart Mines group.

base metal sulfide minerals in these lodes, and suggest that higher-grade ores may occur in scattered, highly localized shoots along generally weakly mineralized structures. The association of base metals in the Stewart group of mines may also suggest a weak VMS system that has been strongly deformed within the Gold Hill fault, but there is no detailed mapping or exploration data to present further evidence.

Sawyer-Keystone Trend, Randolph County, North Carolina

An irregular alignment of over a dozen known gold deposits trends about 065° for 21 kilometers across western Randolph County in central North Carolina (Figs. 3 and 16), informally known as the Sawyer-Keystone trend. Most of these occurrences are described as indefinite zones of cleavage-parallel silicic to sericitic alteration with disseminated pyrite ± arsenopyrite, hosted by shear zones with local brecciation. This alignment is not consistent with observed major tectonic fabrics or trends in this portion of the Carolina Terrane.

From east to west, deposits are hosted by the Uwharrie, Tillery and Cid Formations of the Albemarle Sequence. The western deposits, including the Jones-Keystone, Southern Homestake, Lofflin and Parrish-Kindley, are hosted by the Mudstone Member of the Cid Formation. The Hoover Hill, Wilson-Kindley, and Pierce Mountain mines occur in the Tillery Formation. The Sawyer, New Sawyer, Merrill and Jones and Laughlin occurrences are in the Uwharrie Formation.

Stromquist et al. (1971) located the Jones-Keystone and Lofflin Mines on a northeast-

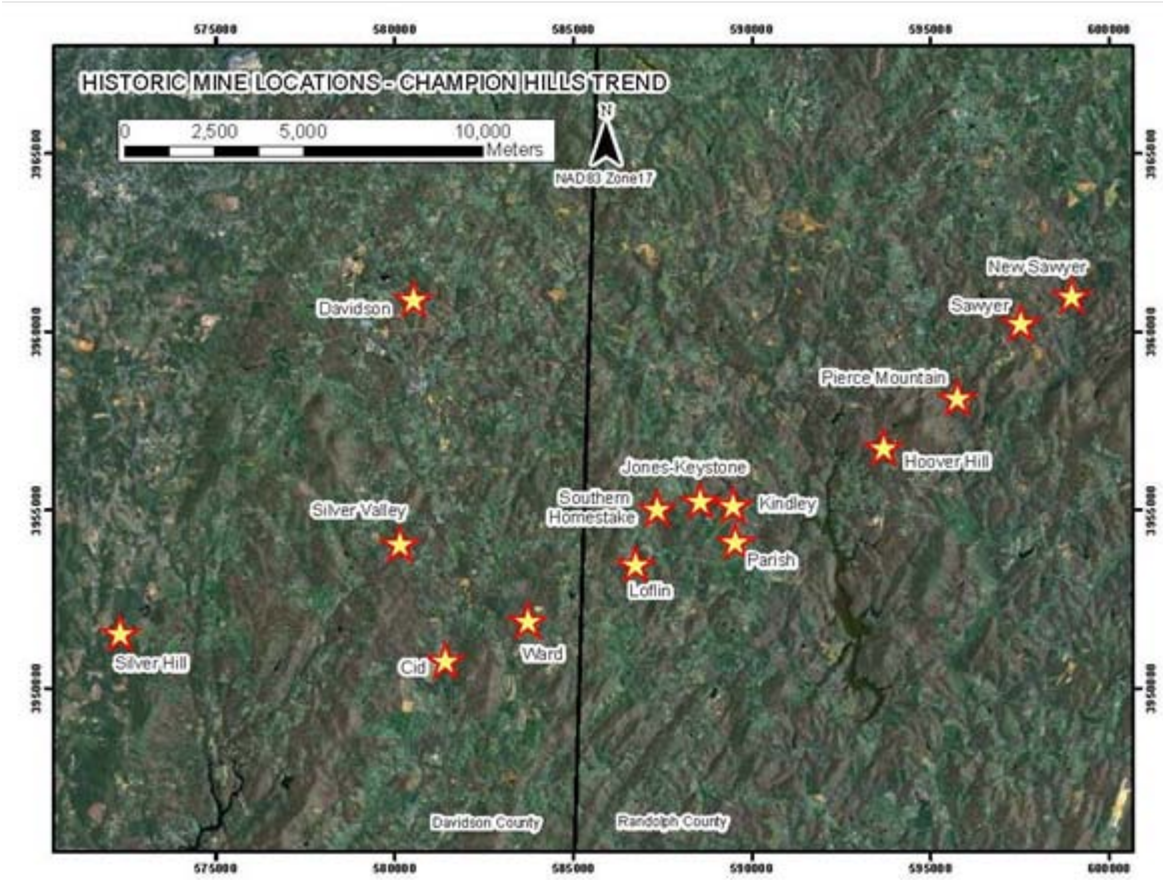

Figure 16. Keystone Jones to Sawyer mine trend with historic mines (Lucas, 2013). The Silver Hill, Silver Valley, and Cid are VMS deposits.

-trending shear zone. Kinkel (1974) reports that Stromquist suggested that this shear zone cut across lithology, with mineralization developed where the structure intersect favorable host rocks. The same controls were proposed for the Lofflin Mine area by Noranda (Lucas, 2013). Work in the Lofflin Mine area and the Jones-Keystone Mine area by Resolution Resources, suggests that this shear zone is axial planar to meso-scale folds and may consist of *en echelon* segments that step left to the north and east (Figs. 17 and 18). Hydrothermal alteration and gold mineralization is discontinuous and most strongly expressed in specific lithologic units. These units may be favored hosts due to compositional, textural, or rheological characteristics.

The absence of a linked, through-going major structure suggests that total strain along this shear zone is relatively low, characterized by en echelon shear segments axial planar to meso-scale folds, which may also be *en echelon* and appear to overprint an earlier generation of larger-scale folds. Folding, shearing and faulting associated with this structure may be locally perturbed and deflected by older structures or rheological buttresses, such as the Shepherd Mountain and Caraway Mountain rhyolite magmatic centers.

The structural controls of Au-mineralization along the Sawyer-Keystone trend suggest that mineralization post-dates deposition of the Uwharrie, Tillery and Cid Formations, as well as initial large-scale folding during the Late Ordovician Cherokee Orogeny (Hibbard et al. 2012).

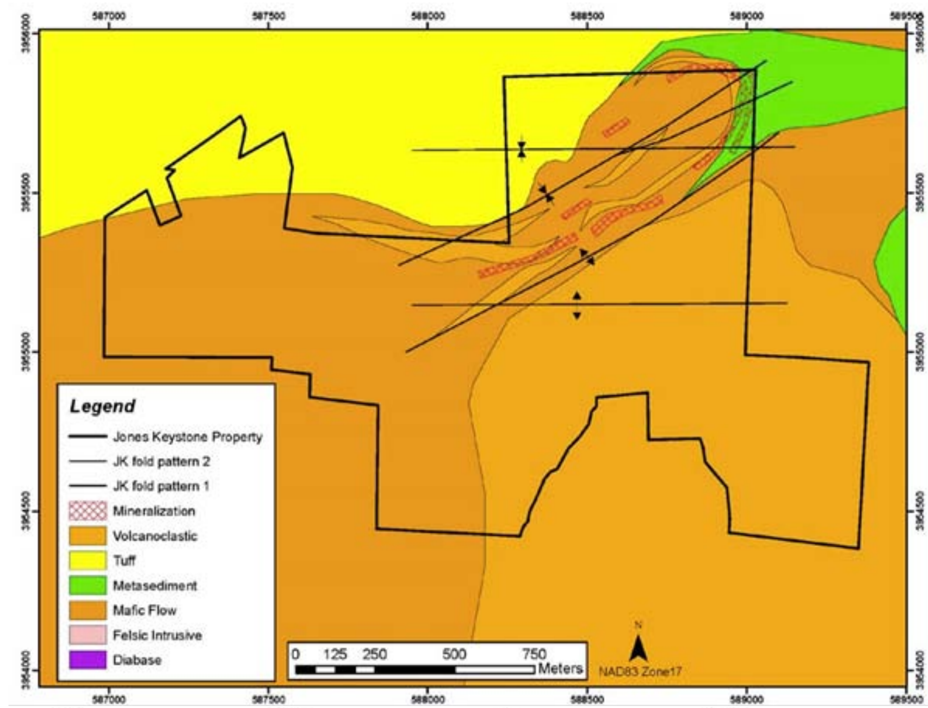

Figure 17. Geology of the Keystone-Jones (Lucas, 2013).

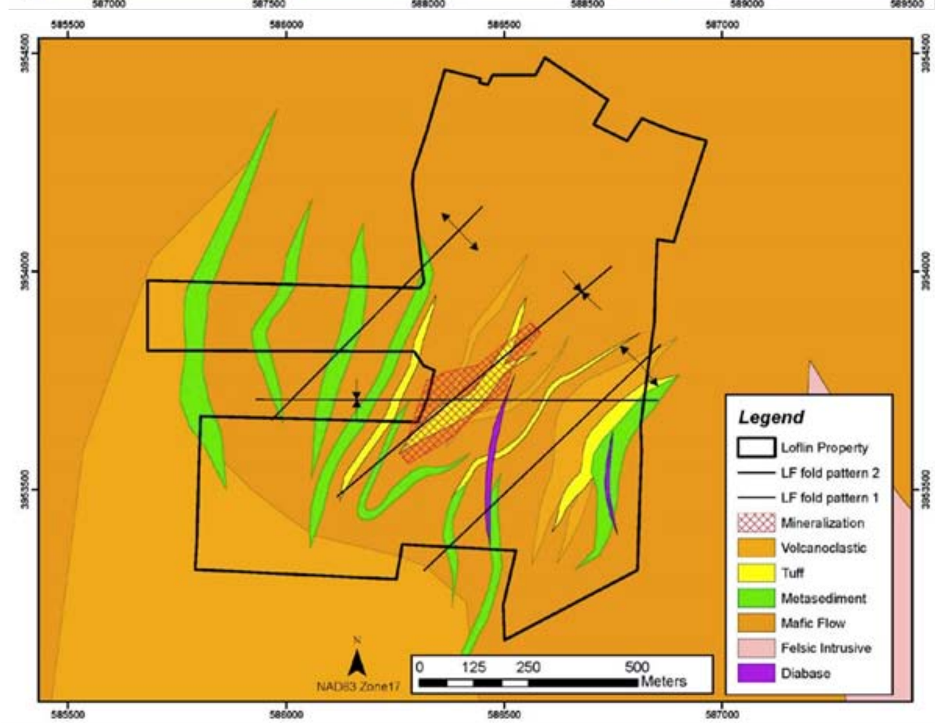

Figure 18. Geology of the Loflin Mine (Lucas, 2013).

All of the known gold mines, prospects and occurrences along this trend have been examined and evaluated by numerous exploration and mining companies and the most extensive work, including rotary or diamond core drill holes, has been conducted at the Jones-Keystone and Loflin Mines by Revolution Resources with the intent to expand the gold resource (Lucas, 2013). In addition Romarco Minerals has acquired the Sawyer and New Sawyer Mines from private investors, but little data is publically available.

The Jones-Keystone Mine is located 29 km east-southeast of Lexington and 19 km south-southeast of Thomasville, or 19 km west of Asheboro, on the west side of the Uwharrie River, opposite the Hoover Hill mine. In 1852 the mine was in active operation and was equipped with a 40-stamp mill, probably one of the first in North Carolina. The recovery was said to be very low because much of the gold was exceedingly fine. The mine was closed during the Civil War, but was reopened in the late 1870s and operated for short periods in 1880, 1884, 1894, 1895, 1896, and 1903. In 1896, the 40-stamp mill from the Coggins mine in Montgomery County was moved to the Jones mine. Between 30,000 and 40,000 tons of material has been removed from the pits. If all of this material was milled the total production was about 5000 of gold. As depth was reached and sulfides were encountered, the value of the ore apparently decreased, and the mine was abandoned. Bryson reported that around 1936 the mine was operated by the Keystone Mining Company on ore averaging $3.00 per ton. A 200-ton mill was erected on the property and several hundred tons of ore were treated. Two large open pits, several shafts, remnants of two Chilean mills and evidence of cyanide vats remain on the property.

Asarco Exploration leased the Jones-Keystone in 1969, and completed soil sampling, trenching and three core holes totaling 454 meters. Cyprus Mines and Louisiana Land and Exploration held the property in 1975-1976. Piedmont Land and Exploration Company then held the property from 1981-1991, and completed additional sampling, two new surface trenches and drilled one core hole to 154m. Numerous companies, including Noranda, Phelps Dodge and BP Minerals examined the property and worked in the surrounding region during this time.

Revolution Resources Corporation completed additional geologic mapping, soil and rock sampling, and a ground magnetic survey in 2010-2011. Forty eight drill holes totaling 10,442 meters were completed during this period along 1000 meters of strike. Initial drilling targeted below the historic mine workings in two locations on the property. From these initial drill holes, 50-100 meter step outs in the northeast and southwest direction were drilled. Where gold mineralization was encountered, up and down dip holes were drilled. The drilling covered 1000 meters of strike length. Holes were drilled at dips ranging from -45 to -90, and azimuths from 144-150 degrees and 326-330 degrees. This orientation gave the most perpendicular intersections on the NE trending zones. True thicknesses of the zones are approximately 70% of the downhole length. Drilling defined a large, synclinally folded gold-bearing mineralized zone in the NE corner of the property, as well as several other zones along the southern limb of this fold. Two drill holes tested the northern limb of the fold, both intersecting gold-bearing horizons. The mineralization remains open along both limbs in the NE-SW direction and down plunge (Lucas, 2013).

The main geologic units on the Jones-Keystone property are mafic flows, volcanoclastic rocks, tuffs and metasedimentary rocks. There is extensive interbedding of the mafic flows and the volcanoclastic rocks, although all lithological contacts are fairly distinct. Small diabase dikes, trending NNW, occur in the northern portion of the property. There are also large felsic intrusions that have been identified on surface, but never encountered in diamond drilling. Geochemical studies indicate that the majority of the mafic flows are of basaltic composition, with a small percentage being andesitic. Locally these flows will be amygdaloidal. The volcanoclastic units are composed mainly of tuffaceous and metasediment material. The metasedimentary rocks are typically argillites that will locally grade into greywacke. Preserved bedding in the argillite is prominent in both surface outcrop and drill core (Fig. 17, Lucas, 2013).

The rocks exhibit greenschist-grade metamorphism, and there is weak pervasive chlorite alteration through the entire Jones-Keystone property (Klein et al., 2007). Locally sericite will become prominent as a secondary alteration. Silicification occurs in all units, but tends to be confined to small areas. There is a late carbonate overprinting of all other alteration that is manifested as millimeter scale stringers and as fracture fill (Lucas, 2013).

According to Lucas (2013), there are two distinct episodes of folding that can be defined, although there are several more that have been described for the area in the literature. The older folding is oriented in the east-west direction and the second, younger in the north-east direction. There is a strong NE fabric in all geologic units that runs axial planar to the younger folding episode, with a steep dip to the NW. The plunge of the NE trending folds is approximately 10-12 degrees to the southwest. This plunge changes where the two fold axis intersect. Geophysical work on the property defined two possible late NW trending faults that offset the fold patterns (Lucas, 2013, Fig. 17).

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Gold mineralization on the Jones Keystone Property is typically confined to the volcanoclastic units, but can occur in the mafic flows and to a lesser extent, in the argillites. The sulfide assemblage is pyrite+pyrrhotite +/- arsenopyrite. In gold-bearing areas, pyrite will occur as stringers, fine disseminated and dendritic. The pyrrhotite is typically disseminated to blebby. Arsenopyrite occurs as small 2-3mm blebs where the pyrite+pyrrhotite concentrations are high. Gold bearing intervals typically contain greater than 3 percent combined sulfide (with py>po), a very strong foliation and more intense sericite alteration than the surrounding rocks. Occasionally the mineralization will be accompanied by millimeter scale quartz stringers running parallel to the foliation (Fig. 17, Lucas, 2013).

The Homestake site is one kilometer due west of the historic Jones Keystone mine workings. Records indicated that the Homestake mine was operated around 1910 with a 52 foot shaft and minor drifting. The gold bearing horizon was described as a brecciated zone of grey-black rhyolite porphyry that had been bleached, silicified, sericitized and iron stained (Carpenter, 1976).

Mining activity at the Loflin Mine, located in Trinity, NC, began in the mid 1800's, and carried through until 1910. There is no clear record of the continuity of this activity, or under what company the mine operated. Over the years this mine site has gone by many names, including but not limited to, Laughlin, Loflin, Delk, Delft, Delph, and Herring. There are a number of small pits as well as several tunnels remaining on the mine site, but many of these tunnels are caved in, and most of the pits are filled with sediment, making it difficult to ascertain the extent of the underground workings. There is no evidence of a mill or any other processing equipment on the Loflin mine site.

Exploration of the Loflin Mine was renewed in 1975, and has been almost continuous since then. Cyprus Mines and Louisiana Land and Exploration explored the Loflin Mine property in 1975 and 1976 as part of a joint-venture project involved in reviewing gold occurrences in North Carolina. New Jersey Zinc explored the Loflin Mine property in 1981. Sparse records indicate that New Jersey Zinc drilled at least eleven rotary holes, to an average depth of approximately 30m, in the immediate areas of the historic Loflin Mine workings. Phelps Dodge Corporation resumed exploration of the Loflin property in the mid to late 1980's. The company conducted preliminary geologic mapping, limited surface sampling and possibly and IP survey. The company conducted no diamond drilling. In 1988, Carolina Resources drilled three reverse-circulation drill holes. These holes were drilled to an average of 50 meters depth, designed to target below mineralized zones in surface trenches. Noranda Exploration explored the Loflin mine property from 1989 through to 1992. The company conducted bedrock mapping, soil surveying, channel sampling of old workings and drilled 20 diamond drill core holes. Noranda conducted a VLF, VLF-R and ground magnetic survey over 15 line kilometers of the Loflin property. Twelve kilometers of this grid were covered by a self-potential survey (Lucas, 2013)

Revolution conducted diamond core drilling on the Loflin property in 2010 and 2011. Twenty seven drill holes were completed during this time for a total of 4,720 meters. Initial drilling targeted historic results from the Noranda Exploration 1989-1992 program. In order to gain a better understanding of the geology and orientation of the gold zone, the initial eight drill holes were completed in a variety of orientations. From this, it was determined that the best orientation for drilling was at an azimuth of 135 degrees, with dips between -45 and -65 degrees. Drilling was then conducted in 50 meter step outs in both the NE and SW directions, covering 500 meters of strike length was covered. Where gold mineralization was encountered, up and down dip holes were drilled. Drilling defined a gold-bearing mineralized zone within the core of a NE-SW trending syncline. This zone has a shallow plunge to the NE, and was drilled off to surface at the SW corner of the zone. The zone remains open down plunge in the north east direction, as well as up and down dip on several sections (Lucas, 2013).

The main geologic units on the Loflin property are mafic flows, volcanoclastic, metasediment and tuffaceous rocks. There are two diabase dikes that cross the property in a NE direction, cross cutting all units (Fig. 18). The mafic flows on the Loflin site can be amygdaloidal (amygdules up to 5mm in diameter and up to 5-7 percent of the unit). The volcanoclastic unit is composed of amygdaloidal flows and metasedimentary rocks, locally this unit will have a large percentage of quartz fragments. The metasedimentary units are argillite-rich and locally grade into small intervals of greywacke. There is a weak pervasive chlorite alteration through the entire property due to metamorphism. Locally sericite alteration becomes prominent, often masking the original protolith. Silicification occurs in the tuffaceous intervals, but tends to be patchy within the other geologic units. Fuchsite will occur as small patches and halos around quartz veins in areas of better mineralization (Lucas, 2013).

Anomalous As is typically correlative with Au, but two styles of mineralization were noted. Gold + arsenic is associated with strong sericite alteration in zones of intense cleavage development, but stockwork quartz-sulfide veins that occur in relatively unaltered rocks peripheral to the zones of strong cleavage carry gold without arsenic. Drilling results suggest that gold mineralization is controlled by the intersection of steeply NW-dipping structures parallel to foliation with favorable lithologies, specifically the two crystal tuff units. Like the Keystone Jones, Revolution geologists observed two distinct episodes of folding at Loflin The surface expression of these folds creates an undulating pattern in the geology, strongest where the two fold axes intersect. The folds exhibit a very shallow (3 to 4 degree) dip to the NE (Fig. 18, Lucas, 2013).

Gold mineralization at Loflin is typically confined to a specific tuffaceous unit in the core of a large syncline. To a lesser extent, gold mineralization occurs in the volcano-clastic rocks and flows that sit adjacent to the tuff. The saprolite will contain gold in areas where it overlies the tuff (where it is most likely a saprolitized version of the same unit). The typical sulfide assemblage is pyrite+pyrrhotite+arsenopyrite. The pyrite occurs as stringers, fine disseminated and dendritic as well as fill in brecciated areas. The pyrrhotite is typically disseminated to blebby and will be conspicuously absent in areas with the highest gold concentrations. Arsenopyrite is typically very fine and disseminated throughout the mineralized areas, both with and without the presence of gold. Gold bearing intervals typically contain greater than 5 percent combined sulfide (with py>asp>po), a very strong foliation and more intense sericite alteration than the surrounding rocks. It is common at Loflin to see this mineral assemblage and to have it be devoid of gold (Lucas, 2013).

The Hoover Hill Mine, located 20 kilometers west of Asheboro, NC, was discovered in 1848 by Joseph Hoover. The land was worked by the Hoover family for several years, until it was purchased by the Hoover Hill Gold Mining Company of London. The mine operated under this company from 1881 to 1895, when operations ceased. Some production was reported in 1914-1917, although records of this are incomplete. The property was then sold to the Briles family, who leased the land only once for exploration, in 1982, to Piedmont Land and Exploration Company. Over the 15 years that the Hoover Hill mine operated, five shafts were sunk (Briols, Gallimore, Hawkins 1 and 2, Provost), with one winze, and several drifts. Seven small surface pits were also worked during this time frame. At its deepest point, in the Briols Shaft, the mine extends to 350 feet. The company erected a steam powered, 20-stamp mill that operated at varying capacities over the years. The average processing rate was 40 tons in a 24 hour period, and over the 15 years, the mine produced over 11,000 ounces of gold (Pogue, 1910). The main shafts line up in a north-south direction, along a series a gold bearing quartz veins and breccia zones. The highest grade ore was contained in shoots within the vein system, the richest being the 13 foot wide, 70 foot long, Briols shoot, that was mined from both the Briols and Gallimore shafts (Hoover Hill Gold Mining Company notes, 1881-1895). It is reported that the main ore shoots have a north dip, while the rest of the deposit had a steep northwest dip. Throughout the life of the mine, minor placer mining was also carried out along the Uwharrie River that runs through the mine property (Lucas, 1913).

The main geologic units at the Hoover Hill mine are mafic flows, volcanoclastic rocks and porphyritic dikes. Historic reports mention rhyolites, but these were not encountered in drill core or surface mapping by Revolution. The volcanoclastic rock intervals often appear brecciated, but contain tuffaceous and metasediment rock fragments. Quartz veining is prominent on the property, with vein width ranging from 2 to 50 centimeters wide. Alteration at Hoover Hill is minimal, and is mainly pervasive chlorite alteration due to the greenschist facies metamorphism. Sericite occurs as halos around some of the larger veins. Where the concentration of veining increases, some silicification occurs in the mafic flows. Shear zones and large brecciated zones are mentioned in the historic reports, but were not encountered in drill core or field mapping by Revolution. Gold mineralization at Hoover Hill was historically confined to the quartz veins and healed breccia zones that carried pyrite and free gold. Older reports state that sphalerite is commonly disseminated through the sheared and brecciated zones in the rhyolite (Carpenter, 1976). Drilling by Revolution did not encounter any new mineralized zones (Lucas, 2013)

The Sawyer Mine, now called the Hickory project by Romarco, was discovered in the early 1800s and produced gold until the Civil War. Approximately 5,000 meters of drilling has been completed at the site by prior exploration companies. The historical drilling consists predominately of shallow holes searching for a shallow oxide resource. Romarco drilled an initial 16-hole program.

The New Sawyer Mine, now called the Ironwood target by Romarco is located approximately five kilometers northeast of the Sawyer Mine. Early exploration occurred on the property during the 1800s and until the 1930s. These workings consisted of trenches, pits and a few shallow shafts (10 to 30 meters). Battle Mountain Gold drilled six shallow RC holes and two shallow core holes. Six additional shallow RC holes were drilled in 2009 in order to identify a shallow oxide resource. Romarco initiated drilling at Ironwood with a six-hole program in 2011. For both the Sawyer and New Sawyer, very little exploration data is publically available or available to the authors.

CONCLUSIONS

The VMS deposits of the Carolina Terrain fit well in to known models related to hydrothermal fluids venting onto the ocean floor, and they represent syngenetic mineralization and associated stockwork alteration and mineralization. In spite of deformation related to the Gold Hill fault, these syngenetic features can still be mapped and recognized.

The disseminated gold-pyrite deposits represent a distinctive but problematical style of gold mineralization in the Carolina Terrane of central North Carolina. All are characterized by strong structural controls and gold associated with low sulfide, pyrite-dominated silicic to sericite alteration. Variations may be attributed to differences in the type of controlling structures and the physical and chemical properties of the host rocks. Available evidence suggests that these deposits are synkinematic with ductile-brittle strain and syn-metamorphic rather than epigenetic gold systems associated with Uwharrie volcanism. There may be some igneous component in the generation of ore fluids or remobilization from gold enriched source rocks, but this association remains untested and thus unsupported.

The age of the Howie and Lewis Group mines in Union County is constrained to the age of deformation along the Gold Hill Fault Zone, which appears to be early Cambrian to late Ordovician (Standard 2003, Allen 2005). The gold deposits along the Sawyer-Keystone Trend in northern Randolph County appear to be aligned on an ENE-trend that cuts across the Cid, Tillery, and Uwharrie Formations. If these deposits are linked by a low-strain fault or shear zone, then their age must also post-date deposition of their host rocks and be at least as young as early Cambrian. If the gold deposits of the Ophir District are similar in genesis to those of the Sawyer-Keystone Trend and those within the Gold Hill Fault Zone, then they are also likely to be younger than the host Tillery Formation. The age of these deposits relative to their host rocks appears to preclude a direct volcanogenic-syngenetic origin.

The Russell and Coggins deposits in the Ophir District and the Sawyer and Jones-Keystone deposits have also been compared to the Ridgeway and Haile deposits of the Carolina Terrane in north-central South Carolina. Although there are similarities in the style and controls of alteration and mineralization, the Ridgeway and Haile hydrothermal systems and gold deposits include potassium feldspar as a stable alteration phase, are strongly anomalous in molybdenum and fluorine, and well constrained to a late Proterozoic age, circa 550 Ma. This would suggest that the Sawyer-Keystone Trend and Ophir District deposits formed during a separate and distinct metallogenic event.

The Ridgeway and Haile deposits appear to have formed during latest Proterozoic collision and amalgamation of the Carolina and Charlotte terranes (Moye, 2012). Age constraints on the Sawyer-Keystone Trend and Ophir District deposits suggest association with deformation and metamorphism resulting from Cambrian to Ordovician docking of Carolinia with Laurentia. Compressive deformation and metamorphism of the Albemarle Sequence, development of large-scale en echelon folds in the Albemarle Group, and deformation along the Gold Hill Fault Zone are associated with this event (Hibbard et al. 2008, Offield et al. 1995, Ayuso et al. 1997, Standard 2003, Allen 2005).

Classic quartz veins with gold often represent open space development within brittle rocks during seismic events and sealing with quartz due to pressure release and cooling. If gold is present in the fluids, it will also be deposited. Historic mines such as the Iola offer potential development as an underground mine.

Models applicable to other major gold mines in the world are valid in the Carolina Terrane. With further exploration and drilling, economic development is possible. Based on historic and recent drilling, the Sawyer-New Sawyer, Jones-Keystone and Deep River prospects have the potential to be economically minable resources. However, currently the region suffers from a lack of continuity in exploration and a lack of sufficient drilling of individual targets to define an economic gold resource. Other known deposits that were not discussed in this paper remain also valid targets for exploration and development.

The rural portions of the state are favorable for mineral development, but a growing population places limits on areas of new mine development. Examples are the Howie mine which is now a subdivision and the high real estate prices around the Reed gold mine. Governmental institutions can substantially encourage and support. exploration and mining in the state through the collection and archiving of historic data resources, renewed emphasis on geologic mapping and sample analysis in mineralized areas, and making this information available in digital formats. Additionally, companies and individuals that have been active in minerals exploration in the Piedmont are encouraged to share nonproprietary data resources with governmental institutions to expand the existing informational resources. Finally there is a real lack of economic geology programs in the Universities of the region to continue to support research on the deposits of the region.

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CAROLINIA – A DISTINCT ELEMENT IN THE APPALACHIAN PERI-GONDWANAN REALM? HOW OXYGEN-ISOTOPE TERRANE MAPPING PROVIDES INSIGHTS INTO TECTONOMAGMATIC HISTORIES AND ROCK-WATER INTERACTION

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EXTENDED ABSTRACT

The pre-accretion history of peri-Gondwanan terranes in the Appalachian orogen can control certain geochemical characteristics of individual terranes components. In the best case, these traits can be used to trace the relative positioning of individual terranes along the Gondwanan margin and determine the timing of their rift-drift history and subsequent accretion to Laurentia. Ganderia, Avalonia and Carolinia form a sizeable fraction of the Appalachians (Fig. 1) and they share many gross similarities in their pre-Paleozoic magmatic histories; consequently they were initially interpreted to constitute a single, coherent Neoproterozoic microcontinent. More recent fieldwork, radiometric dating and geochemical analysis demonstrate that these terranes have distinctly different crust-building, rifting, and collisional histories (e.g. Hibbard et al., 2007).

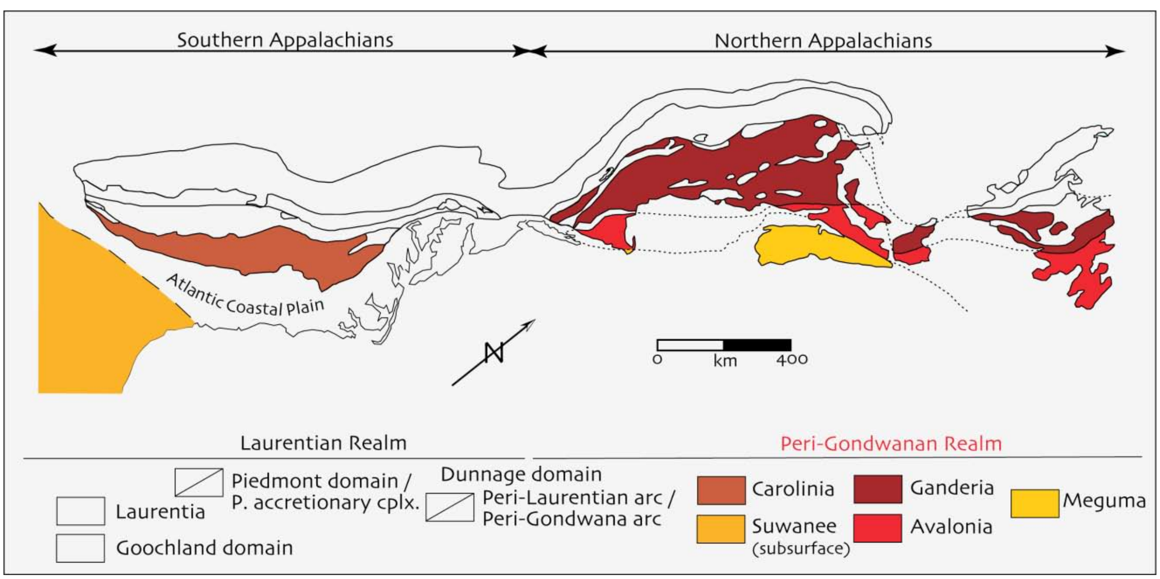

Fig. 1: The Appalachian peri-Gondwanan realm.

We have used whole-rock and mineral oxygen-isotope compositions to obtain information on the source characteristics and regional hydrothermal processes that affected each of these terranes. Previous oxygen-isotope studies showed the Neoproterozoic igneous rocks in West Avalonia are significantly depleted of ^{18}O ($\delta^{18}O_{WR}$ as low as –3‰)(Potter et al., 2008; 2012). These $\delta^{18}O$ results have been attributed to regional-scale hydrothermal meteoric and seawater alteration during late-Neoproterozoic rifting and extension (~590-550Ma). No signs of regional ^{18}O-depletion have been observed in Ganderia. Oxygen-isotope data for Carolinia reveal ^{18}O-depletion in the 630-615 Ma Hyco arc and ~580 Ma Virgilina sequence ($\delta^{18}O_{WR}$ = +0.4 to +5.4‰), suggesting a possible linkage with West Avalonia. However, the lower $\delta^{18}O_{WR}$ values of the Hyco arc and Virgilina sequence are succeeded by normal-high $\delta^{18}O_{WR}$ values in the younger ~545-540 Ma Albermarle arc (+8.6 to +11.4‰), a transition not observed in West Avalonia.

Here, we summarise these geochemical features and propose how they may indicate different tectonomagmatic processes that define each individual terrane. Two processes were probably most influential in producing the oxygen isotopic signatures of Carolinia, Avalonia and Ganderia. First, one should consider the nature of cessation of subduction and arc formation leading to collapse of the arc: (i) rift-trench collision associated with transtensional extension of the crust as proposed for Avalonia and the Hyco arc/Virgilina sequence in Carolinia versus (ii) arc-arc collision and associated metamorphism observed in Ganderia and bracketing the formation and termination of the Albermarle arc sequence. Second, the nature of the crust appears to have been important. Where ^{18}O-depletion has been observed, ε_{Nd} results indicate association with thin juvenile crust; more evolved crust retains normal $\partial^{18}O$ signatures.

Collectively, the oxygen-isotope, field and other geochemical data suggest that Carolinia has had a distinct tectonomagmatic history from other previously associated peri-Gondwanan terranes.

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The Virgilina sequence redefined, north central North Carolina

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Abstract

Traditionally, the Virgilina sequence has been viewed as the oldest exposed component of the Carolina terrane, one of the best-known subdivisions of the Appalachian peri-Gondwanan crustal block of Carolinia. The Virgilina sequence was thought to be a Neoproterozoic assemblage with volcanics of the basal Hyco Formation conformably overlain by the metaclastic Aaron Formation and interlayered Virgilina volcanics; however, detrital geochronologic studies indicate a time gap of approximately 37 m.y. between the Hyco and Aaron formations. Multiple hypotheses concerning the cause of the gap were identified for investigation: 1) slow deposition of the upper Hyco Formation and a conformable contact with the overlying Aaron Formation, 2) there is a significant fault between two distinct sequences, or 3) an unconformity between the Hyco and Aaron formations. Observations from detailed geologic mapping of the Virgilina area at a scale of 1:24,000 indicate that strata on either side of the Hyco-Aaron formation contact are concordant and that no significant faulting modified an originally stratigraphic contact, thus excluding hypothesis 2. We also report a new U-Pb TIMS zircon age of 616.5 ± 1.2 Ma from a felsic tuff near the top of the Hyco Formation; considered in conjunction with a previous date of 615 +4/-2 on Hyco volcanics not near the top of the formation, this date indicates that deposition of the upper Hyco Formation was rapid and precludes hypothesis 1. These dates, combined with the detrital ages from the Aaron Formation, suggest the Hyco-Aaron lacuna to be on the order of 37 m.y. Accordingly, we remove the Hyco Formation from the Virgilina sequence and assign it to a new lithotectonic unit, the Hyco arc, and we redefine the 'Virgilina sequence' to include only the Aaron Formation and the interlayered Virgilina member. Further research is needed in order to clarify the tectonic setting of the new Virgilina sequence.

Introduction

The Virgilina sequence is one of the major lithotectonic elements that constitute the Carolina terrane, the best-known subdivision of the southern Appalachian peri-Gondwanan block of Carolinia (Fig. 1). Traditionally the sequence has been viewed as a magmatic arc sequence consisting of low-grade metamorphic felsic - mafic volcanics and associated volcaniclastics and clastic sedimentary rocks of the Hyco Formation and Aaron Formation and a associated Virgilina volcanics (e.g. Harris and

Glover, 1988; Hibbard et al., 2002). The sequence was thought to form the oldest exposed portion of the Carolina terrane. It had been recognized by some geologists that the contact between the Hyco and Aaron formations was likely an unconformity, but the time gap was thought to be minor and contained within a single arc sequence (e.g. Newton, 1983; Harris and Glover, 1988; Hackley et al., 2007). However, detrital zircon geochronology implies that there is a major time gap of approximately 37 m.y. between the Hyco and Aaron formations (Samson & Secor, 2001, Pollock, 2007). Such a hiatus between the two main units of the sequence casts doubt that the Hyco and Aaron formations constitute portions of a single arc, thus motivating the present study into the relationship between the Hyco and Aaron formations (Bowman, 2010). Resolution of the relationship between the Hyco and Aaron formations is significant for the comparison and correlation of the Carolina terrane with other components of Carolinia as well as with elements throughout the Appalachian peri-Gondwanan realm (e.g. Hibbard et al., 2007).

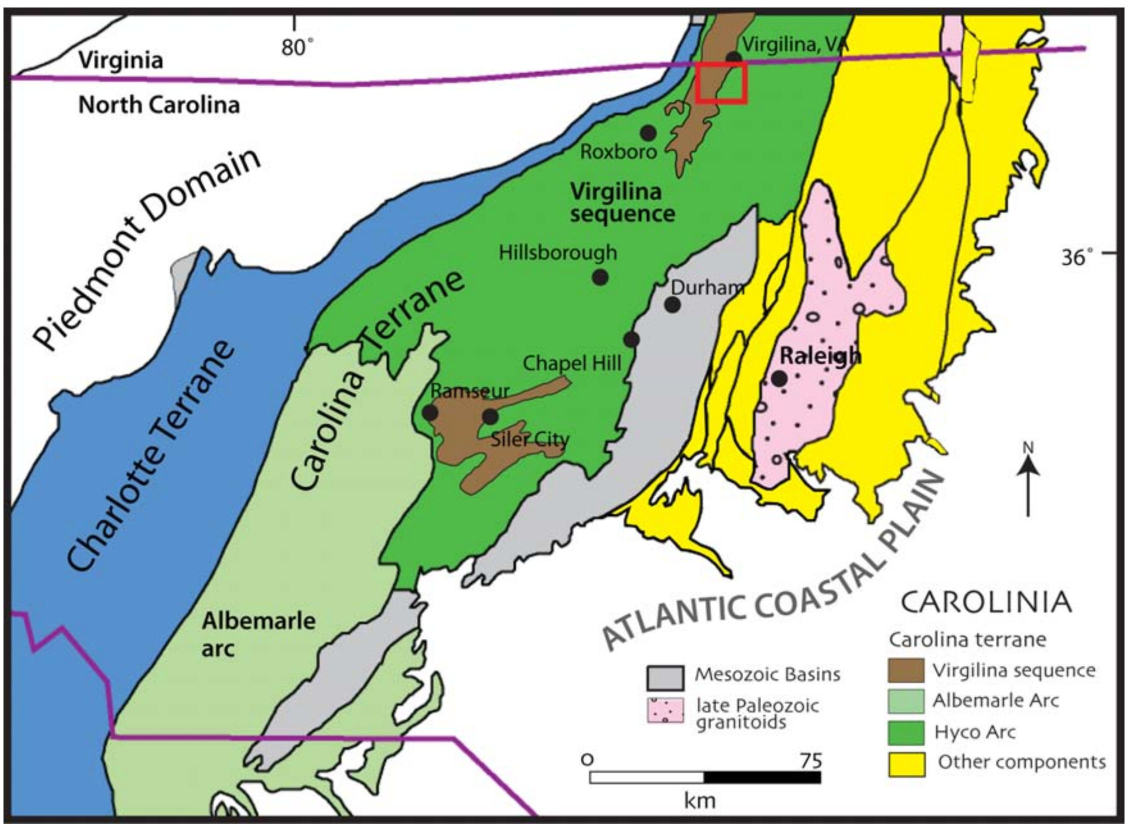

Figure 1: Subdivisions of the Carolina terrane in North Carolina.

This study is directed at testing three hypotheses we formulated to explain the time discrepancy between the Hyco and Aaron formations, including the following: 1) previously dated samples of the Hyco Formation are not from the top of the formation, thus the time gap could be apparent if the upper Hyco Formation represents continuous, slow deposition, 2) the time gap is real and a significant fault separates two distinct sequences, and 3) the time gap is real and an unconformity separates the Hyco and Aaron formations. In order to determine the relationship between the formations, we undertook unprecedented 1:24,000 scale geological mapping of the

Virgilina sequence in its 'type' location in the immediate vicinity of Virgilina, Virginia, on the Virginia-North Carolina state line. In addition, we tested hypothesis one, above, by U-Pb TIMS zircon dating of felsic tuff in the uppermost Hyco Formation. The results of these studies have led us to redefine the traditional Virgilina sequence.

Geologic Context

The traditional Virgilina sequence was estimated to be at least 8 km thick (Glover and Sinha, 1973) and composed of three distinct units, the Hyco Formation and the Aaron Formation and its Virgilina member. The Hyco Formation is the oldest unit and consists of a thick, 2-5 km, pile of felsic to intermediate volcanics in North Carolina. High precision U-Pb zircon age dating from volcanic rocks has shown the youngest age of the Hyco Formation to be 615.7 +4/-2 Ma (Wortman et. al, 2000); this date is from within the bulk formation and not at its top.

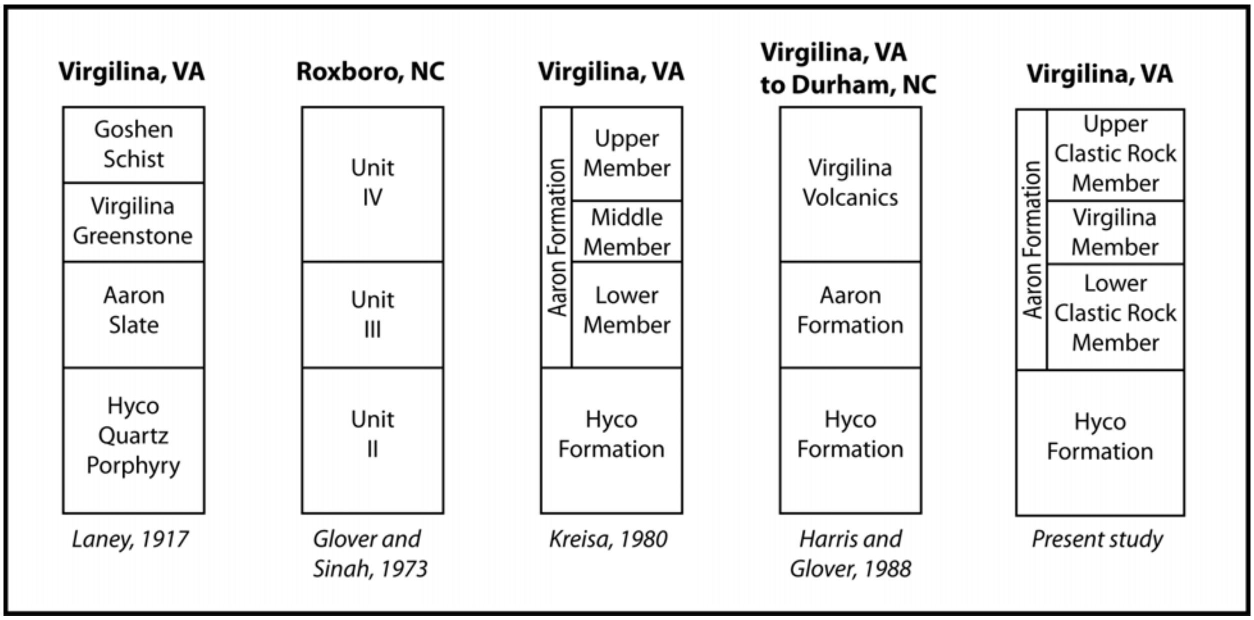

Figure 2: Previous and current nomenclature for stratigraphic units of the Hyco and Aaron, formations. Modified from Harris and Glover (1988).

Previous workers in the area have subdivided the mainly metaclastic rocks that overlie the Hyco Formation have been subdivided into multiple different stratigraphic schemes (Fig. 2). Our mapping in this study confirms that a volcanic unit within the metaclastics is not present everywhere, and where absent, it is difficult to identify a boundary between the metaclastics below the projected volcanic horizon from those above. Consequently, our favored stratigraphic scheme (Fig. 2) described below corresponds to that of Kreisa (1980), wherein all of the metaclastic rocks in the area that overlie the Hyco Formation are assigned to the Aaron Formation, which is composed of conglomerates, other metaclastic rocks, and a discontinuous volcanic member, the Virgilina Member (Kreisa, 1980, Bowman, 2010). Aaron Formation sandstones have been shown to be derived from the erosion of the Hyco Formation and detailed sedimentological study of the Aaron formation indicate that it was deposited in a retrogradational submarine-fan sequence (Harris, 1984). Detrital zircon geochronology in the Virgilina area provides a maximum age of deposition for a conglomerate in the Aaron Formation of ca. 578 ± 9 Ma (Samson et al., 2001). This date is within error of a more recently reported maximum age of ca. 588 ± 11 Ma from the formation near Siler City, NC (Pollock, 2007; Pollock et al., 2010). Therefore, there is a minimum time gap of approximately 27 to 37 m.y. between the ca. 615 Ma age of the Hyco Formation and deposition of the Aaron Formation.

Both the Hyco and Aaron formations in the area have been folded by the Virgilina syncline, a subhorizontal, upright, slightly overturned to the northwest regional structure that repeats the Hyco Formation to either side of a core composed of Aaron Formation strata (Fig. 3). Minor map-scale folds inferred from outcrop patterns, bedding-cleavage relationships, and shared axial planar cleavages are present within both limbs of the syncline. These small parasitic folds account for the significant difference in apparent unit thickness between the upright and overturned limb of the Virgilina syncline. The folds are accompanied by an axial planar slaty cleavage and a steep mineral and clast lineation (Bowman, 2010). These structures and accompanying greenschist facies metamorphism have been collectively attributed to the Neoproterozoic Virgilina deformation (e.g. Glover and Sinha, 1973; Harris and Glover, 1988; Hibbard and Samson, 1995; Bowman, 2010).

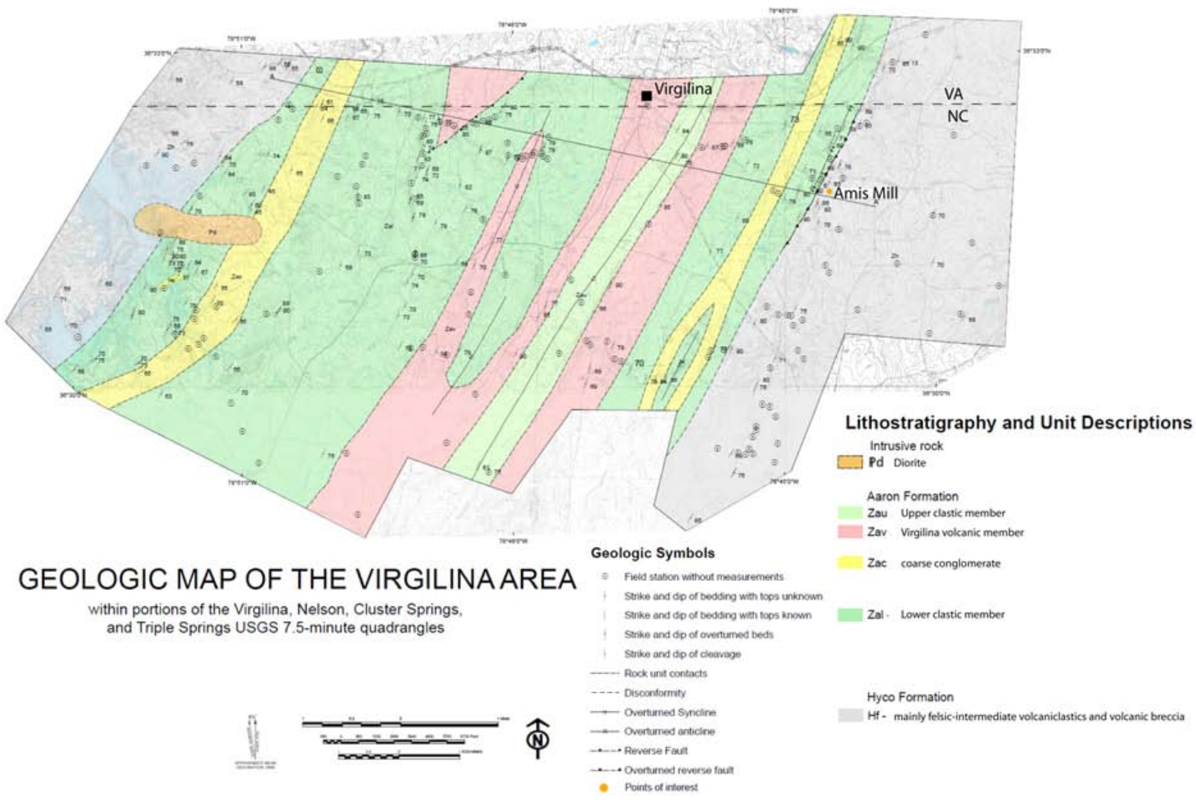

Figure 3: Geologic map of the Virgilina area (Bowman, 2010).

LITHOSTRATIGRAPHIC UNITS

Prior to describing the contact relationship between the Hyco and Aaron formations as well as our geochronology study, it is useful to briefly describe the rock units in the Virgilina area, the 'type area' for the Virgilina sequence.

Our map area is located along the North Carolina-Virginia state line just south of the town of Virgilina, VA and a few miles northeast of Roxboro, NC (Figs. 1, 3). We recognize four major map units in the type area, including the 1) upper Hyco Formation, felsic-intermediate volcaniclastics, 2) Aaron Formation lower member of metasedimentary rocks, 3) felsic-mafic volcaniclastics of the Virgilina member of the Aaron Formation, and 4) Aaron Formation upper member of metasedimentary rocks (Fig. 2). In the Aaron Formation, the lower and upper members are indistinguishable where the Virgilina member is missing, hence the Aaron clastic rocks will be described together. It should be noted that although the rocks have been metamorphosed to the greenschist facies, relict primary structures are commonly preserved; thus for brevity, the prefix "meta" is dropped from the nomenclature for all rock types described below.

The **upper Hyco Formation** in the area is composed of mainly dacitic tuffs and felsic fragmental volcaniclastics. Felsic crystal tuff is typically found stratigraphically within a couple meters of the top of the formation. Fresh exposures of tuffs are foliated, with a light-gray, fine-medium grained groundmass that contains variable amounts of quartz, feldspar phenocrysts, devitrified pumice, and minor amounts of volcanic lithics. An abundance of chlorite is present is some layers. The dacite crystal tuffs are interpreted to be primarily pyroclastic deposits with no evidence of being reworked.

Fragmental volcaniclastics are interspersed with felsic tuffs in the upper Hyco Formation. Rounded to sub-rounded volcanic and devitrified pumice fragments are supported by a light-gray tuffaceous matrix and are interpreted to represent an epiclastic deposit (Bowman, 2010). A volcanic sandstone was found near the Hyco - Aaron formation contact that is typically felsic – intermediate and defined by a fine- to medium-grained, light gray to tan, tuffaceous matrix with an abundance of sub-angular to angular feldspar crystals that are typically < 1 mm in size. In thin section, this rock type is distinctly different from the lower member of the Aaron Formation based on the unusual abundance of feldspar crystals present.

The best age constraint on the Hyco Formation is a high-precisionU-Pb TIMS zircon age of 615 +4/-2 Ma on a dacite tuff (Wortman et al., 2000); however, the dated volcanic was not from near the top of the formation.

The **lower and upper members of the Aaron Formation** have a combined thickness of approximately 2 km in the type area. Volcanogenic sedimentary rocks are the most abundant clastic rock type in the formation. The lower member contains three mappable rock types, including 1) sandstone and siltstone, 2) a distinct conglomerate, and 3) phyllite. The upper member consists primarily of siltstone.

Sandstone layers are stratigraphically concentrated in the lower member and noticeably absent from the upper member. Volcanic sandstones are light gray, grayish-green, or bluish-green, medium-to coarse-grained, containing quartz- and feldspar-rich crystals, volcanic lithics, and opaques that are concentrated in layers parallel to bedding. Primary structures such as bedding (2 mm – 20 cm thick), cross-bedding, and graded bedding are commonly found throughout the unit. Outcrops of siltstones are massive- to thinly-bedded that consist of alternating light and dark greenish-gray laminations.

A consistent conglomerate marker unit is found approximately 300 m stratigraphically above the base of the lower member. The conglomerate is generally massive, consisting of rounded, poorly sorted quartzite, vein quartz, and felsic volcanic clasts that range in size from 2 cm - 15 cm in long dimension. Distinct dark red jasper pebbles ranging in size from 1 - 6 cm in length are present as well. The concentration of larger, rounded, potato-sized clasts within the conglomerate has prompted the local residents to call it, 'Tater Rock'. Massive conglomerate beds range from <1 - 2 m in thickness. The matrix consists of silt to sand sized particles with discontinuous magnetite-rich layers.

The phyllitic rocks of the lower member range from sandstones to siltstones and are generally lithic-rich with moderate amounts of quartz, chlorite and epidote. Bedding ranges from thinly laminated (less than 1mm) to 3 cm thick and are graded.

The **Virgilina member** consists of mafic and felsic volcaniclastics and it has a thickness of at least 300 m in the type area. Although unexposed, the contacts with Aaron metaclastics appear to be conformable, yet abrupt (Bowman, 2010).

Three distinct mafic volcaniclastic rock types were identified in the member, including 1) intermediate-mafic epiclastic, 2) mafic fragmental tuffaceous volcaniclastic, and 3) mafic volcaniclastic. The most predominant type is a fine- to medium-grained, well-sorted massive intermediate–mafic, homogenous, greenish-gray epiclastic with moderately rounded quartz grains. Local pebbles of larger epidote-rich rock and volcanic clasts are common.

The only direct age constraints on the Aaron Formation come from detrital geochronology studies. The youngest reported grain from a sample of the distinct conglomerate near the base of the formation is 578 ± 9 Ma (Samson et al., 2000). A similar conglomerate considered to be part of the Aaron Formation in central North Carolina, near Siler City (Fig. 1) has yielded a maximum age of 588 ± 11 Ma (Pollock, 2007; Pollock et al., 2010).

CONTACT BETWEEN HYCO AND AARON FORMATIONS

The contact between the Hyco and Aaron formations is exposed on both limbs of the Virgilina syncline (Fig. 3); each formation contains distinct marker units that indicate proximity to the contact. For example, we observed that a felsic tuffaceous volcaniclastic unit occurs near the top of the Hyco Formation; Kreisa (1980) also reported the same observation. The contact is unexposed along the western, upright limb of the Virgilina syncline; however it is exposed along the overturned eastern limb, where there are minor fault complications. We will describe the simpler, though unexposed, contact on the western limb of the fold first.

The western contact along the upright limb of the Virgilina syncline near the North Carolina-Virginia state line is unexposed; in addition, in this area it is difficult to distinguish between upper volcaniclastics of the Hyco Formation and the lower volcanogenic sediments of the Aaron Formation, which are derived from the underlying Hyco Formation. However the relationship between formations here can be gleaned from multiple outcrops along the northeastern embayment of Mayo reservoir (Fig. 4). Along the western edge of the embayment, a small outcrop of a tuffaceous volcanic, a rock type common to the Hyco Formation, was found. Continuing clockwise around the embayment, a small outcrop of feldspar-rich volcanic sandstone distinctly different from typical sandstone of the Aaron Formation outcrops within 10 meters of a gray, phyllitic rock similar to the Aaron Formation phyllite found south along the eastern edge. The Hyco – Aaron formation contact is tightly constrained between these two outcrops with feldspar-rich volcanic sandstone defining the top of the Hyco Formation and phyllite defining the base of the Aaron Formation. Bedding in the tuffaceous units of the Hyco Formation was not evident in the area of the contact; however, based on distribution, map pattern, and trend of rock units, bedding within each formation along the entire western limb of the Virgilina syncline, the contact between the two formations is interpreted to be concordant and conformable.

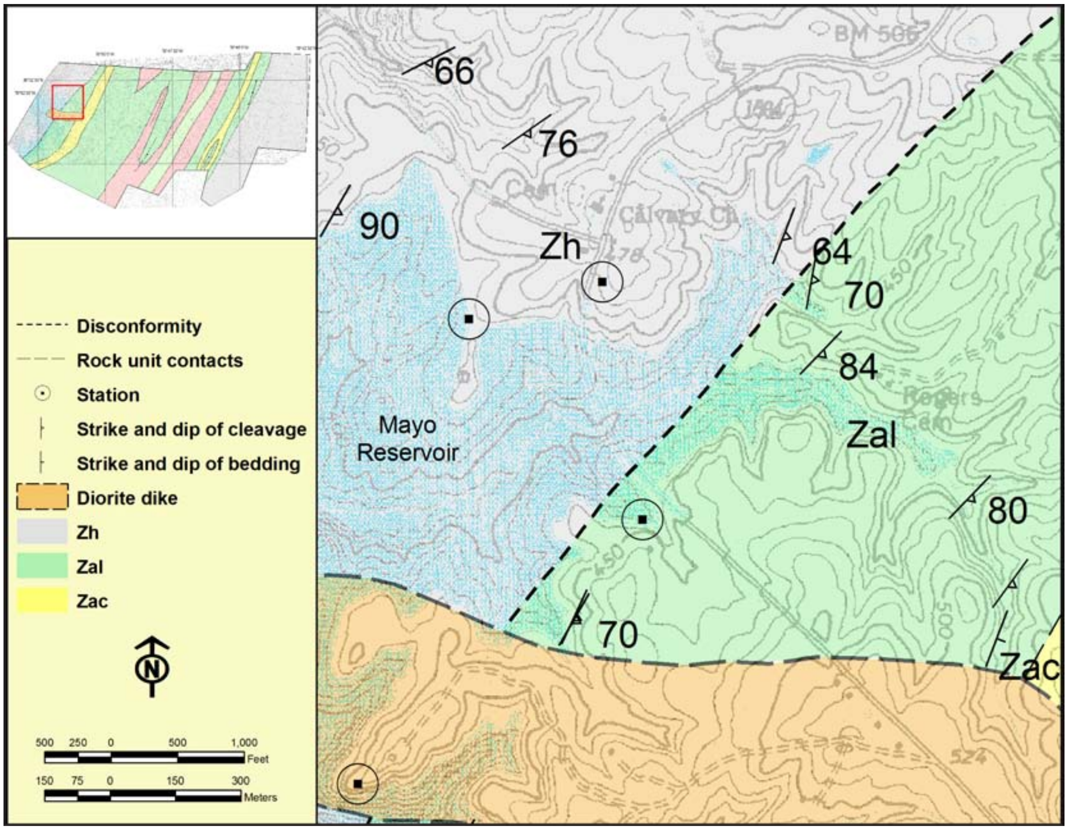

Figure 4: Geology of the northeast arm of Mayo Reservoir with field station location.

The Hyco-Aaron formation contact on the eastern, overturned limb of the Virgilina syncline is well constrained by detailed field observations in the area of Amis Mill. Bedding within the Hyco and Aaron formations within 30 m of each other are strike-parallel but Hyco strata are sub-vertical while bedding in the Aaron dips shallowly. Therefore, bedding within the Hyco and Aaron formations near the eastern contact is discordant.

The cause of this discordancy appears to be a steeply southeast dipping fault that truncates a parasitic, second order, fold along this limb of the Virgilina syncline (Fig. 3). The fault dips steeply to the southeast and is marked by a cataclastic zone less than 3 cm wide (Fig. 5). In hand sample, the fault separating rocks of the two formations is marked by layers of fine-grained, light brown material that is

Figure 5: Cataclastic zone found near Hyco Formation (left side) and lower member of the Aaron Formation (right side) contact.

overprinted by minor folds and minor faults and an intense foliation that is parallel to the regional cleavage in the Virgilina syncline. In thin section, brittle fractures in deformed grains and tension gashes were observed sub-perpendicular to tectonic cleavage. Extension direction, interpreted from microboudins of epidote grains with chlorite and white mica boudin neck infillings, is oriented down dip within the cleavage. The tension gashes and microboudins are confined to cleavage microlithons between cleavage seams. This intensely deformed zone is interpreted to be a cataclastic zone. The down dip extension direction indicates the fault to be a dip slip fault and curvature and orientation of the tension gashes indicate normal sense of shear with respect to the present land surface. However, the confinement of the tension gashes to microlithons between cleavage and their kinematics with respect to the axial planar cleavage strongly suggest that the fault is a reverse fault that is slightly overturned. We envisage the fault as having formed from reverse slip along the east limb of the Virgilina syncline as the fold was forming and material was migrating out of it, only to have the fault become overturned with overturning and further development of the regional fold (Fig. 6).

There is a direct relationship between the length of a fault, the width of the fault zone, and the amount of displacement along that fault (Cowie and Scholz, 1992, Scholz et al., 1993). The amount of displacement along the fault at Amis Mill is interpreted to be insignificant based on the narrow width of the fault zone (3 cm). In addition, the thicknesses of lower Aaron Formation that lie beneath the distinct conglomerate unit ('Tater Rock') is the same on this fault-modified eastern limb as on the apparently conformable west limb of the Virgilina syncline. Consequently, this collection of observations leads us to interpret that the Hyco-Aaron formation contact was originally concordant and stratigraphic; this

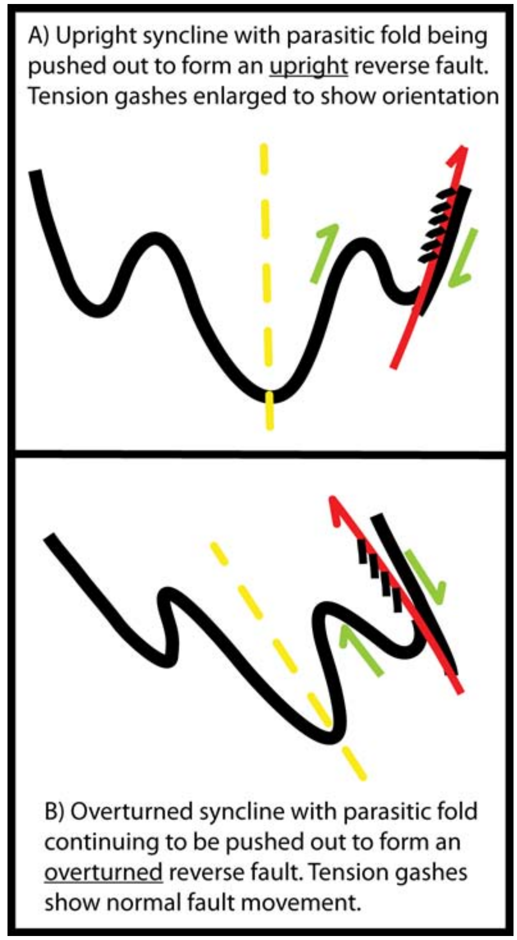

Figure 6: Generalized cross-section showing evolution of overturned reverse fault and tension gashes displaying normal fault motion.

relationship is likely preserved on the poorly exposed west limb of the syncline, but fault modified on the overturned east limb.

Geochronology

In order to test the hypothesis that the time gap between the Hyco and Aaron formations might only be apparent, due to slow deposition of the upper Hyco strata, we initiated a geochronology study focused on the age of the upper Hyco strata. The only high-precision U-Pb zircon age (615 +4/-2 Ma) comes from within the bulk of the Hyco Formation and not from the vicinity of the top of the unit (Wortman et al., 2000). Thus, we set out to obtain an age for strata in the upper portion of the Hyco Formation, near its contact with the Aaron Formation.

Sample

A fresh sample of felsic tuff from the upper Hyco Formation was collected from a small private quarry along the banks of Aarons Creek just south of Amis Mill. The quarry is located approximately 500 m east of the Hyco-Aaron Formation contact on the mill site. The dated sample, # 52, is a dacite felsic tuff that is typical of the Hyco Formation elsewhere in the study area. It ranges from gray to light-gray, fine- to medium-grained, and contains approximately 50% feldspar and 20% quartz crystals, with varied amounts of sericite and volcanic lithic fragments.

Methods and Results

U-Pb geochronology analysis of zircon for this study was conducted in the R. Ken Williams ’45 Radiogenic Isotope Geosciences Laboratory at Texas A&M under the supervision of Dr. Brent Miller. Sample preparation and analytical methods are follow those described in Hughes et al., 2013. More than 65 zircons were carefully selected under a binocular microscope and 24 of those grains, divided into seven fractions (Table 1), were selected for ID-TIMS (isotope dissolution-TIMS) dating. Three of the fractions consisted of small, clear crystals with slightly resorbed corners. Four of the fractions consisted of small - medium, light brown subhedral crystals with cracks. Total procedural blanks for U-Pb protocols during the course of this work were routinely around 1-2 picograms Pb per sample. Raw data were reduced using the “YourLab” algorithms of Schmitz and Shoene(2007) and diagrams plotted and ages calculated in IsoPlot 3.7 (Ludwig, 2008), with data interpretation and visualization aided by the programs Tripoli and U-Pb Redux(M.I.T. unpublished programs). All tables, diagrams, and text report data at 2σ.

The analyzed fractions (Table 1) yielded a concordia age of 616.52 ± 1.2 Ma (Fig. 7)and is taken to represent the crystallization age of the Hyco tuff. This new age is in close agreement with the previous high-precision age for the Hyco Formation (615 +4/-2 Ma) that was obtained from within the formation, not proximal to the upper contact (Wortman et al., 2000). Collectively, these data strongly suggest that the upper Hyco Formation was rapidly deposited, discounting hypothesis 1, that the time gap between the Hyco and Aaron formations may only be apparent due to slow deposition of the Hyco Formation.

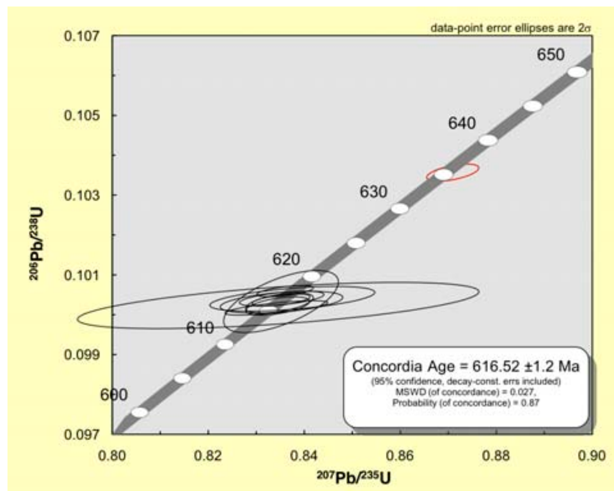

Figure 7: U-Pb concordia plot of zircon data from sample 52; ellipses are 2σ uncertainties. All data lie near the crystallization age 616.5 Ma. The red ellipse has been interpreted to represent an inherited zircon.

Discussion and Summary

The Virgilina sequence was previously thought to represent a single arc sequence composed of the Hyco and Aaron formations. However, a significant time break between the two formations was suggested by the scant available geochronology data. Our study aimed to resolve between three possibly hypotheses for the apparent time discrepancy: 1) the available age constraint on the Hyco Formation at the outset of this study was not from the top of the formation, thus the time gap could be apparent if the upper Hyco

Table 1. U-Pb isotopic data

Sample (# grains)	U	$\frac{Th}{U}$	Pb	$^{206}Pb^*$	mol %	$\frac{Pb^*}{Pb_c}$	Pb_c	$\frac{^{206}Pb}{^{204}Pb}$	$\frac{^{208}Pb}{^{206}Pb}$	$\frac{^{207}Pb}{^{206}Pb}$	% err	$\frac{^{207}Pb}{^{235}U}$	% err	$\frac{^{206}Pb}{^{238}U}$	% err	corr.	$\frac{^{207}Pb}{^{206}Pb}$	±	$\frac{^{207}Pb}{^{235}U}$	±	$\frac{^{206}Pb}{^{238}U}$	±
	Compositional Parameters								Radiogenic Isotope Ratios								Isotopic Ages					
	(ng)		(pg)	$\times 10^{-13}$ mol	$^{206}Pb^*$		(pg)									coef.						
(a)	(b)	(c)	(b)	(d)	(d)	(d)	(d)	(e)	(f)	(f)	(g)	(f)	(g)	(f)	(g)		(h)	(g)	(h)	(g)	(h)	(g)
M-052																						
(Z6) small prismatic (n=1)	216.8	0.732	36.9	0.9060	85.4%	1.9	12.82	125	0.228	0.060388	3.829	0.834494	4.093	0.100224	0.472	0.598	617.5	82.7	616.1	18.9	615.7	2.8
(Z38) small prismatic (n=2)	300.5	0.627	36.2	1.2573	96.6%	8.9	3.66	541	0.195	0.060382	1.161	0.835158	1.242	0.100313	0.225	0.438	617.3	25.1	616.5	5.7	616.2	1.3
(Z39) small prismatic (n=2)	280.5	0.625	32.6	1.1723	97.8%	13.7	2.21	830	0.194	0.060378	0.574	0.834317	0.648	0.100220	0.188	0.514	617.1	12.4	616.0	3.0	615.7	1.1
(Z41) small prismatic (n=2)	225.0	0.683	26.7	0.9412	97.5%	12.5	1.97	748	0.212	0.060367	0.601	0.834775	0.683	0.100292	0.208	0.525	616.8	13.0	616.3	3.2	616.1	1.2
(Z42) small prismatic (n=2)	183.4	0.831	23.8	0.7679	95.6%	7.2	2.89	425	0.259	0.060494	1.556	0.837386	1.674	0.100395	0.254	0.522	621.3	33.6	617.7	7.7	616.7	1.5
(Z43) small prismatic (n=2)	263.0	0.598	30.8	1.0988	97.2%	11.0	2.57	673	0.186	0.060391	0.949	0.834109	1.047	0.100172	0.143	0.721	617.6	20.5	615.9	4.8	615.4	0.8
(Z44) small prismatic (n=2)	274.2	0.753	35.6	1.1480	95.0%	6.2	4.96	370	0.234	0.060332	0.779	0.835220	0.855	0.100404	0.157	0.553	615.5	16.8	616.5	3.9	616.8	0.9
(Z132) small prismatic (n=2)	308.3	0.968	38.3	1.2934	98.2%	18.5	1.97	1023	0.301	0.060277	0.516	0.835986	0.575	0.100588	0.113	0.593	613.5	11.1	616.9	2.7	617.9	0.7
(Z136) small prismatic (n=2)	204.1	0.739	25.9	0.8539	95.7%	7.3	3.13	434	0.230	0.060371	0.913	0.835083	1.167	0.100323	0.631	0.628	616.9	19.7	616.4	5.4	616.3	3.7
(Z141) small prismatic (n=3)	378.9	0.622	46.4	1.6364	97.1%	10.6	4.00	642	0.194	0.060994	0.438	0.870947	0.509	0.103563	0.170	0.555	639.0	9.4	636.1	2.4	635.3	1.0

(a) Z1, Z2 etc. are internl laboratory labels for fractions composed of single zircon grains or two-grain aliquots; all fractions annealed and chemically abraded after Mattinson (2005).
(b) U and total Pb content of zircon remnants after chemical abrasion.
(c) Model Th/U ratio calculated from radiogenic 208Pb/206Pb ratio and 207Pb/235U age.
(d) Pb* and Pbc represent radiogenic and common Pb, respectively; mol % $^{206}Pb^*$ with respect to radiogenic, blank and initial common Pb.
(e) Measured ratio corrected for spike and fractionation only.
Daly Pb analyses corrected for 0.22%/AMU mass bias based on repeat analysis of NBS-981.Faraday U analyses corrected for mass bias based on measured 233U/235U ratio.
(f) Corrected for fractionation, spike, and common Pb; up to 1 pg of common Pb was assumed to be procedural blank: 206Pb/204Pb = 18.66 ± 0.60%; 207Pb/204Pb = 15.54 ± 0.25%; 208Pb/204Pb = 37.62 ± 0.55% (all uncertainties 1-sigma). Excess over blank was assigned to initial common Pb.
(g) Errors are 2-sigma, propagated using the algorithms of Schmitz and Schoene (2007) and Crowley et al. (2007).
(h) Calculate ages are based on the decay constants of Jaffey et al. (1971).

Formation represents continuous, slow deposition, 2) the time gap is real and a faulted contact separates two distinct sequences, or 3) an unconformity separates the Hyco and Aaron formations.

Our field based observations on the nature of the contact between the Hyco and Aaron formations on either side of the Virgilina syncline strongly suggest that, although structurally modified on the east limb, overall the contact was originally stratigraphic. This interpretation is supported by the observation that the thickness of lower Aaron Formation between the top of the Hyco Formation and the distinct conglomerate in the lower Aaron Formation remains constant along strike and from limb to limb of the Virgilina syncline. These observations allow us to eliminate hypothesis 2, that the contact between the formations is a significant fault.

A new U-Pb zircon age from a felsic tuff of the upper Hyco Formation yielded a high-precision age of 616.52 ± 1.2 Ma. In conjunction with the pre-existing age of c. 615 for tuffs lower in the Hyco Formation, we conclude that deposition of the upper Hyco Formation was rapid, thus precluding our hypothesis 1.

In light of both the field observations summarized above, our new age date on the Hyco tuff from the top of the formation, and the existing detrital zircon data (Samson et al., 2000; Pollock et al., 2010), we interpret the contact between the Hyco and Aaron Formations to be a disconformity. Our new age date on the Hyco tuff in conjunction with the existing detrital zircon data from the Aaron Formation indicate that the time break represented by the disconformity is on the order of at least 28 m.y.

Our confirmation of a substantial time gap at the Hyco-Aaron formation boundary, strongly suggests that the Aaron Formation and its Virgilina member are not genetically related to the Hyco Formation volcanic arc. Consequently, this observation leads us to propose that the Hyco Formation constitutes a distinct lithotectonic element, the Hyco arc, and that the Aaron Formation forms a younger lithotectonic unit, the redefined Virgilina sequence. The tectonic nature of the redefined Virgilina sequence is ambiguous at this time, and should provide a prime target for future studies.

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The Carolina terrane on the west flank of the Deep River Triassic Basin in the northern Piedmont of North Carolina – A status report

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Abstract

Rock types in the Carolina terrane, in the vicinity of Chapel Hill, Hillsborough, and Durham, consist of various metamorphosed intrusive and extrusive rocks. The primary volcanic and volcano-sedimentary rock types are grouped into map units based on related chemical and/or interpreted genetic relationships. Deposition of the primary volcanics ranged from subaerial to subaqueous with concomitant deposition of various types of volcanic-derived sediments. Grouping the lithologies based on chemical and/or interpreted genetic relationships, coupled with available geochronologic data, has lead to the interpretation that the Hyco Formation in the study area may be divided into lower (ca. 630 Ma) and upper (ca. 615 Ma) members (informal) with an apparent intervening hiatus of magmatism.

At the base of the sequence is the lower member of the Hyco Formation, which is composed of ca. 633 – 629 Ma metamorphosed extrusive and intrusive rocks consisting of granite to granodiorite plutons; dacitic shallow intrusives and lavas interlayered with tuffs; and tuffs with lesser amounts of interlayered volcano-sedimentary rocks. Rocks assigned to the upper member of the Hyco Formation are composed of ca. 616 – 612 Ma metamorphosed volcano-sedimentary rocks, dacitic lavas and tuffs, andesitic to basaltic lavas and tuffs, and granodiorite to gabbro plutonic rocks.

Immediately south of Chapel Hill, Hyco Formation units are intruded by the ca. 579 Ma East Farrington pluton and associated West Farrington pluton. The northwest of the study area is underlain by the Prospect Hill pluton. The Prospect Hill pluton intrudes foliated and folded Hyco Formation units and is correlated with the ca. 546 Ma Roxboro pluton.

Introduction

Preliminary results of North Carolina Geological Survey (NCGS) mapping in the vicinity of Chapel Hill, Hillsborough, and Durham (Fig. 1) were presented during the 2006 Carolina Geological Society annual meeting (Bradley et al., 2006a). Since 2006, several years of additional geologic mapping by the NCGS, new geochronologic data (Bradley and Miller, 2011), and new data and interpretations by other workers (e.g. Pollock, 2007; Bowman, 2010) have been generated. This new information requires modifications to earlier stratigraphic interpretations. This paper serves as a 'status report' of the understanding of the subject area. Detailed geologic mapping was partially funded through the STATEMAP component of the National Cooperative Geologic Mapping Program. Detailed 1:24,000 – scale geologic maps of the area are available from the NCGS. Geologic data in Figures 2 and 3 are based on detailed geologic data from: Bradley et al. (2004a); Bradley et al. (2004b); Bradley and Gay

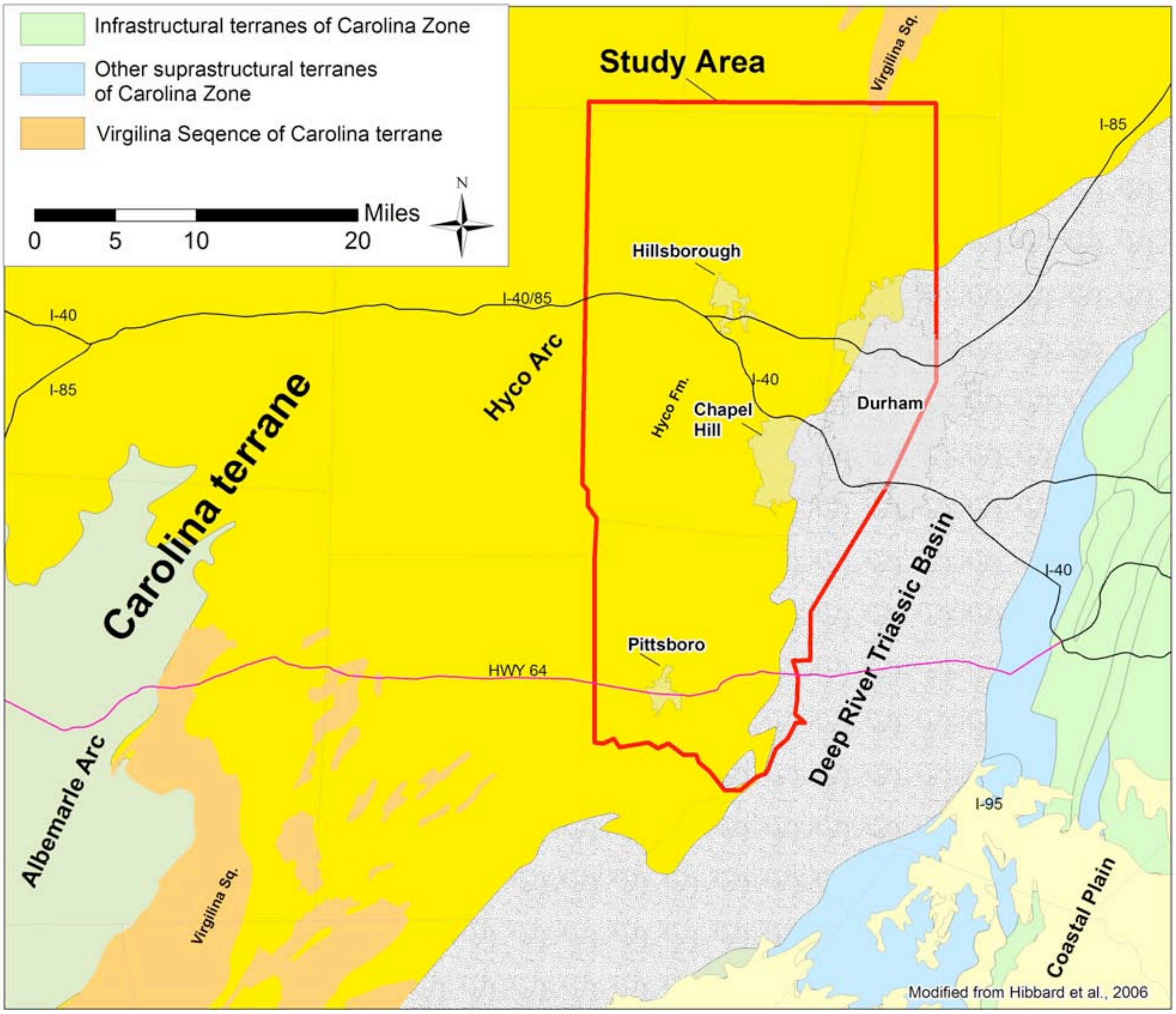

Figure 1: Terrane relationships and study area location (after Hibbard et al., 2006).

(2005); Bradley et al. (2006b); Bradley et al. (2007); Bradley and Stoddard (2008); Bradley and Hanna (2010) ; Hanna et al. (2010); Bradley et al. (2011); Bradley and Hanna (2012a); Bradley et al. (2012b); and Bradley et al. (2013).

Previous and recent work

The study area is located within the newly redefined Hyco Arc (Bowman et al., this volume) – the oldest portion of the Carolina t terrane in north-central North Carolina (Fig. 1). The stratigraphy of the region was first described by Laney (1917) and later modified by Glover and Sinha (1973) and Harris and Glover (1988). Various other workers have conducted mapping in the Chapel Hill, Hillsborough and Durham area, including a NCGS geologic map of Orange county (Allen and Wilson, 1968) to multiple graduate student theses (ex. Wagener, 1965; Bland, 1972; Wright, 1974; McConnell, 1974; Hauck, 1977; Wilkinson, 1978; Newton, 1983; and Chiulli, 1987). Other published work within the region includes papers by McConnell and Glover (1982) and Green et al. (1982). McConnell and Glover (1982) describe intru-

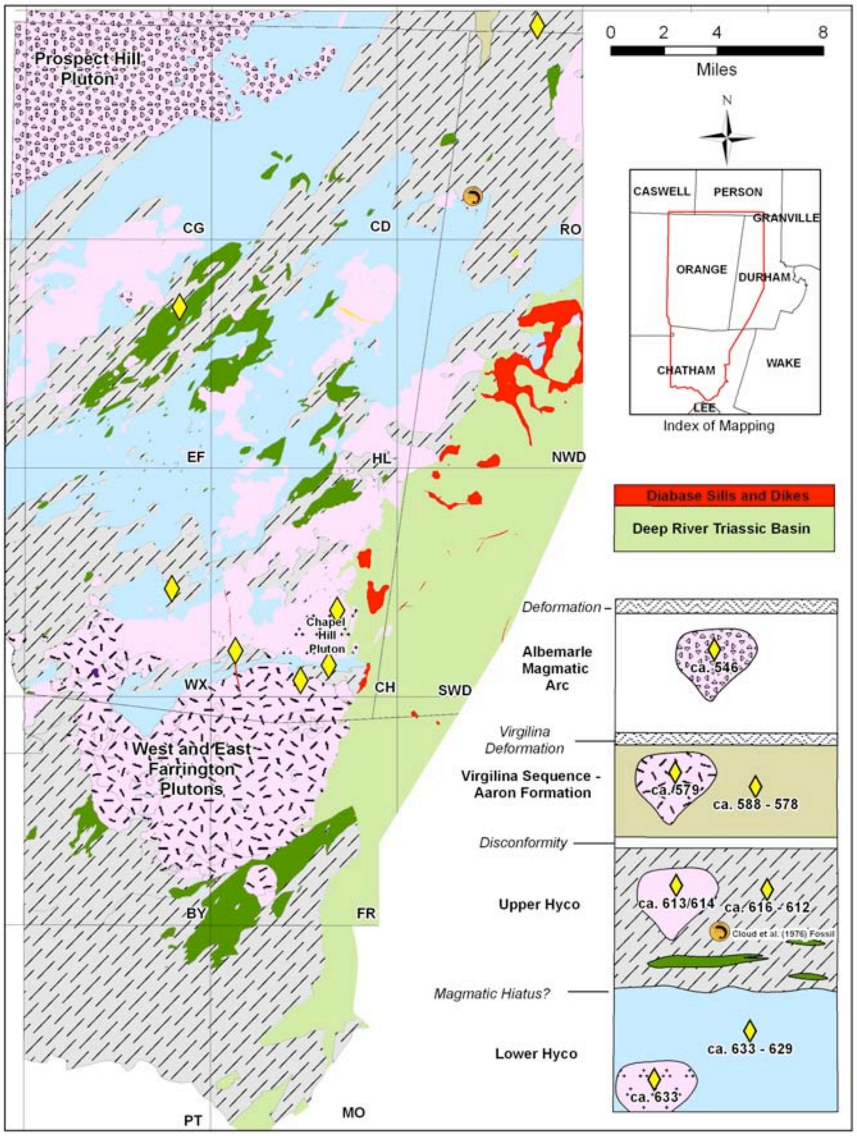

Figure 2: Simplified bedrock geologic map of the west flank of the Deep River Triassic Basin in the northern Piedmont of North Carolina - Chapel Hill, Hillsborough, and Durham vicinities, North Carolina. Diamond shapes indicate U-Pb zircon age-date locations of Wortman et al. (2000); Tadlock and Loewy (2006); and Bradley and Miller (2011). USGS 7.5 – minute quadrangle names: CG – Cedar Grove, CD – Caldwell, RO – Rougemont, EF – Efland, HL – Hillsborough, NWD – Northwest Durham, WX – White Cross, CH – Chapel Hill, SWD – Southwest Durham, BY – Bynum, FR – Farrington, PT – Pittsboro, and MO – Merry Oaks.

sive rocks of the Flat River complex that underlie a portion of the northeast section of the study area; Green et al. (1982) present the results of geologic mapping, interpretations of the stratigraphic sequence, and depositional framework of the rocks a few miles southwest of the study area in southern Chatham and northern Moore Counties.

NCGS mapping in the study area (reported in Bradley et al. (2006a) and Bradley and Gay (2007)), correlates the lithologies in the Chapel Hill, Hillsborough, and Durham vicinities with portions of the Hyco and Aaron Formations of the Virgilina sequence as defined by Harris and Glover (1988). Geochronologic data and new interpretations of recent workers in the region (Pollock, 2007;

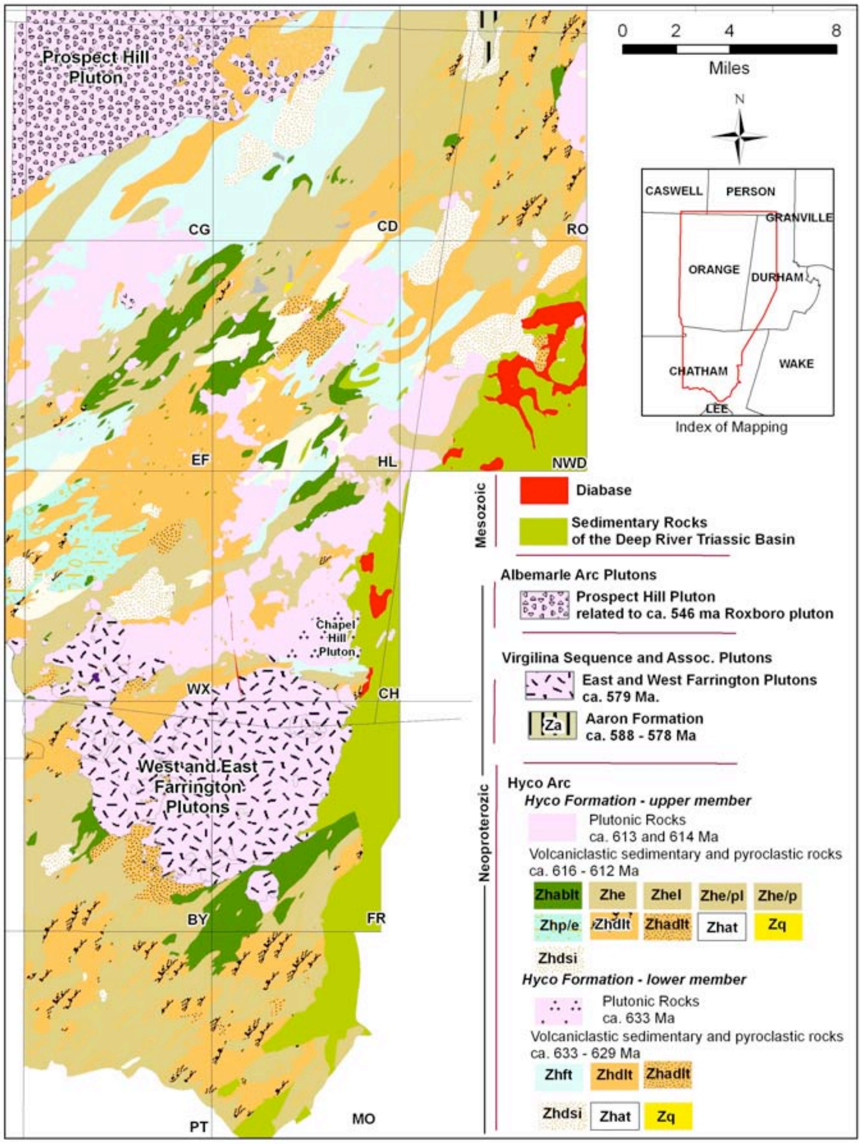

Figure 3: Generalized bedrock geologic map of the west flank of the Deep River Triassic Basin in the northern Piedmont of North Carolina - Chapel Hill, Hillsborough, and Durham vicinities, North Carolina. USGS 7.5 – minute quadrangle names: CG – Cedar Grove, CD – Caldwell, RO – Rougemont, EF – Efland, HL – Hillsborough, NWD – Northwest Durham, WX – White Cross, CH – Chapel Hill, BY – Bynum, FR – Farrington, PT – Pittsboro, and MO – Merry Oaks.

Bowman, 2010), have led to the need to reinterpret the stratigraphy of the northeastern portion of the Carolina terrane. Hibbard et al. (this volume), detail the revised stratigraphy of the Carolina terrane. In light of these new interpretations, subsequent geologic mapping by the NCGS, and recent geochronologic data (Bradley and Miller, 2011), significant areas previously interpreted as Aaron Formation in Bradley et al. (2006a) and Bradley and Gay (2007) are now interpreted to be part of the Hyco Formation.

STRATIGRAPHY OF THE CAROLINA TERRANE IN THE CHAPEL HILL, HILLSBOROUGH AND DURHAM AREA

The study area includes portions of three distinct lithotectonic units within the Carolina terrane: 1) the Hyco arc, 2) the Aaron Formation of the redefined Virgilina sequence, and 3) plutonic rocks of the Albemarle arc. Triassic sedimentary rocks underlie the eastern portion of the study area. Detailed geologic mapping in the Carolina terrane on the west flank of the Durham sub-basin of the Deep River Triassic basin has differentiated the Hyco Arc into upper and lower members (Figure 2). At the base of the sequence, the lower member of the Hyco Formation is composed of ca. 633 – 629 Ma (Wortman et al., 2000; and Bradley and Miller, 2011) metamorphosed intrusive and extrusive rocks including granite to granodiorite plutons, dacitic shallow intrusions, dacitic lavas interlayered with tuffs, and tuffs with lesser amounts of interlayered volcaniclastic sedimentary rocks. In the study area, the lower member consists of mainly primary pyroclastic rocks, lavas, and plutons with a relatively small component of volcaniclastic sedimentary rocks interlayed with pyroclastic lithologies.

Rocks assigned to the upper member of the Hyco Formation (Figure 2) are composed of ca. 616 – 612 Ma (Wortman et al., 2000; Bowman, 2010; and Bradley and Miller, 2011) metamorphosed intrusive and extrusive rocks consisting of granodiorite to gabbro, volcaniclastic sedimentary rocks, dacitic lavas interlayered with tuffs, and andesitic to basaltic lavas and tuffs. In the study area, the upper member of the Hyco consists of abundant volcaniclastic sedimentary rocks with map-scale and local-scale interlayered lavas and tuffs. The Cloud et al. (1976) *Vermiforma antiqua* fossil locality (Fig. 2) is present in the northeastern portion of the study area in rocks assigned to the upper member of the Hyco Formation. Recent work by Rhodes (2013) and Rhodes et al. (2012) in the Lake Michie Quadrangle area, indicate that lithologies related to the upper member of the Hyco Formation continue on-strike to the northeast from the study area.

The Aaron Formation is identified in a small portion of the northeastern corner of the study area (Figs. 1, 2, 3) at the southernmost extent of the Aaron Formation in the Virgilina synclinorium as depicted in Figure 7 in Harris and Glover (1985). Additional detailed mapping and geochronology to the north of the study area is required to confirm if this area is appropriately correlated with the redefined Aaron Formation. The Aaron Formation unconformably overlies the Hyco Arc (Bowman, 2010) and consists of mainly metamorphosed sedimentary rocks. The Virgilina member of the Aaron Formation (Bowman, 2010) consists of mafic volcanic rocks and felsic volcaniclastic rocks. Detrital zircon data yield a ca. 588 to 578 Ma age for the youngest detrital zircons from the Aaron Formation portion of the sequence (Samson and Secor, 2001; Pollock, 2007). Within the study area, rock types include metamorphosed sandstones and siltstones. In southern Orange County and northeastern Chatham County, Hyco Formation units are intruded by the ca. 579 Ma (Tadlock and Loewy, 2006) East Farrington pluton and associated West Farrington pluton. The East and West Farrington plutons likely represent the magmatic pulse associated with the deposition of the redefined Virgilina sequence of Bowman et al. (this volume).

The northwestern corner of Orange County is underlain by the Prospect Hill pluton (Hanna et al., 2010). The Prospect Hill pluton truncates map-scale Hyco Formation units (Fig. 3) and locally contains foliated enclaves of Hyco Formation lithologies. A similar relationship was reported by Hibbard and Samson (1995) in the Roxboro, NC, area, where foliated enclaves occur in the ca. 546 Ma Roxboro pluton (Wortman et al., 2000). Based on lithologic characteristics and cross cutting relationships, the Prospect Hill pluton is correlated with the ca. 546 Ma Roxboro pluton.

ROCK TYPES, ROCK UNITS, AND INTERPRETED VOLCANIC AND SEDIMENTARY FACIES OF THE HYCO FORMATION IN THE CHAPEL HILL - HILLSBOROUGH - DURHAM AREA

Along strike and across strike traverses indicate that individual rock types commonly vary over distances of just a few feet, leading to an apparent chaotic assortment of rock types. Coupled with the fine-grained nature of the rocks, overprint of metamorphism, local hydrothermal alteration, local brittle overprint, and general poor exposure, the rocks are challenging to decipher. However, relict volcanic and sedimentary structures are present locally and help greatly in the assigning of rock types. These individual rock types are grouped together into rock units. Plutonic rocks are grouped based on their bulk composition and may vary from nearly homogeneous plutonic bodies to composite bodies with a range of composition (e.g. diorite to gabbro; granite to granodiorite). Due to the general poor exposure of rock and the, metamorphic and/or alteration overprint of many of the outcrops in the study area, often the rock type name is assigned as a general rock type. For example, a rock interpreted as a dacite may have been a lava flow or a shallow intrusion. Locally, relict textures may allow for the further refinement of the rock type and the method of emplacement/deposition. For most outcrops it is not possible to assign specific environment of deposition or mode of emplacement characteristics.

Volcano-sedimentary rocks of the Hyco Formation

Primary volcanic rocks (pyroclastics, lavas, and shallow intrusions) and volcaniclastic sedimentary rock types of the Hyco Formation are grouped into map units that are packages of rocks that have close chemical and/or interpreted genetic relationships (e.g. dacitic lavas and tuffs; andesitic to basaltic lavas; epiclastics). Deposition of the primary volcanics ranged from subaerial to subaqueous with concomitant deposition of various types and volumes of volcanic-derived sediments. To capture local lithologic subtleties, detailed geologic mapping has separated the study area into over 30 different volcano-sedimentary units and over 30 plutonic units. Although locally variable, there are gross similarities in the units that allow for the units to be generalized (Fig. 3). Some rock types/units (e.g. dacitic lavas and tuffs) are pervasive in both the upper and lower members of the Hyco Formation and are differentiated into the lower or upper members based on their relationship to surrounding rock types. A summary of the generalized map units and corresponding interpreted volcanic and sedimentary facies is provided in Table 1.

Plutonic rocks of the study area

Plutonic rocks, ranging in composition from granite to ultramafic, constitute an appreciable portion of the crystalline rocks within the study area (Figure 2 and 3). Past workers have separated the plutonic rocks within the study area into formally and informally named plutons and intrusive complexes. Names of intrusive bodies include the Chapel Hill, Duke Forest, and Meadow Flats plutons (Black, 1977); Buckwater Creek pluton (Newton, 1983); Flat River complex (McConnell and Glover, 1982); West and East Farrington plutons (Wagener, 1965); and the Prospect Hill pluton (Hanna et al., 2010). The various plutonic rocks can be grouped into three magmatic stages after Hibbard et al. (2002). Stage I magmatism is represented by the plutonic rocks associated with the Hyco Arc (e.g. Chapel Hill, Meadow Flats, Duke Forest, and Flat River complex). Stage II

Table 1: Generalized map units and interpreted volcanic and sedimentary facies of the volcano-sedimentary rocks of the Hyco Formation in the Chapel Hill, Hillsborough and Durham Area.

Map Unit	Interpreted Volcanic and Sedimentary Facies	General Description and Distinctive Characteristics	Notes:
Primary Volcanic Rocks			
Zhdlt	Dacitic lava domes and associated tuffs	Interlayered dacitic lavas and tuffs - Dacitic lavas textures vary: relict vitric texture common, aphanitic, plagioclase porphyritic, amphibole phenocrysts locally, flow banded locally, hyaloclastic texture locally. Tuffs display relict vitric texture, are commonly welded, and identical to Zhft.	Present in lower and upper Hyco.
Zhdsi	Dacitic shallow intrusives	Dacite to fine-grained granodiorite - Includes textures typical of Zhdlt unit dacites and "microgranodiorite" with intergrown plagioclase and amphibole phenocrysts, plagioclase glomerocrysts, 1-3 mm cavities/vugs, hyaloclastic texture locally.	Present in lower and upper Hyco. Possible cryptodomes
Zhadlt	Andesitic to dacitic lavas and tuffs	Interlayered andesitic to dacitic lavas and tuffs - Distinctive black to dark gray aphanitic lava, porphyritic lava with plagioclase phenocrysts (up to 4 mm), and flow banded lava with local amygdules. Interlayed with gray to black welded and non-welded tuffs.	Present in lower and upper Hyco.
Zhft	Tuffs deposited proximal and distal from source	Felsic tuffs (with clast size ranging from 1/16 mm to >64 mm) - Range from no crystal shards to crystal-rich; lithic clast-poor to lithic clast-rich; relict vitric texture common, plagioclase crystal shards dominate with rare quartz crystal shards, commonly dacite clasts as lithic fragments, relict pumice (fiamme), welded locally. Felsic tuffs (with clast size ranging from 1/16 mm to 2 mm) - Mainly fine tuffs with or without crystal fragments, relict vitric texture, locally bedded. Locally interbedded with sparse volcaniclastic sedimentary rock.	Assigned to lower Hyco.
Zhablt	Andesitic to basaltic lavas and tuffs	Interlayered andesitic to basaltic lavas and tuffs – Lavas are typically unfoliated, amygdaloidal, range from aphanitic to plagioclase porphyritic and/or amphibole/pyroxene porphyritic. Hyaloclastic texture is common and imparts a fragmental texture similar to that of a lithic tuff on some outcrops. Locally interlayered with meta-sediments identical to the Zhe/pl and Zhe/p units	Assigned to upper Hyco.
Zhabsi	Andesitic to basaltic shallow intrusives	Andesite to basalt - "Microdiorite/microgabbro" texture, intergrown plagioclase and amphibole phenocrysts, plagioclase glomerocrysts, amgydaloidal.	Assigned to upper Hyco.
Volcaniclastic Sedimentary Rocks			
Zhp/e	Mixed pyroclastic and epiclastic rocks	Felsic tuffs interlayed with mudstone, siltstone, sandstone; and distinctive immature, monomictic, conglomeratic sandstone to conglomerate with subangular to angular clasts of plagioclase porphyritic dacite. Minor andesitic to basaltic lavas and tuffs. Occurs in beds too thick to see in typical outcrop, may be tuffaceous (with relict vitric texture)	Assigned to upper Hyco. The contact with the Zhdlt (upper Hyco) unit is interpreted to be gradational.
Zhe/pl	Mixed epiclastic and pyroclastic rocks and lavas	Conglomerate, conglomeratic sandstone, sandstone, siltstone and mudstone. Lithologies are locally bedded; locally tuffaceous with a relict vitric texture. Siltstones are locally phyllitic. Locally contain interbedded dacitic lavas identical to Zhdlt unit. Contains lesser amounts of fine- to coarse - tuff and lapilli tuff with a relict vitric texture. Minor andesitic to basaltic lavas and tuffs present. Conglomerates and conglomeratic sandstones typically contain subrounded to angular clasts of dacite in a clastic matrix.	Assigned to upper Hyco. Zhe/pl distinguished from Zhe/p by presence of dacites and is interpreted to represent area more proximal to the active volcanic centers compared to Zhe/p.
Zhe/p	Mixed epiclastic and pyroclastic rocks	Tuffaceous sandstones, conglomeratic sandstones, siltstones and minor phyllite. The siltstones may be weakly phyllitic. Contains lesser amounts of fine- to coarse tuff and lapilli tuff. Tuffs are differentiated from other volcaniclastic rocks by the presence of zones of relict vitric texture in between foliation domains.	Assigned to upper Hyco. Unit is interpreted to grade into Zhe/pl unit. Contact with Zhe/pl designated at first occurrence of dacitic lavas.
Zhel	Epiclastic rocks and lavas	Conglomerate, conglomeratic sandstone, sandstone, siltstone and mudstone. Siltstones and mudstones typically display bedding ranging from mm-scale up to 10 cm, bedding layers traceable for several feet locally, may exhibit soft sediment deformation. Locally tuffaceous with a relict vitric texture. Locally contain interbedded dacitic to basaltic lavas. Conglomerates and conglomeratic sandstones typically contain subrounded to angular clasts of dacite in a clastic matrix.	Assigned to upper Hyco. Deposition interpreted as distal from volcanic center, in deep water(?), and via turbidite flows.
Zhe	Epiclastics	Mudstone, siltstone, sandy siltstone, sandstone, pebbly sandstone, and conglomerate. Siltstones and mudstones typically display bedding ranging from mm-scale up to 10 cm, bedding layers traceable for several feet locally, may exhibit soft sediment deformation. Conglomerates include matrix supported and clast supported polymictic conglomerate composed of angular to rounded pebbles to large cobbles (up to 20 cm).	Assigned to upper Hyco. Deposition interpreted as distal from volcanic center, in deep water(?), and via turbidite flows.
Altered Rocks			
Zhat	Altered tuffs	Altered rock - Sericite phyllite, pyrophyllite phyllite, foliated and unfoliated quartz and sericite rock, altered tuff and altered dacite. phyllitic to massive, minerals locally present include sulfides, sericite, chloritoid, rare andalusite; quartz veining and quartz pods locally present.	Present in lower and upper Hyco. Hydrothermal alteration centers.
Zq	Quartz bodies	Massive to foliated quartz and quartz + sericite rock	Present in lower and upper Hyco. Interpreted as hydrothermal alteration centers.

Notes: Relict vitric texture refers to a rock with a cryptocrystalline groundmass that with the unaided eye or with hand lens display concoidal-shaped fractures whose flake-like terminations may be weakly translucent. Thin section analysis of many rocks with cryptocrystalline groundmass show a completely recrystallized groundmass consisting of a mosaic of primarily quartz and feldspar. Locally relict textures indicating features of a once glassy groundmass are preserved (e.g. spherulitic and perlitic textures). All volcanogenic rocks in the study area have been metamorphosed to at least the chlorite zone of the greenschist metamorphic facies.

magmatism is represented by the ca. 579 Ma East and West Farrington plutons (Tadlock and Loewy, 2006) and likely represents the magmatic pulse associated with the deposition of the redefined Virgilina sequence. Stage III magmatism is represented by the Prospect Hill pluton which is correlated with the ca. 546 Ma Roxboro pluton (Wortman et al., 2000). It is located in the northwest portion of the study area and is interpreted to be associated with the Albemarle Arc.

Plutonic Rocks Associated with the Hyco Arc
Available age dates indicate that the plutonic rocks associated with the Hyco Arc cluster in two groups: 1) a ca. 633 Ma (lower Hyco) and 2) ca. 614-613 Ma (upper Hyco). The Chapel Hill pluton is the only example of the ca. 633 Ma group known. 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 Mehlhop (1994) for the Chapel Hill pluton. The Chapel Hill pluton ranges from granite to granodiorite, is typically massive, fine- to medium-grained with dark green amphiboles (commonly rimmed by epidote and chlorite) and with or without biotite. Light pink- to pink- alkali feldspars are prominent in the granite and give the rock its characteristic hue. Texturally similar granitic to granodioritic rocks mapped in the vicinity of the age date locations that *do not* have xenoliths of volcano-sedimentary rocks are grouped with the Chapel Hill pluton.

Generally, all other plutonic rocks (excluding rocks associated with the East and West Farrington plutons and the Prospect Hill pluton) are tentatively assigned to the upper Hyco. Only two dates are available from upper Hyco plutonic rocks: they are from a hornblende diorite and a hornblende-biotite granite in the Flat River complex which yielded U-Pb zircon crystallization ages of 613.9 +1.6/-1.5 Ma and 613.4 +2.8/-2.0 Ma, respectively (Wortman et al., 2000). Plutonic rocks assigned to the upper Hyco range from granite to ultramafic but the majority are granodiorite to diorite in composition. Grain size ranges from fine- to medium-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 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 saussuritization of the plagioclase, which makes the distinction between the green fine-grained intrusive rocks and surrounding volcaniclastic rocks difficult. The intrusive texture of the green fine-grained outcrops is discernible only using a 7x or greater hand-lens.

Structural geology

Relict layering within Hyco Formation lithologies range from shallowly to steeply dipping (Fig. 4). Relict stratigraphic facing direction was determined in several locations from cross beds, scour surfaces and graded bedding. Rocks in the subject area display a non-penetrative metamorphic cleavage that varies in intensity depending on rock type (Fig. 5).

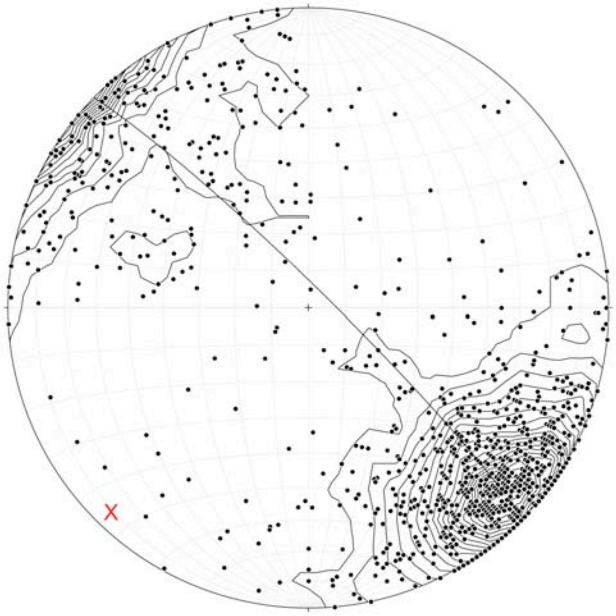

Figure 4: Equal area Schmidt net projection of poles to primary bedding, layering, and welding/compaction foliation in crystalline rock of the Carolina terrane in the study area, (n=999); Kamb contour of poles at 2 sigma contour interval, counting area = 0.9% of net area. Best-fit great circle for the profile plane of interpreted folds plotted (315/85 right hand rule). Point identified with letter "X" indicates trend and plunge of the interpreted fold axes (225/5 right hand rule). Plot and calculations created using Stereonet v. 8.6.0 based on Allmendinger et al. (2013) and Cardozo and Allmendinger (2013).

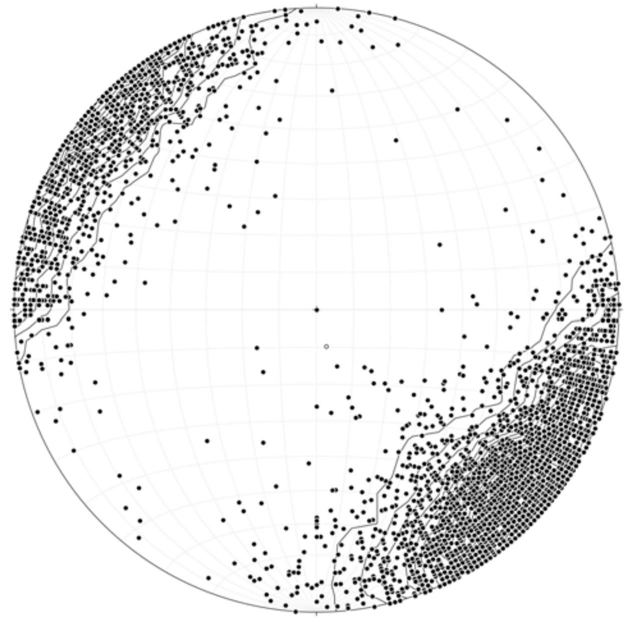

Figure 5: Equal area Schmidt net projection of poles to cleavages and foliations in crystalline rock of the Carolina terrane in the study area, (n=4254); Kamb contour of poles at 2 sigma contour interval, counting area = 0.2% of net area. Plot and calculations created using Stereonet v. 8.6.0 based on Allmendinger et al. (2013) and Cardozo and Allmendinger (2013).

The cleavage is best displayed in metasedimentary rocks and is most intense in phyllitic epiclastic rocks, altered phyllitic tuffs and mafic to intermediate tuffs, but is typically absent in the plutonic rocks and lavas. In the areas in between the Prospect Hill pluton and the East and West Farrington plutons, the majority of cleavages and relict bedding are steeply dipping to the northwest with lesser amounts dipping to the southeast. The foliation is generally parallel to relict bedding and compositional layering (Figures 4 and 5). The cleavage is locally observed at an angle to relict bedding in numerous outcrops throughout the study area with a high concentration of locations in the Bynum Quadrangle (southwest of the West Farrington pluton) and in the southern portion of the Rougemont Quadrangle. These locations are underlain by units with abundant thinly bedded siltstones whose bedding can be traced for multiple feet in outcrops.

The northwestern corner of Orange County within the study area is underlain by the Prospect Hill pluton. The Prospect Hill pluton truncates map-scale Hyco formation units (Fig. 3), contains several locations of foliated enclaves of Hyco Formation lithologies, and is correlated with the ca. 546 Ma Roxboro pluton. Based on the strong northeast/southwest trend of map units, apparent repetition of map-scale units, parallelism of relict layering and cleavage, the dominant structures are interpreted to be open to isoclinal folds that are locally overturned to the southeast. One outcrop scale fold of relict bedding has been observed in the White Cross Quadrangle, but has not been investigated in detail. This folding and accompanying low grade metamorphism is attributed to the ca. 578 to 554 Ma (Pollock, 2007) Virgilina deformation (Glover and Sinha, 1973; Harris and Glover, 1985; Harris and Glover, 1988; Hibbard and Samson, 1995).

Regionally, lithologies of the Hyco Formation and Virgilina sequence are unconformably overlain by the Albemarle sequence in the Carolina terrane. Rocks of the Albemarle sequence have been overprinted by upright folding with an axial planar cleavage accompanied by greenschist facies metamorphism. Timing of this deformation has been interpreted as ca. 450 Ma (Hibbard et al., 2002; Hibbard et al., 2012). Folds associated with the Virgilina deformation may have been tightened and experienced reverse faulting during the ca. 450 Ma or later event. Additional modifications to foliations, folds and other structures may have occurred during subsequent deformation events recorded in other locations within the Piedmont.

Several outcrop locations with folded foliation have also been observed in the northern and central portions of the study area. Some of these locations (e.g. active pyrophyllite mine in Hillsborough), also exhibit an apparent composite foliation locally. In a simplistic structural model, the composite fabrics and folded foliation could be attributed to deformation associated with the documented ca. 450 Ma event elsewhere in the Carolina terrane. However, the nature of these structures is not well understood. In the southern portions of the study area (Merry Oaks and Pittsboro Quadrangles – north of the Colon Cross structure (Reinemund, 1955)) – anomalous shallowly dipping foliations (dips less than 40 degrees) were observed in several locations. Additionally, several locations of brittle overprinted foliations have been observed. The nature of these foliations and brittle overprinting is not well understood and may be of significance in light of recent observations by Blake et al. (2011 and 2012) and Rhodes (2013). Blake et al. (2011 and 2012) and Rhodes (2013) have identified mild to intensely foliated volcano-sedimentary rocks and plutonic rocks near the northern termination of the Deep River basin and interpret this foliation (in part or in whole) to be from ductile deformation associated with latest Paleozoic to early Mesozoic rifting.

SUMMARY

The study area includes portions of three distinct lithotectonic units within the redefined Carolina terrane: 1) the Hyco arc, 2) the Aaron Formation of the Virgilina sequence, and 3) plutons of the Albemarle arc. Triassic sedimentary rocks underlie the eastern portion of the study area. The majority of the area is underlain by metamorphosed primary volcanic, volcano-sedimentary, and plutonic rocks of the Hyco arc. In the study area, the Hyco arc has been separated into upper and lower members (Fig. 2). At the base of the sequence is the lower member of the Hyco Formation, which is composed of ca. 633 – 629 Ma (Wortman et al., 2000; Bradley and Miller, 2011) metamorphosed intrusive and extrusive rocks consisting of granite to granodiorite plutons, dacitic shallow intrusions, and lavas interlayered with tuffs, and tuffs with lesser amounts of interlayered volcaniclastic sedimentary rocks. In the study area, the lower member consists of mainly primary pyroclastic rocks, lavas and plutons with a relatively small component of volcaniclastic sedimentary rocks interlayed with pyroclastic lithologies. The upper member of the Hyco Formation is composed of ca. 616 – 612 Ma (Wortman et al., 2000; Bowman, 2010; and Bradley and Miller, 2011) metamorphosed intrusive and extrusive rocks consisting of granodiorite to gabbro, volcaniclastic sedimentary rocks, dacitic lavas interlayered with tuffs, and andesitic to basaltic lavas and tuffs. In the study area, the upper member of the Hyco consists of abundant volcaniclastic sedimentary rocks with map-scale and local-scale interlayered lavas and tuffs.

The Aaron Formation, of the redefined Virgilina sequence (Bowman et al., this volume), is identified in a small portion of the northeastern corner of the study area (Figures 1, 2, and 3). In southern Orange County and northeastern Chatham County, Hyco Formation units are intruded by the ca. 579 Ma (Tadlock and Loewy, 2006) East Farrington pluton and associated West Farrington pluton. Previously (Bradley et al., 2006a; Bradley and Gay, 2007), the volcaniclastic sedimentary lithologies in the study area were assigned to the Aaron Formation. Based on subsequent detailed geologic mapping by the NCGS and recent geochronologic data (Bradley and Miller, 2011), significant areas previously interpreted as Aaron Formation are now interpreted to be part of the Hyco Formation. The extent of rocks assigned to the Aaron Formation within the study area has been greatly reduced; it is now interpreted to be present only in a small portion of the study area located north of Durham.

ACKNOWLEDGEMENTS

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The Flat Swamp Mountain caldera and related mineral deposits, Carolina slate belt, central North Carolina [1]

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The Flat Swamp Member (FSM) of the Cid Formation (Neoproterozoic) and related volcanogenic deposits in the Carolina slate belt of central North Carolina constitute a submarine downsag caldera complex, mildly deformed and metamorphosed to lower greenschist facies. The intracaldera facies are 1.2 to 1.8 km thick in the Denton area. Near Badin, the FSM thins abruptly and changes laterally into extracaldera facies less than 150 m thick of crystal-rich ashfall tuffs and devitrified vitric tuffs. Bodies of metarhyolite as much as several km across are emplaced within the FSM and underlying units, beneath the main caldera complex. This paper considers the caldera model in interpretation of known mineral deposits and exploration for new deposits. The following types of deposits may be formed in the main region of downsagging: (1) exhalative, precursory to main volcanic outbreak, (2) exhalative, formed during waning stages of volcanism, (3) massive deposits and stockworks along fault zones related to downsagging, and (4) vein and stockwork deposits related to syn- and post-caldera intrusions. Some of the known mineralized areas in Davidson and western Randolph counties appear to fit the caldera model.

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FIELD RELATIONSHIP BETWEEN THE UWHARRIE FORMATION AND THE LOWER ALBEMARLE GROUP AND GEOCHEMISTRY OF THE 'MORROW MOUNTAIN RHYODACITES', CENTRAL NORTH CAROLINA: IMPLICATIONS FOR THE STRATIGRAPHY OF THE ALBEMARLE ARC

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ABSTRACT

Our 1:24,000 field mapping in the Morrow Mountain, Badin, and Handy, NC 7.5' quadrangles was motivated by the report of Paleozoic fossils in the lower Albemarle Group, traditionally thought to be mainly Neoproterozoic. A resulting proposal introduced major modification of the regional stratigraphy and structure in which an Ordovician Tillery Formation, at the base of the Albemarle Group, was significantly younger and overthrust on the Neoproterozoic Uwharrie Formation. Our observations show that the contact is conformable. Thus our study confirms the conventional view that the Uwharrie Formation and the Tillery Formation at the base of the Albemarle Group form a conformable Neoproterozoic succession.

In addition, we demonstrate that rocks lithically identical to the Morrow Mountain member of the Tillery Formation occur in both the underlying Uwharrie Formation and the overlying Cid Formation. Geochemical analyses of these 'Morrow Mountain rhyodacites' indicate that there are two major geochemical groups representing two different magmas. Members of each geochemical group occur throughout the Uwharrie – lower Albemarle Group sequence, magmatically linking these units. This geochemical evidence supports field interpretations. Namely, if the Uwharrie, Tillery, and Cid formations are magmatically linked by the 'Morrow Mountain rhyodacites', then it is likely that no major gap exists in the ages of the three formations. Consequently, our results cast grave doubt on the proposed revision of the stratigraphy and structure of the Albemarle Group.

INTRODUCTION

The Neoproterozoic-earliest Paleozoic Albemarle arc (Hibbard et al., this volume) of central North Carolina is one of the most extensive, best-documented, and controversial portions of the Carolina terrane (Fig. 1). The arc has traditionally served as a reference section for the terrane (e.g. Butler and Secor, 1991) in comparisons with other Neoproterozoic island arc systems preserved along the eastern edge of North America and along the western edge of Europe (e.g. Nance and Thompson, 1996; Hibbard et al., 2007). Consequently, as noted in the overview of the Carolina terrane

(Hibbard et al., this volume), accurate documentation of the geology of both the arc and the terrane is prerequisite for the comparison and determination of the interrelationship of these arc systems. In turn, knowledge of these interrelationships figures prominently in our understanding of the Neoproterozoic era, a unique period of global climate change associated with rapid evolution and a profound increase in biodiversity (e.g. Knoll, 1992; Hoffman and Schragg, 2002).

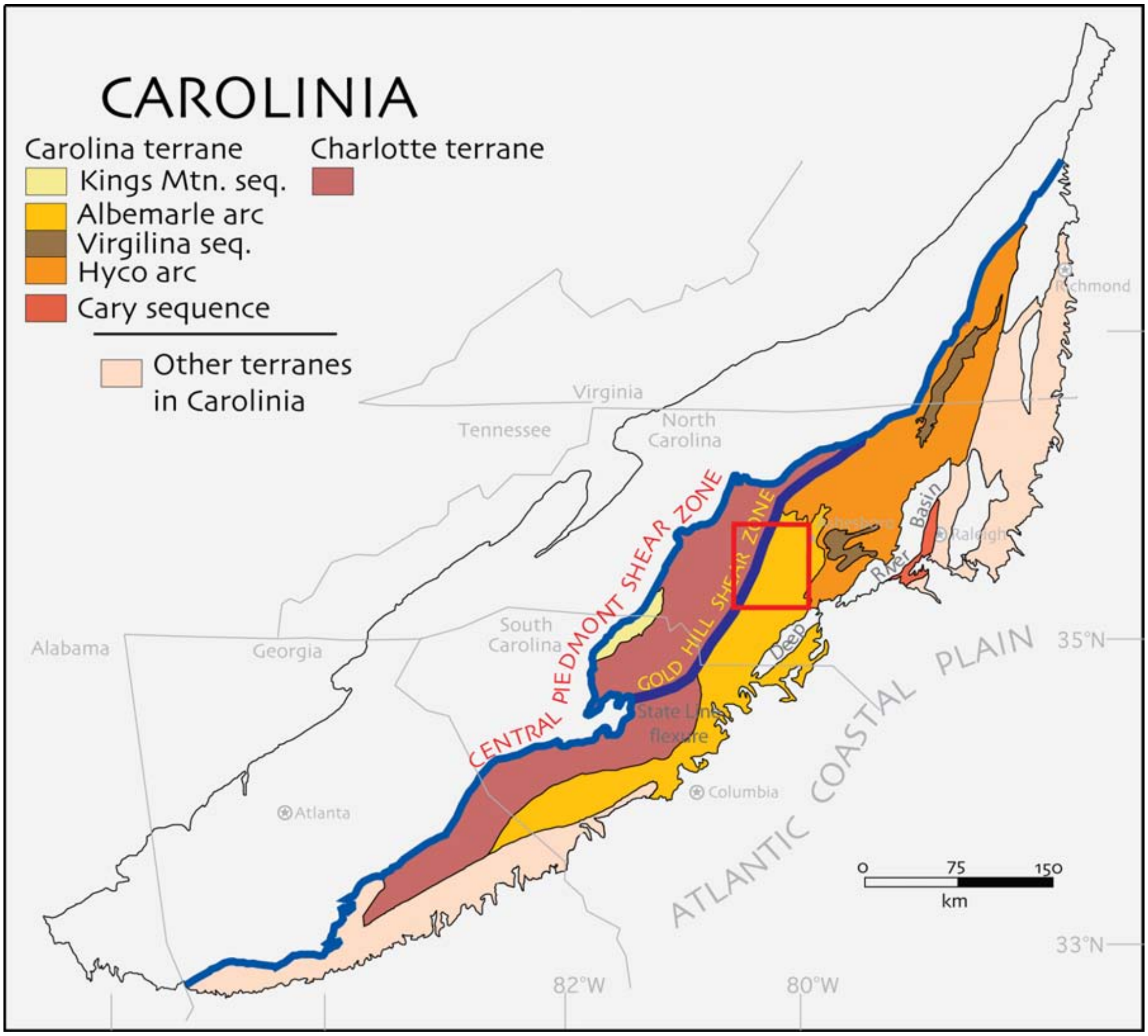

Figure 1: Geological setting of the Carolina terrane in the southern Appalachians (modified from Hibbard et al., 2012). Red box delineates area of figure 2.

For most of the late 20th century, the major constituent of the arc, the Albemarle Group, was thought to be a conformable sequence of Neoproterozoic-earliest Paleozoic volcanic and clastic sedimentary rocks. The group, at least in part, overlies a thick sequence of isotopically dated Neoproterozoic felsic volcanic rocks; in addition, isotopically dated Ediacaran volcanics occur just beneath the base of the upper portion of the group. However, in 1995, U.S. Geological Survey geologists reported fossils from the lower part of the Albemarle Group indicating that confidence in this conceptualization may have been premature (Koeppen et al., 1995). The purported fossils indicate that the lower portion of the Albemarle Group is Paleozoic. If these data are valid, then Paleozoic rocks are apparently sandwiched between Neoproterozoic rocks; such a sequence poses a significant problem that demands stratigraphic and/or structural resolution.

The goal of this study is to accurately portray the stratigraphy of the lower portion of the Albemarle arc in an attempt to resolve this apparent stratigraphic paradox (Ingram, 1999). We focused on the area of the Morrow Mountain (N half)(Ingram, 1999), Badin (Oliver, pers. comm., 2000), and Handy (S half)(Brennan, 2009) *7.5'* quadrangles (Figs. 2, 3) because 1) here, all units in the Albemarle Group are exposed on the northwest limb of the Troy anticline (Fig. 2), 2) the area includes one of the reported U.S.G.S. fossil locales (Fig. 2), and 3) the Albemarle Group is well-exposed in the hills, along streams, and on the shores of Tillery and Badin lakes (Fig. 2). Our project involved 1:24,000 scale mapping, in the region, under the auspices of the U. S. Geological Survey EDMAP program, the North Carolina Geological Survey, and the National Science Foundation. We have focused on field mapping of critical contacts in the lower part of the Albemarle arc. In addition, our mapping led to the recognition that the Morrow Mountain rhyolite (Conley and Bain, 1965), a felsic member previously thought to be confined to the lowest formation of the Albemarle Group, is identical in occurrence and composition to felsic volcanic centers that are found throughout the lower part of the group as well as in the underlying Uwharrie volcanics (Ingram, 1999). Subsequently, we undertook a geochemical survey of these Morrow Mountain-like volcanics and shallow intrusions in order to confirm lithic correlation of the rhyolite throughout the section. Collectively, the results of determining the nature of contacts within the lower portion of the arc and determining the petrochemical character of the Morrow Mountain rhyolite have important implications for the age and stratigraphic succession of the Albemarle Group.

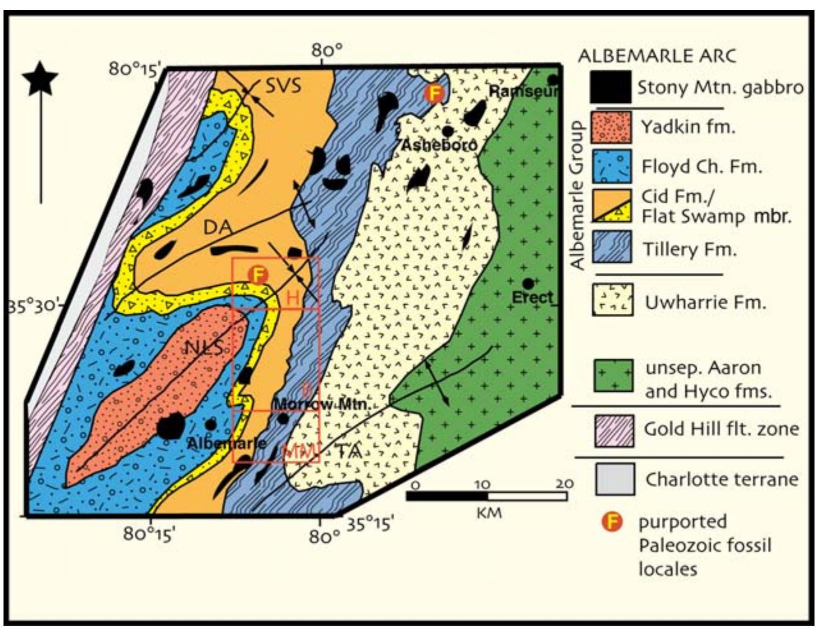

Figure 2: General geology of the Carolina terrane in central North Carolina. Red box delineates area of quadrangles mapped in this study; B=Badin *7.5'* quadrangle, H=southern portion of the Handy *7.5'* quadrangle, MM=northern portion of the Morrow Mountain *7.5'* quadrangle.

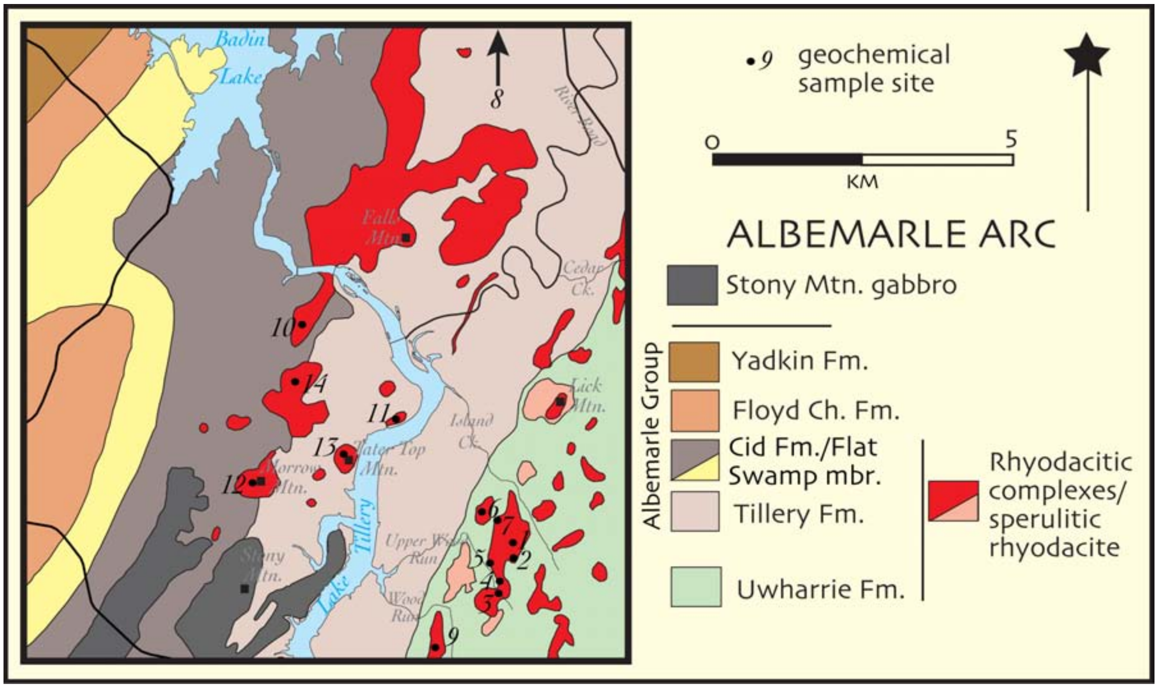

Figure 3: Geology of the northern portion of the Morrow Mountain 7.5' quadrangle and the southern portion of the Badin 7.5' quadrangle. See figure 2 for regional context. Geology by S. Boorman (Ingram,1999), Jill Oliver and J. Hibbard (unpublished).

REGIONAL CONTEXT OF THE PROBLEM

The Albemarle arc (Figs. 1, 2) is a sequence of volcanogenic rocks ranging from subaerial to subaqueous with mainly subaqueous clastic sedimentary rocks that is more than 9000 m thick (Conley and Bain, 1965). It unconformably overlies older volcanics of the Hyco arc and mainly sedimentary rocks of the Virgilina sequence (Harris and Glover, 1985, 1988; see Hibbard et al., this volume). All workers agree that the Uwharrie Formation, a thick section of dominantly felsic volcanic and volcaniclastic rocks forms the oldest part of the arc and is overlain by the Albemarle Group. The Uwharrie Formation is Neoproterozoic, ca. 555 Ma, on the basis of U-Pb zircon TIMS analyses (Mueller et al., 1996; Ingle et al., 2003). The Albemarle Group forms the upper portion of the Albemarle arc (Fig. 2). The stratigraphy most commonly accepted for the group in the late 20th century included four formations; from bottom to top, these are the Tillery, Cid, Floyd Church, and Yadkin formations (Fig. 2)(e.g. Milton, 1984; Butler and Secor, 1991). These formations are dominated by volcanic-derived clastic sedimentary rocks and overall display a general coarsening-up character upwards through the entire group. Volcanic members are found in most of the formations; most notable are the Morrow Mountain rhyolite, considered by many to be confined to the Tillery Formation, and the rhyolitic Flat Swamp and the Badin greenstone members in the Cid Formation.

Considering the thickness of the Albemarle arc, reliable age data through the section are sparse (Fig. 4). The Uwharrie Formation has yielded a U-Pb zircon SHRIMP age of c. 554 Ma (Ingle et al., 2003). Fossils commonly associated with the Ediacaran have been reported from the Cid Formation (Weaver et al., 2008; Hibbard et al., 2009) and the Floyd Church Formation (Gibson et al., 1984). The Morrow Mountain rhyolite has been dated at

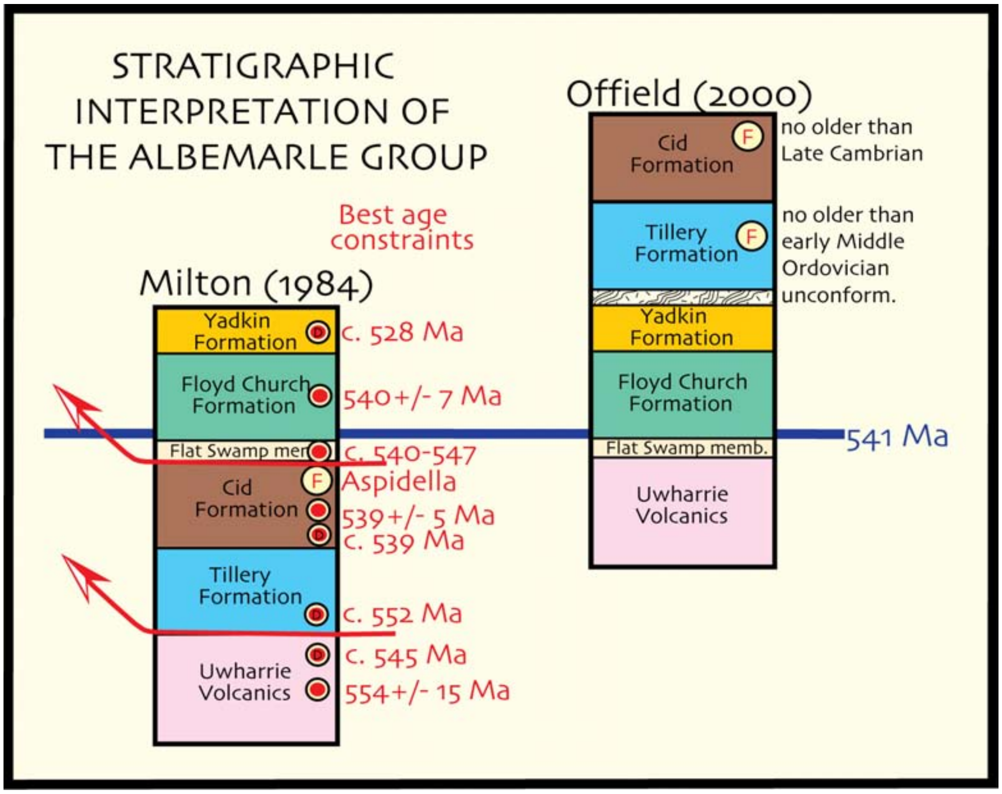

Figure 4: Stratigraphic interpretation of the Albemarle arc. Left column depicts the conventionally accepted stratigraphy (Milton, 1984) along with the most reliable age constraints on different units. Method of analysis in each case given in text. Bullseye = radiometric age, Bullseye + D = detrital zircon age, Bullseye + F = fossil constraint. Red arrowheads indicate position of thrust faults required by stratigraphic/structural interpretation of Offield (2000). Right column depicts the proposed stratigraphy of Offield (2000), following report of Paleozoic fossils in the Tillery and Cid formations. Solid line represents the Neoproterozoic-Cambrian boundary.

c. 539 $\pm$ 5 Ma by U-Pb zircon TIMS analyses (Ingle et al., 2003). The Flat Swamp member has yielded U-Pb zircon ages (ca. 540-547 Ma) that are close to that of the Precambrian-Cambrian boundary (here taken at 541 Ma)(Ingle et al., 2003; Hibbard et al., 2009; B.V. Miller, pers. comm., 2012). A 540+7 Ma Rb/Sr whole rock age was obtained on the Badin greenstone (Black, 1978). Detrital zircon age populations from the Uwharrie, Tillery, Cid, and Yadkin formations are consistent with the conventional stratigraphic sequence outlined above and indicate that the basal part of the Uwharrie Formation is at least locally, younger than c. 545 Ma and that the Yadkin Formation is at least locally younger than c. 528 Ma (Pollock et al., 2010).

The Albemarle arc is deformed by regional, upright, southeast-vergent folds that have an associated axial planar cleavage (e.g. Butler and Secor, 1991; Offield et al., 1995, Hibbard et al., 2012). The timing of deformation and metamorphism is constrained to the Late Ordovician, c. 450 Ma, by $^{40}Ar/^{39}Ar$ spectra on micas that define cleavage in the group (Noel et al., 1988; Offield et al., 1995; Hibbard et al., 2012).

In 1995, two new fossil locales were reported from within the Albemarle Group (Koeppen et al., 1995). One site was in a quarry within the Tillery Formation near Asheboro, North Carolina, and the other was in the Cid Formation at Jacob's Creek quarry, near the hinge of the New London syncline (Fig. 2).

The euconodonts, bryozoa, and gastropods reported indicate that the Tillery Formation was no older than early Middle Ordovician and that the Cid Formation was no older than Late Cambrian. Since the original report, the same results have been triplicated (J. Repetski, pers. comm., 1998). The report of Paleozoic fossils in the lower portion of a sequence believed to be largely Neoproterozoic led to a proposal for major revision of the stratigraphy of the Albemarle Group (Offield, 2000)(Fig. 3). This stratigraphic modification also required structural reinterpretation of the outcrop pattern of the group; 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, both formerly thought to be conformable, were reinterpreted as representing major thrust faults (Fig. 3) (Offield, 2000).

Since the turn of the 21st century, the perceived stratigraphy of the Albemarle Group has lingered in limbo between the conventional stratigraphy based on regional mapping (Milton, 1984; Butler and Secor, 1991) and the more recent stratigraphic/ structural interpretation based on the Paleozoic fossil report (Koeppen et al., 1995; Offield, 2000). Recently, on the basis of new stratigraphic, paleontological, and geochronological studies at Jacob's Creek quarry it has been confirmed that the conventional view of the stratigraphy of the Albemarle Group is most apropos (Brennan, 2009; Hibbard et al., 2009) for rocks in the vicinity of the quarry. In this contribution, we expand the scope of these studies by looking at the relationships between units comprising the Uwharrie Formation and the lower Albemarle Group (Tillery and Cid formations).

In order to further resolve the problem of the stratigraphy of the Albemarle Group we set out to map the relationship between the Uwharrie and Tillery formations. New mapping indicates that the Morrow Mountain rhyolite is not confined solely to a member of the Tillery Formation, but also forms unnamed members in the Uwharrie and Cid formations, thus apparently stratigraphically linking the Uwharrie Formation to the lower Albemarle Group. These two observations led us to undertake a petrochemical study of the rhyolites in each unit. The results of this investigation provide strong evidence that the Uwharrie Formation and Albemarle Group forms a conformable sequence in the area mapped.

CRITICAL CONTACT RELATIONSHIPS

The contacts with critical bearing on the stratigraphic problem at hand are those between the Uwharrie and Tillery formations and the Cid Formation and its Flat Swamp member, for these are the boundaries that apparently sandwich the presumed Paleozoic units between the presumed Neoproterozoic units and that have been reinterpreted to represent major thrust faults within the sequence (Offield, 2000). The Cid Formation-Flat Swamp member contact has already been described as a conformable, gradational contact (Brennan, 2009; Hibbard et al., 2009); this section will focus on the Uwharrie-Tillery contact following a brief introduction to the lithic character of the units involved.

The Uwharrie Formation in the area is composed mainly of massive to layered, fine-grained grey felsic tuff with local lithic fragments, rhyolitic porphyry, spherulitic rhyolite, and local felsic rhyolite. The structurally overlying Tillery Formation is typified by distinctly laminated siltstone and argillite with subordinate shale chip conglomerate and pebble to boulder conglomerate.

The contact between the Tillery and Uwharrie formations trends northeast because of regional northeast-rending folds; it occurs just east of Lake Tillery and it is locally obscured by intrusive units (Figs. 3, 5). The nature of the contact between the Uwharrie and Tillery formations can be gleaned from exposures at Lick Mountain, Upper Wood Run Creek, Wood Run Creek, and in the vicinity of Cedar Creek, but it is best observed in Island Creek, east of the Lake in the Pine Campground (Figs. 3, 5).

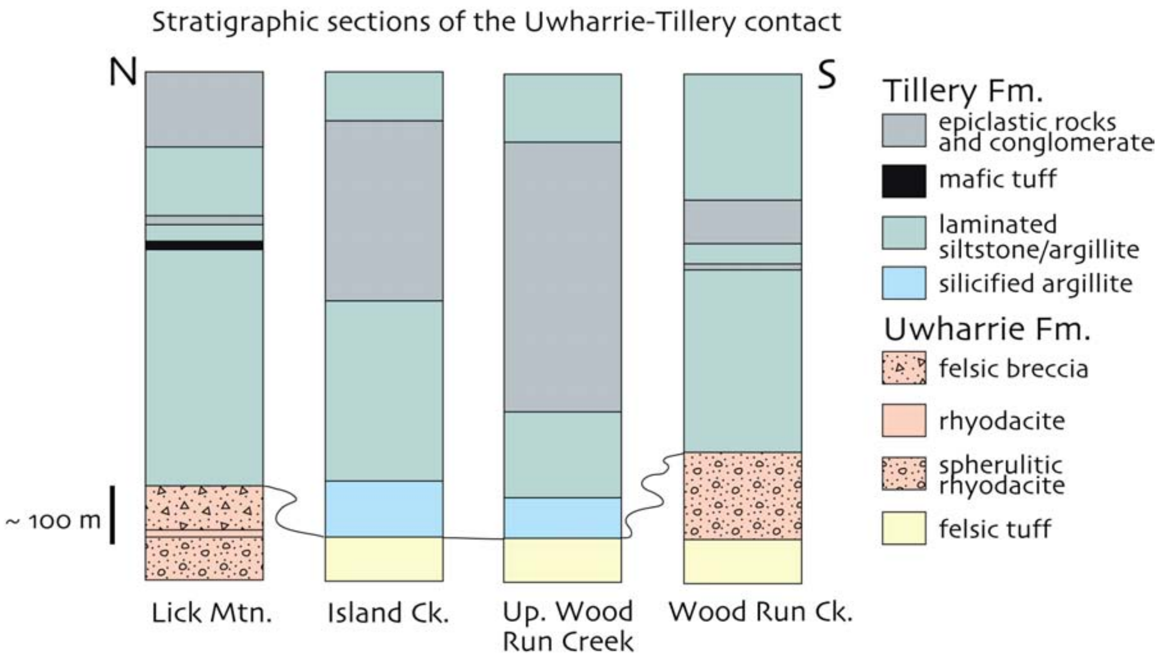

Figure 5: Schematic stratigraphic columns of the Uwharrie-Tillery formations contact to the east of Lake Tillery.

At Island Creek, the contact zone is characterized by interlayered felsic tuffs typical of the Uwharrie Formation and sedimentary rocks of the Tillery Formation over a thickness of approximately thirty meters. The contact between the formations is placed where clastic sedimentary rocks predominate over tuffs. Locally, highly silicified argillites of the Tillery Formation are interbedded with tuffs identical to those of the Uwharrie Formation on a scale of 15-20 cm. Additionally, lithic clast conglomerates typical of the Tillery Formation are interlayered with tuffs characteristic of the Uwharrie Formation. Shale chip conglomerates also occur locally in the contact area. Significantly, there is no sign of structural disruption across this well-exposed contact zone. Collectively, these field observations indicate that there is a gradational contact between the Uwharrie Formation and the Tillery Formation.

To the north, along Cedar Creek (Figs. 3, 5), the contact is unexposed; however, typical fine-grained tuff of the Uwharrie Formation comes within 50 m of an overlying cobble-boulder conglomerate of the Tillery Formation. A black, porphyritic rhyolite occurs to both sides of the northeastward, along-strike, projection of the contact; based on this map pattern, the contact is apparently intruded by the rhyolite. The rhyolite is lithologically identical to the Morrow Mountain rhyolite of the Tillery Formation. Interestingly, the basal volcanic conglomerate of the Tillery Formation contains cobbles identical to the black rhyolite, suggesting that intrusion and deposition of the conglomerate at this locality may have occurred simultaneously. Alternatively, we have mapped similar rhyolites lower in the Uwharrie section; perhaps these rhyolites form the source for the cobbles. Again, at this locality there is no evidence of structural disruption in the vicinity of the Uwharrie-Tillery contact.

On the basis of the observations described above, as well as our mapping of the contact at other localities in the area, it appears as though the Neoproterozoic Uwharrie Formation is in conformable, gradational contact with the overlying Tillery Formation. In addition, it appears that rhyolitic porphyry, lithologically identical to the Morrow Mountain member, occurs in the Uwharrie Formation and appears to intrude across the Uwharrie-Tillery contact. This conclusion is strongly supported by observations on the character and geochemistry of the Morrow Mountain rhyolite.

MORROW MOUNTAIN RHYODACITE

The name "Morrow Mountain" was first applied to a dark grey to black, commonly flow-layered, porphyritic rhyolite that outcrops in the area of Morrow Mountain (Fig. 3) (Conley and Bain, 1965). The unit was considered to represent a sequence of flows that formed the upper portion of the Tater Top Group (Conley and Bain, 1965), a dominantly volcanic unit thought to be unconformable above the Albemarle Group throughout the Albemarle region (Conley, 1962). Subsequent workers demonstrated that the Tater Top Group does not form a distinct unit and that the "Morrow Mountain rhyolite" forms domes and associated volcanic lentils within the Albemarle Group (Stromquist and Sundelius, 1969; Milton, 1984; Butler and Secor, 1991). Consequently, Milton (1984) abandoned the Tater Top unit and informalized the term "Morrow Mountain rhyolite," although most workers retained the term and depicted the unit as an extrusive and/or intrusive member of the Tillery Formation (Stromquist and Sundelius, 1969; Milton, 1984; Butler and Secor, 1991). Our geochemical analyses (see below) indicate that contrary to previous field-based descriptions, these rocks are rhyodacitic in composition and will from here on in be called rhyodacites.

Our recent mapping indicates that felsic rocks, lithologically identical to the rhyodacite at Morrow Mountain, forms irregular-shaped intrusive stocks and associated lentils of extrusive rock in the Uwharrie Formation and the Tillery and Cid formations of the Albemarle Group, e.g. at Lick Mountain (Uwharrie Formation), Tater Top and Morrow mountains (Tillery, Cid formations) and at Falls Mountain (Cid Formation)(Fig. 3). This lithologic correlation is compellingly supported by our geochemical study reported below. We thus view the Morrow Mountain member to represent an eruptive increment of rhyodacite during Tillery deposition; this increment was part of a longer-lived magmatic episode that is also responsible for the intrusion and eruption of rhyodacite complexes during deposition of the Uwharrie and Cid formations. We herein refer to all of these felsic magmatic rocks, informally, as the 'Morrow Mountain rhyodacites'.

Aphanitic, massive rhyodacite and rhyodacite porphyry commonly occur as dikes, stocks, and flows that form hilltops throughout the study area (Fig. 3). Intrusive rhyodacites also form fine-grained dikes locally exposed in topographic lows. All of the rhyodacites are gray to black on fresh surfaces, with a white chalky rind characteristic of weathered surfaces and they all break with a distinct conchoidal fracture. The rhyodacites are locally flow-banded. Both aphyric and plagioclase -phyric varieties of rhyodacites are found in the area. Plagioclase laths, where present, are either elongate and euhedral with an aspect ratio of about 1:3 and a long dimension up to 10 mm, or less commonly are blocky and subhedral. Quartz-phyric rhyodacite is rare; where present, quartz crystals are paramorphic after beta quartz. Commonly, the rhyodacites display a fragmental texture wherein angular clasts of the aphyric black rhyodacite up to 3 cm across occur as angular lithic clasts in the aphyric gray rhyodacite, thus forming a breccia.

Nodular, or 'spherulitic', rhyodacite is also a conspicuous variety of rhyodacite. In map view, nodular-weathering rhyolite commonly encircles outcrops of the hilltop forming massive, laminar flow-banded or turbulent flow-banded rhyolites (Fig. 3). The semi-spherical nodules are commonly 1 cm in diameter, although locally, nodules as large as 3-4 cm in diameter are found. In thin section, these features are commonly an aggregate of fibrous quartz and plagioclase radiating out from a nucleus, a texture suggestive of devitrification spherulites (Fig. 6). However, some of these nodules are filled with concentric rings of mineral growth, a texture indicative of true lithophysae growth (Fig. 6). Thus, in hand sample it is difficult to determine whether the nodular features are devitrification spherulites, as previously interpreted (Dover, 1985; Burt, 1967) or as syn-eruptive vapor release lithophysae, although both features are present. While devitrification spherulites have no depositional significance, lithophysae suggest that the rocks were shallowly intrusive to extrusive.

A typical rhyodacite sequence is exhibited on the west slope of Lick Mountain (Fig. 3). Here, lithic clast rhyodacite breccia is overlain by nodular rhyodacite that is locally flow-banded. The nodular rhyodacite encloses turbulent flow-banded rhyodacite without nodules, which occur interfingered with laminar flow-banded rhyodacite; the flow-banded rhyodacite encloses enclaves of massive rhyodacite, which are overlain by a rhyodacite breccia wherein angular clasts of dacitic material are surrounded by a quartz filling. This sequence of rhyodacite is suggestive of silicic lava flow origin (Cas and

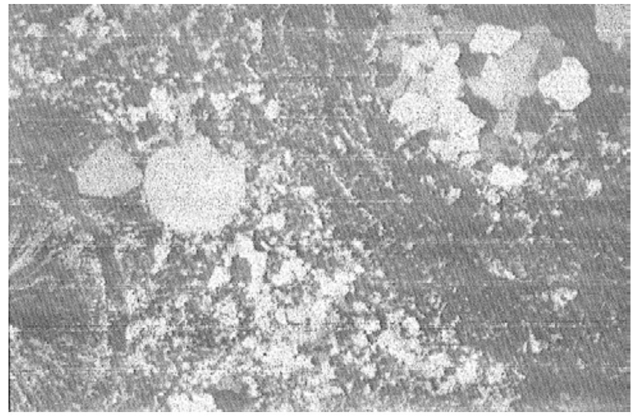

Figure 6: Nodular or 'spherulitic' rhyolite in thin section (40X) under crossed polarized light. Note the concentric banding around the quartz cluster in the northeast corner of the photo, which is indicative of lithophysae. The radiating texture in the southwest corner of the photo is a devitrification texture. Sample from Lick Mountain.

Wright, 1987); where present, this rhyodacite sequence is interpreted as largely extrusive. The extrusive rhyolite sequences tend to occur in elongate bodies roughly parallel to regional strike in the Uwharrie, Tillery, and Cid formations. These sequences are conformable with flows in the surrounding formations.

PETROCHEMISTRY OF THE 'MORROW MOUNTAIN RHYODACITES'

The primary goal of our geochemical study is to test the lithic correlation between the rhyodacite occurrences in the Uwharrie, Tillery, and Cid formations. Specifically, we are interested in determining if the formations are magmatically linked, suggesting a similar age, or if they are magmatically distinct, which would betoken that the formations may be of different ages.

The rocks of the Uwharrie - Albemarle sequence have been classified as calc-alkaline (Black, 1982; Feiss, 1982) and they plot in volcanic arc areas of tectonic discrimination diagrams (Black, 1982; Rogers, 1982). Based on these data, previous workers have interpreted the major element geochemistry of a range of rocks in the area as indicative of a supra-subduction zone magmatic arc setting (Black, 1982; Feiss, 1982; Rogers, 1982).

In this geochemical analysis, we are specifically concerned with felsic igneous rocks of the Morrow Mountain member of the Tillery Formation as to how they relate to other lithically similar felsic centers in the Uwharrie and Cid formations. Fourteen samples of 'Morrow Mountain rhyodacite' were analyzed for major and trace element concentrations (Tables 1, 2). Of these, 6 are flows and plugs within the Tillery and Cid formations, primarily to the west of Lake Tillery, and the remaining 8 samples are from hill-forming black aphanites from the Uwharrie Formation. Because the goal of this geochemical study is to determine if the 'Morrow Mountain rhyodacites' are geochemically correlative across Uwharrie Formation-Tillery Formation contact, we designate those samples from east of Lake Tillery, in the Uwharrie Formation, with an 'E' before the sample number (EHTM, E2, E3, E4, E7, E9, E11, and E12; Tables 1,2), and they are shown as blue dots in our geochemical plots. Samples that occur within the Tillery and Cid formations to the west of the Lake Tillery, are designated in the text with a 'W' before the sample number (WMMR, WTTM, WMIM, WHTW, W98-10, WSLM; Tables 1, 2) and are denoted by red dots in our geochemical plots.

Analytical Techniques

Major element analyses were performed using a Direct Coupled Plasma-Mass Spectrometer at Duke University. Analytical methods as described in Meurer (1995) were followed and results are listed in Table 1. Trace element analysis was performed using the Inductively Coupled Plasma-Mass Spectrometer (ICP-MS) facilities available at Duke University, following the methods of Meurer et al., (1999). Results are listed in Table 2.

Results

The rocks that we collected for analyses were unweathered and lacked visible veining. However, there are three lines of evidence that indicate these aphanitic rocks have been altered: the presence of quartz micro-veins, altered plagioclase compositions in some aphanites, and uncharacteristically high SiO_2 weight % values of the samples collectively suggest that fluid mobilization has altered the original chemistry of the rocks. Although we tried to avoid analyzing samples with veining, quartz micro-veins (< 1 mm wide) were observed in some thin sections of the samples. Microprobe analyses of plagioclase grains from these aphanitic rhyolites yield anorthite (An) contents of about 3-7 mole percent (Ingram, 1999). This range in An values strongly suggests alteration due to the greenschist facies metamorphic overprint. Finally, SiO_2 weight percent values, in some cases greater than 80%, are outside the field for silica contents of unaltered felsic igneous rocks (Rollinson, 1993). These samples have likely had a silica-rich fluid permeate them, increasing their silica contents and possibly leading to the redistribution of mobile elements such as K. However, on the igneous spectrum of Hughes (1973), a measure of spilitization and K-metasomatism, all of the samples lie within the igneous spectrum (Fig. 7A), suggesting that alkali element alteration was not significant.

The 'Morrow Mountain' rocks have traditionally been classified as rhyolites based on their alkali contents (e.g. Butler and Ragland, 1969); however, it should not necessarily be inferred that these rocks were originally rhyolitic in composition, due to the potential mobility of elements (Rollinson, 1993) discussed above. Geochemical discrimination diagrams have been developed for altered volcanic rocks, allowing them to be assigned an igneous classification by utilizing immobile trace elements (Jenner, 1996; Winchester and Floyd, 1977). Ratios of non-

TABLE 1: Major element data from the 'Morrow Mountain rhyodacites'; values given as weight percent oxides.

Sample	SiO2	Al2O3	Fe2O3 +FeO	MgO	CaO	Na2O	K2O	TiO2	P2O5	MnO	TOTAL
1. E11	74.73	12.34	2.12	0.304	0.8	4.62	2.65	0.281	nd	0.102	97.94
2. E12	75.46	12.39	2.22	0.218	0.75	4.58	2.75	0.305	nd	0.145	98.81
3. E2	75.58	12.72	2.11	0.273	0.9	4.49	2.81	0.284	nd	0.105	99.28
4. E3	73.34	13.2	2.54	0.392	1.71	4.35	2.66	0.395	nd	0.115	98.72
5. E4	72.94	13.02	3.08	0.351	1.37	4.76	2.57	0.384	nd	0.124	98.6
6. E7	76.64	12	1.12	0.112	0.21	3.78	4.87	0.115	nd	0.038	98.88
7. E9	78.13	11.26	1.8	0.156	0.18	3.96	3.07	0.318	nd	0.088	98.96
8. EHTM	76.03	11.51	1.11	0.096	0.18	4.56	2.97	0.097	nd	0.04	96.59
9. W98-10	73.61	13.81	2.61	0.307	1.2	5.33	2.33	0.256	nd	0.111	98.96
10.WHTW	80.99	9.34	1.19	0.048	0.16	3.4	2.93	0.094	nd	0.043	98.2
11. WMIM	79.31	11.02	1.34	0.1	0.25	4.17	3.21	0.092	nd	0.06	99.54
12.WMMR	78.44	12.23	1.23	0.049	0.47	3.96	4.19	0.113	nd	0.033	100.71
13. WTTM	79.12	12.06	1.45	0.213	0.4	4.2	3.74	0.107	nd	0.073	101.36
14. WSLM	77.1	12.55	1.6	0.092	0.34	5.49	2.44	0.124	nd	0.063	99.8

-mobile trace elements (Zr/Ti and Nb/Y) are used to define the fields. According to this plot (Fig. 7B) the samples have rhyodacitic compositions.

Major Elements: SiO_2 variation diagrams for Al_2O_3, total Fe as $FeO+Fe_2O_3$, and CaO (Fig. 7C-E) show that eastern and western samples combined form a compositional continuum of decreasing major element abundances with increasing SiO_2. Within these inverse correlations, there is intermingling of eastern and western samples (e.g., Fig. 7E). In contrast, the TiO_2 panel (Fig. 7F) shows a gap between two groups of higher and lower TiO_2 abundances, where most of the eastern samples and one western sample have the higher TiO_2.

Trace elements: SiO_2 variation diagrams for incompatible elements Nb and Zr and the transition metal Sc are in Figures 7G,H, 8A. Only the Nb panel (Fig. 8A) shows an overall inverse correlation for the collective samples, where the lowest abundances are largely in western samples. Most trace elements do not show good correlations with SiO_2 for the combined western and eastern samples (e.g., Zr, Fig. 7H). However, when five samples with the highest SiO_2 are viewed as a group, some trace elements, such as Nb and Zr (Figures 7H, 8A), show a compositional continuum as an inverse correlation with SiO_2. The Sc abundances, like TiO_2, show two compositional high and low abundance groups (Fig. 7G). These groups are better illustrated in the TiO_2 vs Sc plot (Fig. 8B). Because some samples have clearly different TiO_2 and Sc abundances at similar SiO_2 (Figs. 7F, G), it is unlikely that the two groups are related by fractional crystallization involving a mineral that incorporates both TiO_2 and Sc, such as amphibole or ilmenite. Furthermore, a trace element abundance ratio that is controlled largely by zircon crystallization, Zr/Hf (e.g., Clairborne et al., 2006), forms two groups (Fig. 8C) -- one that is ~36-38, or chondritic (e.g., David et al., 2000), and corresponds to the high TiO_2 and Sc groups, and another that is lower, ~25-30 (Fig. 8C). Some samples in these two Zr/Hf groups have similar SiO_2 concentrations. The Zr/Hf ratios, then, also suggest it unlikely that the two distinct compositional groups represented among Morrow Mountain rhyolites are related by differentiation.

TABLE 2: Trace element data from the 'Morrow Mountain rhyodacites'; values given as ppm.

Sample	Li	Be	P	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr
1. E11	7.011	2.375	156.429	11.001	1.783	1.483	60.174	<.5	1.596	80.758	13.575	78.483	105.151
2. E12	6.922	2.257	165.084	10.577	1.909	1.853	55.288	<.5	2.043	86.77	13.784	89.185	126.419
3. E2	7.922	2.474	165.16	11.126	2.715	1.433	39.698	1.041	4.225	85.279	15.172	87.092	114.998
4. E3	7.496	2.406	281.199	12.591	4.188	1.438	36.358	1.725	5.518	82.196	15.79	79.032	177.673
5. E4	6.32	2.295	264.853	12.068	3.839	1.396	37.315	1.136	2.683	84.486	14.23	72.527	142.204
6. E7	6.679	1.686	195.624	4.037	1.135	1.28	36.19	<.5	1.791	57.963	7.359	118.989	57.443
7. E9	7.179	1.723	127.269	12.547	1.921	1.345	57.149	<.5	1.654	63.384	11.429	85.717	68.169
8. EHTM	6.532	1.813	42.218	3.29	0.914	1.45	62.083	<.5	3	39.096	11.468	55.32	27.592
9. W98-10	6.699	2.355	189.648	11.326	1.024	1.526	44.184	<.5	1.235	102.457	18.418	61.884	105.513
10.WHTW	6.179	1.911	51.161	3.662	0.671	1.48	42.353	<.5	2.525	36.759	11.639	76.687	31.094
11. WMIM	6.793	1.563	34.283	5.335	0.902	1.621	36.154	<.5	2.678	58.84	9.222	89.277	45.161
12.WMMR	6.065	2.045	53.874	6.005	0.584	1.397	48.421	<.5	1.916	54.343	13.569	127.083	92.676
13. WTTM	8.197	1.956	38.164	5.527	0.637	1.351	34.743	<.5	2.635	69.688	15.887	118.755	32.903
14. WSLM	6.596	2.391	61.133	5.54	0.528	2.867	45.264	<.5	5.769	68.994	18.115	62.696	51.516
	Y	Zr	Nb	Cs	Ba	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb
1. E11	43.918	185.465	8.492	1.123	644.743	26.573	55.193	6.784	26.99	5.874	1.373	6.355	1.054
2. E12	42.69	179.271	7.786	1.766	533.574	24.643	51.338	6.319	25.013	5.554	1.248	6.016	1.01
3. E2	50.186	198.301	9.426	2.286	624.284	30.109	57.232	7.557	30.168	6.692	1.511	7.277	1.211
4. E3	41.927	144.793	9.772	1.11	583.832	25.018	52.339	6.43	25.855	5.646	1.431	6.169	1.007
5. E4	38.865	195.104	9.58	1.474	588.195	23.661	50.454	6.219	25.007	5.544	1.373	5.936	0.975
6. E7	30.033	96.943	6.738	1.038	812.335	25.895	50.405	5.779	21.444	4.203	0.709	4.318	0.694
7. E9	43.432	230.172	11.076	1.316	699.225	30.56	59.98	7.147	27.686	5.996	1.296	6.313	1.064
8. EHTM	21.474	98.837	8.819	1.061	539.501	12.405	29.28	3.273	12.666	3.129	0.439	3.404	0.591
9. W98-10	49.095	214.351	8.289	0.657	412.084	23.738	50.694	6.553	26.692	6.207	1.399	6.904	1.176
10.WHTW	46.904	127.27	5.992	1.228	499.088	20.065	46.037	4.901	19.323	4.612	0.784	5.662	1.021
11. WMIM	55.866	123.376	6.836	0.59	659.193	27.313	54.371	6.583	25.971	5.86	0.699	6.986	1.197
12.WMMR	49.311	145.476	6.787	0.759	761.609	26.6	55.436	6.711	26.261	5.949	0.818	6.709	1.153
13. WTTM	38.82	132.813	7.25	0.742	614.585	19.957	47.546	4.964	19.199	4.324	0.581	4.939	0.865
14. WSLM	57.1	164.734	8.059	0.67	596.233	30.62	63.783	7.895	31.607	7.497	1.069	8.443	1.432

TABLE 2 (cont.): Trace element data from the 'Morrow Mountain rhyodacites'; values given as ppm.

Sample	Dy	Ho	Er	Yb	Lu	Hf	Ta	Pb	Th	U	Eu*	Ti
1. E11	6.635	1.459	4.191	4.501	0.706	4.905	0.801	12.656	7.606	1.961	6.11	2810
2. E12	6.38	1.404	4.018	4.323	0.677	4.736	0.751	13.852	6.888	1.806	5.78	3050
3. E2	7.674	1.674	4.853	5.046	0.773	5.308	0.746	14.442	7.498	1.963	6.98	2840
4. E3	6.368	1.39	3.959	3.869	0.576	3.779	0.721	17.456	6.718	1.704	5.91	3950
5. E4	6.15	1.336	3.88	4.065	0.641	5.117	0.715	14.462	6.888	1.716	5.74	3840
6. E7	4.321	0.95	2.752	3.043	0.502	3.111	0.644	35.098	7.984	1.91	4.26	1120
7. E9	6.808	1.514	4.501	5.146	0.85	6.387	0.988	6.827	9.987	2.387	6.15	3180
8. EHTM	3.969	0.898	2.743	3.274	0.503	3.923	0.952	11.211	7.409	2.085	3.27	940
9. W98-10	7.602	1.673	4.881	5.365	0.862	5.497	0.667	8.929	6.905	1.704	6.56	970
10.WHTW	6.887	1.534	4.534	5.02	0.803	4.237	0.661	12.39	7.144	1.597	5.14	920
11.WMIM	7.905	1.774	5.099	5.093	0.799	4.104	0.691	14.586	8.863	2.06	6.42	1130
12.WMMR	7.534	1.636	4.785	5.198	0.801	4.698	0.781	15.415	10.013	2.942	6.33	1070
13. WTTM	5.665	1.296	3.873	4.519	0.741	4.389	0.719	22.832	8.535	2.373	4.63	1240
14. WSLM	9.203	1.977	5.774	6.447	1.042	5.725	0.869	14.106	9.484	2.477	7.97	2560

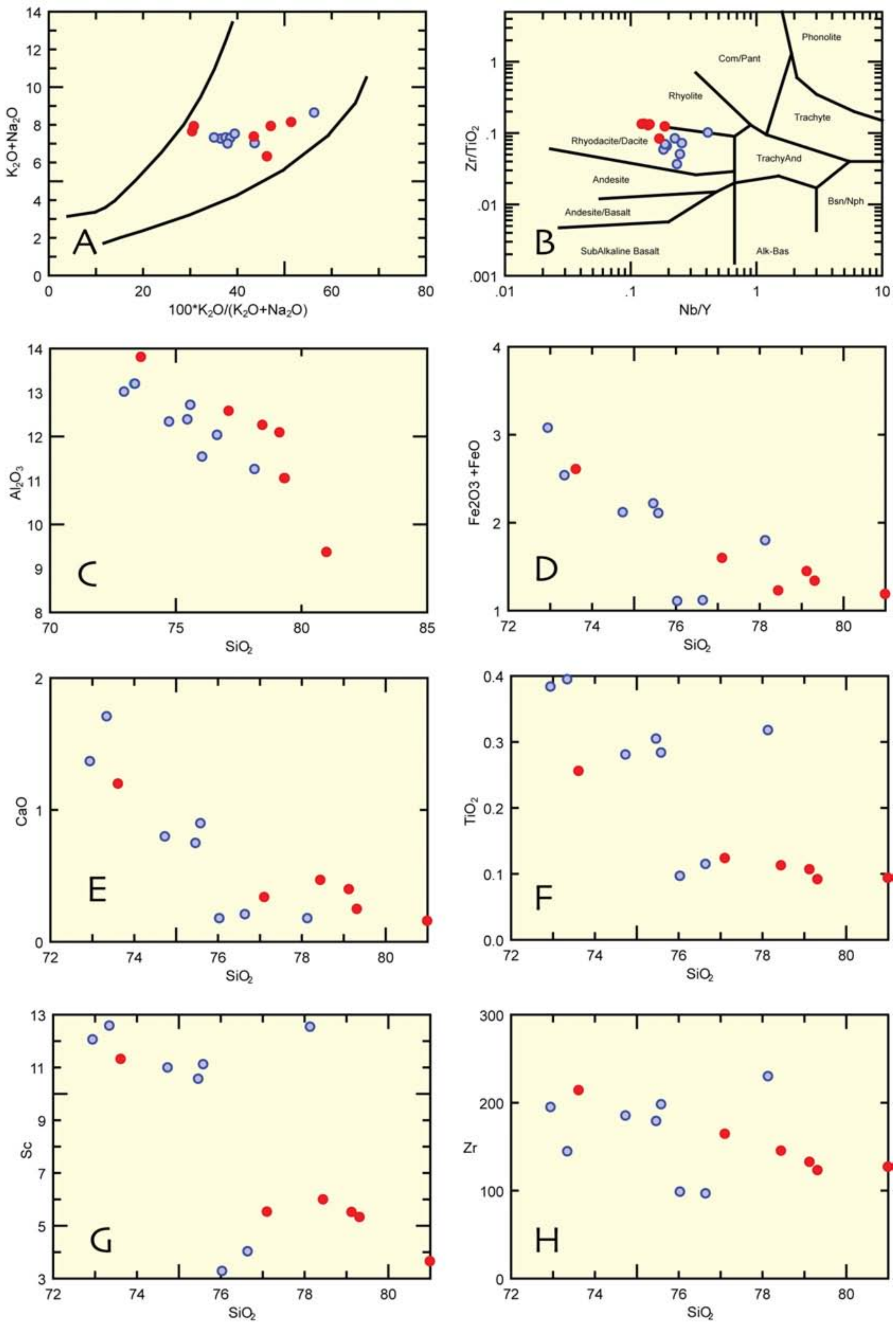

Figure 7: Geochemical plots as discussed in text. Blue dots represent samples from the Uwharrie Formation, red dots represent samples from the Albemarle Group.

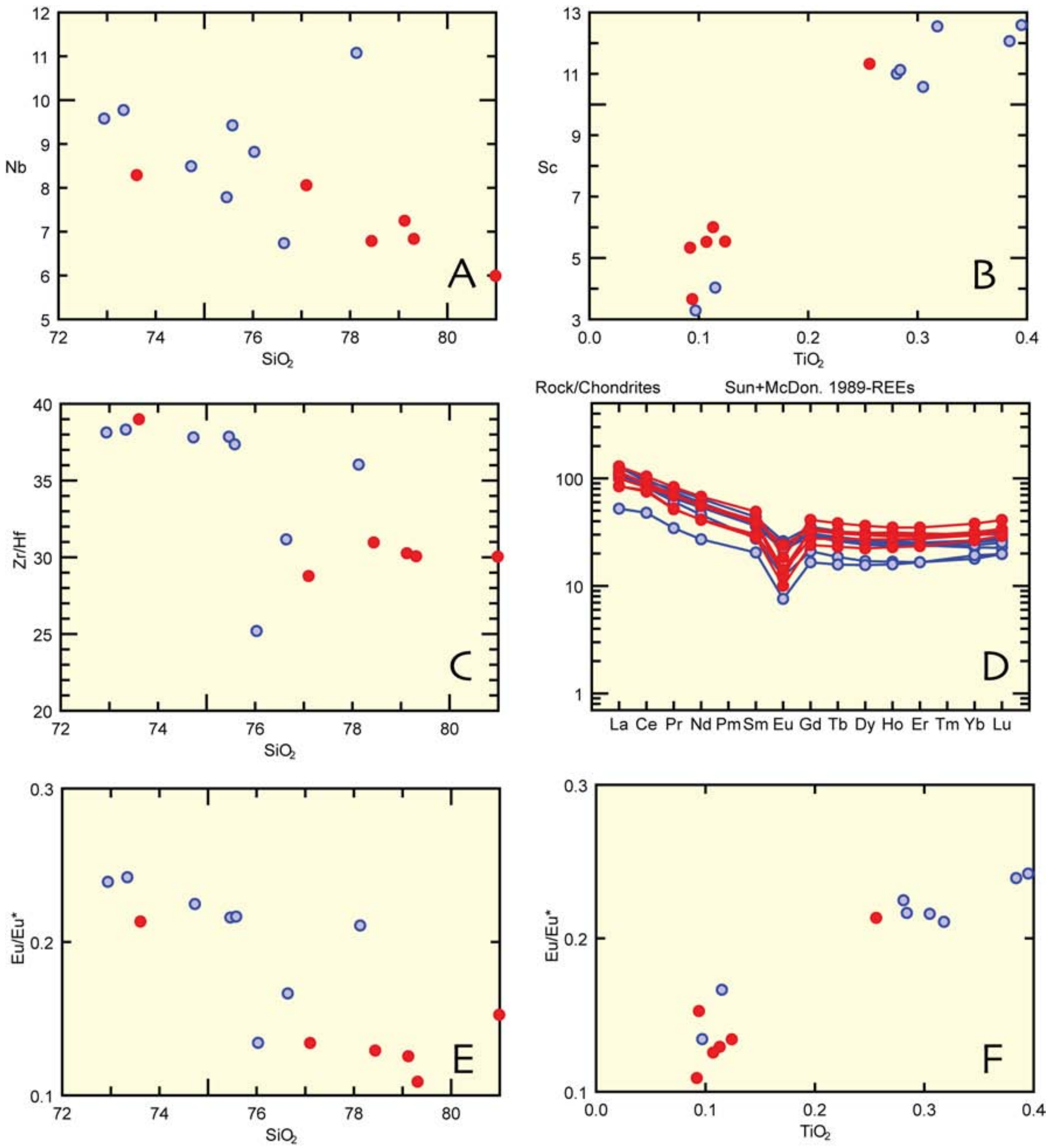

Figure 8: Geochemical plots as discussed in text. Blue dots represent samples from the Uwharrie Formation, red dots represent samples from the Albemarle Group.

Chondrite-normalized REE (rare-earth element) patterns (Fig. 8D) show that, in general, eastern and western samples overlap, and that all samples have relative light-REE enrichments. All samples also have strong negative anomalies that suggest histories of feldspar segregation (as Eu partitions into feldspar more readily than other REE). The decreasing trends of Al_2O_3 and CaO (Figs. 7C, E) are also consistent with feldspar fractionation in the histories of the magmas that represent both the eastern and western samples.

To evaluate whether the various samples represent similar or different histories of feldspar in their magma systems, we plot Eu/Eu*, a ratio that evaluates the 'depth' of the Eu 'troughs' in REE patterns with respect to patterns not having a Eu anomaly. In

Figures 8E,F, Eu/Eu* ratios show compositional gaps that correspond to those observed for TiO_2 and Sc. They point to the samples in the two TiO_2 (and Sc) groups having experienced different magmatic histories with respect to feldspar, whether it was by fractionation or by the percentage of feldspar in their magma sources.

Summary: Based on some major and trace element abundances (e.g., TiO_2, Sc, Eu) and the groupings they form among the combined eastern and western samples, there are at least two major rhyolitic magma groups represented in the Morrow Mountain region. These two groups do not appear to be stratigraphically controlled, as members of each geochemical group occur within the Uwharrie Formation to the east and in the Albemarle Group rocks to the west, thus suggesting that the entire Uwharrie - Albemarle sequence is magmatically linked. In each of the two magma groups, feldspar appears to have left a strong signature as negative Eu anomalies. These anomalies may represent the fractional crystallization of feldspar in these rhyolitic magma systems, but alternatively, Eu anomalies may reflect the abundance of feldspar in the source materials partially melted to yield the rhyolitic magmas. Highly-incompatible trace-element abundances (e.g., Zr, Nb) in five of the western samples, which collectively represent the highest SiO_2 Morrow Mountain rhyolites, form coherent trends that suggest these five samples are from a single magma reservoir and related by magma differentiation.

Trace element data compiled from scant other geochemical data sets available from earlier studies of 'Morrow Mountain rhyodacites' are in agreement with our results given above (Butler and Ragland, 1969; Dover 1985; Ingle, 1999). These earlier geochemical studies, although generally not as focused as our study, support a geochemical link between the Uwharrie Formation and the lower Albemarle Group.

CONCLUSIONS

Our study has confirmed previous regional mapping that the Uwharrie Formation and the Tillery Formation at the base of the Albemarle Group form a conformable succession. Their mutual contact is a zone where strata typical of both units are interlayered without sign of tectonic disturbance. This observation indicates that revision of Albemarle Group stratigraphy and introduction of a major thrust fault at the Uwharrie-Tillery contact (Offield, 2000) is unwarranted.

In addition, we observed rocks that are lithically identical to the Morrow Mountain member rhyodacite of the Tillery Formation in both the underlying Uwharrie Formation and the overlying Cid Formation. Geochemical analyses of these 'Morrow Mountain rhyodacites' indicates that there are two geochemical groups representing at least two magmas. The distribution of these two groups is not controlled by the stratigraphy. That is, members of each group occur throughout the Uwharrie –lower Albemarle Group sequence, magmatically linking these units. This geochemical evidence supports field interpretations; namely, if the Uwharrie, Tillery and Cid formations are magmatically linked by the 'Morrow Mountain rhyodacites', then it is likely that no major gap exists in the ages of the three formations. The odds are strongly against a scenario implied by the revisions of Offield (2000), which requires that two magma types erupted in the late Neoproterozoic, during Uwharrie deposition, followed by a hiatus of ca. 75 m.y., only to have identical magma types generated in the early Middle Ordovician. It is much more geologically reasonable to interpret the Uwharrie-Tillery-Cid sequence as a conformable sequence that was deposited during a single magmatic episode during which at least two magma types were erupted.

Our study has provided further evidence to dispel the regional significance of the Paleozoic fossil report (Koeppen et al., 1995), although it still remains a possibility that the fossils occur in very limited pockets of Paleozoic strata that form erosional outliers in the largely Neoproterozoic lower Albemarle arc. In addition, our study has brought up some interesting questions concerning the possibility that the lower Albemarle Group and the Uwharrie Formation may largely overlap in time. These questions can only be answered with a more comprehensive geochemical and geochronological campaign within the Albemarle arc.

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GEOLOGY IN THE VICINITY OF THE MARTIN MARIETTA ASHEBORO QUARRY, NORTH CAROLINA: ASSESSMENT OF THE STRATIGRAPHY OF THE LOWER ALBEMARLE ARC

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ABSTRACT

The Albemarle arc is a major defining component of the Carolina terrane, the largest terrane in, and the heart of Carolinia. A report of Paleozoic fossils from two units in the arc that are traditionally considered Late Neoproterozoic has brought the generally accepted stratigraphic and structural interpretation for the Albemarle sequence into question. This study seeks to clarify stratigraphic relationships in the lower Albemarle sequence in the vicinity of the Martin Marietta Asheboro quarry, one of the reported Paleozoic fossil locales. Stratigraphic revision proposed for the Albemarle sequence in light of the reported paleontological data requires that the contact between the Tillery Formation and underlying Uwharrie Formation is a significant thrust fault; however, observations made in our study lead us to interpret the contact to be conformable, lacking any evidence of structural disruption. In addition, felsic dikes cutting strata in the quarry are more consistent with the Tillery Formation being Neoproterozoic. Therefore, the Tillery rocks at the Asheboro quarry and surrounding area are here considered to be Late Neoproterozoic and we conclude that revision of the stratigraphy of the Albemarle arc is unwarranted.

INTRODUCTION

The Albemarle arc is a major lithotectonic component of the Carolina terrane, one of the largest and best-known of the elements that form the southern Appalachian peri-Gondwanan block of Carolinia (e.g. Hibbard et al., this volume). As such, the stratigraphy of the arc is significant because it provides a basis for correlation of Carolinia with other peri-Gondwanan crustal blocks in both the Appalachians as well as globally (e.g. Hibbard et al., this volume; 2007). The stratigraphy of the Albermarle arc has been problematic. In particular, the main unit within the arc in North Carolina - the Albemarle Group (Conley and Bain, 1965) - 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; also see Butler and Secor, 1991; Hibbard et al., 2002). In Milton's version of the stratigraphy, the Albemarle Group is considered to be mainly Neoproterozoic, and consists of a succession of four conformable formations, which includes from bottom to top, the Tillery, Cid, Floyd Church, and Yadkin formations; the group is viewed as conformable with the underlying Neoproterozoic Uwharrie Formation and to have an erosional top. Collectively, the Uwharrie Formation and Albemarle Group constitute the Albemarle arc in North Carolina (Hibbard et al., this volume).

In 1995, an abstract reported two new fossil locales from within the Albemarle Group (Koeppen et al., 1995). One site was in a quarry within the Tillery Formation near Asheboro, North Carolina, and the other was in the Cid Formation at Jacob's Creek quarry, near the hinge of the New London syncline (Fig. 1). 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. The report of Paleozoic fossils in the lower portion of a sequence believed to be largely Neoproterozoic led to a major revision of the stratigraphy of the Albemarle Group (Offield, 2000)(Fig. 2). Stratigraphic modification also required structural reinterpretation of the outcrop pattern of the group; the contact between the Uwharrie volcanics and the Tillery Formation, as well as the contact between the Flat Swamp Member of the Cid Formation and the underlying Cid mudstones, both formerly thought to be conformable, were reinterpreted as representing major thrust faults (Fig. 2) (Offield, 2000). Recent studies in the area of the Jacob's Creek quarry fossil locale have cast doubt on the validity of the structural and stratigraphic modifications proposed to accommodate the Paleozoic fossil report and they conclude that either the fossils occur in Paleozoic outliers of very limited

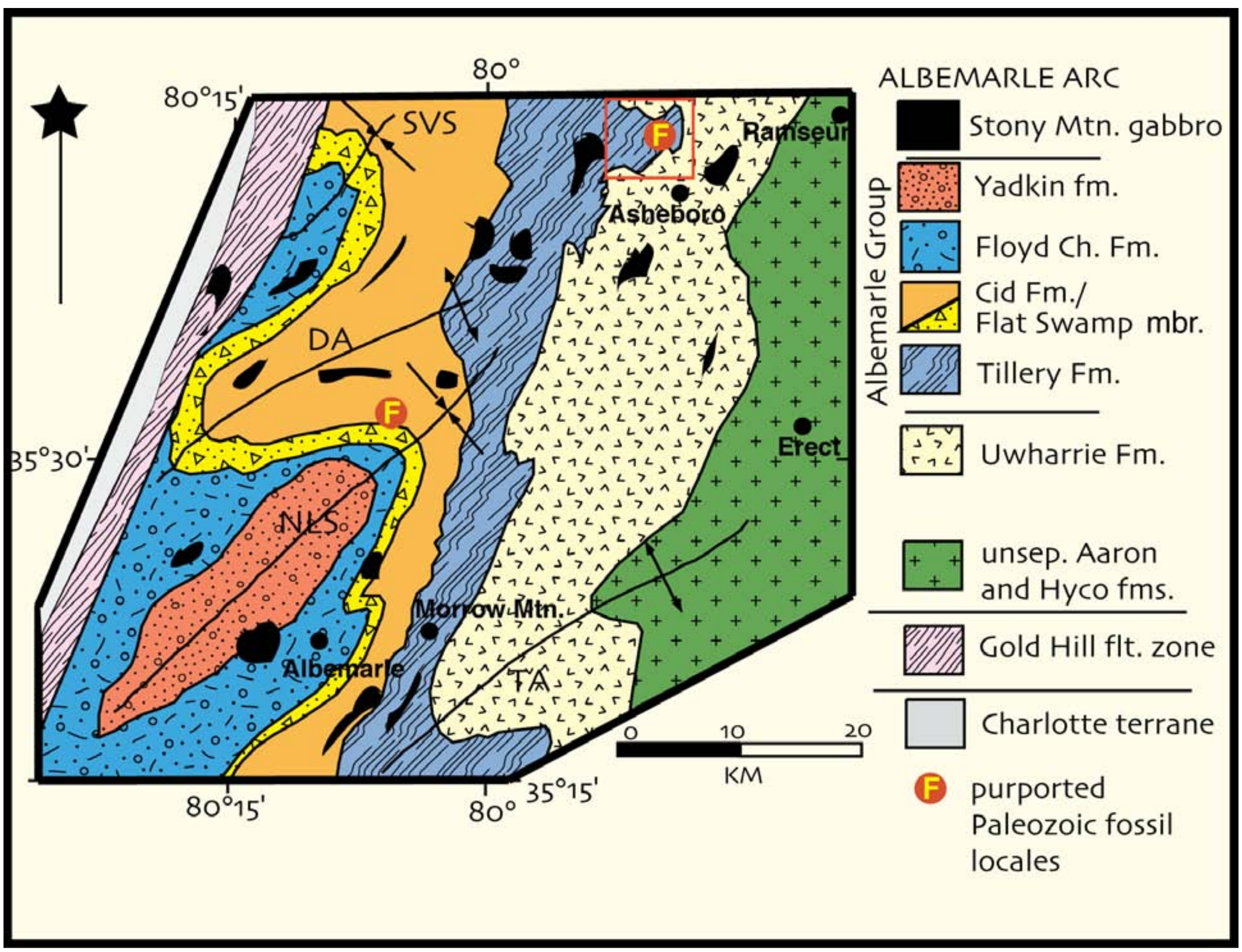

Fig. 1: General geology of the Carolina terrane in central North Carolina. Circled 'F' indicates location of the reported Paleozoic fossils, DA = Denton anticline, NLS = New London syncline, SVS = Silver Valley syncline, TA = Troy anticline, red box delineates approximate area of figure 3.

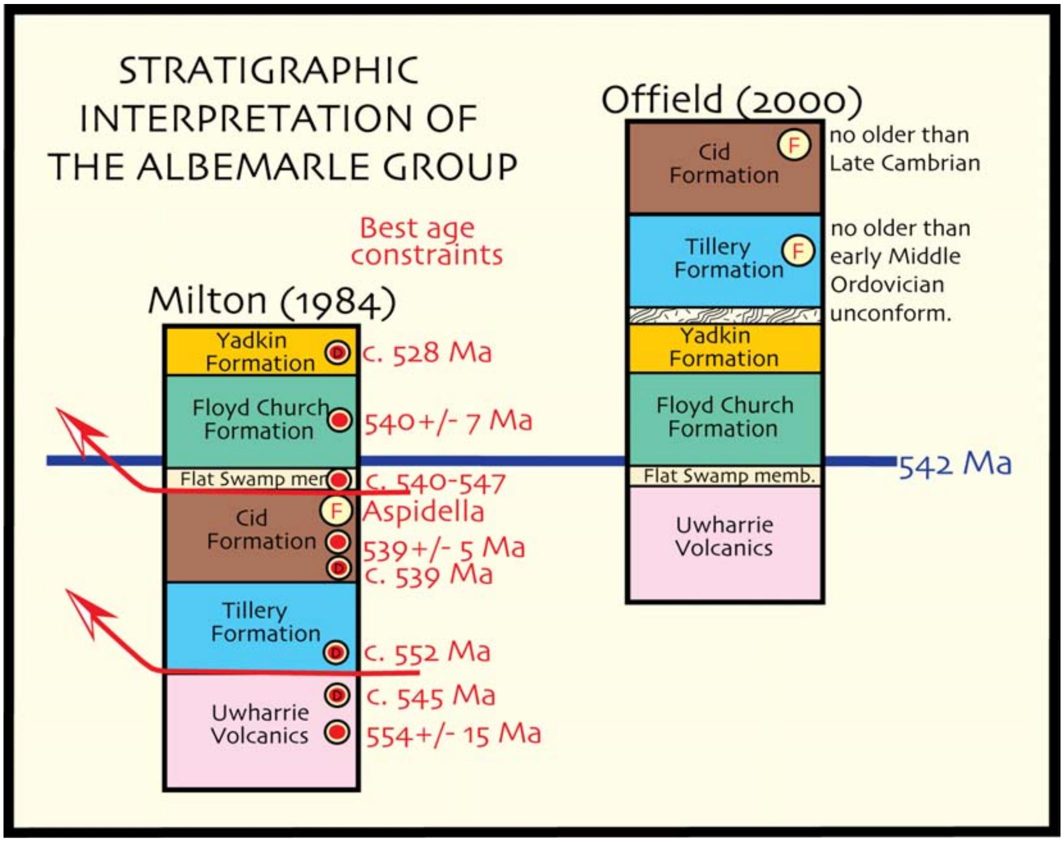

Figure 2: Stratigraphic interpretation of the Albemarle arc. Left column depicts the conventionally accepted stratigraphy (Milton, 1984) along with the most reliable age constraints on different units. Method of analysis in each case given in the text of Boorman et al., this volume. Bullseye = radiometric age, Bullseye + D = detrital zircon age, Bullseye + F = fossil constraint. Red arrowheads indicate position of thrust faults required by stratigraphic/structural interpretation of Offield (2000). Right column depicts the proposed stratigraphy of Offield (2000), following report of Paleozoic fossils in the Tillery and Cid formations. Solid line represents the Neoproterozoic-Cambrian boundary.

area or that the fossil data are erroneous (Hibbard et al., 2009; Boorman et al., this volume). However, the fossil locale in the Asheboro quarry has not received such scrutiny. In an attempt to rectify this situation and to further assess the proposed structural/stratigraphic framework of the Albemarle arc as proposed by Offield (2000), we have undertaken studies (Kurek, 2010) in the vicinity of the Asheboro quarry (Figs. 1, 3), the location where fossils no older than early Middle Ordovician were reportedly found (Koeppen et al., 1995). The Asheboro quarry is important for several reasons: 1) the quarry contains the carbonate rocks purported to contain the Paleozoic fossils, 2) the quarry has fresh exposures of Tillery rocks that are virtually absent in the areas outside of the quarry, and 3) the quarry contains numerous cross-cutting felsic dikes that provide the potential opportunity to obtain an age constraint on strata in the quarry. We herein consider three viable hypotheses for the stratigraphy of the Albemarle Group and we use the results of our studies at the quarry to test these hypotheses.

TESTABLE HYPOTHESES FOR THE STRATIGRAPHY OF THE ALBEMARLE ARC

At present, there are three possible hypotheses to account for the stratigraphy of the

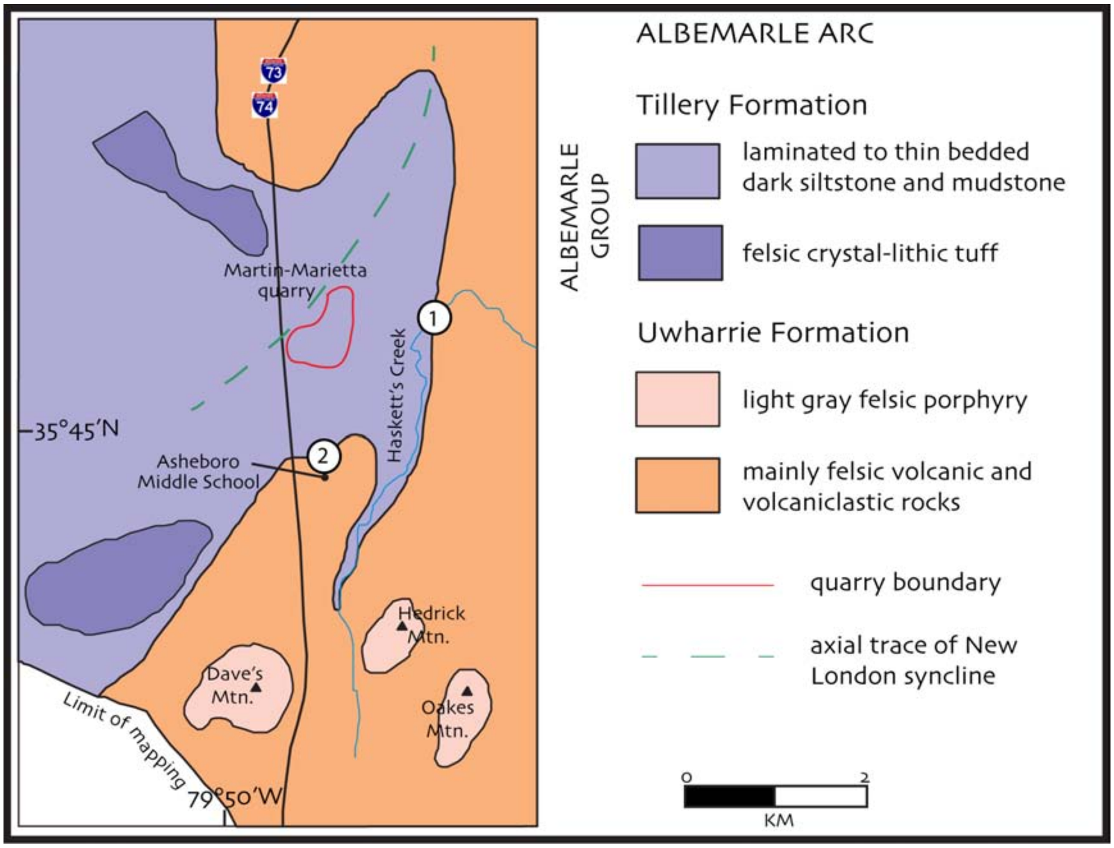

Figure 3: Geologic map of the area between Asheboro and Randleman, North Carolina (Kurek, 2010). Circled numbers refer to locales described in text.

Albemarle Group. The first hypothesis is that the entire mapped extent of Tillery and Cid formations is Paleozoic, on the basis of the reported fossils (Koeppen et al., 1995) and that major stratigraphic and structural reinterpretation of the Albemarle Group (Offield, 2000) is valid. A second alternative possibility is that the Paleozoic fossils occur in limited erosional remnants of once larger basins, unconformable atop the mainly Neoproterozoic Albemarle Group. This interpretation constitutes a 'compromise' between the reported Paleozoic fossil data and the traditional stratigraphic/structural view of the Albemarle Group. The final hypothesis is that the reports of Paleozoic fossils in the group are erroneous and that the generally accepted stratigraphic and structural interpretation of Milton (1984) is correct.

In order to test these hypotheses, our investigation in the vicinity of the Asheboro quarry focused on 1. the nature of the contact between the Uwharrie Formation and the Tillery Formation, 2. the strata of the quarry fossil locale, and 3. the nature and age of felsic dikes cross-cutting the Tillery Formation in the quarry (Kurek, 2010). Our studies involved 1:24,000-scale mapping (Fig. 3) with more detailed geology undertaken in the quarry and along the Uwharrie-Tillery contact; we also attempted to date the dikes in the quarry. The results from our study clearly support the stratigraphic/structural interpretation of Milton (1984).

DATA FROM THE AREA OF THE ASHEBORO QUARRY

Martin Marietta Materials operates a crushed stone/aggregate quarry (Figs. 1, 3) in the lower part of the Tillery Formation of the Albemarle Group on the north side of Asheboro, NC. The quarry is located near the hinge of a second-order syncline, apparently parasitic on the northeastward extension of the regional New London syncline (Fig. 1). The area was previously mapped at a scale of 1:62,500 and the contact between the Uwharrie and Tillery formations was considered to be conformable and gradational (Seiders and Wright, 1977; Seiders, 1981). Offield et al. (1995) reported on the detailed structure and timing of deformation in the Asheboro quarry, concluding that the Tillery Formation was overprinted by a single generation of Late Ordovician folding and cleavage. All of the rocks in the study area have been subjected to lower greenschist facies metamorphism; for the sake of brevity, we drop the prefix 'meta-' from rock names in descriptions below.

The contact between the Uwharrie and Tillery formations

The contact between the Uwharrie and Tillery formations lies less than a mile to the north, east, and south of the quarry (Fig. 3) and has been interpreted to represent either a conformable contact (Seiders, 1981) or a major thrust within the Albemarle arc (Offield, 2000). We will briefly describe the rock types in the formations before discussing the contact between them.

The Uwharrie Formation in the study area is composed dominantly of felsic volcanic and volcaniclastic rocks with subordinate felsic porphyry and intermediate volcaniclastic rocks. The felsic volcanic rocks are generally massive and rarely display foliation; however, the rocks in a few places appear to be flow banded. The porphyry unit outcrops as rounded, positive topographic features at Dave's Mountain, Oakes Mountain and Hendrick Mountain (Fig. 3); the porphyry and associated volcanics at these locales appear to be relict volcanic domes (Kurek, 2010).

The characteristic rock type of the Tillery Formation is dark gray to black, laminated to thinly interbedded, siltstone and mudstone. Outcrops of the Tillery Formation outside of the quarry are usually deeply weathered to light gray, tan or white, with a dull, earthy luster. The fresh clastic rocks in the quarry commonly have a slightly phyllitic sheen. Also in the quarry, fine-grained dark gray to black carbonate forms a limited number of beds approximately 6-8 cm thick that are sparsely interbedded with the typical Tillery siltstone/mudstone. The carbonate rocks weather to a distinctive chocolate brown. The composition of the carbonate was determined by X-ray diffraction techniques as pure calcite (J. Potter, pers. comm., 2009). Locally, grey felsic crystal-lithic tuffs form small outcrop areas within the Tillery mudstones (Fig. 3).

Although the Uwharrie-Tillery contact is unexposed in the area, the nature of the contact is can be gleaned from detailed field mapping at two locales (Fig. 3). At locale one on Haskett's Creek, just east of the quarry, rock units trend approximately perpendicular to the creek. Typical Tillery Formation metaclastics are concordant with, and lie within approximately ten meters of Uwharrie felsic volcanics without evidence of structural disruption. At the second locale, just north of Asheboro Middle School (Fig 3), a small branch of Haskett's Creek trends roughly parallel to the contact for approximately 250 m. The topographically higher south bank consists of rounded outcrops of Uwharrie felsic volcanics that are cut by thin quartz veins; the flatter north bank consists of deeply weathered Tillery mudstone that exhibits continuous bedding trending subparallel to the stream. Two features, here, strongly suggest that the contact is depositional; first, mudstone at the base of the Tillery contains several ovalshaped felsic nodules approximately 1 cm in diameter that are very similar to lithophysae and spherules seen elsewhere in the Uwharrie Formation (e.g. Boorman, this volume). Secondly, an outcrop of Tillery mudstone adjacent to the contact contains several interbedded felsic ash layers, up to 5 cm thick; these layers are similar to beds found elsewhere in the Uwharrie Formation and do not occur elsewhere in the Tillery Formation in the area. Again, rocks in the contact area show no signs of structural disruption.

In summary, the formations at each contact locale are concordant and at the second locale, the middle school, there is evidence of depositional communication between the units, as the near basal beds of the Tillery Formation contain lithophysae-like nodules and the beds are interbedded with felsic ash; both of these features occur elsewhere in the Uwharrie Formation. In addition, there is no sign of structural disruption or a strain gradient at either locale. Based on these observations, we interpret the contact to be depositional and conformable.

The Tillery Formation in the Asheboro quarry

Our second hypothesis, that the purported fossil-bearing strata in the quarry form a small outlier of Paleozoic strata atop an otherwise Neoproterozoic Tillery Formation, was tested by comparing the mudstone strata in the Asheboro quarry with mudstone strata in the immediately surrounding areas. Other than the degree of weathering, no significant differences exist, in either outcrop or thin section, between mudstone rocks from throughout the study area. No evidence for depositional or structural discontinuities were observed within the Tillery Formation that may indicate a separate Paleozoic outlier unit to account for the fossil data (Koeppen et. al., 1995).

In addition, personnel from the North Carolina Museum of Natural History sampled one bed of limestone from the quarry and processed it in search of fossils and/or microfossils (Chris Tacker and Patricia Weaver, pers. comm., 2010). The sample yielded no fossils.

Felsic dikes in the Asheboro quarry

A sparsely distributed swarm of felsic dikes, with individual bodies up to 2 m wide, intrude across bedding of Tillery strata in the Asheboro quarry. They stand out prominently in the quarry, as their lighter-color contrasts sharply with the dark gray to black Tillery strata (Fig. 4). The felsic dike rocks are medium green-gray containing a few light colored feldspar phenocrysts. In thin section, mineral abundances are approximately 60% quartz, 25% plagioclase, 10% sericite, 5% chlorite and minor amounts of zoisite and carbonate. Minerals additionally found during mineral separation for U-Pb geochronology sample preparation include apatite, monazite, epidote, and pyrite.

The dikes pre-date deformation in the quarry as they are cleaved, boudinaged, and folded by the one phase of deformation recorded in the area (Offield et al., 1995; Kurek, 2010) (Fig. 4). In addition, dikes appear to be altered based on heterogeneous textures observed in thin section, as well as the presence of thin carbonate veins in the dikes. Because the felsic dikes intrude across the Tillery strata, a geochronological study of the dikes has the potential to place minimum age limitations on the Tillery Formation. In addition, if the maximum age of the Tillery Formation is early Middle Ordovician as indicated by the fossil report, the pre-tectonic dikes must be Middle or Late Ordovician in age. In order to test these ideas, we attempted to obtain a crystallization age on the dikes.

Figure 4: A. Folded and boudinaged felsic dike (light-toned body) in Martin Marietta Asheboro quarry; trend of bedding in Tillery strata highlighted with black lines. **B.** Boudinaged felsic dike in Martin Marietta Asheboro quarry

Geochronology

Two separate felsic dikes from the quarry were sampled for geochronological analyses. High-precision TIMS U-Pb geochronology was attempted at the R. Ken Williams '45 Radiogenic Isotope Geosciences Laboratory at Texas A&M University. Of the two samples, only one contained zircon; zircon grains for ID-TIMS dating were carefully selected from this sample (ASH-05-02). The zircons were large, clear, and prismatic, with pristine faces and most had one crystal termination. They contained few visible fractures or inclusions. The annealing, chemical abrasion and thermal- ionization mass spectrometry (CA-TIMS) methods were largely followed as described in Mattinson (2005). All clean sample preparation and separation chemistry for U-Pb dating was conducted in the Class 100 ultra-clean laboratory. An internally calibrated, mixed ^{205}Pb-^{233}U-^{235}U spike for routine U-Pb analysis was used. U and Pb isotopic compositions were analyzed on a ThermoFisher Triton thermal-ionization mass spectrometer. This instrument is equipped with a RPQ energy filter and a modified 14-dyanode MassCom SEM. Mass bias is determined by repeat analysis of NIST 981. Zircon samples with 10 to 100 pg Pb are measured by peak-hopping on the SEM, and U is analyzed as the dioxide in static Faraday mode.

Unfortunately, the zircons analyzed contained virtually no U and therefore very little radiogenic Pb. The suspicious appearance (large size, prismatic) of the zircons suggests that they formed more recently than the parent rock, and may have crystallized from hydrothermal fluids, rather than magmas; however, this inference can only be confirmed by measuring isotopic and trace element compositions of the zircons, which is beyond the scope of this study (Rubin et al., 1989; Fu et al., 2009).

CONCLUSIONS

Our studies in the area of the Martin Marietta Asheboro quarry have elicited new observations with respect to stratigraphy of the Albemarle arc. We interpret our field observations to indicate that the Uwharrie volcanics are in depositional, conformable contact with the stratigraphically overlying Tillery Formation. This conclusion is consistent with the conventional view that the Tillery Formation is Neoproterozoic. In addition, the Tillery

Formation in the quarry is indistinguishable, in the field and in thin section, from the strata in the Asheboro quarry, from where the fossils were reported; consequently, we strongly doubt that the strata in the quarry represent a small outlier of Paleozoic rocks within the Neoproterozoic Tillery Formation.

Although the analyses of felsic dikes that cross-cut Tillery strata in the quarry did not yield geochronological results, the dikes do provide circumstantial evidence as to the age of the Tillery Formation. As noted above, if the strata in the quarry are Paleozoic as indicated by the fossil report (Koeppen, 1995), then the dikes must be younger than the fossils (no older than early Middle Ordovician) and younger than the Late Ordovician deformation that overprints them. If so, then the dikes in quarry would represent the *first* and *only* example of Middle to Late Ordovician magmatism in the Carolina terrane. Presence of the felsic dikes is more consistent with a Neoproterozoic age for the Tillery strata in the quarry, as felsic volcanics occur in the overlying Cid and Floyd Church formations of the Albemarle Group.

The available data thus lead us to the conclusion that our hypothesis 3 - that the Paleozoic fossil report is erroneous - is the only valid alternative. We conjecture that samples could have either come from an exotic block, unrelated to the bedrock on the quarry grounds, or were mistakenly mixed up with Paleozoic samples before submittal for analyses, or that there was contamination in the lab during processing of the samples. Consequently, we also contend that major revision of the stratigraphy and structure of the Albemarle arc (Offield, 2000) is unwarranted.

ACKNOWLEDGMENTS

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Ediacaran trace fossils from the Albemarle Group of the Carolina terrane, North Carolina (USA): Marks of a mobile lifestyle on a Precambrian sea bottom

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Abstract

Body and trace fossils from the Ediacaran Period (635-542 *mya*) comprise the strongest evidence for the early evolution of animals in marine environments. Considering that most Ediacaran fossils were previously known from outside of the United States, the discovery of Ediacaran fossils in the Neoproterozoic Carolina Terrane of North Carolina during the 1980s was an exciting one, expanding the known geographic range of Ediacaran biota to the southeastern United States. However, subsequent studies of these fossils and their diagnoses have generated more disagreement than accord, such as the recent reinterpretation of "*Oldhamia recta*" as an unknown body fossil, rather than a trace fossil.

In our study, we focus on describing and interpreting undoubted trace fossils from Ediacaran (~545 *mya*) rocks from the Floyd Church Formation of the Abermarle Group of the Carolina Terrane in North Carolina. Most of the trace fossils are identifiable as *Helminthopsis* isp. and are expressed as negative-relief features on bedding planes; these are simple meandering to looping furrows with pronounced levees. Less common are simple positive-relief burrows, identified as *Planolites* isp. Consistent dimensions and overall forms of these trace fossils suggest they were made by similar mobile tracemakers. Tracemaker behavior was either surface feeding (grazing) or deposit feeding just below microbial mats (undermat mining). Other specimens of *Helminthopsis* are in geologically older rocks of the Tillery Formation of the Abermarle Group, which we report here for the first time. Lastly, we propose that some ichnogenera identified by Gibson (1989), such as ?*Tomaculum* and "*Neonerites*" [sic], are probably body fossils, thus demonstrating a need for further refinement of Ediacaran ichnology in the Carolina Terrane.

Introduction

The Ediacaran Period (635-542 *mya*) is the most significant time in the evolution of animal life during the Proterozoic Eon (Jensen, 2003; Vickers-Rich and Komarower, 2007; Fedonkin *et al*., 2008; Liu *et al*., 2010; Menon *et al*., 2013). Although lineages for most Ediacaran forms apparently did not survive into the Phanerozoic Eon, their body and trace fossils represent some of the earliest evolutionary innovations in animals adapting to shallow- and deep-marine environments, including initial attempts at burrowing and nutrient cycling on and in seafloors (Seilacher and Pflüger, 1994; Seilacher, 1999; Bottjer et al., 2000; Seilacher *et al*., 2005; Droser *et al*., 2006; Herringshaw *et al*., 2010; Menon *et al*., 2013). Such fossils have been reported from Australia, Argentina, England, Russia, Namibia, Newfoundland (Canada), as well as California and North Carolina (USA), with a surprising amount of overlap in taxa and ichnotaxa

(Vickers-Rich and Komarower, 2007; Fedonkin *et al*., 2008).

Ediacaran fossils of the Carolina Terrane in North Carolina are therefore important for the insights they reveal about Ediacaran life in this part of Laurasia. When reported by Gibson *et al*. (1984) and Gibson (1989), these were the first known body and trace fossils in the southeastern United States comparable to Ediacaran assemblages elsewhere in the world. However, since then, a few body fossils in the Carolina Terrane assemblage have been reinterpreted, and some are now considered as pseudofossils (Weaver and Ganis, 2013, this volume). Trace fossils are probably the most problematic of the Carolina Terrane assemblage, with some misinterpretations, such as the naming of a new ichnospecies, "*Oldhamia recta*" (Seilacher *et al*., 2005), which was later determined to be an unknown body fossil (Tacker *et al*., 2010).

The two main purposes of this study are to: (1) describe two of the undoubted trace fossils in the Carolina Terrane Ediacaran fossil assemblage, *Helminthopsis* isp. and *Planolites* isp., from rocks recovered in the Floyd Church and Tillery Formations of the Abermarle Group; and (2) affirm the identity of a few trace fossils identified by Gibson (1989), but also propose that others are more likely body fossils. As a result, we echo previous cautionary tones issued by many previous workers about maintaining a healthy skepticism when diagnosing suspected Ediacaran fossils (Jensen, 2003; Droser *et al*., 2005; Jensen *et al*., 2006; Cohen *et al*., 2009; Gehling and Droser, 2009; Liu *et al*., 2010; Tacker *et al*., 2010; Sappenfield *et al*., 2011).

DESCRIPTION OF EDIACARAN TRACE FOSSILS

Ediacaran trace fossils from the Carolina Terrane found thus far are preserved in silty mudstones that are slightly metamorphosed (greenschist facies), but still have bedding planes (Milton, 1984). Some of the best-preserved and most well-expressed Ediacaran trace fossils known from the Carolina Terrane are those seen on the surface of sample NCSM10530, studied by Tacker *et al*. (2010). Trace fossils are relatively uncommon compared with the clusters of rod-like and pellet-like body fossils in the same specimen, as well as wrinkle marks that are likely microbially induced sedimentary structures (*sensu* Hagadorn and Bottjer, 1997; Noffke *et al*., 2001). Nonetheless, trace fossils are evident as negative- and positive-relief features on the bedding plane (Figs. 1, 2). These are mostly expressed as horizontally oriented, simple meandering to looping furrows, some of which have pronounced marginal levees. Furrows have internal widths of 0.6-1.1 mm, and of three measured, these were 104, 120, and 122 mm long; shorter segments of 10-20 mm are also apparent on the same surface. Marginal levees are as much as 2.5 mm wide, but only 0.2 mm high and somewhat ephemeral, either present or absent along the continuous length of a furrow (Fig. 2). In two separate furrows, meanders have nearly identical breadths, 62.4, and 65.5 mm, but widths of these turns ("amplitudes") differed, at 24.1 and 39.4 mm, respectively. In several areas on NCSM10530, furrows intersect, superficially resembling branching. Furrows are also short and discontinuous in places, with gradually reduced depths along their lengths that result in terminations. Differing from these are a few positive-relief traces, which are evident as short, slightly sinuous segments with similar diameters, about 0.6-1.0 mm wide (Fig. 2B).

A sample from the Tillery Formation (NCSM10531) also contains trace fossils similar to those from NCSM10530, although these are considerably shorter, measuring only about 10-20 mm long, and narrower, at about 0.4-0.5 mm wide (Fig. 3). Nonetheless, these trace fossils consist of two parallel, slightly

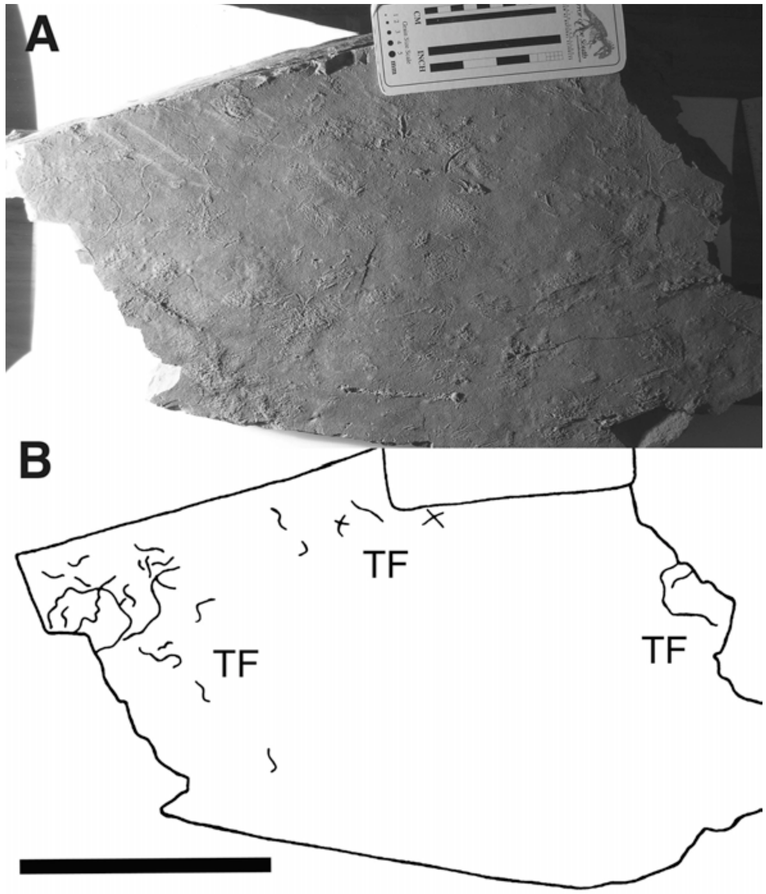

Figure 1. Specimen NCSM-10530, showing locations of trace fossils on bedding-plane surface. A – Overall view of specimen. B – Map of specimen with trace fossils (TF) outlined; scale = 20 cm.

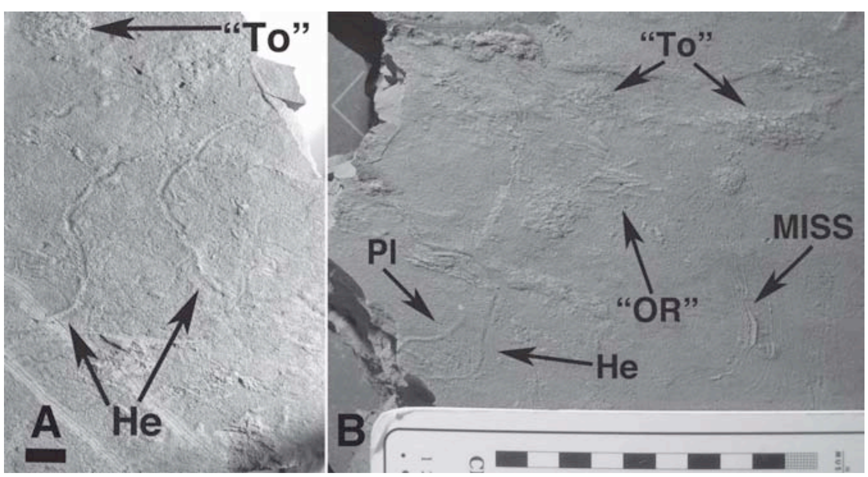

Figure 2. Trace fossils, body fossils, and physical sedimentary structures in NCSM-10530. A – *Helminthopsis* isp. (He), either a shallow burrow or surface trail; ?"*Tomaculum*" ("To"), which is likely an unknown body fossil; and note other fainter meandering trace fossils associated with *Helminthopsis*. Scale = 1 cm. B – *Planolites* isp. (Pl), a shallow burrow, and *Helminthopsis* isp. (He), either a shallow burrow or surface trail; "*Oldhamia recta*" ("OR") and ?"*Tomaculum'* ("To"), which are unknown body fossils; microbially induced sedimentary structures (MISS). Scale in cms.

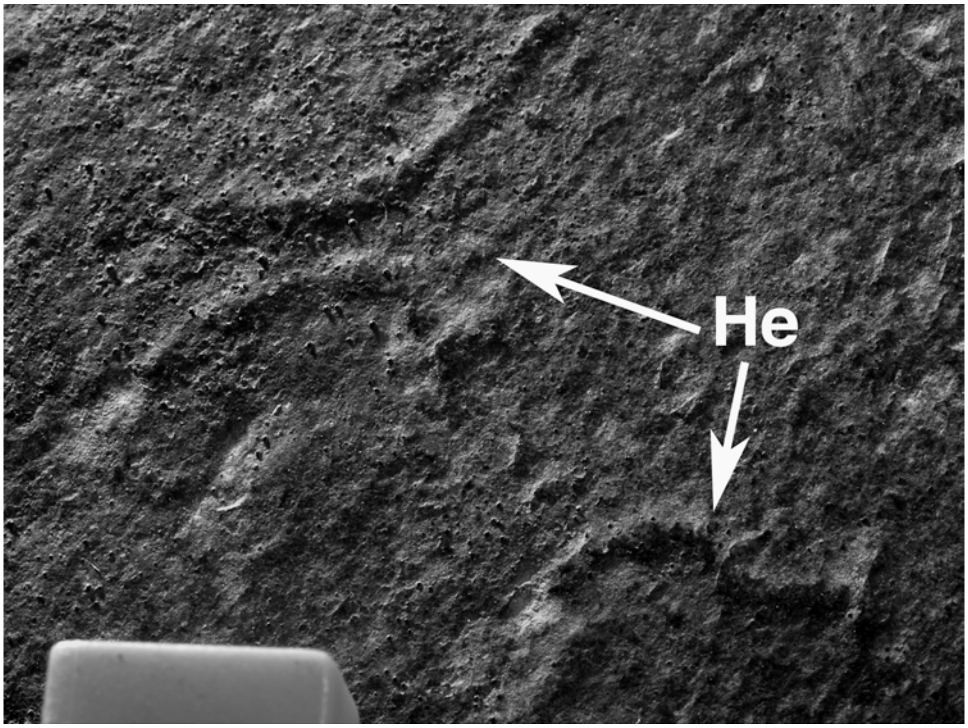

Figure 3. Two examples of ?*Helminthopsis* isp. (NCSM-10531) from the Tillery Formation. Scale = 1 cm.

meandering positive-relief features separated by indentations, similar to the levees and grooves observed in most of the trace fossils of NCSM-10530. Hence these are comparable to those from the Floyd Church Formation, albeit more poorly preserved or incompletely expressed.

DIAGNOSES OF EDIACARAN TRACE FOSSILS

Based on their traits, most of the furrowed-and-leveed trace fossils from the Floyd Church Formation in NCSM10530 are *Helminthopsis* isp. This ichnogenus was originally defined by Heer (1877) but reevaluated by Wetzel and Bromley (1996). Possible ichnospecies for the Carolina Terrane trace fossils are *H. hieroglyphica* Wetzel and Bromley 1996 or *H. tenius* Książkiewicz 1968, depending on relative regularity (or lack thereof) of their overall patterns (Wetzel and Bromley, 1996). Gibson (1989) likewise identified *Helminthopsis* in the McManus (= Floyd Church; Milton, 1984) Formation, which agrees with our overall diagnosis. The Tillery Formation trace fossils also resemble *Helminthopsis*, although these may be incompletely preserved examples. Hence we designate it as ?*Helminthopsis* for now until better specimens are recovered from this formation, or a closer examination of the current examples reveals a better ichnotaxonomic fit.

Some of the positive-relief, short, sinuous segments in NCSM10530 that lack furrows are more akin to *Planolites* isp. (Fig. 2B). However, this designation may be too glib, as *Planolites* is often used as a convenient name applied to any simple meandering burrow (Pemberton and Frey, 1982; Keighly and Pickerill, 1995). More examples of this trace fossil and a quantitative analysis of these should help in testing our identification. For example, ?*Helminthopsis* identified from the Tillery Formation in NCSM10531 actually may be two parallel *Planolites*. Nevertheless this would have required two sets of tracemakers to make burrows identically sized and spaced from one another, which we deem as less likely as two tracemakers forming separate furrow-groove burrows or trails.

In these examples, we interpret *Helminthopsis* as either horizontal surface trails or shallow burrows made under a biomat surface, and *Planolites* as a shallow, unlined horizontal burrow. In the case of *Helminthopsis*, if these were originally burrows, their covering layers were eroded before final burial and lithification. The levees represent a pushing aside of fine-grained sediment by the tracemakers, and irregular widths of these structures suggest a peristaltic movement. In modern intertidal and shallow-marine environments, small gastropods make equivalent-sized surface trails with such irregular levees (e.g., fig. 6.6f, Martin, 2013), but Carolina Terrane rocks thus far contain no body-fossil evidence of these or other molluscans. Other possible tracemakers might be vermiform animals that used alternating expansions and contractions to intrude and push aside sediment while feeding (Bromley, 1996).

Perhaps the most interesting trait of the more complete *Helminthopsis* specimens is their expression as loops (turns) of nearly equidistant width length and width. We interpret these similarities as a function of: body size, in which the tracemaker's length confined it to a certain turn radius; a feeding strategy, in which it was maximizing its grazing or deposit-feeding potential through turning (Koy and Plotnick, 2007); or a combination of the two factors.

Where separate furrows intersect one another, we suspect these are examples of "false branching," rather than a splitting of a single furrow into two, which would have been caused by an animal making repeated feeding probes from a main burrow or trail. This supposition is supported by an elevated position of one furrow over another at their point of intersection (e.g., Fig. 2A), suggesting they were formed at fractionally different depths. There is a possibility that this and other intersections are non-coincidental, reflecting some sort of chemotaxis (e.g., Rindsberg and Martin, 2003), but more such examples are needed to test or support whether the tracemakers may have been attracted to one another's burrows.

REEVALUATION OF PREVIOUSLY IDENTIFIED TRACE FOSSILS

Based on the figures in Gibson's (1989) report on Ediacaran trace fossils from the Carolina Terrane, we confirm that a few of the ichnogenera he identified are very likely trace fossils. Among these are *Helminthopsis* and *Planolites*, and possibly *Gordia*, although the last of these was only identified from one specimen in the Floyd Church Formation and no other examples have been found since.

However, at least three ichnogenera listed by Gibson (1989) – *Syringomorpha*, ?*Tomaculum*, and "*Neonerites*" [sic] – are probably body fossils. Seilacher and others (2005) renamed Gibson's (1989) *Syringomorpha* as "*Oldhamia recta,*" a then-new ichnospecies of a valid ichnogenus. Tacker *et al*. (2010), though, argued that these supposed "burrows" were actually clumps of rod-like structures (i.e., body fossils) with statistically significant bimodal orientations, which were likely attributable to current alignments. Consequently, they recommended abandonment of "*Oldhamia recta*" as an ichnospecies. This correction also means that *Oldhamia* is not represented as an ichnogenus in Ediacaran rocks of the Carolina Terrane, an absence consistent with its rarity in Ediacaran rocks elsewhere (Lindholm and Casey, 1990; Seilacher *et al*., 2005; McNaughton, 2007). NCSM10530 contains these rod-like structures, but also clusters of pellet-like structures identical to what Gibson (1989) identified as ?*Tomaculum* (Fig. 2A).

These same structures are visible in NCSM4278 from the Floyd Church Formation, alongside actual trace fossils that are likely *Helminthopsis* (Fig. 4). These clusters may be preservational variants of the "*Oldhamia recta*" body fossils, which have a similar grouping and diameters. We are also doubtful of Gibson's (1989) identification of "*Neonerites*" [sic] (= *Neonereites*), which consist of parallel and adjacent strings of pellet-like structures. This arrangement lends to a biserial appearance, like that of a trail or shallow burrow bordered by fecal pellets. Similar fossils in Ediacaran rocks of South Australia are now known to have been body fossils. In these specimens, single strings of "pellets," attributed to aggregate growth stages, were aligned next to one another, thus giving the false appearance of a *Neonereites*-like trail (Droser and Gehling, 2008).

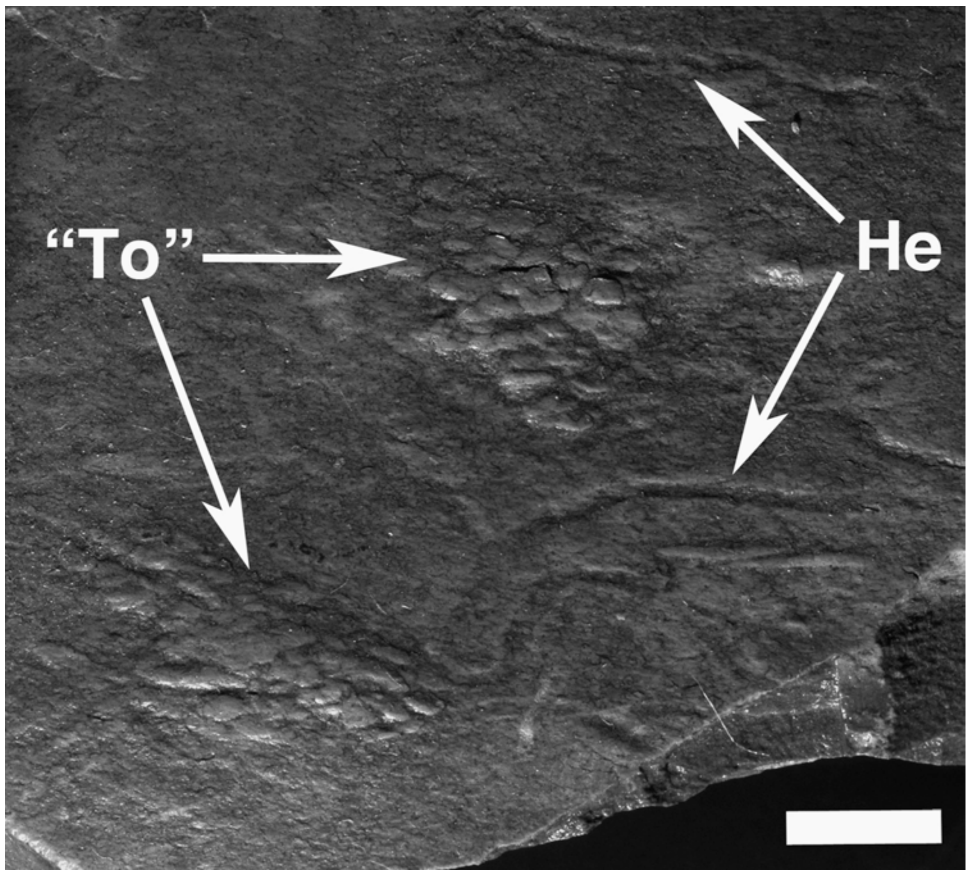

Figure 4. Examples of co-associated trace fossils, *Helminthopsis* isp. (He), and probable body fossils, ?"*Tomaculum*" ("To"), NCSM-4278, from the Floyd Church Formation. Scale = 1 cm.

Lastly, another "trace fossil" identified by Gibson actually may be a pseudofossil: ?*Monocraterion*, which he reported from the Tillery and Yadkin Formations. The diagnosis of ?*Monocraterion* was based on two specimens that apparently had a funnel connected to a simple vertical tube. Alternatively, these structures could have been gas-bubble escape structures, or cross sections of shrinkage fractures, rather than vertical burrows. Vertical burrows are extremely rare in Ediacaran rocks worldwide, as nearly all bioturbation was restricted to horizontal zones, whether intrastratal or on bed tops (Bottjer *et al.*, 2000; Jensen *et al.*, 2005, 2006), therefore lending doubt to a trace fossil interpretation for vertical structures.

Weaver and Ganis (2013, this volume) provide a list of other trace fossils reported thus far from the Tillery, Floyd Church, and Yadkin Formations. We anticipate that this list may be reduced with further scrutiny of entities identified initially as "trace fossils," although the converse may also happen as more people look more closely for actual trace fossil evidence in the Ediacaran rocks of the Carolina Terrane.

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The Deep River gold–copper–molybdenum prospect: Potential subvolcanic porphyry mineralization, Moore and Randolph counties, central North Carolina

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Abstract

The Deep River gold prospect is located in the Carolina terrane's older Virgilina sequence, which also hosts gold–pyrophyllite and pyrophyllite deposits, such as Robbins, Glendon and Pilot Mountain. Mapping, drill core examination, petrographic and geochemical studies have shown that gold–copper–molybdenum mineralization at Deep River is hosted by volcanic, volcaniclastic and epiclastic rocks, which have been intruded by porphyritic, felsic and andesitic dikes, and mafic dikes.

U–Pb zircon geochronology gives ages between 547.0±0.7 and 550.6±1.1 Ma for a non–mineralized felsic dike, while Re–Os molybdenite ages place the mineralization between 532±2 and 543±2 Ma. These dates, geologic observations and Nd isotopic data suggest that gold mineralization is hosted by volcaniclastic and epiclastic rocks belonging to the Hyco formation, but that the mineralizing fluids are related to Uwharrie magmatism.

Gold anomalies in soil fall along a northwest trend, which lies within an area marked by structural complexity. Along this zone the attitude of bedding and foliation are highly variable and incongruous with adjacent areas. To the northeast and southwest of this disrupted zone, the bedding and foliation follow the regional northeast strike of the Carolina terrane. Locally the erratic distribution of bedding and foliation is possibly linked to intrusions distorting pre–existing structures formed during Virgilina deformation and subsequent influence these intrusions exerted during Late Ordovician–Silurian deformation.

Additionally the data presented here hold broad implications for understanding the tectonic history of the Carolina Zone. One of these implications is that during gold mineralization at the Deep River prospect, the older Virgilina and younger Albemarle magmatic arcs, as well as the Charlotte terrane had already been amalgamated. Another is that progressively deeper gold deposit types are exposed along a northwest to southeast transect along the Carolina

terrane, suggesting that the terrane is tilted to the west, which might be a reflection of intra–arc rifting that took place during the Early Cambrian.

INTRODUCTION

The Carolina terrane of the Southern Appalachians is host to several economically significant gold deposits. There are no currently operating mines in this region, although some remained in production until the 1990s (Ayuso et al., 2005). Barite Hill, Haile, Ridgeway and Brewer in South Carolina were all gold producing mines in the 1980s and 1990s. The Gold Hill, Russell and Silver Hill mines in North Carolina were operated during the late 1800s to the early 1900s. The Snowcamp–Saxapahaw, Pilot Mountain, Robbins and Glendon pyrophyllite mines were active from the early to late 1900's (Fig. 1). Field, geochemical and isotope studies have led to a variety of models for the origin of these deposits, ranging from formation in an epithermal environment associated with subaerial or subaqueous hot springs (McDaniel, 1976; Scheetz, 1991; Feiss et al., 1993; Powers, 1993; Zwaschka and Scheetz, 1995; Ayuso, et al., 2005; Klein et al., 2007) to a structurally controlled or orogenic origin (Tomkinson, 1988; Offield and Klein, 1991; Hayward, 1992). Defining the host–rock settings, alteration styles and timing of ore formation is critical in developing a model for their origin.

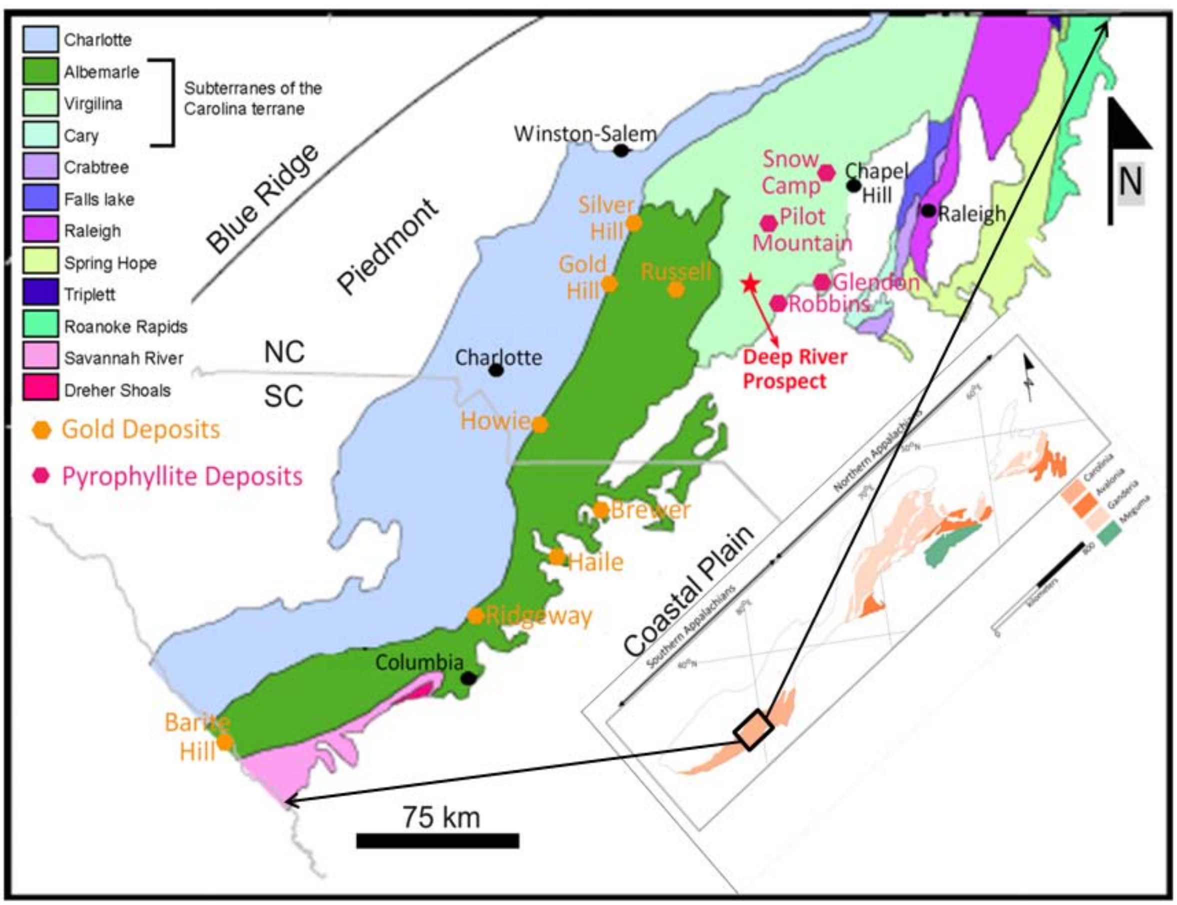

Figure 1. Regional geologic map of the Carolina terrane, showing selected mineral deposits and the location of the Deep River prospect. Modified from Seal et al. (2001), Hibbard et al. (2002), Schmidt et al. (2006), Klein et al. (2007) and Pollock et al. (2010). The inset map is modified from Hibbard et al. (2007).

The Deep River gold–copper–molybdenum prospect is located in the Carolina terrane of central North Carolina, 95 kilometers southwest of Chapel Hill, NC, in Moore and Randolph Counties, where the Deep River crosses the Moore County–Randolph County line (Figs. 1, 2).

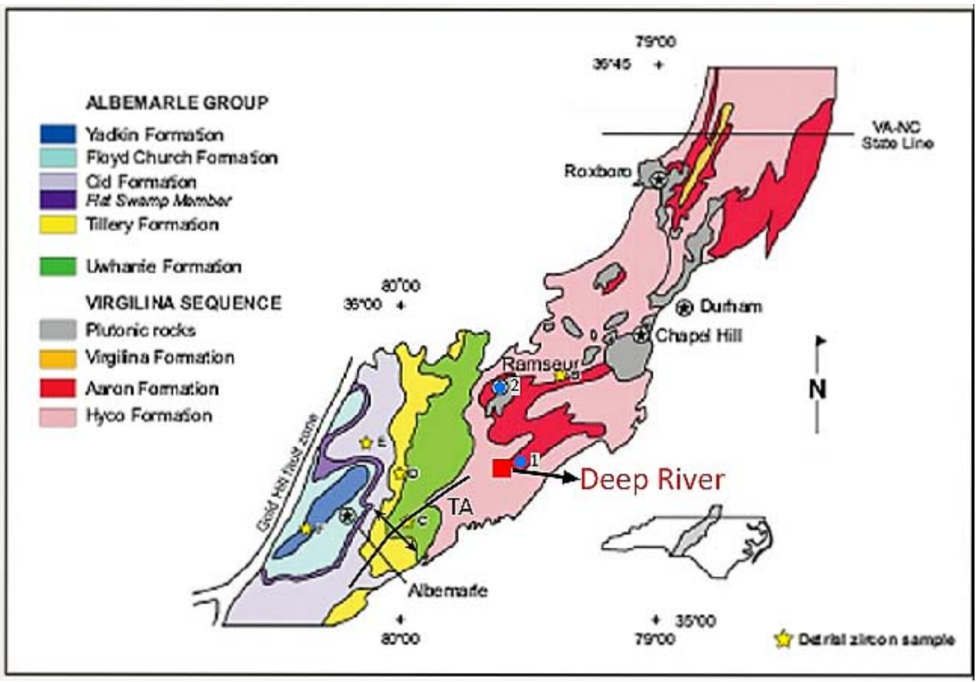

Figure 2. Regional geologic map of the Carolina terrane in North Carolina and southern Virginia, showing location of the Deep River prospect (modified after Hibbard, 2000 and Pollock et al., 2007). TA = Troy anticlinorium. Locations 1 and 2 are discussed in the text.

The Deep River project is not a historic gold mine, but was first recognized by Noranda Exploration based on water well cuttings showing alteration and anomalous metal values. Exploration activities were carried out by Noranda Exploration, from 1989 to 1991 and included soil sampling, trenching, airborne magnetic and radiometric surveys, and RC–and diamond core drilling. Results were positive, but when Noranda closed their eastern office, Appalachian Resources LLC acquired the leases and Cyprus completed a trenching program in 1994 (Juhas and McDaniel, 2008, unpublished report; Capps, 2010, unpublished report). These exploration activities delineated significant gold mineralization with associated molybdenum and copper enrichment in the Deep River area. Further field and alteration mapping by Capps et al. (1997) showed that the gold, molybdenum and copper soil anomalies occur in a north–northwesterly and a northeasterly trend, with the former being the largest anomaly. It is thought that the NNW trend is an overprint on the more regional NE trend. They also observed that individual porphyritic quartz–feldspar andesitic or dacitic intrusions fall along a similar trend. In fresh rock samples lead, zinc, arsenic and locally fluorine are also present in anomalously high concentrations and gold mineralization is associated with quartz – pyrite and quartz – sericite – pyrite alteration. Capps et al. (1997) were the first to suggest that this prospect could be part of a gold porphyry system.

In 2007 and 2008 Carolina Gold Corp., Ltd. (CGC), as subsidiary of Erin Ventures, in agreement with Triangle Minerals LLC, carried out a diamond drilling program located in the center of the largest gold soil anomaly (Juhas and McDaniel, 2008, unpublished report; Capps, 2010, unpublished report). Twelve vertical diamond drill holes reached depths between 92 and 236 meters.

Based on their drill core observations and geochemical data they suggested that the gold mineralization tested by drilling coincides with a zone of silicified rock reaching depths of 100 meters and dips shallowly to the southwest where it may split into an upper and lower portion (Juhas and McDaniel, 2008, unpublished report; Capps, 2010, unpublished report). The gold–copper–molybdenum mineralization with high fluorine, the style of silicification in conjunction with circular hydrothermal alteration patterns noted by field observations, radiometric and aeromagnetic data, Juhas and McDaniel (2008, unpublished report) support the porphyry gold model proposed earlier by Capps et al. (1997).

This paper discusses results of a field, geochemical and geochronological study completed on the Deep River gold–copper–molybdenum prospect in central North Carolina as a Master's thesis at the University of North Carolina. The results of geochronology and Nd–isotopic data presented here will elucidate whether the mineralization at the Deep River prospect is related to older Hyco or younger Uwharrie rocks and help to better delineate and understand the nature of the boundary between the two magmatic arc terranes. Furthermore the record of local stratigraphy and structure in combination with geochronologic data will be useful in ongoing correlations of lithotectonic units throughout the Carolina terrane, which will in turn be relevant to understanding the geologic history of one of the major peri–Gondwanan terranes in eastern North America.

Geology and Stratigraphy of the Carolina Terrane in Central North Carolina

The Deep River prospect is located in central North Carolina and has been mapped as part of the former Virgilina sequence, now the Hyco magmatic arc (Fig. 2).

In the study area the Carolina terrane consists of the older Virgilina and younger Albemarle sequence (Harris and Glover, 1988; Hibbard et al., 2008). Bowman (2010) has redefined the Virgilina sequence into the Hyco magmatic arc, which is disconformably overlain by the Aaron formation. The Hyco arc is dominantly characterized by felsic to intermediate magmatic arc rocks, with a juvenile isotopic signature, formed over a time span of 20 m.y. starting at ca. 633 Ma (Wortman et al., 2000). The Aaron formation, however, comprises dominantly clastic sedimentary rocks with minor volcanics formed at least at ca. 580 Ma (Hibbard et al., 2008; Pollock et al., 2010). The Albemarle sequence, which unconformably overlies the Hyco arc and Aaron formation consists of a thick package of felsic volcanics at the base (Uwharrie formation), which is overlain by Ediacaran to Early Cambrian clastic sedimentary rocks interfingered with volcanic lenses and intruded by dikes and stocks of felsic to mafic composition. Zircons from the Uwharrie formation have ages of ca. 551±8 Ma and geochemical signatures suggest formation in a continental margin tectonic environment (Ingle et al., 2003; Hibbard et al., 2008).

Mapping in and near Moore, Randolph and Chatham counties was carried out by Conley (1962), Green et al. (1982), and Harris and Glover (1988). Conley (1962) reported that the geology of Moore County is dominated by metamorphosed volcanic and sedimentary rocks. He interpreted the sequence as subaerial, transitioning to subaqueous with textures and sedimentary structures that are indicative of a transition from a shallow to a deeper marine environment (Conley, 1962). A similar stratigraphy was noted by Green et al. (1982) who mapped in southern Chatham and northeastern Moore counties (Fig. 2; location 1). However, Green et al. (1982) note that these lower units are in abrupt contact with overlying felsic dominated volcanic, pyroclastic and related sedimentary rocks, which they interpret as a local center of subaqueous, felsic volcanism. This is followed by deposition of fine to medium–grained epiclastic rocks showing sedimentary textures that they interpret as indicating deposition in a subaqueous environment and contemporaneous deformation. The overall stratigraphic sequence is interpreted as the transition from a subaerial environment to a subaqueous environment, possibly within an intra–arc basin (Green et al., 1982).

Harris and Glover (1988) mapped the Ramseur area in Randolph County, (Fig. 2; location 2). They interpret most of the stratigraphic sequence as having been deposited subaqueously, possibly in a submarine environment and having been intruded by mafic to felsic stocks, dikes and sills of Late Precambrian to Cambrian and Triassic–Jurassic ages (Harris and Glover, 1988). Contrary to Conley (1962) and Green et al. (1982), they note an unconformity between the sedimentary rocks of the Aaron formation and the bimodal volcanic rocks of the Uwharrie formation.

The earliest deformation event in the area is the Neoproterozoic Virgilina deformation (Glover and Sinha, 1973; Harris and Glover, 1988; Hibbard et al., 2002). This event has only been recognized in rocks of the older magmatic arc, which were deformed between 578 and 550 Ma (Harris and Glover, 1988; Hibbard and Samson, 1995; Hibbard et al., 2002). In central North Carolina, this event is marked by an angular unconformity between the older Hyco and the younger Uwharrie formation (Harris and Glover, 1988).

The main structure described in the project area is the younger, doubly plunging Troy anticlinorium, which trends northeast. It includes several parasitic folds along its flanks that are asymmetric and commonly overturned to the southeast (Conley et al., 1962; Powers, 1993). The slaty cleavage is axial planar and dips consistently between 55 and 70 degrees to the northwest (Conley, 1962). This structure is suggested to be of Ordovician–Silurian age, resulting from the accretion of Carolinia to the Laurentian margin, recently redefined as the Cherokee Orogeny (Conley et al., 1962; Bain, 1964; Hibbard et al., 2012).

GEOLOGIC CHARACTERISTICS OF THE DEEP RIVER PROSPECT AREA

Interpreted geologic setting and stratigraphy of the Deep River Prospect

Based on the regional geology and observations discussed below, we interpret Deep River as hosted by Hyco magmatic arc rocks. On published and unpublished state geologic maps this area is part of an elliptical window within which strata do not follow the northeast strike observed regionally throughout most of the Carolina terrane (Fig. 3 inset) (Carpenter, 1982; Brown, 1985). On helicopter supported airborne survey by Noranda and reprocessed by Erin Ventures, the area falls within a semi–circular magnetic low that is cut by at least two north–south oriented Triassic or Jurassic diabase dikes (Fig. 3 inset). Potassium radiometric data show that the area is marked by several semi–circular radiometric lows, surrounded by radiometric highs that are seen in the field to represent intense sericite alteration, but could also be a reflection of early advanced argillic alteration.

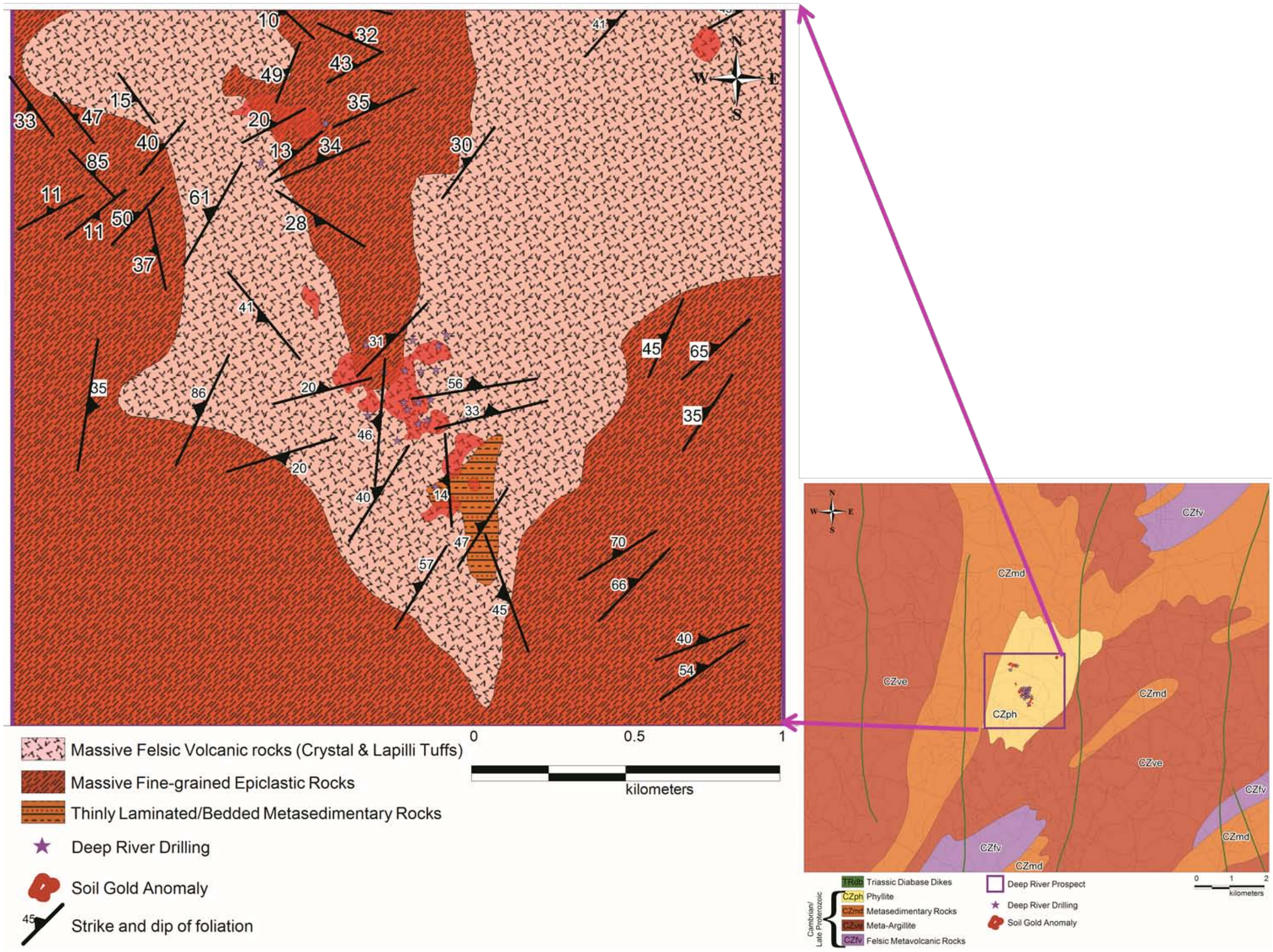

Figure 3. Local scale geologic map of the Deep River study area with regional geology as inset map (modified after Carpenter, 1982; Capps et al., 1997 and inset modified after Brown, 1985).

Outcrops are sparse in the deeply weathered area that has a gentle topography, except along the banks of Fork Creek and parts of the eastern bank of Deep River, as well as several road cuts. In the creek and river beds, which provide a less weathered exposure of the rocks, massive, intensely silicified and usually sulfidized, felsic volcanic rocks or silicified volcaniclastic rocks were observed. These are capped by shallowly dipping, occasionally subhorizontal fine–grained, intensely silicified sedimentary rocks most likely felsic in composition. Along Fork Creek the massive volcanic rocks are lenticular and appear to be capped by fine–grained, foliated sedimentary rocks.

In road cuts in the northern part of the project area, intensely sericitized and in some cases, fine–grained sedimentary rocks are common. In the southern part of the area poorly sorted, medium–grained sedimentary rocks are present. These are locally interbedded with conglomerate layers up to ten meters thick and contain rounded volcanic clasts, locally up to ten centimeters in diameter. Volcanic clasts contain pumice fragments and minor feldspar crystals.

These field observations in conjunction with drill core examination have resulted in a tentative geologic map (Fig. 3), which is a modified version of Capps et al. (1997). It includes massive, felsic volcanic rocks, including silicified and reworked, crystal tuffs, lapilli tuffs and massive flow units that are in contact with massive, fine–grained, sericitized sedimentary rocks to the southeast. Further southeast, however, the sedimentary rocks observed are massive and interbedded with sandstone layers and locally conglomerate layers, made up of volcanic material. To the northwest, the massive volcanic rocks are in conformable contact with thinly laminated fine–grained sedimentary rocks. Further northwest, however, fine–grained, intensely sericitized sedimentary rocks or air–fall or water–laid ash tuffs are observed. These appear very similar to strongly foliated, metasiltstone or very fine-grained sandstone or tuffs observed in several of the examined drill holes. This package of metavolcanic and metasedimentary rocks was intruded by three units: a weakly altered, felsic, porphyritic stock, intensely altered mafic dikes and weakly altered porphyritic, andesitic dikes.

The entire sequence from the massive vitric tuffs intercalated with lapilli tuffs, overlain by lithic crystal–rich tuffs, indicate an episode of mafic to felsic volcanic activity. However, the lowermost unit observed in drill core is a sequence of siltstones, locally interlayered with fine sandstone (possibly lithic wackes), which is in gradational contact with the overlying massive crystal–poor or vitric tuffs. The deposition of these lower epiclastic rocks could have been the result of a brief episode of volcanic quiescence. The presence of slump features and graded bedding observed in the sequence of lithic crystal tuffs are suggestive of reworking of volcaniclastic material and deposition in a subaqueous environment (Fisher and Schminke, 1984; Cas and Wright, 1987; Boggs, 2006). The overlying sequence of fine–grained, possibly intermediate epiclastic rocks interbedded with coarse–grained sandstones may indicate another episode of waning volcanic activity when sediments were deposited. Since this sequence is thinly bedded and interbedded with immature, coarse–grained sandstones, deposition is likely subaqueous. The uppermost sequence observed in drill core, a fine–grained epiclastic rock was deposited distal to its source or represents a felsic air–fall or water–laid ash tuff (Fisher and Schmincke, 1984; Cas and Wright, 1987).

This stratigraphic package represents a sequence of volcaniclastic and epiclastic rocks that were deposited subaqueously. The slump folds observed in the crystal–poor or massive vitric tuffs are indicative of soft–sediment deformation, which is indicative of reworked volcanic material and deposition in a turbulent environment (Fisher and Schminke, 1984; Cas and Wright, 1987; Boggs, 2006). According to Glover and Sinha (1973) and Harris and Glover (1988) the Virgilina sequence rocks, now redefined by Bowman (2010), were mostly deposited in a shallow submarine environment. Therefore deposition in a submarine environment as is characteristic for Hyco magmatic arc rocks, is likely.

The main observed structural feature in the area is localized and is an interpreted reverse fault dipping steeply to the northwest. It has juxtaposed lapilli tuffs against a sequence of fine–grained, air–fall ash tuffs or epiclastic sedimentary rocks, made up of felsic material. This fault has not been observed in any outcrops or any of the adjacent drill holes and is interpreted as localized and dipping steeply to the northwest. The interpreted reverse movement and orientation are based on the presence of folded lapilli fragments adjacent to the fractured zone in drill core. The folding diminished further away from the fracture zone, where lapilli fragments are elongated or flattened. Since the folding appears localized, it is thought to be the result of drag folding associated with reverse movement. Lithologic units in this faulted zone and the zone of associated folding were barren of gold, therefore the gold and associated alteration, likely predate this fault.

North of the area of drilling activities and south of Deep River, is the only place where bedding was observed in the field area. The exposure was at the bottom of a creek bed and bedding could not be measured directly, but appeared to be sub parallel to the foliation, which was measured as striking 240 to 266 degrees and dipping between 12 and 17 degrees to the north–northwest.

In most of the outcrops that were studied, foliation was well developed, except in the massive volcanic units along Fork Creek and Deep River. Locations of foliation measurements are shown in Fig. 4. This figure also shows bedding measurements that were extracted from maps by Conley (1962), Carpenter (1982), and Capps et al. (1997). Bedding in the area dips between 15 and 35 degrees generally to the northwest, while foliation dips are highly variable between 11 and 86 degrees in different directions. Foliation strikes northeast in the northeastern and southwestern parts of the area although dips range between 15 and 75 degrees. Remarkable, however, is the wide variability in the attitude of foliation in the center of the map along a northwesterly trend that coincides with the largest gold soil anomaly detected in the area. Capps et al. (1997) and Capps (2010) noted individual intrusions along a similar trend.

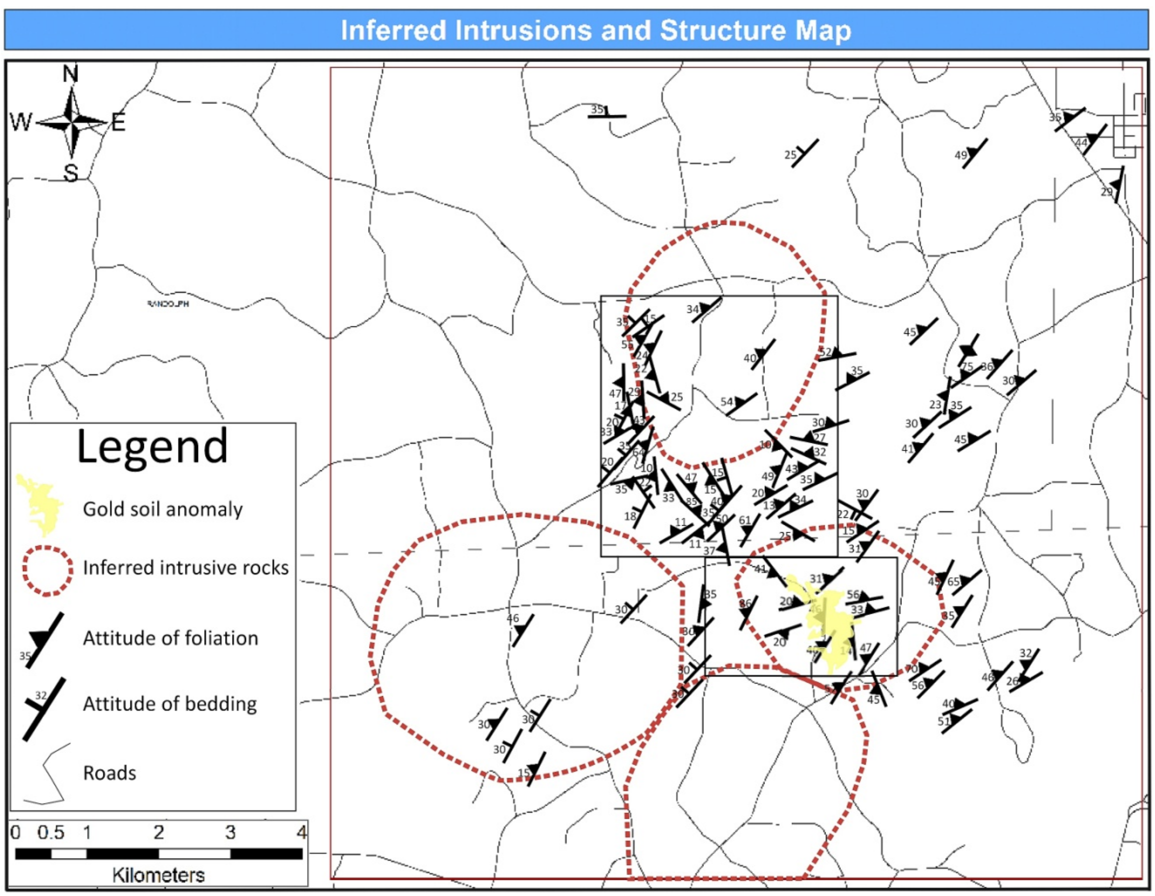

Figure 4. Structural data and possible locations of intrusive rocks based on intensity contrasts observed on potassium radiometric maps. Data include measurements taken by the author, and data compiled from Conley (1962), Carpenter (1982) and Capps et al. (1997).

The poles to foliation and bedding in this central area were plotted on an equal area net (Fig. 5), which shows some scatter, mostly because of variability in the attitude of foliation as discussed above. This plot shows that bedding and foliation are generally sub parallel, which could suggest that the area is located on the limb of a fold. Based on the scatter of the poles to foliation, the foliation was subjected to at least one non–cylindrical folding event, possibly associated with the Late Ordovician–Silurian accretion of the Carolina terrane to Laurentia, the Cherokee Orogeny (Hibbard et al., 2012). Bedding has been folded during two events: the Neoproterozoic Virgilina deformation and this later orogenic event. However, not enough data are available for structural analysis to fully support this. We suspect that at least some of the intrusions in the area postdate the Virgilina deformation, but predate the Ordovician–Silurian Cherokee orogenic event.

U–Pb geochronology of host rocks

The results of U–Pb geochronology for an un-mineralized, felsic, porphyritic dike have shown two distinct age groups (Figs. 6A, B) at 550.27 ± 0.74 Ma and 547.00 ± 0.83 Ma.

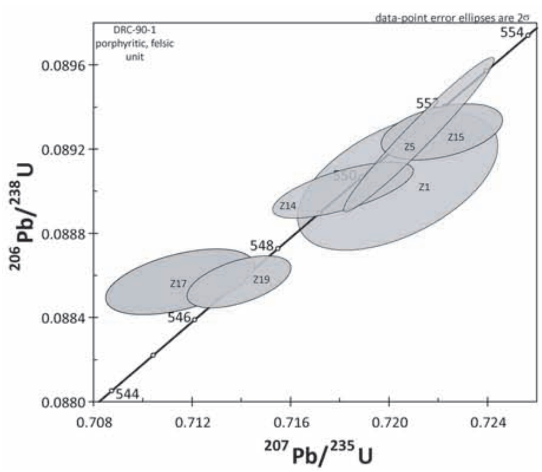

Figure 6A. Concordia plot showing ages from zircons extracted from the felsic, porphyritic dike or stock (DRC–90–1 at 551 to 555 feet). Data has shown two zircon populations with ages of 550.27 ± 0.74 Ma and 547.00 ± 0.83 Ma, respectively.

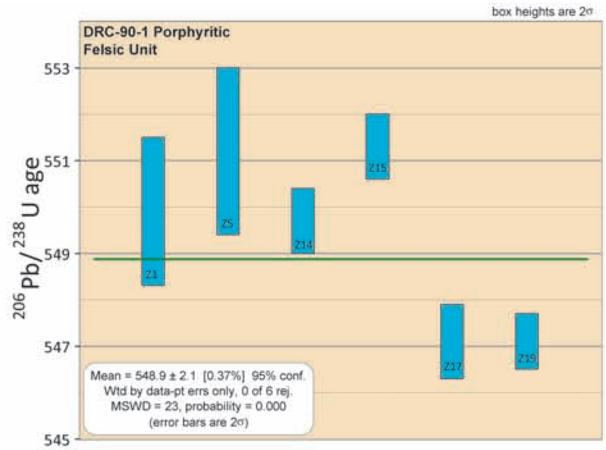

Figure 6B. Weighted average plot of ^{206}Pb/^{238}U ages for zircon fractions from the felsic, porphyritic dike or stock (DRC–90–1 at 551 to 555 feet). Note the different age groups for this sample.

Several zircon grains were selected and imaged using scanning electron microscopy (SEM) to determine whether any of the grains show inherited cores (Fig. 7). These grains show no evidence of inheritance and therefore, the two different age groups are different zircon populations present in the sample. One population consists of long, thin grains; the

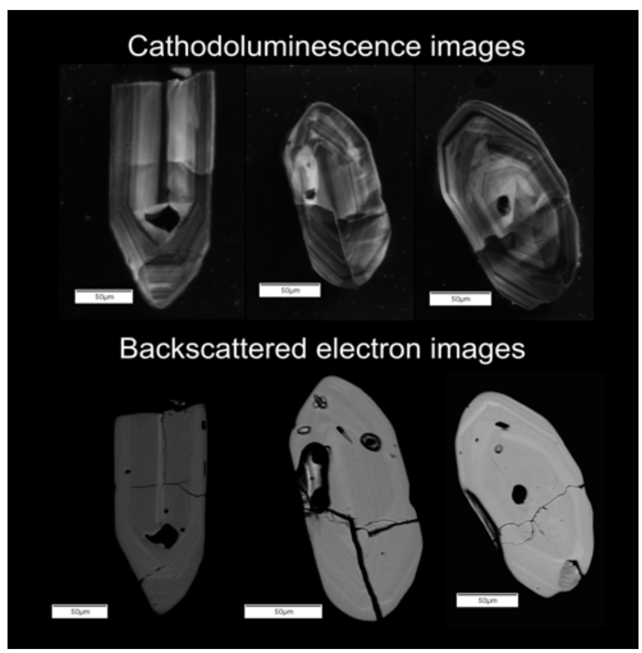

Figure 7. SEM cathodoluminescence and back-scattered electron images of the two main zircon populations observed in the felsic, porphyritic dike.

other population consists of short, stubby grains (Fig. 7).

The U–Pb ages are significantly younger than the 630 to 610 Ma ages that have been reported for rocks from the Hyco Formation (Wortman et al., 2000; Pollock, 2007). These new data are interpreted as ages from a shallow or subvolcanic dike emplaced into the rocks of the Hyco arc. Another line of evidence that the porphyritic dike intruded these rocks is that in the dike, primary textures are preserved, while the host rock is strongly foliated and locally folded.

The two distinct age groups may be explained in two ways:

1. The zircon population of 550.27 ± 0.74 Ma represents the actual age of the dike, while the 547.00 ± 0.83 Ma population reflects the occurrence of Pb–loss shortly after the crystallization of these zircons.
2. The zircon population of 547.00 ± 0.83 Ma represents the actual age of the dike, while the 550.27 ± 0.74 Ma population is the result of older inherited cores, which were not observed during SEM imaging.

The geologic relationships between the dated porphyritic dike and its host rock in conjunction with the regional geology and the Nd–isotopic data presented in this paper, suggest that the gold mineralization at Deep River is hosted by rocks of the Hyco arc, that are intruded by dikes that are 550.27 ± 0.74 million years in age or younger. These dikes are concurrent with Uwharrie magmatism, post–date Virgilina deformation and predate Cherokee Orogeny.

Re–Os geochronology of molybdenite

Three samples of molybdenite show three distinct age groups, 539 ± 2 Ma (sample DRC–07–6), 532 ± 2 Ma (sample DRC–07–7) and

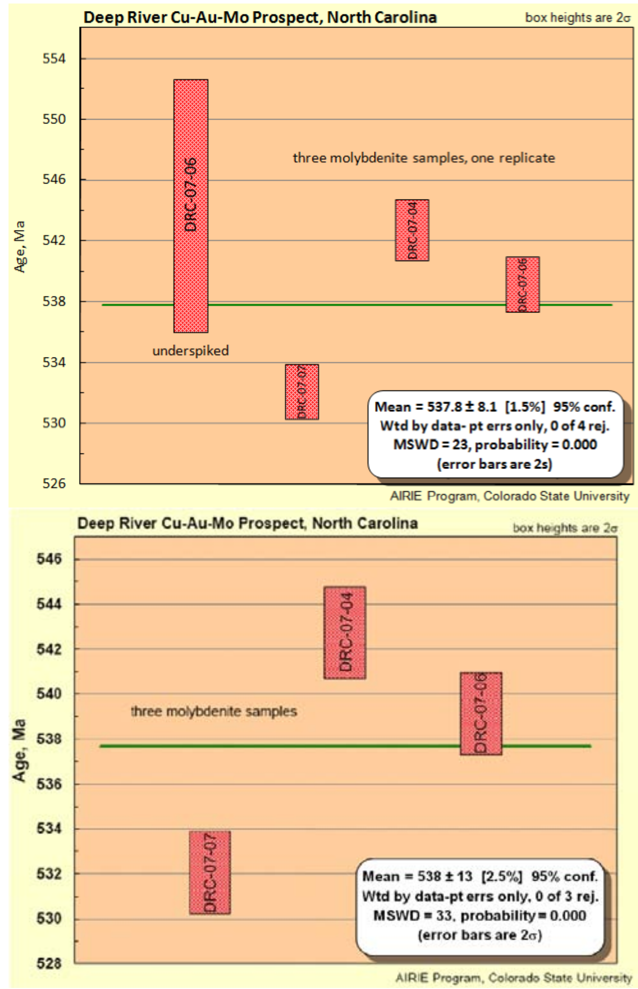

Figure 8A,B. Re–Os model ages for molybdenite from DRC–07–6, DRC–07–7 and DRC–07–4. Re–Os data courtesy of Dr. Holly Stein (AIRIE Program, Colorado State University).

lastly 543 ± 2 Ma (sample DRC–07–4) (Fig. 8). Sample DRC–07–6 was underspiked, which is reflected by the large 2σ error and the erroneously high age. In order to obtain a more accurate age, the sample was run again. The erroneous age will be discarded from the discussion.

The Re–Os molybdenite ages that do not overlap with their 2σ errors may be interpreted as representing separate stages of fluid flow within a time span ca. 10 million years. Since gold and molybdenum are both chalcophile elements, they tend to travel together in magmas (Schaefer, 2004).

Therefore, the obtained Re–Os ages are assumed to be proxies for the age of gold mineralization. This was supported by a comparison of the available Au and Mo geochemical data obtained from drill core.

The Re–Os ages do not overlap with the U–Pb ages, but instead are significantly younger, which suggests that molybdenite crystallized in stages of fluid flow that occurred later than the emplacement of the unmineralized, felsic, porphyritic dike. Bingen and Stein (2003) and Stein and Markey (2006) have shown that molybdenite ages are not reset by hydrothermal events or metamorphic events weaker than granulite facies. Because there is no known regional deformation event throughout the Carolina terrane that coincides with these ages, it is not likely that the fluids that caused the gold mineralization were metamorphic. Therefore, an intrusion–related source is more likely. The relatively high Re concentration of 900 ppm detected in one of the samples, could also reflect a porphyry–type origin (Stein et al., 2001).

In a comparison of geochronologic data from magmatic and tectonothermal events throughout the Carolina terrane it is possible that the fluids that introduced the gold mineralization were derived from magmatism related to intra–arc rifting within the former Virgilina sequence (Feiss et al., 1993; Pollock et al., 2010). Gold mineralization related to Uwharrie age magmatism was also reported by Stein et al. (1997) and Ayuso et al. (2005) for the Brewer, Haile and Ridgeway deposits.

Sm–Nd whole rock geochemistry

In order to determine whether rocks that host the Deep River gold mineralization are volcanic and volcaniclastic rocks belonging to the Hyco arc or the Uwharrie Formation, Nd–isotope signatures are a useful indicator (Figs. 9, 10). The volcanic and volcaniclastic rocks of the Hyco arc are characterized by highly positive ε_{Nd}–values, which are indicative of their juvenile mantle–derived nature (Kozuch, 1994; Samson et al., 1995; Ingle et al., 2003). Based on their Nd–isotopic study, Samson et al. (1995) described the former Virgilina Sequence as a long–lived arc built on a substrate of oceanic crust. According to Samson et al. (1995), the majority of ε_{Nd}–values (at 600 Ma) for Virgilina sequence rocks are greater than + 3.4. Kozuch, (1994) divides the εNd–values (at 575 Ma) for the Virgilina sequence rocks into a range between + 4.9 and + 5.4 and a second group between + 0.1 and + 2.9. They describe the latter group to reflect the involvement of older, more evolved, crustal material. Ingle et al. (2003) also used these data in their interpretations, but they group the ε_{Nd}(575 Ma) for the Virgilina sequence into values between +0.1 and +5.8.

In contrast, the rocks belonging to the Uwharrie formation, are characterized by ε_{Nd}–values (at 575 Ma) between – 0.3 and + 2.3 (Kozuch, 1994) or ε_{Nd}–values (at 550 Ma) between – 0.7 and + 4.1 (Ingle et al., 2003). These lower initial ε_{Nd}–values for Uwharrie formation rocks suggest the involvement of a substrate of older, evolved continental litosphere, which has been interpreted as reflecting formation in a continental margin environment, i.e. magmatism related to a subducting slab (Kozuch, 1994; Ingle et al., 2003). Based on calculations of depleted mantle model ages and U–Pb SHRIMP dating on inherited zircons from rocks belonging to the Albermarle sequence, Mueller et al. (1996) and Ingle et al. (2003) suggest that arc magmatism involved Mesoproterozoic basement.

The new Nd–isotopic data presented in this paper are for five whole rock samples of a feldspar–quartz crystal tuff, an intensely altered, felsic volcanic rock, a lapilli tuff, a felsic tuff and a lithic crystal tuff respectively. Initial ε_{Nd}–values were calculated for ages of This was done because the purpose of the

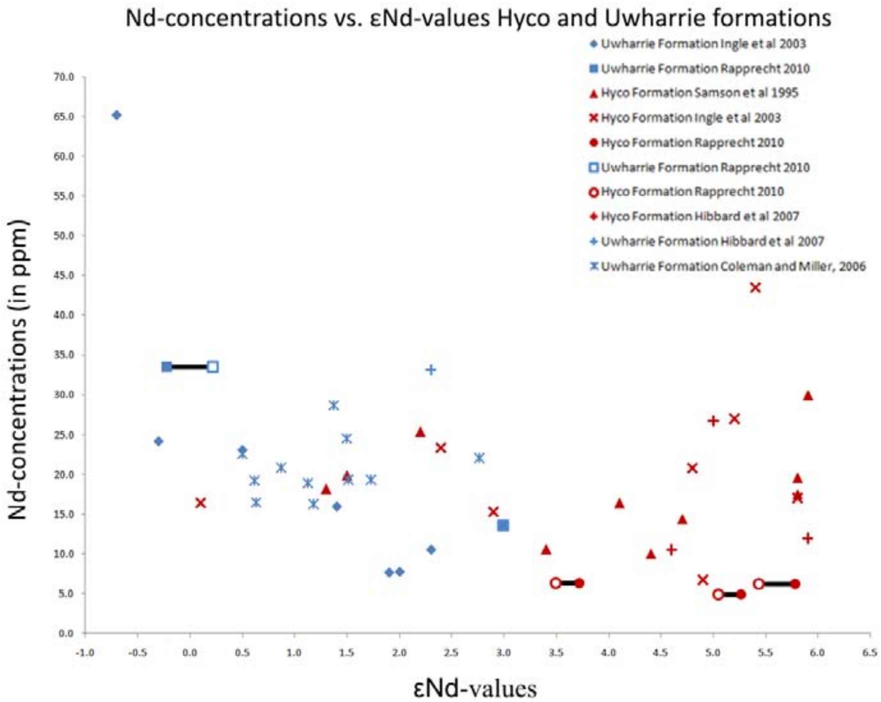

Figure 9. Plot showing Nd–concentrations against ε_{Nd}–values. The data are from samples analyzed during this study and those compiled from Samson et al. (1995), Ingle et al. (2003), Coleman and Miller (2006) and Hibbard et al. (2007).

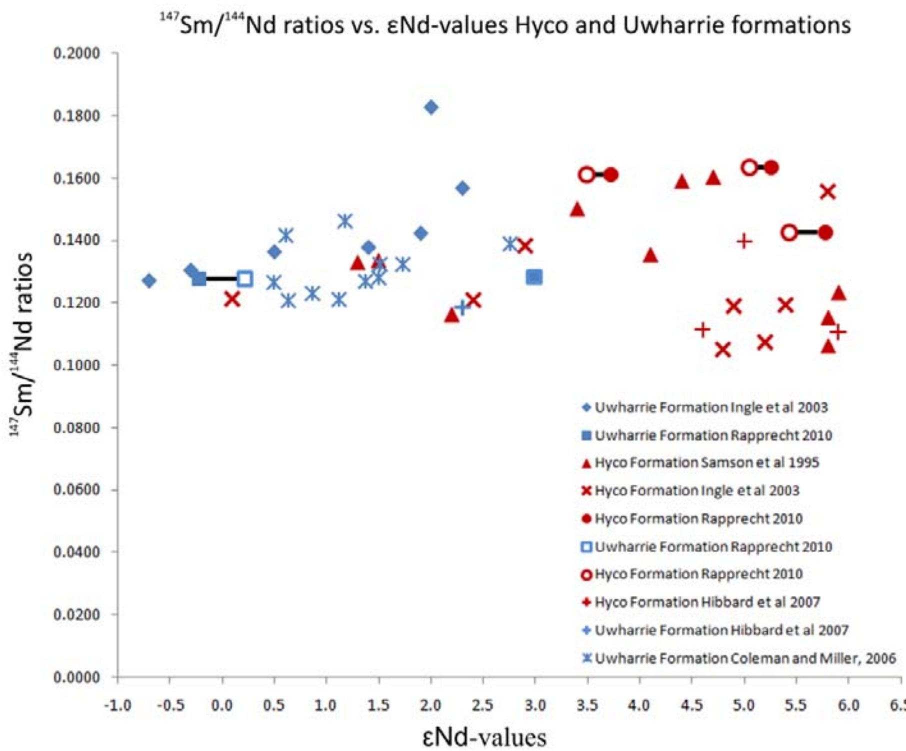

Figure 10. Plot showing $^{147}Sm/^{144}Nd$ ratios against ε_{Nd}–values. The data are for samples analyzed during this study and those compiled from Samson et al. (1995), Ingle et al. (2003), Coleman and Miller (2006) and Hibbard et al. (2007).

Sm–Nd whole rock analyses is to make a distinction between Hyco magmatic arc rocks (600 Ma) and Uwharrie magmatic arc rocks (550 Ma). These data are compared to that published by Samson et al. (1995), Ingle et al. (2003), Coleman and Miller (2006) and Hibbard et al. (2007).

These plots show that three of the Deep River samples with ε_{Nd}–values (at 600 and 550 Ma) fall well within the range of the Hyco Formation volcanic and volcaniclastic rocks. They are characterized by highly positive ε_{Nd}–values, which are indicative of the juvenile mantle–derived nature of the magmas that formed the Hyco Formation. Whereas the ε_{Nd}–value (550 Ma) for the porphyritic dike dated through U–Pb zircon geochronology in this study, plots within the overlapping range of ε_{Nd}–values for the Uwharrie and Hyco magmatic arc rocks, respectively. This ε_{Nd}–value is interpreted to reflect a mixed isotopic signature between the juvenile, mantle–derived material of the Hyco formation and the evolved lithospheric material involved in early Albermarle arc magmatism. Since this is a dike intruding the Hyco volcaniclastic rocks, assimilation of crust during its emplacement, resulting in inheritance of the isotopic signature of overlying crustal material, is a possibility (Ingle et al., 2003).

Finally, one sample, lies well within the ε_{Nd}–range of the Uwharrie formation volcanic and volcaniclastic rocks. However, based on the regional geology (Figs. 1, 2) the Deep River area is located within the Hyco formation. Some Hyco formation volcanic and volcaniclastic rocks may show a more evolveed signature (Kozuch, 1994; Ingle et al., 2003). Kozuch (1994), Mueller et al. (1996) and Ingle et al. (2003) also report an ε_{Nd}–value as low as + 0.1 and a calculated depleted mantle extraction age of 1128 Ma for an extrusive rock belonging to the Hyco formation. While it is evident that the unusually low ε_{Nd}–value for the felsic tuff exhibits the influence of older, more evolved lithosphere, the nature of this material remains ambiguous and is beyond the main scope of this study.

In summary, the Sm–Nd isotopic data presented here support the conclusion that the Deep River gold mineralization is hosted by Uwharrie age intrusions into the volcaniclastic and epiclastic rocks of the Hyco arc.

Characteristics of Deep River gold mineralization

In a comparison of the gold anomalies in drill core with the lithologic cross sections it appears that gold mineralization is distributed throughout both the volcaniclastic and epiclastic rock units. However, the strongest anomalies are observed in the coherent volcaniclastic units, where sheet–like and stockwork quartz – sericite ± pyrite veining are abundant. Gold enrichment associated with pyrite + molybdenite veinlets is common as well. The association of gold and molybdenite with sheet–like and stockwork quartz + sericite ± pyrite veining is common in porphyry–style deposits, where they are both spatially and genetically related to felsic to intermediate porphyry intrusions (Robert et al., 1997; Sinclair, 2007). The different vein sets all exhibit some deformation, either being folded locally or offset along fractures. Since we believe that these veins were emplaced by fluids related to Uwharrie magmatism, this folding suggests is more likely related to Cherokee deformation than Virgilina deformation.

Gold anomalies in soil and to some extent at depth coincide with enrichment in molybdenum and copper. Capps et al. (1997) and Capps (2010) also report enrichment in iron, nickel, cobalt, chromium, vanadium and magnesium and arsenic, lead and fluorine in fresh rock samples. According to White and Hedenquist (1995) the association of gold, copper and molybdenum are more characteristic for emplacement by fluids related to a high rather than low sulfidation system. They note that with high–sulfidation systems the mineralized structures are common near or above the subvolcanic magma chamber. Therefore the geochemical associations and geometry at Deep River could suggest that the mineralization is related to subvolcanic intrusions below a high–sulfidation system that is no longer preserved.

In a comparison of the gold anomalies with the types and patterns of alteration, it appears that the strongest gold enrichment is associated with both intense silicification and quartz – sericite (phyllic) alteration. However, in the few zones of potassic alteration, weaker gold enrichment is observed as well. These observations in conjunction with available potassium radiometric data show concentric patterns of intense silicification, haloed by strong quartz – sericite or locally, potassic alteration and potential propylitic alteration.

The rare occurrences of potassic alteration may be caused by overprinting due to quartz – sericite (phyllic) alteration (Thompson and Thompson, 1996). It is possible that potassic alteration predates phyllic alteration and was masked by it. This is common in porphyry deposits where both types of alteration are present (e.g. Sinclair, 2007).

Advanced argillic alteration, marked by sericite, pyrophyllite and minor kaolinite is only observed within a fault zone over an interval of seven meters in drill core which shows some enrichment of gold, but not enough to be considered anomalous. Capps et al. (1997) also report quartz – pyrophyllite alteration to the north and west of the gold mineralization, close to a contact between volcanic and epiclastic rocks. While gold and advanced argillic alteration, do not appear to coincide, there may be some link in terms of spatial distribution. According to Taylor (2007) high–sulfidation epithermal systems are commonly characterized by host rocks and mineralization that are similar in age, and mineralization may occur in veins, brecciated zones, stockworks, replacements or disseminations or a combination thereof. Furthermore, these systems are characterized by alteration zones of vuggy silica, quartz – alunite (advanced argillic) and argillic alteration respectively (Taylor, 2007). Based on the style of alteration and host rock to mineralization relationship, it is not likely that gold mineralization at Deep River fits directly into this high–sulfidation epithermal model. It is, however, possible that it is spatially and genetically related to a high–sulfidation system.

The epidote + clinozoisite (or zoisite) ± chlorite alteration is most widespread and could either be a reflection of sodic or propylitic alteration or it may be a complete overprint by greenschist facies metamorphism. It appears to be locally associated with weak and rarely, strong gold enrichment. Since, propylitic alteration, typically represents regimes distal to center of the porphyry system, it is suggested that this alteration assemblage associated with strong gold anomalies is more likely a reflection of greenschist facies metamorphism. However, this requires further investigation. Propylitic alteration may be distinguished from a greenschist facies metamorphic assemblage if the growth of the propylitic mineral assemblage is not along cleavage planes. Alternatively, if the mineral growth is along cleavage planes of the same orientation as those formed during Late Ordovician–Silurian regional metamorphism (Offield et al., 1995) then it is less likely that this assemblage is the result of propylitic alteration.

The style of potassic alteration ± fluorite, haloed by quartz + sericite (phyllic) alteration, in turn surrounded by potential propylitic alteration may also be indicative of alteration in a porphyry system (Robert et al., 1997; Sinclair, 2007).

Based on the mineralization characteristics, style of alteration and their relative timing compared to the host rocks, the Deep River prospect may be classified as a porphyry–type deposit with high–sulfidation epithermal mineralization at one time in proximity.

SUMMARY AND CONCLUSIONS

The main purpose of this study at the Deep River gold prospect was to interpret the detailed stratigraphy of the host rocks, define the style of mineralization and alteration and determine their timing. This is to gain a better understanding of the geologic setting of the gold mineralization at the Deep River prospect and to place it into a genetic model. This will be useful in future exploration programs in the Carolina terrane.

Drill core examination, macroscopic and microscopic petrography and geochronology of host rocks and mineralization have shown that:

• Gold mineralization at Deep River is hosted by a package of subaqueously deposited felsic to intermediate volcaniclastic and epiclastic rocks that are intruded by felsic, andesitic and mafic dikes. Also based on the regional geology and the Nd–isotopic data presented here, the gold mineralization is interpreted as being hosted by volcaniclastic and epiclastic rocks belonging to the Hyco arc, but with gold mineralization emplaced by fluids related to Uwharrie magmatism.

• The 547.00 ± 0.83 Ma and 550.27 ± 0.74 Ma zircon ages obtained for a porphyritic felsic dike intruding the package of volcaniclastic and epiclastic rocks, suggest that it was emplaced during early Uwharrie magmatism.

• The three distinct Re–Os model ages of 543 ± 2 Ma, 539 ± 2 Ma and 532 ± 2 Ma, show that the gold mineralizing event is significantly younger than the host rocks and that the fluids emplacing the gold may be were derived from late Uwharrie age magmatism related to intra–arc rifting (Feiss et al., 1993; Pollock et al., 2010). Gold mineralization related to Uwharrie magmatism was also reported by Ayuso et al. (2005) for the Brewer, Haile and Ridgeway deposits. In order to identify the intrusive units that the gold mineralization might be the result of, the relatively unaltered and undeformed porphyritic, andesitic dike may be dated. A better understanding of the source of the fluids introducing the gold mineralization may be obtained through a stable isotope or fluid inclusion study would be useful as these could help constrain their temperature regimes.

• Gold anomalies in soil fall along a northwest trend (Capps et al., 1997; Juhas and McDaniel, 2008, unpublished report; Capps, 2010, unpublished report), which coincides with an area marked by structural complexity. Along this zone the attitude of bedding and foliation are highly variable and incongruous with adjacent areas. To the northeast and southwest of this disrupted zone, the bedding and foliation follow the regional northeast strike of the Carolina terrane. The local erratic distribution of bedding and foliation is linked to a combination of intrusions distorting pre–existing structures formed during the Virgilina deformation and these intrusions influencing the deformation that occurred during the Late Ordovician–Silurian Cherokee Orogeny (Hibbard et al., 2012).

• Gold mineralization occurs throughout both the volcaniclastic and epiclastic rock units, but higher gold values are more common in crystal–rich and massive crystal–poor tuffs, in which sheet–like and stockwork veining are ubiquitous. The association of the gold with sheet–like and stockwork quartz veining is common in porphyry–style deposits, where they are related to felsic to intermediate porphyry intrusions, both spatially and genetically (Robert et al., 1997; Sinclair, 2007). Even though the intrusions in the Deep River area have not been observed directly, their presence is reflected in potassium radiometric data, lidar data and the aforementioned structural data.

• The style of potassic alteration ± fluorite, haloed by quartz + sericite (phyllic) alteration, in turn surrounded by potential propylitic alteration may also be indicative of alteration in a porphyry system (Robert et al., 1997; Sinclair, 2007).

Based on the mineralization characteristics, style of alteration and their relative timing compared to the host rocks, the Deep River prospect may be classified as a porphyry–type deposit with high–sulfidation epithermal mineralization at one time in proximity.

Implications for the Carolina terrane

Based on the geologic, geochronologic and isotopic data presented here the following may be implied: the timing of gold mineralization at Deep River is coeval with Uwharrie age felsic magmatism. Other mineralizing events coeval with Deep River are observed throughout the Carolina terrane (e.g. Brewer, Haile, Ridgeway in Ayuso et al., 2005). Feiss et al. (1993) relate this to intra–arc rifting and opening of a back–arc basin, which they suggested to have resulted in Neoproterozoic Virgilina deformation. However, Pollock et al. (2010) bracketed the Virgilina deformation between 578 and 554 Ma. and reported that the Uwharrie formation remained undeformed from this event. Therefore the data presented here help support the latter statement that events resulting in Virgilina deformation ended shortly before Uwharrie magmatism commenced. It also helps support the idea that the contemporaneous Neoproterozoic deformation observed in the western part of the Charlotte terrane might have resulted from arc–arc collision amalgamating the Carolina terrane and Charlotte terrane (Dennis and Shervais, 1991; Dennis and Wright, 1997; Barker et al., 1998; Hibbard et al., 2002).

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ADVANCED ARGILLIC EPITHERMAL ALTERATION SYSTEMS (AES) IN THE CAROLINA TERRANE OF CENTRAL NORTH CAROLINA: POSSIBLE STRUCTURAL CONTROLS AND ASSOCIATION WITH NEOPROTEROZOIC UWHARRIE FELSIC MAGMATISM

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ABSTRACT

Advanced argillic epithermal alteration systems (AES) are large (1-20 km^2) hydrothermal mineral deposits characteristic of the Carolina Terrane in central North Carolina. They are strongly zoned, with core areas of intense advanced argillic (andalusite-pyrophyllite) and silicic alteration enclosed by a broad envelope of quartz-sericite-pyrite alteration, often with a peripheral propylitic alteration halo. These systems are typically anomalous in fluorine (topaz, fluorite and fluorapatite) and often associated with Au ± Ag ± Cu ± Mo mineralization, similar to epithermal expressions of porphyry-related Cu-Mo-Au systems.

The distribution of known AES is not random, but clusters in a series of six 20-40 km long alignments that may post-date Virgilina deformation fabrics. Four *en echelon* 025°-030° alignments step north and east across the Hyco and Aaron Formations in Randolph (Pilot Mountain-Staley), Alamance (Snow Camp-Saxapahaw), Orange (Teer-Hillsborough) and Granville (Bowlings Mountain-Daniels Mountain) counties. A fifth alignment (Cottonstone Mountain-Ammons) trends about 045° near the axis of the Troy Anticlinorium in Montgomery County, and is also hosted by the Hyco Formation. This alignment may extend southwest to include the Standard Minerals deposit near Wadesville, which is hosted within the Uwharrie Formation. A sixth alignment is the Glendon-Robbins trend in Moore County, oriented about 060° and traced for over 20 km along the Glendon Fault.

Two types of AES are present, intrusion-centered and fault-hosted. Intrusion-centered AES are ovate to irregularly shaped, concentrically zoned, and may be centered on, or peripheral to, a potentially causal igneous intrusion. The type example is Pilot Mountain, Randolph County. Fault-controlled AES are strongly elongated parallel to the regional tectonic fabric, and typically formed along major reverse fault zones. Alteration zonation is asymmetric and they typically lack any direct igneous association. The type example is the Phillips-Womble deposit on the Glendon Fault at Glendon, Moore County.

The ages of AES, possible structural controls, and associated magmatic phases are poorly constrained. The southern end of the Pilot Mountain-Staley trend in Randolph County is aligned with and overlaps the Seagrove Complex, an apparently Uwharrie-age felsic intrusive-extrusive complex centered on a major dike swarm 3-5 km wide that strikes 030° for at least 30 km. The complex appears to cut across the unconformable Uwharrie Formation contact with the older Aaron and Hyco formations to the northeast, with dikes intruding the Uwharrie, Aaron, and Hyco formations. The timing of emplacement of the Seagrove Complex dikes relative to the Pilot Mountain AES is uncertain, but a similar

structural control appears likely. Despite strong similarities, all AES in the Carolina Terrane are not necessarily the same general age or associated with a single magmatic or tectonic event. However, it appears likely that at least some AES in the Carolina Terrane in central NC may be associated with early Uwharrie-age felsic magmatism in linear arrays that suggest post-Virgilina Deformation structural controls.

Acknowledgments

This study salutes the life and work of Robert G. Schmidt.

Introduction

Large hydrothermal alteration systems and associated base and precious metal mineral deposits are local-scale products of large, often district or regional-scale, geodynamic processes. Plate tectonic settings are a first order control on the formation of mineral deposits, and many mineral deposit types are characteristic of specific plate tectonic environments and processes. Conversely, mineral deposit types act as a constraint on interpretations of plate tectonic environments and processes. The effectiveness of this constraint is well represented globally by the work of Sillitoe (1972a, 1972b), and in the terranes of Carolina by the work of Feiss et al. (1993). The utility of this application is contingent on the accurate assignment of mineral deposits to established ore deposit models and the timing of their formation relative to specific tectonic events in the evolution of the host terrane.

The Carolina Terrane in central North Carolina is endowed with widespread and varied occurrences of precious and base metal deposits associated with hydrothermal alteration systems. Exploration and evaluation of these deposits as potential economic resources is facilitated by accurate classification relative to well-established ore deposit models. Those deposit types with the potential to form economically exploitable resources are viable exploration targets. In particular, favorable deposit types correlated with specific metallogenic events that produced known economic ore deposits become priority targets that justify expenditures for acquisition and evaluation.

Among the largest and most recognizable hydrothermal alteration systems associated with base and precious metal mineralization in the Carolina Terrane are those characterized by areas of advanced argillic epithermal alteration, typically referred to as "pyrophyllite deposits" (Stuckey 1965, 1967). They are rich in Al-silicate minerals, specifically polymorphs of $AlSi_2O_5$ (andalusite, kyanite, sillimanite) and associated hydrated phases (especially pyrophyllite), and typically minor components of often large, strongly zoned epithermal alteration systems. They are widespread in the Carolina and Charlotte terranes, the two dominant components of Carolinia (Hibbard et al. 2002). The distribution and diversity of these systems was reviewed by Espenshade and Potter (1960).

Despite the often well-documented character of hydrothermal alteration in AES and associated base and precious metal mineralization, the regional and district scale controls of their distribution and their formation relative to specific magmatic and tectonic events remain poorly constrained. There are virtually no reliable geochronologic age dates for the hydrothermal alteration or intrusive phases that may be directly or indirectly associated.

The present work reviews previous studies of selected AES in the context of more recent constraints on the tectonic evolution of the Carolina Terrane in central North Carolina, and attempts to better constrain the timing and tectonic-magmatic controls of their formation. It will focus specifically on deposits of the Snow Camp-Saxapahaw area of Alamance and Chatham counties and the Ramseur-Pilot Mountain area of Randolph County, where local geology and relative and geochronologically constrained age relationships are documented in sufficient detail to support this analysis.

Advanced argillic epithermal alteration systems (AES)

Core areas of intense silicic and advanced argillic alteration are enclosed within a broad envelope of quartz-sericite-pyrite (phyllic) assemblages, typically grading into a peripheral propylitic alteration halo. These systems are commonly strongly anomalous in fluorine and often associated with subeconomic Au ± Ag ± Cu ± Mo mineralization. Fluorine is usually contained in topaz, fluorite, and fluorapatite and may range from tens to hundreds of ppm to several percent by volume, especially in areas of intense silicic alteration.

The silicic-altered core is commonly a zone of intense textural destruction and hydrothermal replacement composed of up to 90% quartz. Areas of intense silicic alteration may also contain disseminated, vein, breccia-hosted, or irregular masses of topaz. Advanced argillic alteration is strongly aluminous and characterized by the minerals andalusite, pyrophyllite, kaolinite, sericite and locally diaspore. Andalusite and pyrophyllite appear to be primary alteration minerals. Kyanite is present in some systems as a product of prograde metamorphism, and some pyrophyllite, kaolinite, and sericite appear to result from retrograde reactions.

These deposits typically contain a distinctive suite of minor and trace accessory minerals and elements, including sulfides, phosphates, fluorides, and titanites (McDaniel 1976). Sulfides are overwhelmingly pyrite, although trace amounts of chalcopyrite, sphalerite, galena, and molybdenite may be present. Pyrite is often ubiquitous as 1-5% disseminated grains in all alteration facies, is also commonly present in quartz veins, and may locally form small massive to submassive lenses. Large (1-10 cm) euhedral pyrite crystals are often observed in the quartz-sericite-pyrite zone of many AES, typically near the periphery.

Common phosphates include apatite and lazulite. Fluorine-bearing phases include topaz, apatite, and fluorite. Fluorite is typically a rare accessory, but topaz may be locally abundant in the silicic core of some deposits. Apatite appears to be largely fluorapatite, and may often be the dominant primary fluorine-bearing phase, but generally unrecognized due to the very fine grain size. Diaspore is sometimes present in the advanced argillic alteration zones, and chloritoid is common on the margins of the advanced argillic zones and, with chlorite, on the periphery of the quartz-sericite-pyrite zones.

Rutile, typically as fine-grained disseminated grains and aggregates, is a common minor accessory, but platy crystals of ilmenite may also be present. Where pyrite is not present, the dominant iron minerals in the alteration assemblages may be magnetite, often in small (≤ 1 mm) octahedral, or hematite, either as pseudomorphs after magnetite or as small (≤ 1 mm) disseminated platy crystals.

Although alternative origins have been proposed (Zen 1961), there is strong support for an igneous association for the hydrothermal fluids responsible for AES formation in the Carolina Terrane (Espenshade and Potter 1960, Stuckey 1965 and 1967, Worthington and Kiff 1970, Spence 1975, McDaniel 1976, Schmidt 1978, Schmidt 1985a and 1985b, Schmidt et al. 2006). It has been suggested that the advanced argillic mineral assemblage andalusite + pyrophyllite is the product of regional metamorphism (Spence 1975, McDaniel 1976, Sykes and Moody 1978); however, the present consensus opinion suggests that andalusite and most pyrophyllite are primary hydrothermal alteration phases (Harris 1982, Klein and Schmidt 1985, Schmidt et al. 2006).

Espenshade and Potter (1960) classified these deposits as "hydrothermal replacements". They suggested that they formed through intensely acidic hydrothermal leaching that removed almost all rock components except silica, alumina, and titanium oxide; and "might represent the deeper zones of extensive solfataric centers". Schmidt (1983, 1985a) extensively reviewed the global literature on advanced argillic alteration associated with hydrothermal alteration systems, and concluded that many of those in the Carolina Terrane are consistent with a sub-class of hydrothermal alteration systems intermediate in character between subvolcanic porphyry systems and near-surface hydrothermal solfatara and hot spring systems. Schmidt et al. (2006) concluded that the composition and zonation of alteration facies, styles of associated mineralization, and trace element associations are consistent with high-sulfidation epithermal systems following the criteria of White and Hedenquist (1990, 1995).

The source of the responsible hydrothermal fluids is often cryptic; however, the extent and intensity of alteration, the presence of often significant fluorine (± boron), and associated metallic minor and trace elements (Mo, Cu, Bi, Au), strongly suggest a felsic magmatic connection. All AES in the Carolina Terrane are zones of focused hydrothermal fluid flow at high water/rock ratios and low pH. Additionally, they are areas of intense, often pervasive sulfidation, where virtually all available iron has been converted to sulfides, almost entirely pyrite. Ubiquitous minor titanium oxide phases are a by-product of sulfidation of Fe-Ti bearing oxides and silicates.

The distribution of AES in the Carolina Terrane in North Carolina is commonly described as forming two "belts"; a NE-trending belt 120 km long that extends from near Troy in Montgomery County to the NC-VA border in Granville County, and a 20 km long ENE-trending belt in Moore County (Schmidt 1983, Hughes 1987). However, detailed examination of the distribution of alteration centers suggests that they cluster as a series of six 20-40 km long en echelon alignments (Fig. 1). Four of these alignments trend 025°-030° and step north and east across the Hyco and Aaron Formations in Randolph (Pilot Mountain-Staley), Alamance (Snow Camp-Saxapahaw), Orange (Teer-Hillsborough) and Granville (Bowlings Mountain-Daniels Mountain) counties.

A fifth alignment (Cottonstone Mountain-Ammons) trends about 045° along the Troy Anticlinorium in Montgomery County, hosted by the Hyco Formation but parallel and proximal to the contact with the Uwharrie Formation of the Albemarle Sequence to the west. This alignment may extend to the southwest to include the Wadesville pyrophyllite deposit, hosted by the Uwharrie Formation. The sixth alignment is the Glendon-Robbins trend on the Glendon-Robbins fault zone in Moore County, oriented about 060°.

There appear to be two styles of AES present in the Carolina Terrane:

IC-AES are intrusion-centered alteration systems. They are ovate to irregularly shaped, concentrically zoned systems that may be centered on, or peripheral to, a potentially causal igneous intrusion. The type example is Pilot Mountain in Randolph County, NC.

FC-AES are fault-controlled alteration systems that are strongly elongated parallel to the regional tectonic fabric, usually along a controlling structure and typically a major reverse fault zone. They appear to lack any

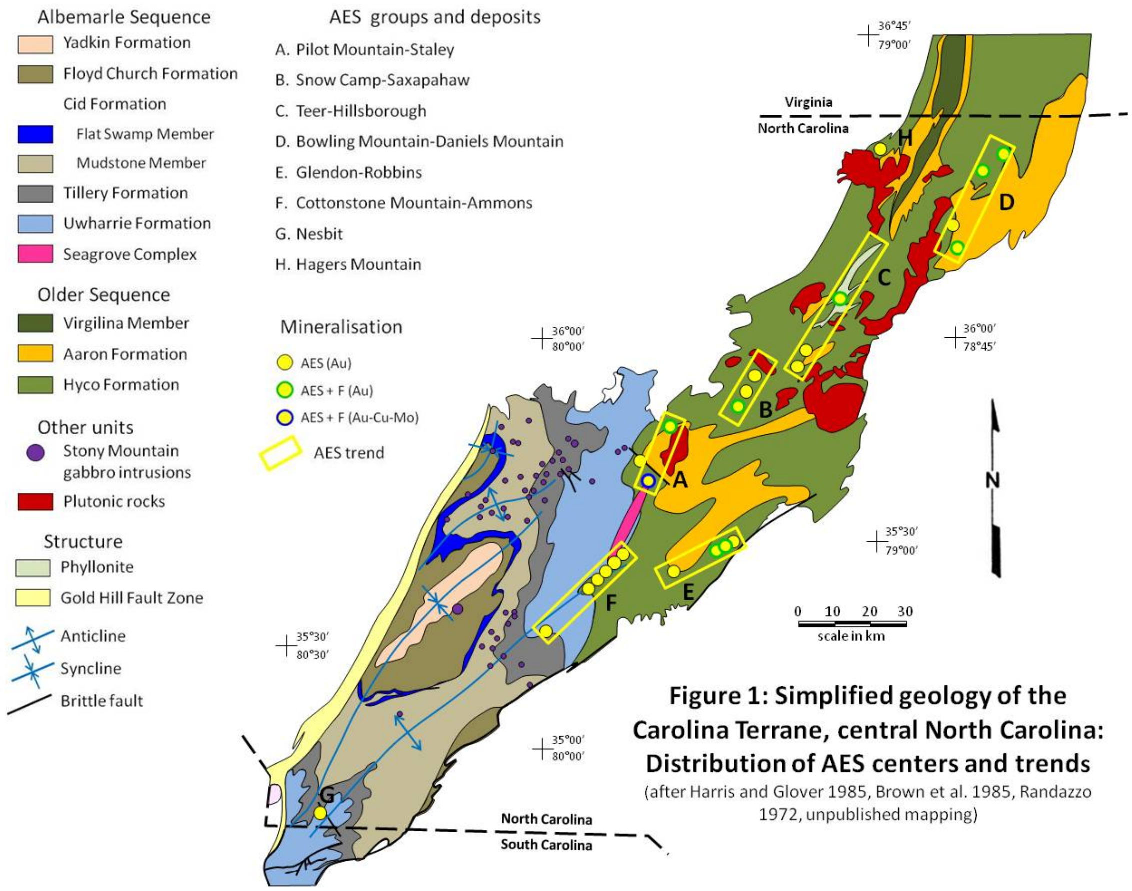

Figure 1: Simplified geology of the Carolina Terrane, central North Carolina: Distribution of AES centers and trends
(after Harris and Glover 1985, Brown et al. 1985, Randazzo 1972, unpublished mapping)

direct intrusive association and are strongly zoned from a silicic footwall, through an advanced argillic main zone, into a quartz-sericite-pyrite altered hangingwall. The type example is the Phillips-Womble deposits on the Glendon Fault at Glendon in Moore County. Deposits of this type are not reviewed in the present study.

SNOW CAMP-SAXAPAHAW

The Snow Camp-Saxapahaw area in southern Alamance and northwest Chatham counties is one of the better documented clusters of advanced argillic alteration centers in the Carolina Terrane (Fig. 2). Lithology, stratigraphy, structure and alteration are described by Schmidt (1985), Hughes (1987), and Schmidt et al. (2006). In this area the timing of AES development in the Carolina Terrane is well-constrained relative to both the Proterozoic Virgilina Deformation (Harris and Glover 1985) and the Late Ordovician Cherokee Orogeny (Hibbard et al. 2012).

Local geologic setting and history

The Snow Camp-Saxapahaw area is dominated by andesitic to dacitic volcaniclastic sequences and subordinate flows, with mafic and felsic units also present (Schmidt et al. 2006) This sequence is intruded by numerous intermediate to felsic plutons, many apparently emplaced at relatively shallow depths and some with hornfelsed contact aureoles (Schmidt, et al., 2006). Harris and Glover (1985) assign these rocks to the Hyco Formation. The rocks were tightly folded

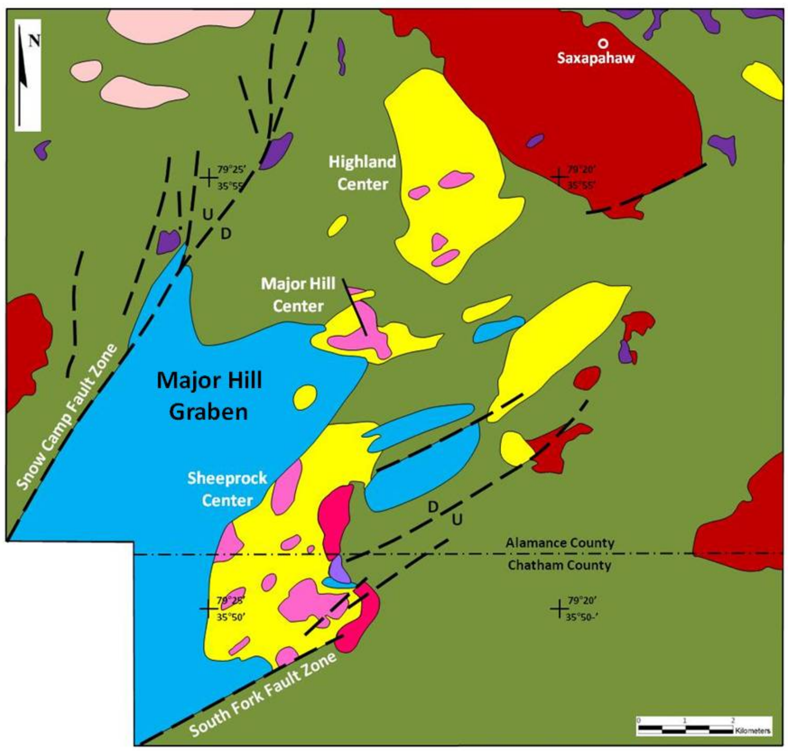

Figure 2: Simplified geologic map of the Snow Camp-Saxapahaw area, Chatham and Alamance Counties, North Carolina
(Modified from Schmidt et al. 2006)

without cleavage development during the Virgilina Deformation (Harris and Glover 1985, Schmidt et al. 2006) and eroded, prior to formation of a northeast-trending caldera-like graben (Schmidt et al. 2006)designated the Major Hill Structural Block.

The graben is bounded to the northwest by the 020°-035° trending Snow Camp fault zone, and to the southeast by 055°-060° trending, left-stepping *en echelon* segments of the South Fork fault zone (Fig. 2). Schmidt et al. (2006) suggest synchronous intrusion of small mafic to felsic plutons along these fault zones. Intrusions along the South Fork fault zone (Fig. 2) include gabbro, porphyritic dacite, the Lindley Farms Quartz Monzonite, and a suite of small plugs composed of granite-quartz monzonite – granodiorite - quartz diorite (Schmidt et al. 2006). Eruption of large volumes of crystal-rich rhyodacitic to dacitic volcaniclastic units of the Reedy Branch Tuff, preserved only within the graben, may have accompanied subsidence (Schmidt et al. 2006). Selective preservation of the Reedy Branch Tuff in the southwestern portion of the Major Hill Structural Block (Fig. 2) suggests that the graben is tilted in that direction (Schmidt et al. 2006).

The Reedy Branch Tuff is composed of abundant 3-8 millimeter plagioclase and quartz crystals in an aphanitic matrix of muscovite, biotite, chlorite, epidote, calcite, ilmenite, and anatase (Schmidt et al. 2006). Plagioclase crystals are euhedral to subhedral and 10-30 times more abundant than quartz. Quartz crystals are typically rounded and often deeply embayed. Primary mafic accessory minerals may have included biotite and hornblende.

The Reedy Branch Tuff is separated from the eroded Hyco Formation basement by an angular unconformity, and tentatively correlated with the Uwharrie Formation (Schmidt et al. 2006). A discontinuous, poorly sorted conglomeratic unit at the base of the Reedy

Branch Tuff unconformably overlies highly altered Hyco Formation rocks south of Mine Ridge (Hughes 1987). The Reedy Branch Tuff and older Hyco Formation were folded, faulted and metamorphosed to greenschist facies during a later orogeny identified as Taconic by Schmidt et al. (2006), and correlative with the Cherokee Orogeny of Hibbard et al. (2012). Schmidt et al. (2006) report widespread shearing and quartz-sericite and propylitic alteration of the Reedy Branch Tuff at this time, unrelated to the earlier AES centers.

Hydrothermal alteration and mineralization

Intense hydrothermal alteration is present in an area of about 22 km^2 in the Snow Camp-Saxapahaw area; almost all confined to the Major Hill graben (Fig. 2), and developed in the Hyco Formation after the Virgilina Deformation and prior to deposition of the Reedy Branch Tuff (Schmidt et al. 2006). According to Schmidt et al. (2006), this alteration event does not extend into the overlying Reedy Branch Tuff, which is widely affected by a later phase of less intense quartz-sericite and propylitic alteration discordant with the older AES centers.

The major silicic-advanced argillic hydrothermal alteration centers of Sheeprock, Major Hill, and Highland are aligned on an approximately 025° bearing for 12 km, subparallel to the Snow Camp fault zone (Fig. 2). Hughes (1987) suggested that this alignment may be controlled by a structural lineament. These alteration centers are classified as high-sulfidation by Schmidt et al. (2006), based on the criteria of White and Hedenquist (1990, 1995). They are characterized by irregularly shaped quartz-rich core zones surrounded by extensive envelopes of quartz-sericite-paragonite-pyrite (phyllic) altered rocks. The core silicic-advanced argillic alteration zones are suggested to be upward-flaring pipe-like bodies up to 1.6 kilometers in diameter that narrow with depth (Schmidt et al. 2006). Phyllic assemblages represent about 86% by area of the hydrothermal alteration present in the area, with core areas of intense silicic-advanced argillic alteration forming only 14% (Schmidt et al. 2006). Andalusite-pyrophyllite rich advanced argillic facies represent less than 10% by volume of the core alteration zones, only 1.4% of the entire AES.

The phyllic alteration is commonly well foliated and locally strongly sheared. Paragonite is probably common in many AES systems of the Carolina Terrane, but only identified through XRF or microprobe analysis (Schmidt et al. 2006). This assemblage is locally gradational into quartz-sericite-pyrophyllite-pyrite and quartz-sericite ± chloritoid ± pyrite ± iron oxide assemblages (Hughes 1987, Schmidt et al. 2006). Supergene weathering of this assemblage is accelerated by acid leaching with the oxidation of disseminated pyrite.

The pervasively silicic altered core areas are typically massive, fine-grained granofels composed of over 90% SiO_2 (Schmidt et al. 2006). Accessory minerals include pyrophyllite, sericite, chloritoid, rutile, hematite and local minor tourmaline, lazulite, and magnetite. The granofels is pale grey to locally reddish, purple or black due to the presence of fine-grained disseminated oxidized pyrite, hematite or magnetite (Schmidt 2006). Although no original protolith textures are retained, brecciation textures are common in the silicic granofels (Schmidt et al. 2006). Silicic granofels clasts 1-5 millimeters across are cemented by silica granofels. It is unclear whether this is a true breccia, crackle breccia, or a pseudo-breccia texture formed by alteration along fractures.

Areas of aluminum silicate-rich advanced argillic alteration assemblages occur within the silicic alteration cores, but typically near their margins (Hughes 1987, Schmidt et al. 2006).

The three most significant bodies are the Snow Camp pyrophyllite mine and the Snow Camp South pyrophyllite prospect at the northern and southern ends of Mine Ridge and the pyrophyllite prospect on Major Hill. These zones are gradational into the enclosing silicic granofels through quartz-dominated assemblages that include pyrophyllite ± kaolinite, andalusite, chloritoid, sericite, paragonite, and iron oxide after pyrite (Hughes 1987, Schmidt et al. 2006).

Although a number of small precious and base metal sulfide mines and prospects associated with quartz veins and shear zones are present in the Snow Camp-Saxapahaw area (Schmidt et al. 2006), there is no recorded production. The extensive Cu-Mo-Au anomalies coincident with AES core zone silicic and advanced argillic alteration documented at Pilot Mountain (Milton et al. 1983, Schmidt 1985a, and Klein and Schmidt 1985) have not been demonstrated for the Snow Camp-Saxapahaw area. It is uncertain whether similar mineralization is present, as no systematic geochemical studies have been published.

Discussion

Schmidt et al. (2006) suggest that AES of the Snow Camp-Saxapahaw district were formed by meteoric-magmatic fluids associated with sub-volcanic plutons intruding the Hyco Formation within a tilted volcano-tectonic graben, possibly a caldera. Graben formation and intense, intrusion-focused hydrothermal alteration are interpreted to post-date the Virgilina Deformation, which is regionally constrained to between 578 and 554 Ma by Pollock et al. (2012), and accompany a period of localized bimodal magmatism associated with extensional north-northeast trending fault zones.

These events precede eruption of large volumes of crystal-rich rhyodacitic to dacitic volcaniclastic units that appear correlative with the Uwharrie Formation (Schmidt et al 2006). Localized rifting and en echelon faulting, bimodal magmatism, and AES formation in the Snow Camp-Saxapahaw district appears to be an early expression of Uwharrie-age deformation and magmatism in the Carolina Terrane of central North Carolina.

PILOT MOUNTAIN AREA

The stratigraphy, structure and hydrothermal alteration and mineralization in the Pilot Mountain area southwest of Ramseur in Randolph County (Fig. 3) are well documented by Harris (1982), Schmidt (1983), Milton et al. (1983), Klein and Schmidt (1985), and Harris and Glover (1985 and 1988). Large zoned advanced argillic hydrothermal alteration centers at Pilot Mountain and Fox Mountain appear to be hosted by metavolcanic and metasedimentary units of the Hyco Formation and the Aaron Formation (Harris and Glover 1985, Klein and Schmidt 1985). The well-supported unconformity between these older units and the overlying Uwharrie Formation and the presence of Uwharrie-age intermediate to felsic plutons and dikes throughout the area (Harris 1982, Harris and Glover 1985) constrain the timing of AES formation relative to deposition of both successions, as well as the late Proterozoic Virgilina Deformation (Harris and Glover 1985) and Late Ordovician Cherokee Orogeny (Hibbard et al. 2012).

Local geologic setting and history

The area is dominated by stratigraphic sequences of the Hyco and Aaron Formations (Fig. 3). The Hyco Formation in this area is largely composed of andesite to dacite pyroclastic and volcaniclastic sequences that include tuff breccia, lapilli, lapilli-crystal and crystal tuffs, and massive to laminated vitric tuffs (Harris and Glover, 1985; Klein and

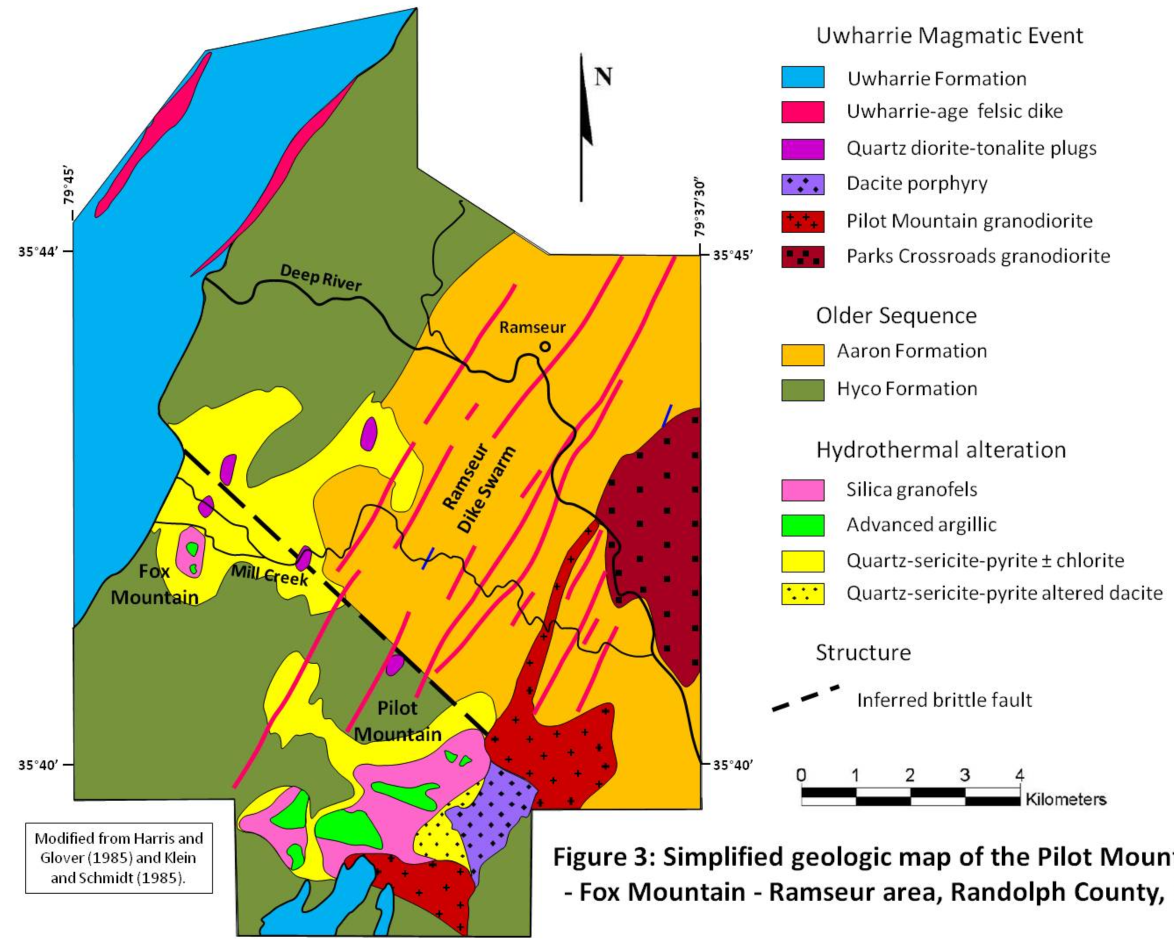

Figure 3: Simplified geologic map of the Pilot Mountain - Fox Mountain - Ramseur area, Randolph County, NC

Schmidt 1985). These units are laterally extensive, may form thick mass flow deposits, and are intercalated with coherent feldspar-phyric and amygdaloidal lava flows. Tuff-breccias contain rounded to angular clasts up to 100 centimeters across that include pyroclastic and epiclastic rocks, porphyritic andesite and dacite, tonalite, and granodiorite (Harris and Glover 1985). The uppermost Hyco Formation is characterized by volcanic epiclastic breccias and/or conglomerates, arenites, and mudstones intercalated with lapilli and crystal tuffs (Harris and Glover 1985).

The Aaron Formation is largely composed of conglomerate, feldspathic arenite, siltstone and mudstone in stacked, upward fining sequences deposited under deep marine conditions (Harris and Glover 1985). Conglomerate clasts include plutonic rocks, quartz arenite, and vein quartz. Bowman (2010) documents a 37 Ma gap between the cessation of Hyco volcanism and Aaron Formation sedimentation and bimodal volcanism. The Virgilina volcanic member of the Aaron Formation is not present in the Pilot Mountain area.

The Hyco and Aaron formations were folded, without metamorphism or development of an axial planar cleavage, and faulted during the Virgilina Deformation (Harris 1982). The Virgilina Deformation is constrained to between about 578 and 554 Ma (Pollock 2007). Tight F_1 folds with wavelengths of 2-3 kilometers and axes oriented 040° to 052° are overturned to the southeast (Harris and

Glover 1985). Lithologic units of the Hyco Formation and F_1 fold axes appear to be offset by a northwest-trending fault zone (Fig. 3) that extends 310°-315° from just north of Pilot Mountain through the Fox Mountain area (Harris 1982, Harris and Glover 1985, Klein and Schmidt 1985). Map patterns (Harris 1982, Harris and Glover 1985) suggest an apparent sinistral offset of up to 500 meters. This fault zone may be truncated by the granodiorite intrusion that borders the Pilot Mountain AES to the east, and does not continue across the Hyco-Uwharrie Formation unconformity (Harris 1982, Klein and Schmidt 1985). Harris (1982) suggests that this fault zone, although not directly observed on the ground, may be associated with the distribution of small intermediate to felsic plugs and hydrothermal alteration between Pilot Mountain and Fox Mountain.

The Uwharrie Formation is less than a kilometer thick in the Pilot Mountain area, and composed of a bimodal sequence dominated by dacite to rhyodacite pyroclastic-volcaniclastic successions intercalated with felsic flows, and subordinate mafic pyroclastic units and flows (Harris and Glover1985). Felsic volcaniclastic units include tuff breccia, lapilli tuff, and crystal to vitric tuffs. Pumice-rich units are common and may contain compressed pumice fiamme, but there is no evidence of welding (Harris and Glover 1985). Felsic flow units are commonly feldspar phyric to spherulitic and flow-banded. Harris and Glover (1985) cite bedded sedimentary structures and the lack of welding in pumiceous felsic units and pillowed mafic flows as evidence for subaqueous deposition of the Uwharrie Formation in this area.

Harris (1982) and Harris and Glover (1985) show unaltered Uwharrie Formation unconformably overlying quartz-sericite-pyrite altered Hyco Formation west of the Fox Mountain advanced argillic alteration center (Fig. 3). Klein and Schmidt (1985) mapped unaltered fine-grained quartz and feldspar phyric volcaniclastic rocks, interpreted as Uwharrie Formation, immediately southwest of Pilot Mountain, unconformably overlying the hydrothermally altered Hyco Formation and preserved in a series of F_2 synclines with wavelengths of 1-3 kilometers (Fig. 3).

Late Ordovician deformation during the Cherokee Orogeny (Hibbard et al. 2012) resulted in generally open F_2 folding of the Uwharrie Formation, refolding of the Hyco and Aaron formations, and regional greenschist facies metamorphism with heterogeneous development of an axial planar cleavage. Fold axes with wavelengths of up to 1-2 kilometers are oriented 020°-040°, often nearly coaxial with Virgilina Deformation folds, and may be overturned to the southeast (Harris and Glover 1985). The well-expressed axial planar cleavage is oriented 035°-045° and typically dips >75° northwest (Harris and Glover 1985). Cleavage development is strongly dependent on the rheology of the lithology; well developed in fine-grained metasedimentary units and quartz-sericite-chlorite alteration zones, but poorly developed in felsic intrusions and quartz granofels (Harris 1982).

Harris (1982) mapped a series of late ductile deformation zones through the Pilot Mountain-Fox Mountain area, interpreted to have formed during the Cherokee Orogeny. They are oriented 030°-040°, largely confined to zones of hydrothermal alteration, and often appear to be developed along existing structures, including fold axes, dikes, and lithologic contacts. These shear zones are 100 to 1000 meters wide, and extend along strike for up to 3 kilometers (Harris 1982). Rocks within these zones are characterized by extreme flattening, attenuation, shortening and recrystallisation, and generally complete destruction of original textures. These shear zones are typically rich in phyllosilicate minerals, quartz, sphene, calcite, and opaque minerals with a strongly developed anastomosing cleavage (Harris 1982). Synkinematic quartz and quartz-epidote-potassium feldspar veins are common, either parallel to the cleavage fabric or variably folded and transposed.

Plutonic rocks and associations

The Hyco and Aaron formations are intruded by a diverse suite of mafic to felsic plutons and dikes in the Pilot Mountain area (Fig. 3). These include a post-Virgilina Deformation suite of small quartz diorite-tonalite-dacite plugs, a younger swarm of northeast-trending felsic dikes centered on Ramseur, and the Parks Crossroads Granodiorite pluton southeast of Ramseur (Harris 1982, Klein and Schmidt 1985). The Parks Crossroads Granodiorite pluton and the felsic dike swarm appear to post-date hydrothermal alteration centered at Pilot Mountain, but the quartz diorite-tonalite-dacite association may be coeval and genetically associated with AES formation.

Parks Crossroads Granodiorite

The composite Parks Crossroads Granodiorite pluton (Fig. 3) intrudes the Aaron Formation east of Pilot Mountain and post-dates the Virgilina Deformation (Harris 1982, Harris and Glover 1985). The pluton is a heterogeneous, composite body formed largely of foliated biotite-hornblende granodiorite to quartz diorite, but with a granitic phase along the western margin and minor gabbroic to dioritic phases (Tingle 1982, Harris 1982, Klein and Schmidt 1985). The pluton covers an area of around 78 km^2 and has a Rb/Sr whole rock age of 566±46 Ma (Tingle 1982). Based on mapping by Tingle (1982), the pluton is elongated on a bearing of around 020°, cutting obliquely across the 060° trend of Hyco and Aaron formation units on the east side, but almost conformable to the west.

The granodiorite ranges from equigranular to porphyritic, and the limited occurrence of granophyric phases suggest crystallization at relatively shallow depths. The granodiorite is composed of quartz (10-25%, plagioclase (50-65%), trace potassium feldspar, and 10-40% mafic minerals including hornblende, biotite, epidote, and chlorite (Klein and Schmidt 1985). Amphibole, probably hornblende, appears to have been the dominant mafic phase, but is largely retrograded to chlorite and epidote. A silicified zone up to several hundred meters wide is present at the contact of the pluton with the Aaron Formation, and may be a contact metamorphic aureole (Harris 1982).

The non-foliated granitic border phase is leucocratic, composed of about 50% quartz, 33% potassium feldspar, and 15% plagioclase with accessory biotite (Harris 1982, Klein and Schmidt 1985). It cross-cuts the granodiorite and Klein and Schmidt (1985) report the presence of potassic alteration and local concentrations of fluorite in this phase.

Small plugs of granodiorite very similar to the Parks Crossroads Granodiorite border the Pilot Mountain AES to the northeast and southeast (Fig. 3) in contact with a body of hydrothermally altered porphyritic dacite that borders the AES to the east (Harris 1982, Schmidt 1985a). The granodiorite plug to the northeast measures about 4 km^2 and is described by Harris (1982) as porphyritic and gradational among granodiorite, dacitic, and tonalite. It features a dike-like apophyse that extends about 025° for over 4 km to intersect the western margin of the Parks Crossroads Pluton. The granodiorite is composed of euhedral to subhedral plagioclase and quartz crystals to 4 millimeters in a matrix of fine-grained microcline, quartz, and biotite (Harris 1982). Harris (1982) suggested that this body may be similar in age and possibly comagmatic with the Parks Crossroad Granodiorite.

Schmidt (1985a) mapped a similar 2 km^2 body of granodiorite-quartz diorite bordering the

Pilot Mountain alteration zone to the southeast and south. Textures range from equigranular to porphyritic, with 2-5 millimeter feldspar grains and subhedral to rounded and possibly embayed quartz phenocrysts. The ratio of plagioclase to potassium feldspar is 3:1 to 4:1, and quartz crystals may form 10-30% of the rock by volume (Klein and Schmidt 1985). Up to 30% biotite is present, but typically altered to chlorite and epidote. Klein and Schmidt (1985) note the similarity of this intrusion to the Parks Crossroad Granodiorite.

Although minor to trace disseminated, fine-grained euhedral pyrite is common in porphyritic phases, these granodiorite plugs are younger than the hydrothermal alteration system centered at Pilot Mountain (Milton et al. 1983, Schmidt 1985a, Klein and Schmidt 1985). Klein and Schmidt (1985) cite drill core observations that the southeastern granodiorite-quartz diorite plug cross-cuts the Pilot Mountain alteration system.

Quartz diorite-tonalite-dacite association

A diverse suite of small intermediate to felsic plugs in the Pilot Mountain area (Fig. 3) are spatially and possibly genetically associated with both the Pilot Mountain and Fox Mountain AES centers (Harris 1982, Harris and Glover 1985, Klein and Schmidt 1985). A larger body of dacite porphyry borders the Pilot Mountain AES to the east, and a series of small quartz diorite-tonalite plugs trend northwest from Pilot Mountain to the Fox Mountain AES, sub-parallel to a major fault zone oriented 310°-315° (Harris 1982, Harris and Glover 1985, Klein and Schmidt 1985).

A 2 km^2 area of quartz phyric dacite porphyry (Fig. 3) borders the Pilot Mountain AES to the east (Schmidt 1985a, Klein and Schmidt 1985). It is characterized by numerous bipyramidal quartz phenocrysts, often partly resorbed, and plagioclase porphyroclasts ranging from 2-5 mm. The western portion of this body is strongly altered within the Pilot Mountain alteration zone, especially the more coarsely quartz phyric phases. To the southeast, the porphyry is intensely altered to quartz-sericite-pyrite with local accessory potassium feldspar (Schmidt 1985a). On the southeast slope of the peak, the porphyry is intensely silicic altered to quartz granofels, with only the quartz phenocrysts remaining from the protolith (Schmidt 1985a). Isolated occurrences of quartz granofels with relict quartz crystals are present near the summit of Pilot Mountain and on the northern slope, and suggest small apophyses of similar porphyritic dacite (Klein and Schmidt 1985).

Harris (1982) mapped a number of small plugs of quartz diorite-tonalite that are roughly aligned along a northwest-trending zone that extends from Pilot Mountain to Fox Mountain (Fig. 3). These plugs are medium to fine-grained and composed of subhedral plagioclase and quartz with accessory biotite, amphibole, and pyroxene that are largely pseudomorphed by metamorphic chlorite, actinolite, and epidote (Harris 1982). They are typically less than 2500 m^2 in area, often elongated north to northeast, and often appear to be central to zones of hydrothermal alteration, especially in the Fox Mountain area. Harris (1982) and Harris and Glover (1985) indicate that the contacts of these small plugs are "gradational with the surrounding altered volcanic rocks". Although the meaning of this statement is not entirely clear, it appears to suggest that these stocks have been affected by the hydrothermal alteration, and are older than or synchronous with the hydrothermal event.

Harris (1982) suggests that these plugs are genetically linked to the associated hydrothermal alteration, possibly as apophyses of a causal intrusive at depth. Harris (1982) also suggested that this aligned series of plugs and the associated hydrothermal alteration are linked to the northwest-trending fault zone indicated in this area, inferred although not directly observed on the ground.

Ramseur dike swarm

Harris (1982) mapped a 5 km wide swarm of subvertical dacite to rhyodacite dikes that trend 030° for over 12 km, centered on the town of Ramseur (Fig. 3). The dikes lie largely west of the Parks Crossroad Granodiorite, but some may intersect the southwest margin. This dike swarm is directly on strike with the AES centered at Pilot Mountain to the south. It is also directly on strike with the Staley pyrophyllite deposit, located about 8 km northeast of Ramseur.

Individual dikes are less than 20 m thick and discontinuous along strike for up to 5 km, some possibly in *en echelon* arrays. They are typically porphyritic or flow-layered and may contain spherulites (Harris and Glover 1985). The dikes are light blue-gray to dark gray and contain phenocrysts of plagioclase, quartz, biotite, and locally minor perthitic potassium feldspar in a recrystallized aphanitic groundmass. The plagioclase is albite-oligoclase and the biotite is largely altered to chlorite (Harris 1982). Harris (1982) reports glomeroporphyritic clustering of phenocrysts, which often formed nucleation foci for spherulite development.

Proximal to the Parks Crossroads Granodiorite, these dikes commonly feature "comb-like" granophyric intergrowths of alkali feldspar and quartz concentrated around phenocrysts of quartz and perthitic potassium feldspar (Harris 1982). This may suggest that the dikes pre-date the pluton, and have experienced potassic metasomatism, possibly associated with the granitic border phase along the western side of the Parks Crossroads Pluton.

The felsic dikes post-date the Virgilina Deformation and intrude the Hyco and Aaron Formations and some older units of the Uwharrie Formation (Harris 1982). Klein and Schmidt (1985) revised and expanded mapping by Harris (1982) around Pilot Mountain, with special emphasis on alteration assemblages. They recognized the presence of felsic dikes, but suggested that some could be Uwharrie Formation tuffs or flows preserved in narrow F_2 synclines. Harris (1982) also indicated the local presence of flow layered porphyritic lava units associated with the dikes.

Compilation and correlation of geologic mapping by Harris (1982) and Seiders (1981) to the southeast suggests that the dike swarm in the Pilot Mountain area is on strike and continuous with northeasterly dike-like extensions of the Seagrove Complex, a Uwharrie-age felsic intrusive-extrusive center (see below). The gap in map coverage between the mapping of Seiders (1981) and Harris (1982) is only about 2.5 km.

Hydrothermal alteration

The Pilot Mountain AES is developed in volcaniclastic and epiclastic sedimentary lithologies of the Hyco and Aaron Formations (Harris 1982, Harris and Glover 1988, Klein and Schmidt 1985). Hydrothermal alteration extends across an irregular area measuring 4.5 x 1.5-2 kilometers (Fig. 3). Schmidt (1985a) and Klein and Schmidt (1985) suggest that the Pilot Mountain AES is strongly zoned outward to the west of the adjacent, intensely altered dacite porphyry, interpreted as the causal subvolcanic intrusive centre of the hydrothermal system. However, the central core of the AES appears to be located 1-2 km west of the dacite plug and zoned concentrically. The apparent asymmetry suggested by Klein and Schmidt (1985) may be due to the variable response of different lithologies to hydrothermal alteration.

The core of the AES is a 3.5 x 1 km area of intense silicic and advanced argillic alteration oriented northeast. A second 1 x 1 km area of similar character is located immediately to the west, separated by a narrow zone of quartz-sericite-pyrite alteration. Metavolcanic rocks in the intensely silicic altered core are relatively homogenous texturally and composed of 80-100% fine-grained quartz, termed "quartz granofels" by Klein and Schmidt (1985), with ubiquitous 2-5% disseminated pyrite and variable minor pyrophyllite and sericite. Original compositions, textures and fabrics are largely destroyed, except for relict quartz phenocrysts (Klein and Schmidt 1985).

The occurrence of topaz at Pilot Mountain appears to be largely restricted to the quartz granofels, where topaz-rich zones may be several meters wide. Topaz-bearing quartz granofels is dark grey, fine-grained and composed of intergrown quartz and topaz. Topaz may form relatively pure, irregularly shaped aggregates a few millimeters to a few centimeters across (Klein and Schmidt 1985). Local irregularly-shaped fragmental textures contain possible clasts with bleached rims replaced by quartz and topaz. Klein and Schmidt (1985) suggest that these may represent late fluorine-rich breccia pipes cutting the quartz granofels cap.

Zones of advanced argillic alteration occur as irregular to lensoidal domains up to a kilometer across enclosed by silica granofels within the silicic core. Advanced argillic alteration assemblages are heterogeneous and include variable proportions of andalusite, pyrophyllite, sericite, kaolinite, chloritoid, topaz, pyrite and rutile (Klein and Schmidt 1985). Characteristic assemblages include pyrophyllite-andalusite-quartz-pyrite-sericite with andalusite crystals up to a centimeter across; pyrophyllite-quartz-pyrite-sericite-chloritoid; and massive, monomineralic pyrophyllite with randomly oriented to radiating crystals (Harris 1982, Klein and Schmidt 1985).

The core zones of quartz granofels and advanced argillic alteration are haloed by a zone of phyllosilicate-rich assemblages dominated by quartz + sericite ± chlorite ± pyrophyllite ± rutile ± albite ± carbonate with 2-5% to locally 30% disseminated pyrite (Harris 1982, Klein and Schmidt 1985). Small, isolated pods or lenses of quartz granofels and advanced argillic alteration are common, especially close to the core areas of more intense alteration (Klein and Schmidt 1985). Enclaves of weakly altered to unaltered metavolcanic or metasedimentary rocks are common within this zone, especially near the periphery, where it grades into the unaltered country rocks, possibly through a propylitic halo that is typically indistinguishable from the regional greenschist metamorphic mineral assemblages (Harris 1982, Klein and Schmidt 1985). A narrow extension of this alteration zone extends northwest to include the Spoon Mine gold prospect.

The west side of the dacite porphyry adjoining the Pilot Mountain AES to the east and immediately adjacent rocks are intensely altered to fine-grained quartz-sericite-pyrite with relict quartz crystals (Klein and Schmidt 1985). Small areas of quartz granofels and advanced argillic alteration are also present. Klein and Schmidt (1985) report the presence of anomalous soil and rock gold values and localized chalcopyrite and molybdenite in outcrop and drill core from this zone near the Pine Hill Mine. Although Klein and Schmidt (1985) suggest that the dacite porphyry is the origin and source for the Pilot Mountain AES fluids, the alteration appears more consistent with the quartz-sericite-pyrite alteration zone peripheral to the silicic-advanced argillic core. The dacite porphyry is considered unlikely to be the source of the fluids, and was probably emplaced prior to development of the hydrothermal system.

A second large AES is around Fox Mountain, located 6 km northwest of Pilot Mountain (Fig. 3). This large, irregularly shaped area of intense hydrothermal alteration is developed in rocks of both the Hyco and Aaron formations and appears to be developed around a number of small quartz diorite to tonalite stocks (Harris and Glover 1985). Mapping by Harris (1982) suggests that the geometry of the system reflects the dominant northeast tectonic trend and a proposed northwest-trending fault that offsets F_1 fold axes.

Quartz granofels similar to those at Pilot Mountain occupy a north-trending zone about 500 meters wide that extends for a kilometer from Fox Mountain southward across a low saddle to Iron Mountain (Schmidt 1985a), and encloses several small zones of pyrophyllite-rich advanced argillic alteration. Outcrops and historic mine workings on the east side of Iron Mountain contain zones of abundant specular hematite, largely hosted by quartz granofels. The Fox Mountain AES is characterized by an extensive area of quartz + sericite ± chlorite ± pyrophyllite ± rutile ± albite ± carbonate alteration with generally about 2-5% disseminated pyrite (Harris 1982, Klein and Schmidt 1985). It is comparable in size to the Pilot Mountain AES, but the intensity of hydrothermal alteration appears to be much lower.

Metallic mineralization associated with the Pilot Mountain AES

More than a dozen small historic gold mines and prospects are present within the area of hydrothermal alteration around Pilot Mountain. The most significant are the Porter Mine, located about 1.5 km north of the peak, and the Pine Hill Mine located 1.2 km south of the peak. The Porter Mine is opened in 3 m wide shear zone that trends 040° and dips 75°NW in the quartz-sericite-pyrite alteration zone of the AES (Klein and Schmidt 1985). Gold occurs with disseminated pyrite and concordant quartz veins with sulfides.

The Pine Hill Mine was probably the largest gold producer in the Pilot Mountain AES (Klein and Schmidt 1985). It is located at the contact between the dacite porphyry plug and Hyco Formation metavolcanic rocks, both altered to quartz granofels. Dacite porphyry at this site contains quartz phenocrysts to 1 cm and is intensely quartz-sericite-pyrite altered with small, localized pods of pyrophyllite-rich alteration (Klein and Schmidt 1985). Two old shafts are centered on a soil Au-B-Mo anomaly up to 150 meters wide that extends northeast for at least 500 meters (Klein and Schmidt 1985). The soil Au anomaly ranges from 0.1 to >1.0 ppm and appears to be located near the contact between the dacite porphyry and altered volcanic rocks of the Hyco Formation. Spoil from the shafts contains traces of copper carbonate and molybdenite, and composite grab samples contained up to 10 ppm Au and 2200 ppm Cu (Klein and Schmidt 1985).

A small separate apophyse of dacite porphyry on the northeast side of Pilot Mountain is intensely altered to quartz granofels with accessory pyrophyllite and sericite and relict 2-5 millimeter quartz phenocrysts (Klein and Schmidt 1985). The rock is strongly foliated, with small, locally numerous anastomosing fractures filled by limonite and hematite. Samples of this lithology contained up to 200 ppm As, 180 ppm Cu, 46 ppm Mo, 18 ppm Sn, and 0.5 ppm Ag (Klein and Schmidt 1985).

Coherent and coincident soil Mo, Cu, Au, B, and Sn geochemical anomalies are centered on the silicic-advanced argillic core of the Pilot Mountain hydrothermal alteration system (Milton et al. 1983, Schmidt 1985a, and Klein and Schmidt 1985). Copper values are typically 30-100 ppm in areas of more coherent anomalies, and a high value of 1200 ppm was obtained from drill core (Klein and

Schmidt 1985). Anomalous Mo values reach 400 ppm, but are generally 20-50 ppm; and anomalous Sn reaches 360 ppm, but is typically 20-50 ppm. Scattered, low-level Au soil and rock geochemical anomalies are present throughout the area, but highly localized.

Discussion

The Pilot Mountain and Fox Mountain AES are developed in both the Hyco and Aaron formations (Harris 1982, Harris and Glover 1985, Klein and Schmidt 1985), and must be younger than both. In his summation of the geologic history of the area, Harris (1982, p. 77) concludes that intrusion of quartz diorite-tonalite-dacite stocks and plugs and associated hydrothermal alteration post-date the Virgilina Deformation. They are broadly coeval with intrusion of the Ramseur dike swarm and deposition of the Uwharrie Formation, and younger than the Cherokee orogenic event.

Harris and Glover (1988) suggest that stock intrusion and hydrothermal alteration pre-date or are synchronous with the Virgilina Deformation, but some stocks may be contemporaneous with intrusion of the Ramseur dike swarm. However, map patterns and the deformation geometry of the Pilot Mountain and Fox Mountain AES (Fig. 3) are not consistent with the tight, larger-scale F_1 folding characteristic of the Virgilina Deformation (Harris 1982). They are consistent with the smaller-scale, more open F_2 folds formed in this area during the Late Ordovician Cherokee Orogeny (Hibbard et al. 2012), and documented by Klein and Schmidt (1985) immediately southwest of Pilot Mountain.

The Pilot Mountain and Fox Mountain alteration systems appear to be in part associated with a northwest trending fault (Fig. 3) that offsets large-scale F_1 folds but is truncated at the basal Uwharrie Formation unconformity (Harris 1982, Harris and Glover 1985). This fault may have in part focused the emplacement of a suite of small granodiorite-tonalite-dacite intrusions that appear to be associated with development of the AES at Pilot Mountain and Fox Mountain (Harris 1982, Klein and Schmidt 1985). The dacite plug on the east side of the Pilot Mountain AES (Klein and Schmidt 1985) and the northwest-tending alignment of small quartz diorite-tonalite plugs in the Fox Mountain area (Harris 1982, Harris and Glover 1982) pre-date or are synchronous with hydrothermal alteration. The small plugs of this plutonic suite may be apophyses of a larger, differentiated plutonic complex at depth that provided heat and magmatic volatiles to drive these intense hydrothermal alteration systems.

The Pilot Mountain AES does not appear to affect the adjacent granodiorite plutons (Fig. 3) that are similar to the Parks Crossroads Granodiorite (Harris 1982, Milton et al. 1983, Harris and Glover 1985, Klein and Schmidt 1985), dated to 566±46 Ma (Tingle 1982). This possibly comagmatic or related plutonism appears to be broadly coeval with the early phases of Uwharrie volcanism and emplacement of the Ramseur felsic dike swarm (Harris 1982), which is continuous with the Seagrove Complex to the southwest. Harris (1982) suggests that some of these dikes may be feeders for locally preserved Uwharrie eruptive units in the Pilot Mountain area, interpreted by Klein and Schmidt (1985) as synclinal infolds.

Both the Pilot Mountain and Fox Mountain alteration systems are unconformably overlain by unaltered Uwharrie Formation strata (Milton et al. 1983, Harris 1982, Harris and Glover 1985, Klein and Schmidt 1985), and demonstrably older. Felsic dikes that are part of the Seagrove Complex appear to post-date the Pilot Mountain alteration zone, Virgilina Deformation folds, and the unconformity at the base of the Uwharrie Formation (Harris 1982). The oldest commonly accepted U-Pb zircon age for the Uwharrie Formation is 568 ± 6 Ma (Kozuch 1994).

The original interpretation of Harris (1982) is consistent with all known geologic relationships in the Pilot Mountain area. Formation of AES centered at Pilot Mountain and Fox Mountain post-date the Virgilina Deformation. They appear to be associated with a renewed period of localized tectonic activity characterized by brittle faulting and low volume intermediate to felsic magmatism that immediately preceded more voluminous felsic-dominated bimodal magmatism and deposition of the Uwharrie Formation.

Like AES in the Snow Camp-Saxapahaw area in Alamance County (Schmidt et al. 2006), the Pilot Mountain and Fox Mountain hydrothermal systems appear to be associated with localized faulting and magmatism that immediately precede initial deposition of the Uwharrie Formation. Unlike the graben structure in the Snow Camp-Saxapahaw area, the dominant structural control in the Pilot Mountain area appears to be a northwest-trending fault (Harris 1982).

However, although the Ramseur felsic dike swarm post-dates the Pilot Mountain AES, it is centered on Pilot Mountain and directly on strike with the AES at Staley to the northeast. The dike swarm is the northeast continuation of the Seagrove Complex magmatic center, with Uwharrie-age felsic intrusive magmatism focused along a major fault zone about 5 km wide and a strike length of at least 35-40 km (Fig. 4). This fault zone may have formed prior to dike emplacement as the primary structural control for the Pilot Mountain and Staley AES. The northwest-trending cross-fault may have localized the Pilot Mountain AES near the intersection with this fault zone, with less intense AES development at Fox Mountain off the main structural trend.

Widespread metallic mineralization associated with the Pilot Mountain AES is consistent with relatively shallow level high sulfidation, silicic-advanced argillic epithermal alteration, possibly associated with porphyry-style mineralization centered on a felsic plutonic complex at depth (Milton et al. 1983, Schmidt 1985a, Klein and Schmidt 1985). Strongly anomalous F and Mo suggest an evolved felsic magmatic connection.

THE SEAGROVE COMPLEX

Seiders (1981) defined a distinct unit of "porphyritic felsite" centered on the town of Seagrove in the southeast corner of the Asheboro Quadrangle, interpreted as part of the Uwharrie Formation. This 3-5 km wide unit, here informally designated the Seagrove Complex, was mapped in detail by Seiders (1981) for over 11 km along a 030° trend (Fig. 4). The felsite is intrusive into, and possibly interdigitated with, thin to thick-bedded felsic tuff, lapilli tuff, and tuff breccia (Seiders 1981). The unit is albite and quartz phyric, flow layered, and locally spherulitic. Phenocrysts are relatively smaller and less abundant south of Seagrove near the Randolph-Montgomery County line, but more abundant and larger (1-3 mm) to the north with flow layering and spherulites generally absent (Seiders 1981).

The northern end of the complex is gradational into a 4-5 kilometer wide swarm of narrow, laterally persistent digitations that continue for up to 6 kilometers on the same 030° trend. Felsic lava flows less than 100 metres thick and continuous over a distance of 6000 m are considered highly unlikely. The digitations at the northern end of the Seagrove Porphyry are interpreted as dikes. These dikes appear continuous with the 5 km wide swarm of subvertical felsic dikes mapped by Harris (1982) that trend 030° for over 12 km along the western flank of the Parks Crossroad Granodiorite. The gap in map coverage be-

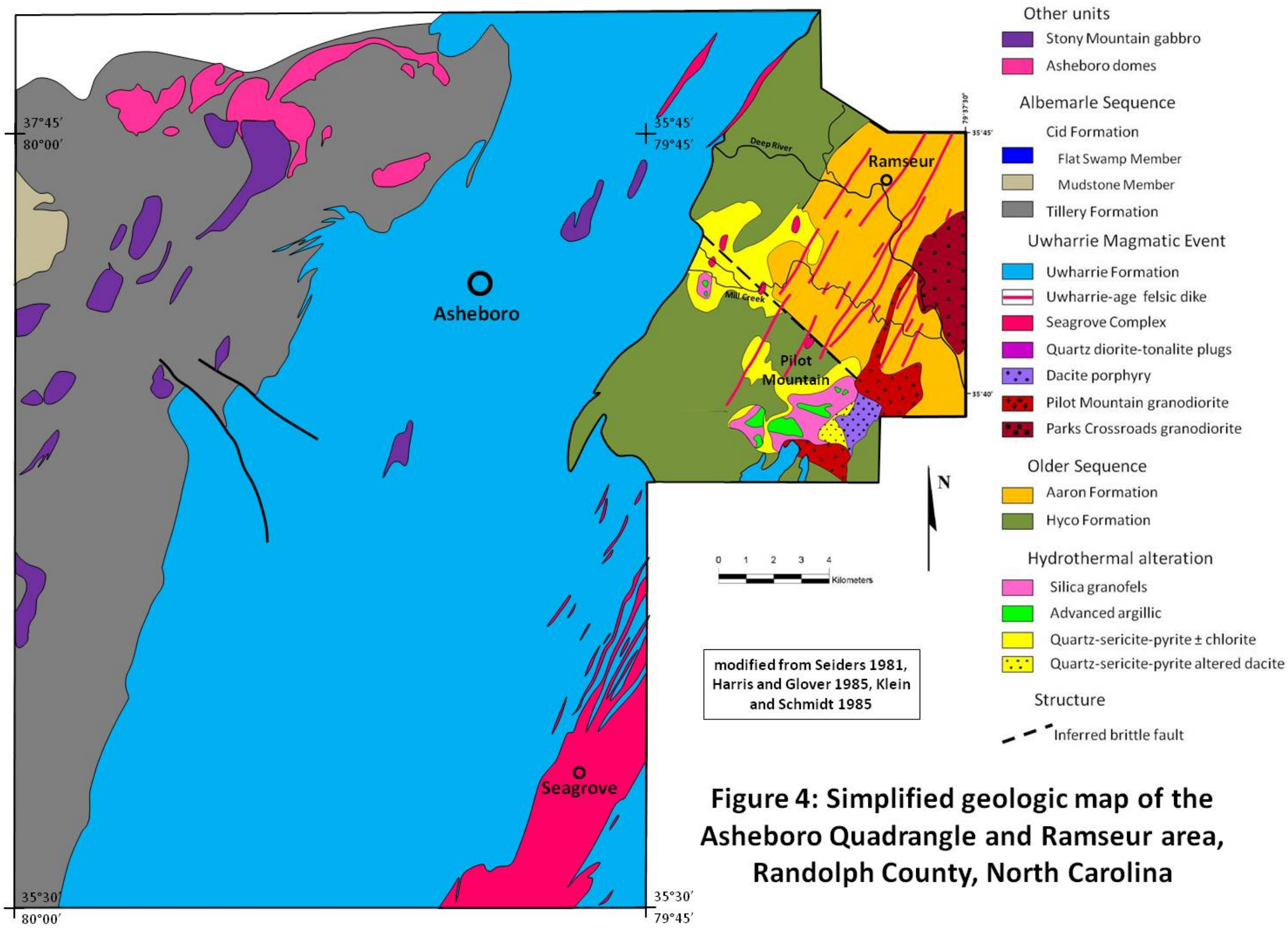

Figure 4: Simplified geologic map of the Asheboro Quadrangle and Ramseur area, Randolph County, North Carolina

tween the mapping of Seiders (1981) and Harris (1982) is only about 2.5 kilometers.

There is no available detailed geologic mapping south of 35°30′, the limit of mapping by Seiders (1981), to constrain the southern extent of the Seagrove Complex. It may terminate as part of the intrusive-extrusive porphyry body or partition into a dike swarm similar to the northern end.

Discussion

The Seagrove Complex connects the Uwharrie Formation with similar age magmatism in the Pilot Mountain-Ramseur area (Fig. 4). The complex is 3-5 kilometer wide and extends along a 030° strike for at least 30 kilometers. The large AES centered on Pilot Mountain (Fig. 4) is directly on strike between the Seagrove Complex to the southwest and the felsic dike swarm mapped by Harris (1982). The Seagrove Complex and Ramseur dike swarm are also directly on strike with the Staley pyrophyllite deposit located about 8 km northeast of Ramseur (Fig. 1). If the dike swarm extends to the Staley AES to the northeast, the total strike length of the Seagrove Complex would be about 36 kilometers. Depending on the continuity of the complex southwest beyond the mapping of Seiders (1981), the total strike length could be 45-50 km.

The Seagrove Complex appears to have developed along a major fault zone trending 030° that post-dates the Virgilina Deformation. It is uncertain whether this fault zone formed prior to, or synchronously with, Seagrove Complex magmatism. If the fault zone extends northeast to the Staley Mine AES north of Ramseur, it may have been the dominant controlling structure for development of both the Staley and Pilot Mountain hydrothermal alteration systems. Dikes of the Seagrove Complex appear to post-date the Pilot Mountain AES, which suggests that the fault zone may be older.

The emplacement of large volumes of felsic magma into the fault zone hosting the Seagrove Complex suggests significant extension to accommodate intrusion. Extensional faulting is also indicated for the graben structure documented by Schmidt et al. (2006) in the Snow Camp-Saxapahaw area to the northeast. The local preservation of Uwharrie Formation volcaniclastic units in the Pilot Mountain area may indicate preservation in narrow grabens, rather than synclines as suggested by Klein and Schmidt (1985). Tensional faulting, localized low volume plutonism, AES formation, and large volume Seagrove Complex felsic magmatism appear to be phases of an evolving Uwharrie tectonic-magmatic event.

Conclusions

The geometry, chemistry, and hydrothermal alteration assemblages of AES centers of the Carolina Terrane in central North Carolina are consistent with features of high sulfidation advanced argillic epithermal alteration systems (Schmidt et al. 2006). Epithermal alteration systems typically form at temperatures of less than 150°C to about 300°C, and from the surface to depths as great as 1-2 km (White and Hedenquist 1995). High-sulfidation epithermal alteration systems form largely from magmatic volatiles transported from the magmatic source reservoir with little fluid-rock interaction.

Vapor phase HCl and SO^2 mix with groundwater to form hot (200-300°C), highly acidic (pH 0-2), oxidized fluids that intensely leach host rocks (White and Hedenquist 1995). High water/rock ratios result in extensive, often pervasive alteration and extensive replacement textures, with disseminated styles of mineralization dominant over vein-type. The presence of primary topaz and andalusite suggest temperatures exceeding 260°C (White and Hedenquist 1995). Intensely leached, silica-dominated alteration assemblages characterize the core of the system, grading outward into advanced argillic assemblages and phyllic (quartz-sericite) alteration with decreasing water/rock ratios and increasing acid neutralization (White and Hedenquist 1995).

The Pilot Mountain-Fox Mountain and Snow Camp-Saxapahaw AES developed at relatively shallow crustal levels in association with largely intermediate to felsic plutonism. They are localized along *en echelon* tensional fault zones oriented 025°-030° that step north and east across the Carolina Terrane in central North Carolina (Fig. 5). These fault zones appear to represent the earliest phase of tectonism associated with post-Virgilina Deformation arc-rifting of the older Hyco and Aaron Formations. Localized faulting and plutonism appear to be precursors to voluminous felsic-dominated bimodal Uwharrie volcanism in the Snow Camp-Saxapahaw and Pilot Mountain areas. Continuity of this early low-volume magmatism with high-volume main-stage Uwharrie magmatism is suggested by the association of early intrusive suites with the Seagrove Complex in the Pilot Mountain area.

The *en echelon* pattern of aligned AES centers appears to continue north and east across the older sequence of the Carolina Terrane as the Hillsborough-Teer alignment in Orange County and the Bowlings Mountain-Daniels Mountain alignment in Granville County (Figs. 1 and 5). However, neither area has been analyzed in detail. The Hillsborough-Teer alignment includes three zones of argillic to advanced argillic alteration 2-3 kilometers long that strike N50°-60°E in southwest Orange County. They include the Martin Morrow-Oaks-North State, Teer, and Brad-

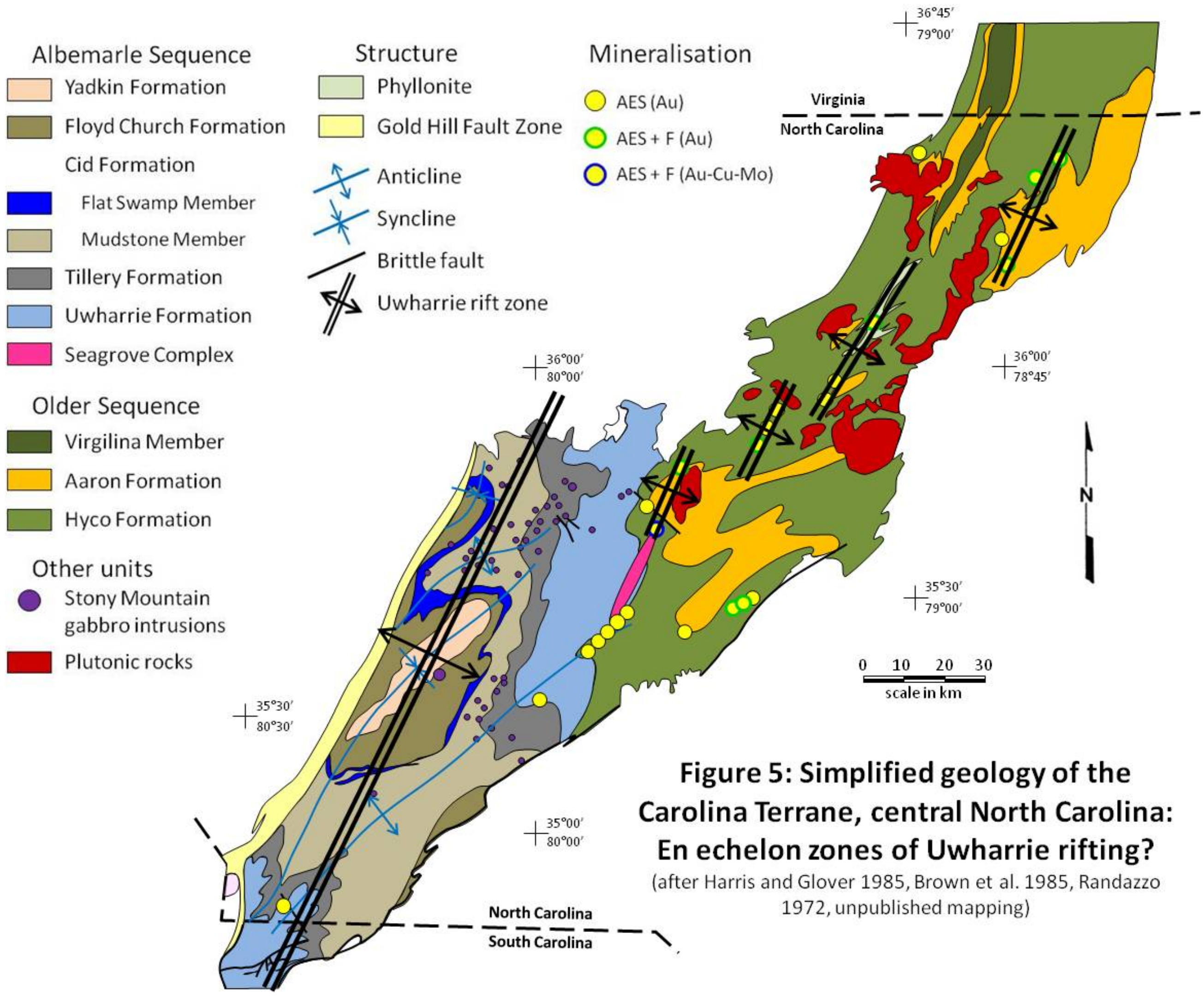

Figure 5: Simplified geology of the Carolina Terrane, central North Carolina: En echelon zones of Uwharrie rifting?
(after Harris and Glover 1985, Brown et al. 1985, Randazzo 1972, unpublished mapping)

shaw pyrophyllite prospects. These zones are aligned *en echelon* for about 5 kilometers at a bearing of N20°E. The trend continues northeast through the large, fluorine-rich AES at Hillsborough, and possibly for another 15-20 kilometers to the northeast. The Hillsborough area and associated AES have been interpreted as a resurgent cauldron (Newton 1983), but may instead represent a Uwharrie-age tectonic-volcanic graben or caldera similar to that proposed by Schmidt et al. (2006) in the Snow Camp-Saxapahaw area.

These early Uwharrie-age fault zones are typically 20-40 kilometers long and include faults oriented 025°-030° that cut across Virgilina Deformation structural fabrics, and fault segments parallel to the older 045°-060° fabric that step north in *en echelon* series to maintain the general 025°-030° trend. This geometry (Fig. 2) is well represented in the Snow Camp-Saxapahaw area (Schmidt et al. 2006). Similar controls are suggested by the distribution of hydrothermal alteration, faults, and units mapped as pyritic phyllite, schist, and phyllonite (Allen and Wilson 1968, Brown et al. 1985, Bradley et al. 2006) associated with the Hillsborough-Teer trend of AES centers in Orange County.

The presence of early Uwharrie-age plutonic rocks along these *en echelon* fault zones suggests that products of Uwharrie-age magmatism may be widespread but localized across the older portion of the Carolina Terrane in central North Carolina. The presence of Uwharrie-age magmatism within the older portion of the Carolina Terrane is supported by a zircon U-Pb age date of 546.5 +3.0/-2.4 Ma for the 150 km^2 Roxboro Pluton, which intrudes the Hyco and Aaron Formations in Person County (Wortman et al. 2000). Additionally, the preservation of possible Uwharrie Formation equivalent strata in the Snow Camp-Saxapahaw area suggests that eruptive units may also be locally preserved elsewhere in grabens or calderas. Detailed geologic mapping and rigorous geochronologic studies are required to better constrain this distribution.

TECTONIC SIGNIFICANCE

Numerous authors have suggested arc-rifting of the Carolina Terrane in central North Carolina and concurrent deposition of the Albemarle Group. Moye and Stoddard (1987) proposed deposition of the Albemarle Group in a transtensional rift basin. Harris and Glover (1988) suggested that the Uwharrie Formation represented renewed volcanism in a possible intra-arc transtensional rift basin. Feiss et al. (1993) proposed Neoproterozoic to Middle Cambrian arc-rifting of the Carolina Terrane based on whole-rock $\delta^{18}O$ isotopic data. An intra-arc or back-arc rift environment for the Albemarle Sequence is strongly supported by the recent work of Pollock and Hibbard (2010) and Pollock et al. (2010).

Intense, large-volume bimodal Uwharrie volcanism and plutonism accompanied development of the depositional basin that hosts the Albemarle Sequence.

The Uwharrie Formation has published U-Pb zircon ages of 558 ± 8 Ma and 568 ± 6 (Kozuch 1994), (SHRIMP) 554 ± 15 Ma (Ingle et al. 2003) and (ID-TIMS) 551 ± 8 Ma (Ingle 1999, Ingle-Jenkins et al. 1999, Ingle et al., 2003). Pollock (2007) reports that 98% of detrital zircons from a metaconglomerate unit near the top of the formation yielded LAN-ICP-MS U-Pb ages between 545 ± 7 Ma and 593 ± 9 Ma, with a unimodal peak around 560 Ma. The youngest concordant detrital zircon U-Pb age dates from the upper Uwharrie Formation are circa 545 Ma (Pollock 2007).

This appears to suggest that deposition of the Uwharrie Formation may have begun as early as circa 560 Ma and continued to around 545 Ma, coincident with deposition of the Tillery and Cid Formations (Pollock 2007). A dacite flow from the Flat Swamp Member of the Cid Formation yielded a U-Pb zircon date of 547 ± 2 Ma (Hibbard et al. 2009).

Rifting and associated magmatism culminated with emplacement of Stony Mountain gabbro intrusions sometime between the end of sedimentation circa 535 Ma (Pollock et al. 2010) and the Late Ordovician Cherokee Orogeny circa 456 Ma (Pollock and Hibbard 2010).

The Albemarle domain of late Proterozoic to early Cambrian arc rifting is *en echelon* with the early Uwharrie-age fault zones and associated AES alignments that right-step across the older Hyco-Aaron portion of the terrane (Figure 5). They appear to precede large-scale Albemarle Sequence arc-rifting in the North Carolina portion of the Carolina Terrane, and may represent a more widespread, low-strain deformation associated with rift initiation. The right-stepping geometry suggests regional transpression or transtension, possibly associated with interaction between the Carolina and Charlotte volcanic arc terranes. Step-over zones between fault segments may be characterized by either compression (sinistral transpression) or tension (dextral transtension). Despite tensional faulting and associated magmatism, arc rifting of the older sequence of the Carolina Terrane failed northeast of the Albemarle domain. Further research is required to fully analyze the implications, constraints, and accuracy of this model.

OTHER AES ALIGNMENTS

Other alignments and individual occurrences of AES are present in the Carolina Terrane in central North Carolina, including the Cottonstone-Ammons trend in Montgomery County, the Glendon-Robbins trend in Moore County, the Standard pyrophyllite deposit near Wadesboro in Montgomery County, and the Nesbit Mine in Union County. These additional alignments and deposits were not analyzed in detail for the present study, and will be the focus of future research. They do not appear to be directly related to the four early-Uwharrie en echelon fault zones to the north, and some appear to post-date the main phase of Uwharrie volcanism.

The Cottonstone Mountain-Ammons Trend

A series of five phyllic to advanced argillic alteration centers were mapped by Burt (1981) along a 15 kilometer long zone trending about 045° in northeast Montgomery County. These centers include Cottonstone Mountain, located 5 kilometers north of the town of Troy, and the Ammons Pyrophyllite Mine on the Montgomery-Moore County line to the northeast. These deposits are hosted by the Hyco Formation immediately adjacent to the contact with the Uwharrie formation, and on the western limb of the Troy Anticlinorium near the axis. They also lie parallel within 1-2 km of the southeastern projection of the Seagrove Complex.

This alignment may extend another 15 km southwest to include the Standard Minerals pyrophyllite deposit located about 2 kilometers northwest of Wadesville. Little information is available, but this deposit is hosted by the Uwharrie Formation and also located near the axis of the Troy Anticlinorium.

The historic Nesbit Gold Mine, located 17 kilometers southwest of Monroe in Union County, is located at the margin of the phyllic alteration halo of a small AES developed in the Uwharrie Formation (McKee 1985b). The geology and alteration are documented by McKee (1985a and 1985b). Like the Wadesville AES, the Nesbit alteration system is hosted by the Uwharrie Formation, on or near the axis of an antiform tentatively correlated with the Troy Anticlinorium. Both were metamorphosed and deformed during the Cherokee Orogeny of Hibbard et al. (2012).

The presence of the Wadesboro and Nesbit AES near the axis of the Troy Anticlinorium, as well as those of the Cottonstone Mountain-Ammons trend, may be coincidental, but no other AES are known from this area of the Carolina Terrane. The Wadesville and Nesbit AES are younger or synchronous with deposition of the Uwharrie Formation, but older than the Cherokee Orogeny. If the Cottonstone Mountain-Ammons trend deposits are related and of similar age, it could suggests a possible pre-Cherokee Orogeny structural precursor for development of the Troy Anticlinorium.

The Glendon-Robbins Trend

Zones of advanced argillic alteration are locally present for over 30 kilometers along the Glendon-Robbins fault zone in northern Moore County. This is a major reverse fault zone axial to large-amplitude folds that strike northeast and are steeply overturned to the southeast (Stuckey 1928, Conley 1962, Green et al. 1982, Klein 1985). It is uncertain whether the fault is related to the Virgilina Deformation (Harris and Glover 1985) or the Cherokee Orogeny (Hibbard et al. 2012). The age of AES formation is unknown, but alteration pre-dates or is synchronous with deformation on the fault (Klein 1985).

The Glendon Fault is a zone of intense ductile-brittle deformation 10-50 m wide characterized by intense cleavage development and abundant small scale folds, fractures and both deformed and undeformed quartz veins, suggesting a complicated rheological evolution (Klein, 1985). Fine-grained epiclastic metasedimentary rocks of the footwall are juxtaposed against felsic, intermediate and mafic tuffs and flows in the hangingwall. Hydrothermal alteration is developed in all lithologies and characterized by extensive argillic (sericitic) alteration and more localized advanced argillic alteration (pyrophyllite-andalusite) and silicification (McDaniel 1976, Klein 1985).

Gold is frequently found in anomalous amounts associated with advanced argillic alteration along the Glendon Fault and anomalous copper and molybdenum are also present (Leisure 1981). A sample of pyritic quartz-sericite-pyrite schist from the Womble Pit contained 500 ppm Mo (Lesure 1981). AES in the Robbins area are spatially and probably genetically associated with extensive historic gold mines and prospects (Powers 1993).

A comprehensive review and analysis of the tectonic and metallogenic character and constraints of the Glendon-Robbins trend AES and associated mineralization are pending. The relationship to other AES alignments is uncertain.

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Preliminary U-Pb TIMS zircon ages from the Stony Mountain gabbro at Ridges Mountain, North Carolina: timing of the birth of the Rheic Ocean?

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Abstract

We report on preliminary U-Pb dates for zircons from the Stony Mountain gabbro at Ridges Mountain, North Carolina. We obtained a preliminary high-resolution U-Pb TIMS $^{206}Pb/^{238}U$ date of 544.81 ± 0.55 Ma, and a $^{207}Pb/^{235}U$ date of 544.73 ± 0.95 Ma; these results in the context of the Albemarle arc sequence geochronology present new questions about the timing of the emplacement of the Stony Mountain gabbro and the birth of the Rheic Ocean. We discuss the possibilities that the zircons may be inherited, or that the emplacement of the Stony Mountain gabbro was time-transgressive.

Introduction

The Stony Mountain gabbro (Ingram, 1999) intrudes the entire Albemarle arc sequence (Fig. 1), the youngest of the major litho-tectonic elements that constitute the Carolina terrane in central North Carolina. The arc is composed of bimodal volcanics and associated volcaniclastic rocks and it ranges in age from ca. 555- <531 Ma (e.g. Ingle, et al., 2003; Hibbard et al., 2009; Pollock et al., 2010). The Stony Mountain gabbro is considered to be the final phase of arc magmatism in the Carolina terrane prior to upright folding and greenschist facies metamorphism attributed to the Late Ordovician accretion of the Carolina to Laurentia (Hibbard, 2000). Consequently, the age of the Stony Mountain gabbro is loosely limited between the Early Cambrian and Late Ordovician.

On the basis of geochemical studies and the relative timing of intrusion, the gabbro has been interpreted as representing the initiation of back-arc rift magmatism along the western margin of Gondwana, which could well represent the inception of the Rheic Ocean (Pollock and Hibbard, 2010). Consequently, dating of the Stony Mountain gabbro should provide the timing of the initiation of the birth of the Rheic Ocean. Dating of the gabbro may also serve to improve the resolution of the depositional chronology of the Albemarle sequence. terrane to Laurentia (Hibbard, 2000). Consequently, the age of the Stony Mountain gabbro is loosely limited between the Early Cambrian and Late Ordovician.

The focus of this study is to obtain the first age data for intrusion of the gabbro into the arc. Following a brief description of the petrology and geochemistry of the gabbro, we report on preliminary high-resolution U-Pb TIMS zircon ages for the gabbro and conclude with a discussion of the implications of these data.

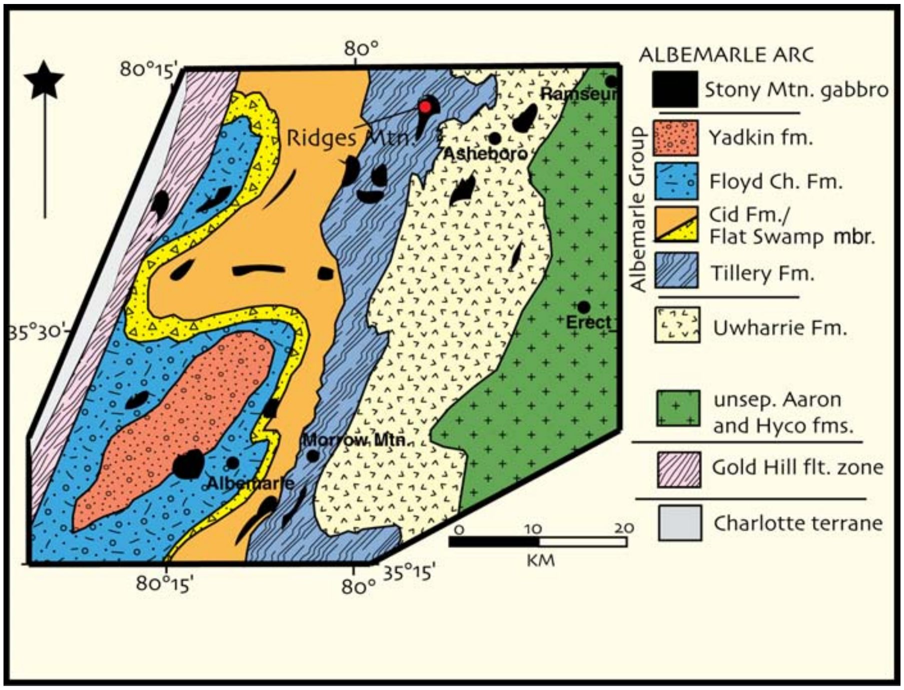

Figure 1: Geology of the Albemarle arc in central North Carolina.

PETROLOGY AND GEOCHEMISTRY OF THE STONY MOUNTAIN GABBRO

The Stony Mountain gabbro forms numerous stocks, sills, and dikes in the Albemarle arc of central North Carolina (Fig. 1), where it mainly underlies hills and ridges (Stromquist and Henderson, 1985). It intrudes the Neoproterozoic Uwharrie Formation, the base of the Albemarle arc, as well as all of the formations in the overlying Neoproterozoic to earliest Paleozoic Albemarle Group, including, from oldest to youngest, the Tillery, Cid, Floyd Church, and Yadkin formations (Stromquist and Henderson, 1985). The reader is referred to the overview (Hibbard et al., this volume) for further description of the geological setting of the arc and the gabbro.

The Stony Mountain gabbro is generally a dark green to greenish-grey, equigranular, medium- to coarse-grained gabbro (Pollock and Hibbard, 2010). The rock contains approx.-imately 50% subhedral to euhedral plagioclase that is variably saussuritized and in places completely altered to sericite and epidote. Clinopyroxene, amphibole, and biotite comprise about 35% of the rock and are variably altered to pleochroic colorless to pale green chlorite and actinolite. The cores of augite crystals are replaced by green-brown and pleochroic hornblende. Hornblende also occurs as poikilitic crystals that enclose aggregates of alteration minerals and plagioclase crystals and is typically altered to fine-grained chlorite. Minor amounts of anhedral quartz occur interstitial to the plagioclase and mafic minerals. Pyrite and other opaque Fe-Ti oxides occur as accessory minerals in the groundmass.

Geochemical studies indicate that the Stony Mountain gabbro was derived from mixing of depleted lithospheric mantle, enriched asthenospheric mantle, and fluids from dehydrated subducted oceanic crust sources (Pollock and Hibbard, 2010). ε_{Nd} values for the Stony Mountain gabbro range from +2 to +3, precluding the assimilation of continental source material (Pollock and Hibbard, 2010).

In the scenario proposed by Pollock and Hibbard (2010), initial magmatism was produced by partial melting of depleted N-MORB lithospheric mantle and decompression melting of upwelling enriched asthenospheric mantle. Magmas from these two sources and slab-derived fluids mixed to produce the Stony Mountain gabbro. On the basis of this model and the relative timing of intrusion (late during Albemarle arc magmatism and prior to regional deformation associated with accretion to Laurentia), the gabbro has been interpreted as representing the initiation of back-arc rift magmatism along the western margin of Gondwana, which could well represent the inception of the Rheic Ocean (Pollock and Hibbard, 2010).

Geochronology

Samples

Our samples of the gabbro were obtained from Ridges Mountain, Randolph County, North Carolina (Fig. 2). There, the gabbro forms a stock within the Tillery Formation, the lowest stratigraphic unit of the Albemarle Group (Seiders, 1981). The Tillery Formation is composed of mainly laminated to thin-bedded, graded, mudstone and lies conformably above the Uwharrie volcanics, the base of the Albemarle arc.

Figure 2: The Stony Mountain gabbro at Ridges Mountain, North Carolina.

Methods

Approximately 25 kg of gabbro was broken into smaller fragments with a rock hammer at the sample site to avoid contamination with foreign zircons during subsequent sample processing. Samples were crushed with a jaw crusher, and disk mill. Heavy mineral separates were concentrated using a water table and heavy liquids. A Frantz magnetic separator was used to isolate minerals with low magnetic susceptibility. Zircons were hand-picked using a binocular microscope, and annealed at 950 °C for 48 hr.

Due to the recovery of only two grains, chemical abrasion was approached conservatively to avoid complete dissolution and loss of the sample. Several stages of chemical abrasion in an HF-HNO_3 solution were performed in Teflon capsules on a hot plate using increased temperature during each stage. The zircons were observed under a binocular microscope after each stage to visually determine the effectiveness of chemical abrasion by noting changes in transparency, crystal shape, and width of fractures.

The zircons were dissolved in HF in a bomb at 220 °C for 48 hours. Then they were converted to chloride salts by dissolution in 6N HCl in a bomb at 180 °C for 16 hours. The chloride salts were dried down and dissolved in H_3PO_4 for column chromatography separation of Pb and U. Both Pb and U were loaded onto Re filaments for analysis of isotope ratios using a VG Sector 54 thermal ion mass spectrometer. See Mattinson (2005) for details on zircon U-Pb chemical abrasion, and thermal ion mass spectrometry.

Results

Both zircons exhibited loss of transparency and acquired a granular appearance following chemical abrasion, however there was little if any change in the appearance of the fractures on all zircons. It is likely that zircons from the Stony Mountain gabbro would survive aggressive chemical abrasion; as such, future analysis of zircon fractions will use aggressive chemical abrasion methods.

SMG F-1 is slightly reversely discordant and, gives a $^{206}Pb/^{238}U$ date of 546.49 ± 0.45 Ma and a $^{207}Pb/^{235}U$ date of 544.52 ± 0.81 Ma. SMG F-2 is concordant and gives a $^{206}Pb/^{238}U$ date of 544.81 ± 0.56 Ma, and a $^{207}Pb/^{235}U$ date of 544.73 ± 0.95 Ma (Fig. 3). The data used to calculate these dates are given in Table 1.

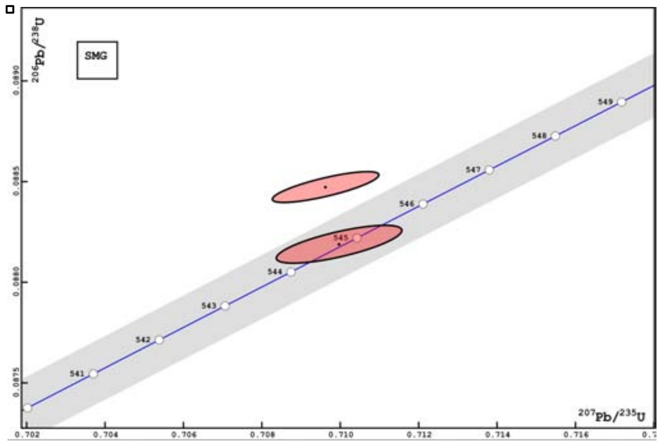

Figure 3: Concordia plot of zircon fractions SMG-F1 (slightly reversely discordant), and SMG-F2 (concordant).

Table 1

U-Pb data for zircons from Stony Mountain gabbro at Ridges Mountain

ID	mass Pb* (pg)	Th/U [a]	$^{206}Pb/^{204}Pb$ [b]	$^{206}Pb/^{238}U$ [c]	% error	$^{207}Pb/^{235}U$ [c]	% error	$^{207}Pb/^{206}Pb$ [c]
F-1	862.37	1.934	8794.32	0.088473	0.09	0.70963	0.19	536.26824
F-2	310.2	1.982	8725.23	0.088189	0.11	0.70997	0.23	544.361

ID	% error	Date $^{206}Pb/^{238}U$ [d]	Error (Ma)	date $^{207}Pb/^{235}U$ [d]	error (Ma)	Date $^{207}Pb/^{206}Pb$ [d]	Error (Ma)	corr. coeff.	com. Pb (pg)
F-1	2.93	546.5	0.45	0.71	0.19	0.06	0.13	0.789	4.37
F-2	3.59	544.82	0.56	0.71	0.23	0.06	0.16	0.733	1.57

a Th contents calculated from radiogenic 208Pb and the 207Pb/206Pb date of the sample, assuming concordance between U-Th and Pb systems.
b Measured ratio corrected for fractionation and spike contribution only.
c Measured ratios corrected for fractionation, tracer and blank.
d Isotopic dates calculated using the decay constants λ238 = 1.55125E-10 and λ235 = 9.8485E-10 (Jaffey et al. 1971).

Conclusions

The Stony Mountain gabbro intrudes the entire Albemarle arc. The body of gabbro dated in this study is intrusive into the Tillery Formation ca. 547-552 Ma (Pollock, 2007). Therefore, an age of ca. 545 Ma for the Stony Mountain gabbro is plausible in local context of Ridges Mountain. However, this age presents problems in the context of the Albemarle Group, as the Yadkin Formation, at the top of the group, is intruded by the gabbro (Stromquist and Henderson, 1985) and is younger than ca. 531 Ma (Hibbard et al., 2006).

There are at least two explanations for this apparent age discrepancy. It is possible that the zircons analyzed are inherited, although the highly positive ε_{Nd} values for the gabbro would argue against this explanation. If future dating of additional zircons from the Ridge's Mountain outcrop shows an absence of a younger population then it is likely that the ca. 545 Ma date represents the crystallization age.

If the ca. 545 Ma age represents the crystallization age, the apparent age discrepancy with the Yadkin Formation could also be explained by Stony Mountain magmatism being time-transgressive. In this case, sampling from other outcrops of Stony Mountain gabbro that are intrusive into younger units, such as the Floyd Church Formation should provide younger dates for the gabbro. These alternative explanations for the apparent age discrepancy of the Stony Mountain gabbro and the Albemarle Group are currently being investigated.

ACKNOWLEDGEMENTS

We thank Ryan Frazer for his advice and instruction on the methods of U-Pb dating of zircons.

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GPR ANALYSIS OF AN UWHARRIE RIVER TERRACE DEPOSIT, UWHARRIE NATIONAL FOREST, NORTH CAROLINA

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ABSTRACT

The Uwharrie River in Montgomery County, North Carolina flows approximately 200° toward its mouth at the Yadkin-Pee Dee River. The Yadkin–Pee Dee River system is a major drainage that transects NE-trending lithostratigraphic boundaries down to the Uwharrie River junction. At that point, the Uwharrie and Pee Dee Rivers turn parallel to major formation boundaries, apparently in response to resistant metavolcanic rocks in the Uwharrie Formation in the core of the Troy anticline. Throughout its course south of El Dorado, NC, the Uwharrie River is confined to a channel bound on the east by metavolcanics of the Uwharrie Formation and on the west by rhyolites in the younger Albemarle Sequence. Though structurally controlled longitudinally, the Uwharrie River has a marked sinuosity within the southern extent of its basin evidently because of bedrock fracture control. Terraces with sharp valley wall terminations are present on the convex margins of narrow, long, box-like meanders with subdued interior surface expression in the interstices between meander limbs.

This paper describes multi-frequency GPR investigations of one section of a terrace on the west side of the Uwharrie River. The site – Thousand Bell Bottoms or Thousand Bale Bottoms (TBB) – appears to have been used for agricultural purposes since European settlement. Archaic and Woodland artifacts have been recovered from the river valley here. Investigation of TBB has two imperatives. These are to assist archaeological assays of the site for the U.S. Forest Service, and to qualify the use of GPR methods as tools to evaluate the extent and geometry of terraces in the river valley. With regards to the TBB site, human activity – both historic and prehistoric – left evidence in only the upper 0.8 m of the subsurface. That evidence thus far is in the form of scattered Archaic and Woodland artifacts probably redistributed by plowing, radar reflections of probably fire rings in the upper 0.5 m of the subsurface, and rectilinear subsurface reflectors possibly related to late 18th century occupation and use of TBB. There is a persistent horizon of relatively higher amplitude reflections all across the site that is here interpreted to be the unconformity (or strath) between meta-sedimentary rocks in the Tillery Formation and fluvial sequences left by the Uwharrie River during meander migration and flooding. The strath sits between depths of 0.8 and 1.3 m and is generally horizontal. Particularly in 100 MHz profiles, there is a marked contrast in overall reflective character between the terrace materials and basement rocks. The strath was detected at both 400 and 100 MHz radar frequencies and was uncovered in a backhoe trench on the site. A well-defined surficial horizon about 0.2 m thick appears in all GPR profiles just below the ground wave, and is characterized by comparatively lower frequencies in the radar signal compared to the lower part of the terrace deposits. Much of

the middle section of the alluvium is poorly reflective, possibly because it is also poorly stratified, but several sections of inclined reflectors, possibly foreset or lateral accretion beds, were identified. In some profiles, swells through the unconformity reflection might indicate point bars within the terrace deposits.

INTRODUCTION

The lower Uwharrie River joins the Yadkin River in Montgomery County, NC, where they form the Pee Dee River. Between NC Highway 109 and the Pee Dee River the Uwharrie River flows to the southwest and is contained within several hairpin meanders (Fig. 1). The main path of the river follows the shared northwest-inclined limb between the

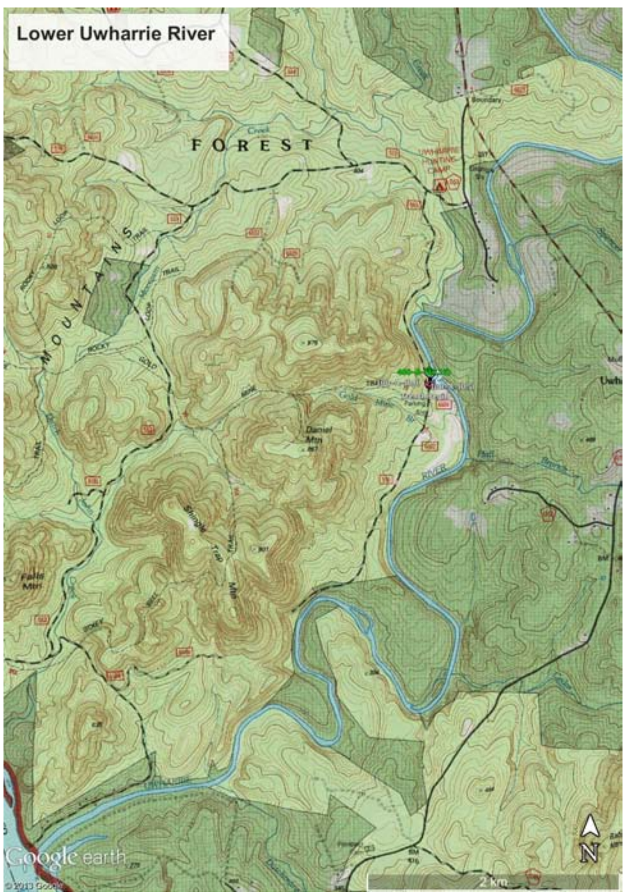

Figure 1. Lower Uwharrie River, Montgomery County, NC in USGS Badin 1:24,000 topographic quadrangle. Thousand Bell Bottoms site is off Forest Service Road 555 north of Goldmine Branch.

Troy anticlinorium to the east and the New London synclinorium to the west. Similarly, the upper Pee Dee River channel makes a 90° angle with the Yadkin River to become parallel to the trend of the Uwharrie River. The Uwharrie River channel is entrenched in laminated meta-siltstone in the Tillery Formation (Fig. 2), the lowest member of the Neo-

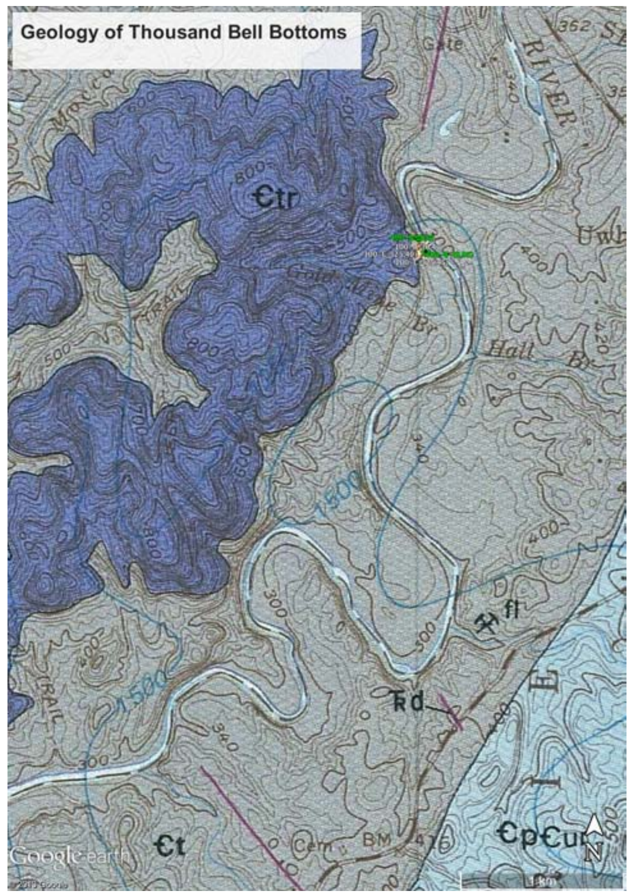

Figure 2. Geology of the lower Uwharrie River and TBB site. This is a section of Sheet 1, Stromquist and Henderson (1985). From older to younger: CpCu - Uwharrie Formation rhyolitic tuffs, Ct - Tillery Formation laminated siltstone, Ctr - rhyolitic rocks of the Tillery Formation. Most current usage renames Ctr to Cid Formation and places this and the Tillery Formation into the lower part of the Albemarle Group.

proterozoic Albemarle Group because erosionally resistant silicic metavolcanics rocks of the Cid Formation (to the west) and the Uwharrie Formation (to the east) occupy highlands on the shoulders of the river valley. The mean position of the river's path, however, is shifted against the lower contact of the Cid Formation with underlying Tillery Formation. It is possible that the regional dip of stratigraphy was responsible for the westward channel migration over time.

Even though the channel of the Uwharrie River is highly sinuous, the river has a narrow flood plain and the one or two terraces along the lower stretches of the river are narrow and moderately inclined toward channel levees that characteristically butt against sharp channel walls. Meander arms are rectilinear along 340°. Highland stream valleys on both sides of the Uwharrie River are similarly linear on the same trend. Geologic and geophysical maps of the area also show several Mesozoic diabase dikes throughout the Carolina terrane in this region (Stromquist and Henderson, 1985).

Given the morphology of the narrow Uwharrie River channel and presence of prominent bedrock lineaments, presumably fractures, and resistant dikes, it is reasonable to assume the sinuosity of the channel is structurally controlled. The river has not been in its present position long enough to mediate the influence of those bedrock structures.

There are, however, terraces on the interior margins of some of the larger meanders in the lower section of the Uwharrie River valley (Fig. 1). European settlers along the river utilized those relative lowlands, and there also are records of Early and Late Archaic period artifacts near the study area described in this report. Middle and Late Woodland artifacts also have been recovered along the west side of the lower Uwharrie River and from excavations conducted for the present paper. Historic records demonstrate that late 18th century homesteads were established in the area, and one of these was located not far from the southwestern corner of the TBB GPR project area (Fig. 3). The historic Cotton Place Road was a18th and 19th century trade route connecting the Salisbury, NC area to points south. Early 20th century maps show home sites along this road, which is approximated by the present Forest Road 555 (Fig. 1). This paper describes the results of a geophysical investigation on part of one of these terraces. The site is known as Thousand Bell Bottoms or Thousand Bale Bottoms (TBB) (Fig. 3). It sits on the west side of the Uwharrie River at the closest approach of the river channel to the base of the Cid Formation. Shallow ground penetrating radar (GPR) profiling is part of a US Forest Service geoarchaeological initiative to document historic and prehistoric human activities at TBB. Deep GPR profiling is used to establish the broad distribution of alluvium in the terrace, to characterize the unconformity between this alluvium and metamorphic bedrock, and to investigate the geophysical properties of bedrock and surficial deposits in the area. Shovel tests and a backhoe trench cut across the observation site (Fig. 4) allowed depth and velocity calibration of GPR data, detection of the plough and occupation zones, and recovery of prehistoric artifacts.

The TBB site lies on the northern tip of a much larger alluvial deposit (Fig. 1), so it does not necessarily show the maximal development of the feature necessarily. The objective of the study was to gather crucial physical data that will be used in further investigations of these and downstream terraces.

Figure 3. Thousand Bell Bottoms GPR survey locations. The Uwharrie River is to the east in the image. Survey 400-A boundaries and corner points are near the center of the image. The footprint of Survey 400-B is laid out by boundary lines, and an integrated Z map fills the footprint. The Z map shows radar features within the 2.2 m thick horizontal slice. Bright spots are stronger positive anomalies. The lines for Survey 100 sections are shown as white lines with waypoints every 5 m. Endpoints of a trench excavation are denoted with targets.

Figure 4. Completed backhoe trench at TBB. (A) The look direction is toward the southwest. Forest Road 555 is behind the trees in the distance. In the foreground, the floor of the trench is saprolite of Tillery Formation. Several round cobbles were recovered *in situ* from the trench floor here and mark the strath. (B) The look direction is toward the northeast. The soil/sediment is yellow-orange below a shallow brown-orange horizon that is inferred to be the near-surface, lower frequency horizon that occurs throughout TBB.

SETTING OF THOUSAND BELL BOTTOMS

K.W. Robinson of Wake Forest University described the cultural and archaeological setting of TBB in a report to the Uwharrie Ranger District, Uwharrie National Forest (Robinson, 2009). The report documented a segment of the historic Cotton Place Road passing through a strip of woods between Forest Road 555 and the up-dip limit of the alluvial terrace under TBB. The tread of Cotton Place Road is visible, and bricks are among surficial debris. No historic map, however, shows a home site at this location. Parcel, rural delivery, and soil maps from 1910, 1912, and 1930 do show a structure about 300 m south of the southwestern corner of the TBB GPR survey area just north of Gold Mine Branch. A 1938 aerial photograph of the area shows rectangular clearings in that area, and prominent furrow lines through TBB oriented at about 340°. It is reasonable to assume that the TBB GPR survey site has been used only for agriculture in historic time. Archaic and Woodland artifacts recovered from TBB and from sites to the south along Forest Road 555 are scattered and rare. Artifacts from the TBB surveys, based on GPR reflectors and excavations, are scattered throughout the plough zone and have probably been redistributed.

The alluvial terrace comprising TBB is essentially the abandoned flood plain of the Uwharrie River, with a moderate surface slope and a levee on its margin that prevents floodwater occupation of the terrace except for exceptionally high discharges in the river. Gold Mine Branch drains through Daniel Mountain and into the Uwharrie River crossing the central part of the TBB super terrace (Fig. 1). It is likely that sheet flow off the higher terrain to the west and possible overbank water flow from Gold Mine Branch inundate TBB during storms. Consequently, TBB is a relatively well-drained terrace/flood-plain to the Uwharrie River.

Setting GPR Methods and Procedures

GPR surveys were collected with a GSSI SIR 3000 system using either 400 MHz or 100 MHz antennas from the Tectonics and Applied Geophysics Lab at UNC Charlotte. The Uwharrie Ranger District, Uwharrie National Forest cut grass and shrubs to near ground level to prepare for the GPR surveys at TBB.

GPR Survey Locations

The GPR database for TBB is contained in three survey zones that were collected at three different times in 2012 and 2013. Ground moisture conditions, however, were approximately constant over the three survey periods. Each of the three GPR surveys used an internal coordinate system based on measuring tapes. Key corner point coordinates for each survey were recorded with a Trimble GeoXT 3000 GNSS receiver generally to positions better than ±1 m. Survey 400-A was collected in March 2012. It was a distance survey over an X=9 x Y=12 m grid in the south central region of TBB (Fig. 3). The X-axis orientation of 400-A was 330° and the Y-axis orientation was 240°. Survey 400-A contains a set of Y-profiles spaced at 0.5 m intervals, and a set of X-profiles spaced at 0.5 m.

Survey 400-B was collected in August 2012 as a distance survey with an X-axis orientation of 235° and Y-axis orientation of 145° (Fig. 3). This survey was conducted as a series of Y-profiles with a spacing of 0.5 m. Because of tree cover, several staggered X-axis baselines were established along the northern part of TBB (Fig. 3). The Y-axis baseline was 95 m long and approximately coincident with a dirt and gravel horse path along the eastern margin of TBB. Three X-profile cross-lines were collected at (0,80) to (44, 80), (0,45) to (29, 45), and (0, 15) to (21, 15) within the 400-B local grid.

Survey 100 comprises four 100 MHz time profiles: 100-A, 100-B, 100-C, and 100-D (Fig. 3). Profile 100-A became the reference Y-axis for survey 100 with an orientation of 072° and a length of 40 m. Survey 100-B originates at local coordinate (0, 5) and extends 25 m along 155°. Survey 100-C originates at (25, 5) in local coordinates and continues 40 m along a trend of 063°. Survey 100-D originates at (10, 10) and extends 25 m along 343°.

In addition to the three GPR surveys, two shallow shovel tests were dug within the survey 400-A site, and a backhoe trench ranging in depth between 0.5 m on the southwestern end and 1.7 m on the northeastern end was excavated. Test Pit 1 in survey 400-A is documented in text below. The trench was 30 m long along an azimuth of 050°.

Data Collection Attributes

Both 400 MHz distance surveys used the same initial collection settings. These were: 120.0 scans/s, 512 samples/scan, 16 bits/sample, 50 ns range, 3 point auto gain, and low/high cut filters of 800 MHz and 100 MHz. In the field, the profiles used a relative permittivity (dielectric constant) of 8.0 that is nominal for many Piedmont soil and saprolite conditions. During processing the dielectric was modified to 9.0. These distance surveys were run with the antenna suspended on a GSSI 623 cart with an integrated survey wheel.

The 100 MHz time profiles were collected with the following settings: 16.0 scans/s, 512 samples/scan, 16 bits/sample, 300.0 ns range, 3 point auto gain, and low/high cut filters of 300 MHz and 25 MHz. The antenna was dragged along pre-laid profile lines, and the operator every 5 m introduced distance marks so that the data could be distance normalized during processing.

GPR Data Processing Workflow

GPR data were processed in GSSI RADAN 7 software. The specific workflow used depended on the condition of target data and what objective was desired. Initially, the 400 MHz profiles were assembled in RADAN to produce a 3D file. As the data files did not have integrated GPS coordinates but did have uniform profile spacing, the sets of files for each 400 MHz survey were processed in batches and placed onto a predefined map. The endpoints of each profile line were then manually adjusted from field notes. The resulting 3D Grid file (.m3d) in RADAN can then be displayed and manipulated as a 3D block model. Surface displays in this paper were produced by simple interpolation within RADAN and thus some surfaces and maps have cross-hatching if orthogonal profile lines were collected, and some maps have stripes parallel to profile directions.

After population, RADAN created a native data file (.dzt) from the 3D Grid file that contains all profiles concatenated. In this form, the entire collection of data files can be manipulated or filtered in one process. All data files were first moved to time zero to eliminate white space in the upper parts of the records. This is accomplished by having RADAN automatically detect the first peak above a selected threshold in each scan, and then move that scan so that the peak identified occurs at zero on the vertical time/distance axis of a radargram. This brings the direct ground-coupled radar pulse to coincide with the actual ground surface (as long as the radar antenna remained in contact with that surface.)

In some profiles, horizontal banding from antenna ringing or multiple surface reflections were removed by full-pass averaging or applying a horizontal FIR filter, but many of the near-surface features at TBB are sub-horizontal, and horizontal filtering removes many of these subtle features. Consequently, in most of the images presented here background removal is very light or not used at all. Depending on the profile, additional processing by deconvolution or migration was used to recover desired features.

As the 100 MHz profiles were collected in time mode, before applying any of the other processes these data were normalized to distance by determining the average numbers of scans between user entered distance marks in the records. RADAN then stretched or stacked each profile so that there are a uniform number of scans per meter. The 100 MHz profiles were not collected with a density sufficient to produce a grid map.

Velocity Determination

Radar velocity is a function of electrical properties of media in the wave path and is thus correlated with the dielectric constant. Velocity also controls two-way travel times of reflected energy and thus the dielectric constant chosen for interpretation of a GPR profile influences the inferred depth of a reflective target. The dielectric constant is most reliably determined by measuring the true depth to a buried object. Then the profile's dielectric constant is adjusted until an accurate depth is displayed in the radargram.

In test pits, we found that depth to targets (roots and stones primarily) agreed with depth to hyperbola crests to ±10% for dielectric constants between 8 and 9. Local velocities estimated by Kirchoff migration of well-formed hyperbolae in sections of survey 400-B produced dielectric constants between about 8 and 11 (Fig. 5). When the entire section was

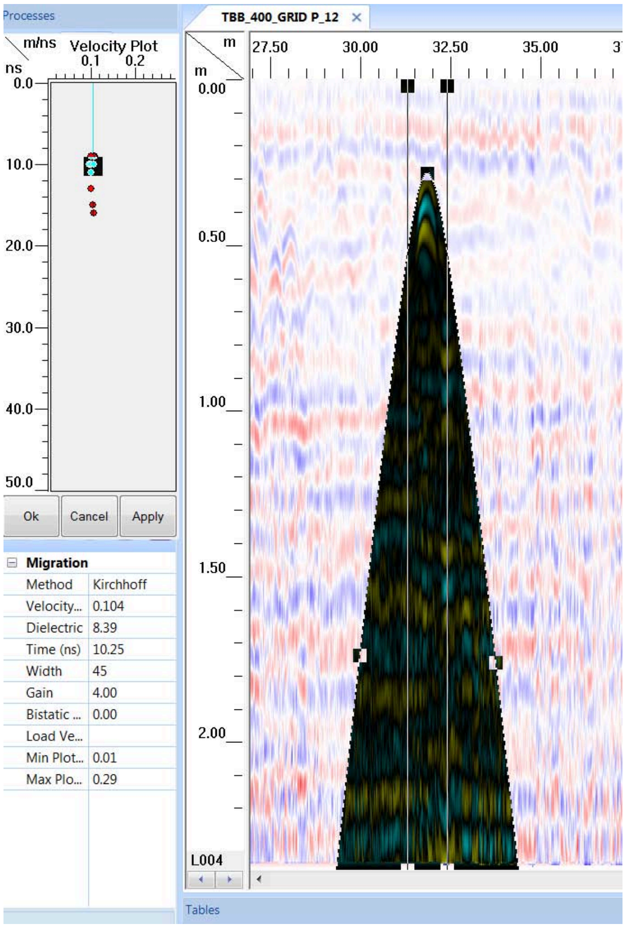

Figure 5. Velocity determination in RADAN 7 from hyperbola. The ghost hyperbola is shaped to match a hyperbolic reflection, in this case one created by a root. The velocity-time plot shows several matches from different depths in the profile. The selected hyperbola produced a dielectric constant of 8.39 and a velocity of 0.104 m/ns. The range of velocities over TBB, however, suggested a dielectric of 9.0, which was used to produce results in this paper.

migrated using these values, however, gently inclined reflective surfaces were marginally improved and many targets were obscured. Migration with much lower dielectric constant values (higher velocities) defocussed the profiles too much. A dielectric constant of 9 is used for depth estimates in profiles in this paper.

Figure 6 is a derivative soils map of the TBB area from the U.S.D.A. Natural Resources Conservation Service Web Soil Survey (Web Soil Survey, 2013). All of the TBB GPR sites are underlain by Shellbluff silt loam. Some of the physical properties of the upper 0.15 m of this soil could cause it to appear as a separate (or possibly gradational) horizon in GPR profiles. Generally, the upper soil layer contains more organic matter, silt and sand than lower layers in Shellbluff soils and can have a potentially lower moist bulk density. The upper part of Shellbluff soils may also have a low plasticity index. These features affect radar velocities. As described below, TBB is underlain by a distinct velocity horizon throughout the TBB area, and soil type among other factors may be responsible for this relationship.

Topography of TBB

There is an approximate 0.5 m drop in elevation from the upslope end of survey 100-A to the horse path to the northeast. The ground slope is non-linear and steeper to the west. Topographic contours at TBB are essentially parallel to the Y-axis of survey 400-B. As ground slopes are small, GPR profiles in this paper have not been reduced to an absolute elevation datum; distances below time and depth origins in the profiles are therefore relative to the local ground elevation. Depths to point reflectors are accurate (although dependent on selection of relative permittivity), but the inclinations of possible reflective surfaces may be slightly distorted.

None of the GPR surveys crossed the boundary between terrace deposits and bedrock at the land surface. That boundary appears to lie under trees between the western margin of the Survey 400-B and Forest Service Road 555. Both 400 and 100 MHz profiles show at least 1 m of sediment at the western margin of 400-B.

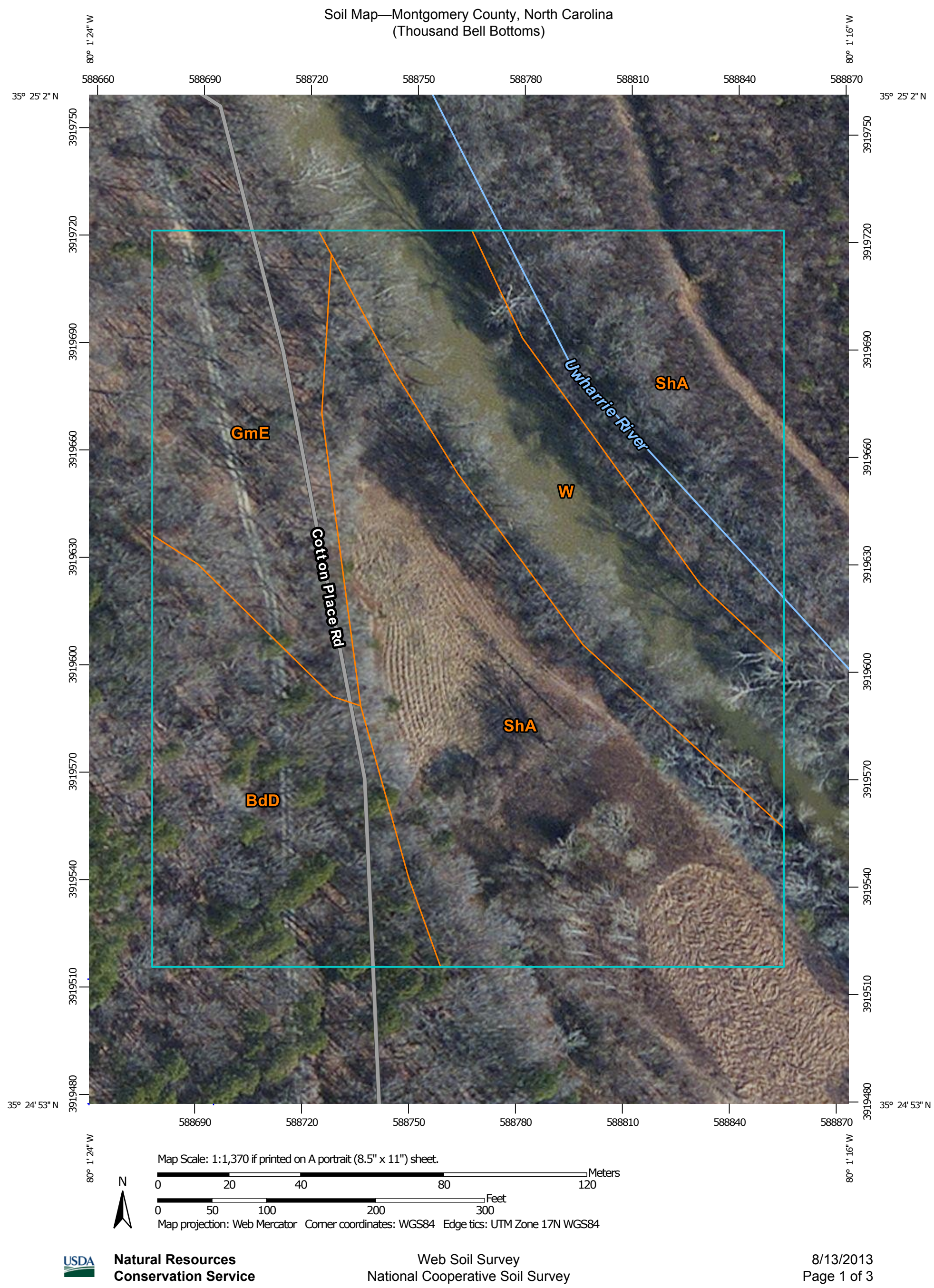

Figure 6. Soils map for TBB. ShA - Shellbluff silt loam, 0 to 2 percent slopes, occasionally flooded; BdD - Badin-Tarrus complex, 15 to 25 percent slopes; GmE - Georgeville silt loam, 15 to 45 percent slopes, extremely bouldery.

Discussion

Survey 400-A

Figure 7 is a summary Z map for the Survey 400-A area with a section thickness of 2.0 m and Z position of 1.0 m. In effect, this map is an integrated nearly full section reflection map of the survey area. A mild median filter has been applied to the map because the very rough ground surface and cross-hatching from gridding originally produced significant clutter. Depths reported here are for a dielectric constant of 9.

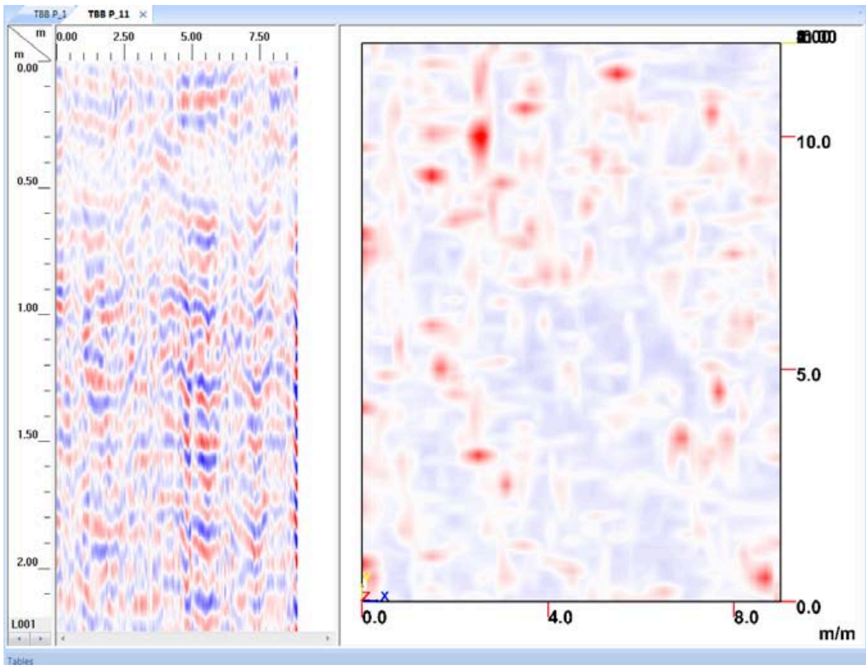

Figure 7. Z map and example profile of Survey 400-A. The map is a full volume display, so it shows most of the stronger reflections in the area. Red colors are high amplitude positive reflections. The left image is an X-profile that runs along the X-axis of the map. The profile has minimally processed. Vertical swaths of weak reflections are most likely the result of the antenna's decoupling as it bounced over very rough ground.

Clusters of point reflections in the upper left quadrant characterize the map and what appear to be crudely linearly aligned points are found elsewhere except in the center part of the map area. Many of the reflections are artifacts from jogs in the survey cart passing over clumps of vegetation, but some are also traceable as roots and a few appear to be isolated point reflectors, most likely cobble-sized rock fragments.

Figure 8 is a profile (map grid line L011) along Y=5 m that shows a well-defined hyperbola associated with a strong map anomaly at a depth of Z=0.5 m. This anomaly does not appear to continue laterally at other depths. It is likely a cobble-sized rock based on similar objects found in test pits, trenches, and on the surface at TBB. It is also of the size, shape, and depth to be a cultural artifact. The radargram in Figure 9 (L020 along Y=9.5 m) includes a group of three hyperbolae that match moderate point reflections on the map at Z=0.8 m. One of these reflections may be a root, and the other two cobbles.

An excavation at Test Pit 1 (Fig. 10) uncovered a number of rhyolite flakes and one Randolph projectile from 1700-1800 AD (Fig. 11). These materials were recovered from depths less than 0.6 m. The pit also revealed a sizeable root (many meters from any living

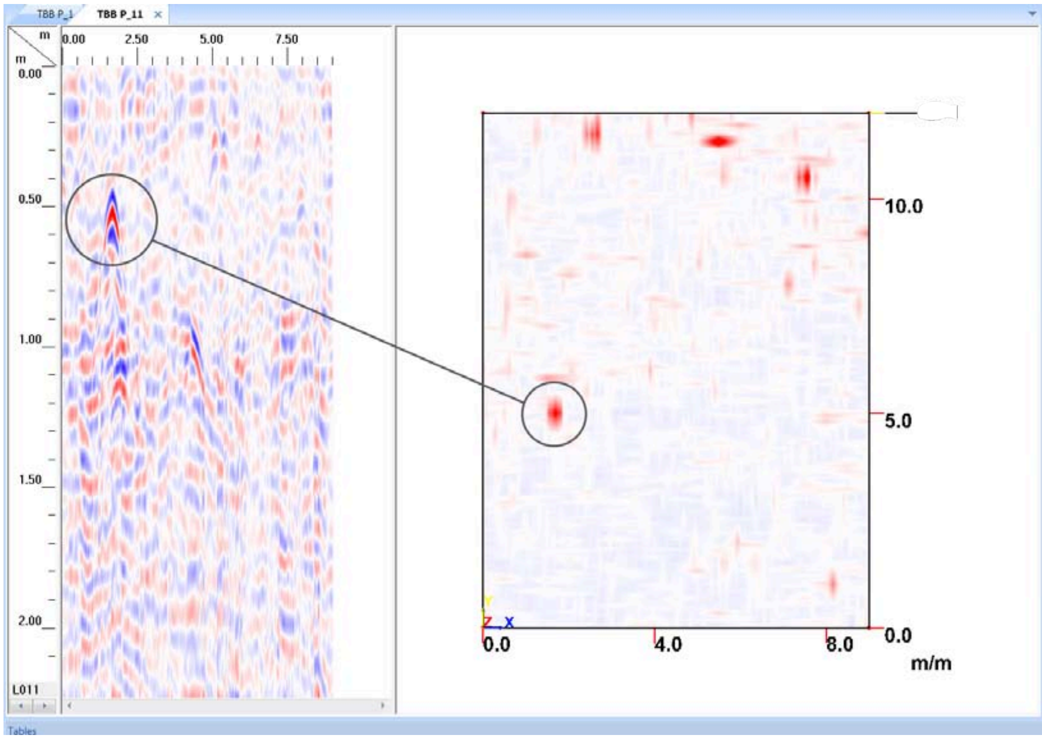

Figure 8. Point anomaly in Survey 400-A. The radar map is a horizontal slice at depth Z=0.5 m, and the profile is line L011, a profile along Y=5 m. Note the higher amplitude horizon around Z-1.0 m. This is the inferred strath at the base of the terrace deposits at TBB.

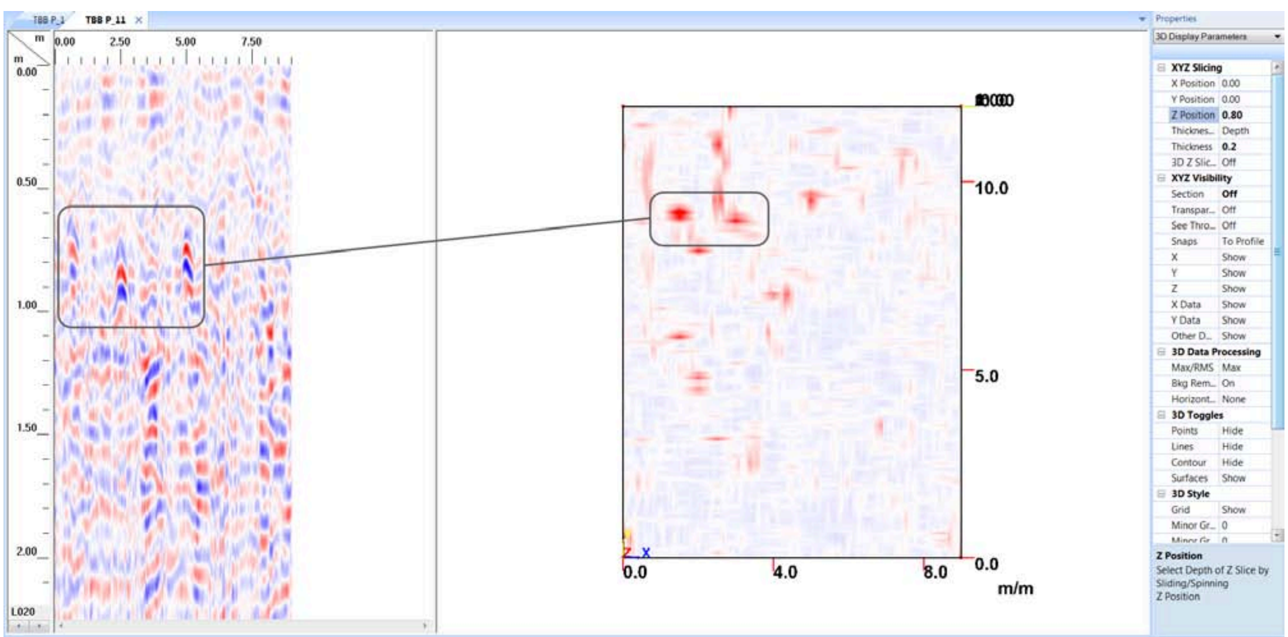

Figure 9. Survey 400-A map at Z=0.8 m and profile along Y=9.5 m. Three hyperbolic reflections are distinctive in the map section.

Figure 10. Root nub and stone artifact in Test Pit 1, Survey 400-A. The pit is 0.6 m deep.

tree) and an elongate, rounded stone (Fig. 10). Mixed Late Archaic points (3000-1000 B.C.) came from a trench excavation south of Survey 400-A in TBB.

Although rough ground prevented a clean rendition of the GPR profile for survey 400-A, there are some notable characteristics of the site. First, all hyperbolic reflections are above about Z=1.0 m. Some of these reflections are demonstrably root profiles, but as noted there are also other targets besides roots. The trench also demonstrated that 1 m is about the maximum depth of roots and artifacts.

Also, there is a weak but traceable horizon of stronger amplitude reflections about 0.5 m thick that underlies the entire area of survey 400-A (Fig. 12). The top and bottom of this horizon are very irregular. In some Y profiles the horizon appears to be gently inclined to the east toward the Uwharrie River. The base of the horizon is variable in detail but generally is at a depth of 1.3 m under 400-A. Similarly, the top of the horizon ranges in depth between 0.8 m and 1.0 m. The base of this reflective horizon is interpreted to approximate the alluvium-bedrock contact in survey 400-A. The depth range is consistent with that contact located in a backhoe trench south of 400-A. Finally, most GPR profiles in survey

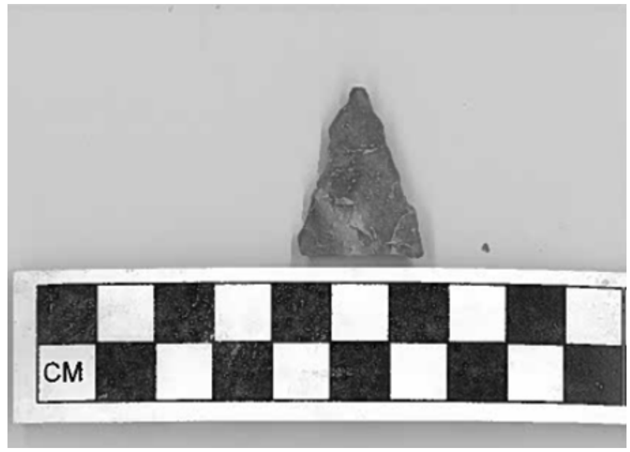

Figure 11. Late Woodland point from Test Pit 1, Survey 400-A.

400-A show a persistent, slightly lower frequency surficial layer about 0.2 m thick. This layer is the most recently disturbed tilled zone on the site, and it correlates with a darker organic soil layer viewed in the trench and test pits. Between the surficial and basal horizons, profile amplitudes are somewhat dampened. This is suggestive of a homogeneous, clay-bearing soil or sediment. The alluvial sequence in the TBB terrace extends across the entirety of survey 400-A, and has a basal depth of about 1.3 m inclined gently toward the Uwharrie River. Pending further post-processing or additional field surveys in point mode to reduce noise, it appears that the terrace deposits have little internal and detectable radar stratigraphy.

Survey 400-B

Survey 400-B covered a much larger area than 400-A, including most of the TBB surface (Fig. 13). 400-B is a series of Y profiles with only a few X profiles for cross checking positions. Most of the GPR characteristics of survey 400-A are of course also in 400-B, but because the area of 400-B is so much larger, certain patterns emerge that were not visible in 400-A. For example, Figure 13 is a map derived from Z thickness=0.2 m and Z position=0.1 m. It is essentially a radar map of the upper 0.2 m of the subsurface. In this map, furrows from tilling and cutting are clearly

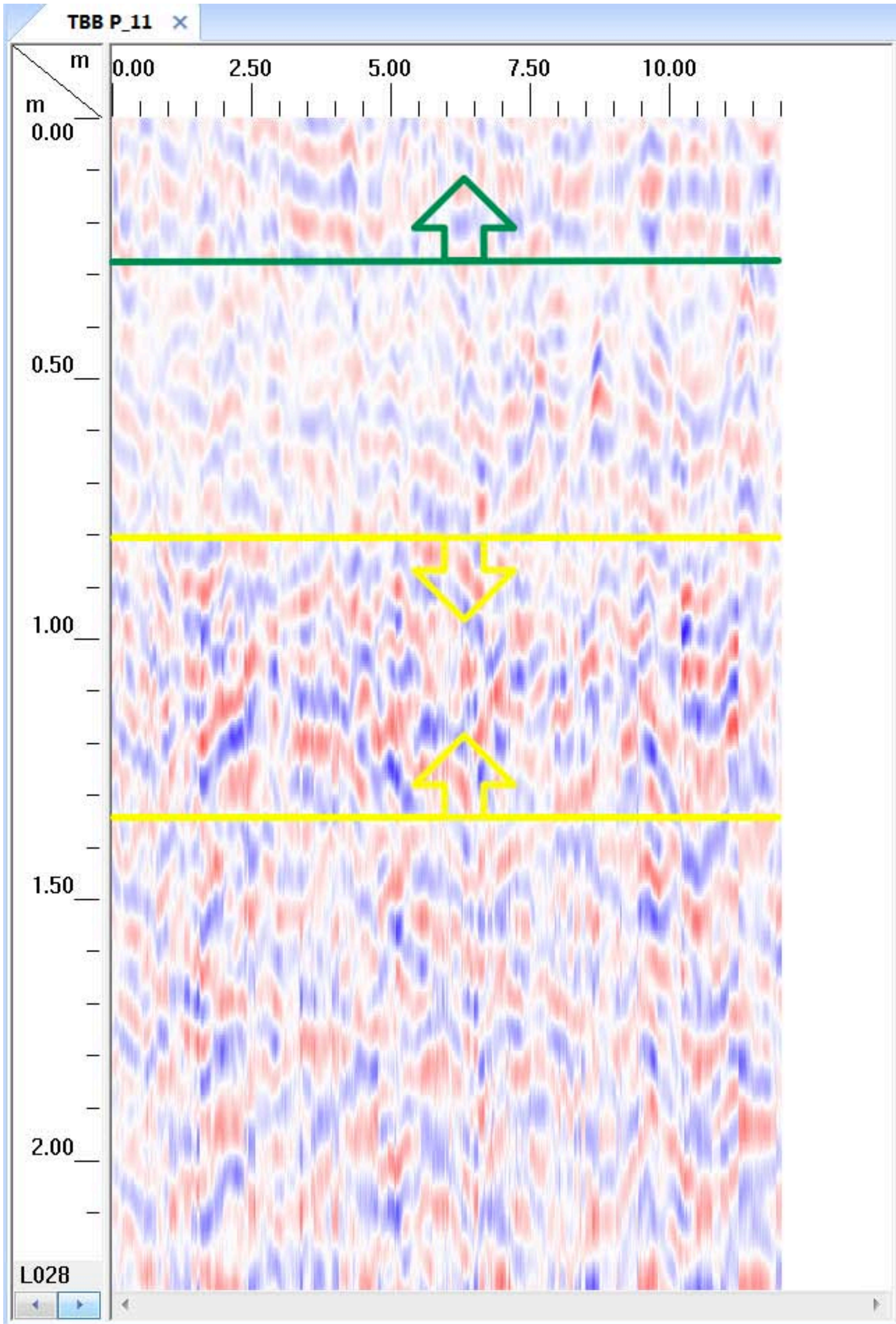

Figure 12. Higher amplitude horizon at about Z=1.0 m, Survey 400-A. The set of irregular reflections between the two horizontal lines are brighter in amplitude than adjacent horizons. The bright horizon is inferred to be the radar expression of the strath between TBB terrace alluvium and underlying bedrock. Also note the lower frequency near-surface zone down to about 0.2 m. This upper horizon is organic loamy soil, possible flood plain deposits, and includes the plough zone at TBB.

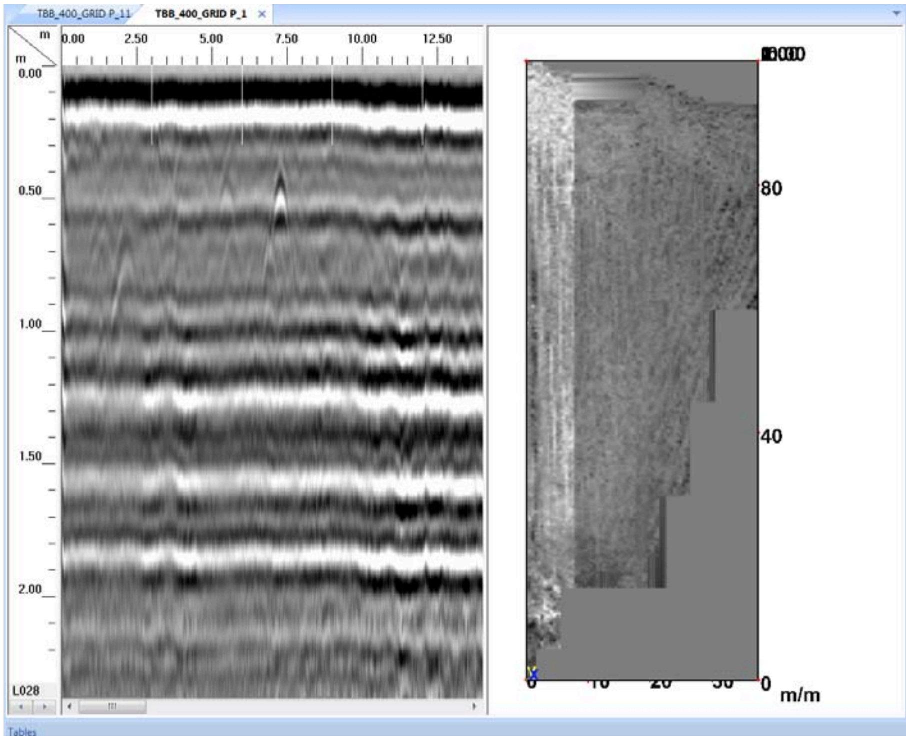

Figure 13. Furrows in TBB, Survey 400-B, and unprocessed profile from center of survey site. The Z map on the right represents the upper 0.2 m of the subsurface. North oriented toward top of image. Other than setting time zero, these data have not been processed. Performing any kind of background removal on the entire set of data obliterates the furrow pattern and any other very shallow cultural details. The bright vertical stripe at the left of the map is made of strong reflections from a bare horse path and just right of the path a zone of bright diffractions off the road material. Clusters of bright spots along the path are mainly rocks and cobbles. The profile on the left shows a well-defined ground wave at the top of the section, horizontal banding from instrument noise and ringing, and at least one root reflection at about 7.5 m on the X axis and a shallow depth of about 0.4 m.

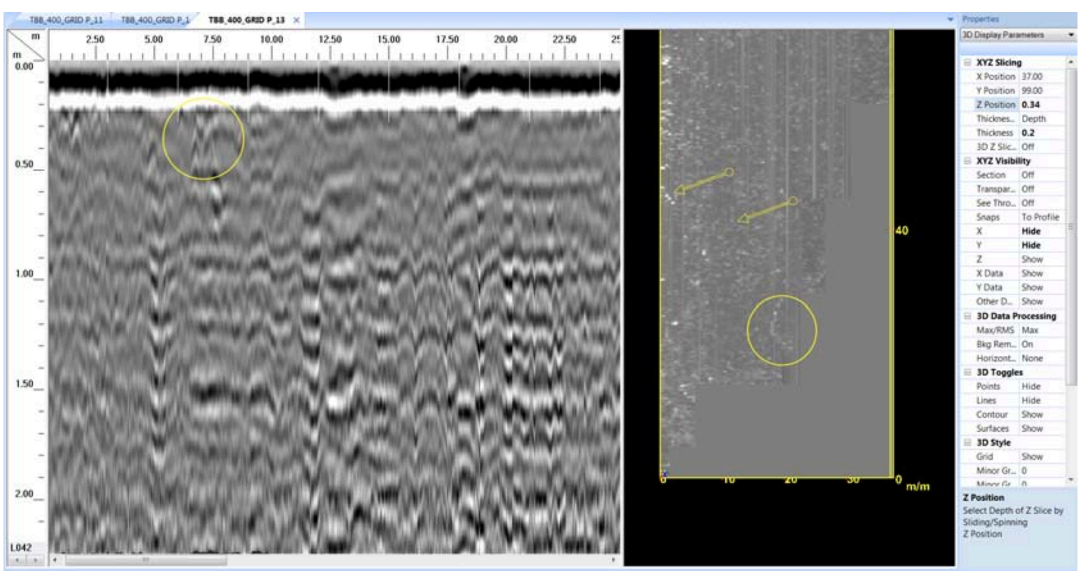

Figure 14. Enlargement of Survey 400-B Z map and a GPR profile crossing root paths. Characteristically root paths are linear and fairly straight (arrows in right figure), but they may also be curved (circle on map). The profile on the left crosses the curved root marked on the map, and shows within the circle how shallow this root is.

visible. The data in Figure 13 have been processed only to move the scan tops to time zero. Strong horizontal banding is still present in the profiles (L028, Y-profile at X=12 m) because no background removal has been applied. Applying an FIR background removal filter to this entire profile would remove furrows and other very shallow features, most of them cultural, while reducing the ground-coupled wave. Any filters applied to 400-B data were therefore limited to scans below 100 samples to retain these fine features.

The dirt and gravel horse path shows up well in this map, as does apparent fill beneath the road in a couple of places. There are also diffractions in profiles close to the edge of the road. The furrow patterns are consistent with historic aerial photos of TBB. As these data have not been heavily gridded, there are also interpolation artifacts in the map running parallel to the Y-axis. A number of roots and root systems are visible in the shallow radar sections (Fig. 14). These are evident as semi-continuous trails of bright spots in the Z maps. Some traces interpreted as roots extend for more than 10 m. Roots are mostly confined to the upper 0.5 m of the sub-surface, although a few reflections occur at depths near 1 m.

There are a number of circular patterns in the Z maps. None of these features were obvious at the surface during the GPR surveys, nor have they been excavated. Certain parts of the 400-B survey area are hummocky with convex upward bumps. These features are the radar expression of the stumps of grasses and shrubs for the most part. More intriguing are perfectly circular rings that have bright, reflective rims and depressed, lesser reflective centers(Fig. 15). These features in places occur on the crests of mound-like swells in the radar stratigraphy (Fig. 15). The largest of these features is about 3 m in diameter. Similar, smaller circular features are in the Z maps.

The tops of several of the circular objects are around 0.5 m depth. TBB has been a popular recreation site for decades. There is currently a large fire ring made from local rocks on the site just south of the 400-B survey area. It is possible that many of the concave, circular features in the radar profiles are fire rings. Without excavating the features it is difficult to assess the ages of these objects. Radar patterns for most of them do not show highly reflective collections of hyperbolae such as one would expect from a cluster of stones. Instead, they form bright swells in lateral reflective surfaces and may also be associated with reflective gaps.

More compelling is a large nearly complete ring about 7 m in diameter; this feature is in the northeast corner of the 400-B survey and by projection is under the horse path. The entire structure seems to be buried. In profile, the rim of the feature is characterized by bright swells and, like the smaller circular objects, has a non-reflective core (Fig. 16). The rim of the feature first appears at a depth of Z=0.4 m (with a Z slice thickness of 0.25 m), and is not visible below 0.7 m. At the latter depth, however, a rectangular, highly reflective structure appears in the Z maps (Fig. 16). The rectangular feature is not present below Z=1.0 m. Both of these structures are near a topographic valley over which the horse path passes and where the GPR records indicate a large amount of fill material may have been brought in to fill that depression. The western arc of the circular feature appears to have a gap in it. These two features are certainly cultural and given their proximities to each other and to fill beneath the horse path they may be related to historic construction in TBB. Robinson (2009) noted that there may have been a ford over the Uwharrie River near here, but that site is farther south near where Gold Mine Branch enters the river.

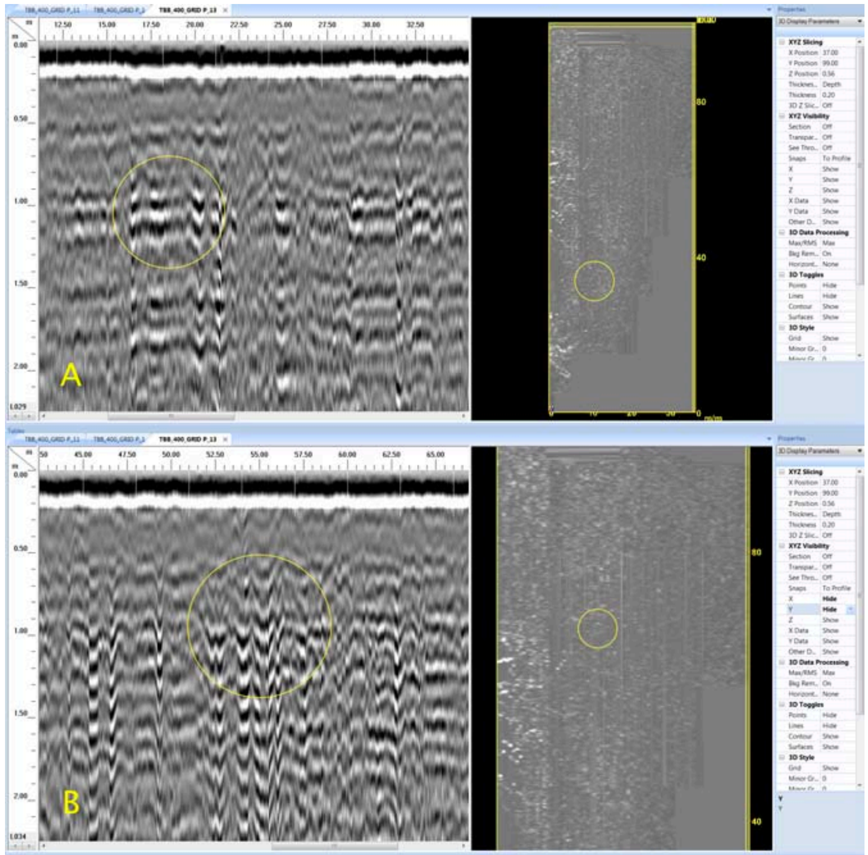

Figure 15. Two examples of shallow circular reflections from Survey 400-B. These and other similar features share characteristics. They are very nearly perfectly circular and expressed as bright rims (marked by yellow circles in the map views). The Z slices in each of these maps are 0.2 m thick and the slice is stationed at depths of 0.56 m, so these are fairly shallow but possibly just below the plough zone. In profiles, the features appear as raised bands of high amplitude reflections with a slightly lower core. In A, the circular reflection actually rests on the crest of a broader upward swell. The broader swell has a width of a few meters. It is not as obvious in B that the reflection is on a broader dome, but that feature is visible when a longer section of the profile is visible.

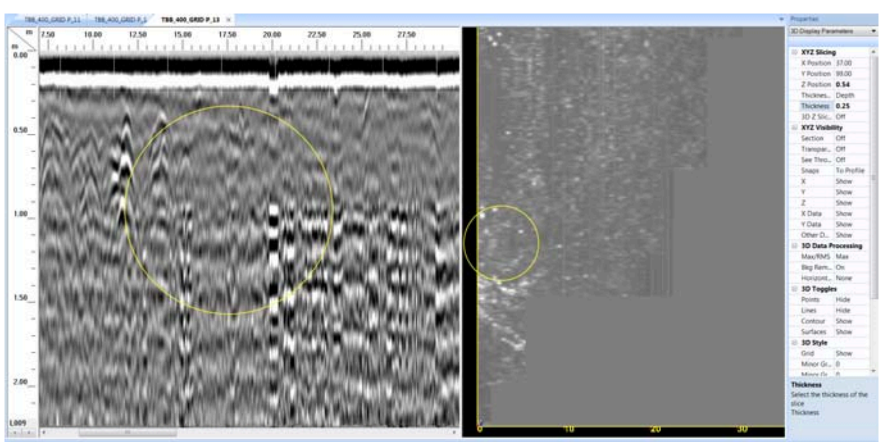

Figure 16. Large circular reflection (circles in yellow in the map view) and rectangular structure just south of the circular reflection in northeastern corner of Survey 400-B, TBB.

Like 400-A, scan tops in survey 400-B are occupied by a laterally continuous, lower frequency horizon created by an upper, organic loamy sand and an underlying brown sandy loam. This horizon incorporates the occupation zone, plough zone, and surficial alluvial component including relatively recent flood plain deposits. Immediately beneath the surficial horizon, there is horizontal band of weak reflections that increase in amplitude downward to about 0.8 m depth. It is possible that the weak reflection zone indicates increased moisture content across a soil or sediment boundary. A similar but discontinuous weak zone also is located around the 0.8 m depth, below which the highly variable higher amplitude horizon described in 400-A appears.

Figure 17 is a radargram along X=16.0 m in the local 400-B coordinate reference frame. (Note that the horizontal distances on the radar profiles in this and other figures are relative to the grid line displayed. In this example, it is RADAN grid line L036. Depths, however, are consistent as a common dielectric constant for the entire survey area.) These data have additionally been processed by deconvolution to sharpen higher amplitude reflections and to remove possible multiple reflections. The inferred unconformity at the base of alluvium is at a depth of about 1.0 m. In places it shallows to a depth of 0.8 m.

Figure 18 shows that the unconformity may not be a simple plane everywhere. A swell (survey coordinates (16.0, 56.0)) with relief of about 0.5 m rises to about Z=0.7 m. Reflections on one flank of the structure suggest the unconformity may be draped over the rise. This structure could be interpreted as a basement topographic high pre-dating deposition. It could also be a point bar in the lower part of the terrace deposits.

The alluvium locally has some detectable internal structure (Fig. 19; line L047, profile along X=21.5 m). Here reflections are inclined gently to the south, probably denoting foreset or lateral accretion bedding in a bar. The reflector we have identified as the base of the alluvial sequence in survey 400-B does not appear to become shallower than 0.8 m. This suggests that the termination of the deposits lies somewhere under the strip of woodland separating TBB fields from bedrock outcrops on Forest Road 555, or that the reflector is tracking some other feature. It is not a water level.

Survey 100

Four 100 MHz profiles were collected at TBB (Fig. 20). Processing was designed to maximize and detect the alluvial package. Processing steps applied to these lines were: (1) distance normalization, (2) background removal with an FIR filter, (3) deconvolution, and (4) range gain. Although the time window for recording allowed for two way travel times of 300 ns (12.7 m at a dielectric constant of 9.0), the effective depths of these surveys was less than 7.5 m. Figure 20 displays the processed profiles.

Lines 100-A and 100-C (Fig. 20) were oriented southwest to northeast and thus traversed the terrace across its width. The other two lines ran parallel to the length of TBB. The results of these surveys are consistent with those of the 400 MHz surveys. Processing in RADAN sharply identified the stratified terrace deposits as somewhat higher frequency sub-horizontal reflections compared to lower frequency more irregular reflections within the basement (Fig. 20).

Depths to boundaries in these lines is measured normal to the ground as no surface normalization is applied. In Line 100-A, depth to the strath at the upper end of the profile is 1.1 m, and depth at the lower end is about 1.3 m. In Line 100-C, those depths are 1.2 m and 1.3 m. For Line 100-B, which crosses both 100-A and 100-C, the depth at 100-A is 1.2 m and at the southern end of the line it is also 1.2 m.

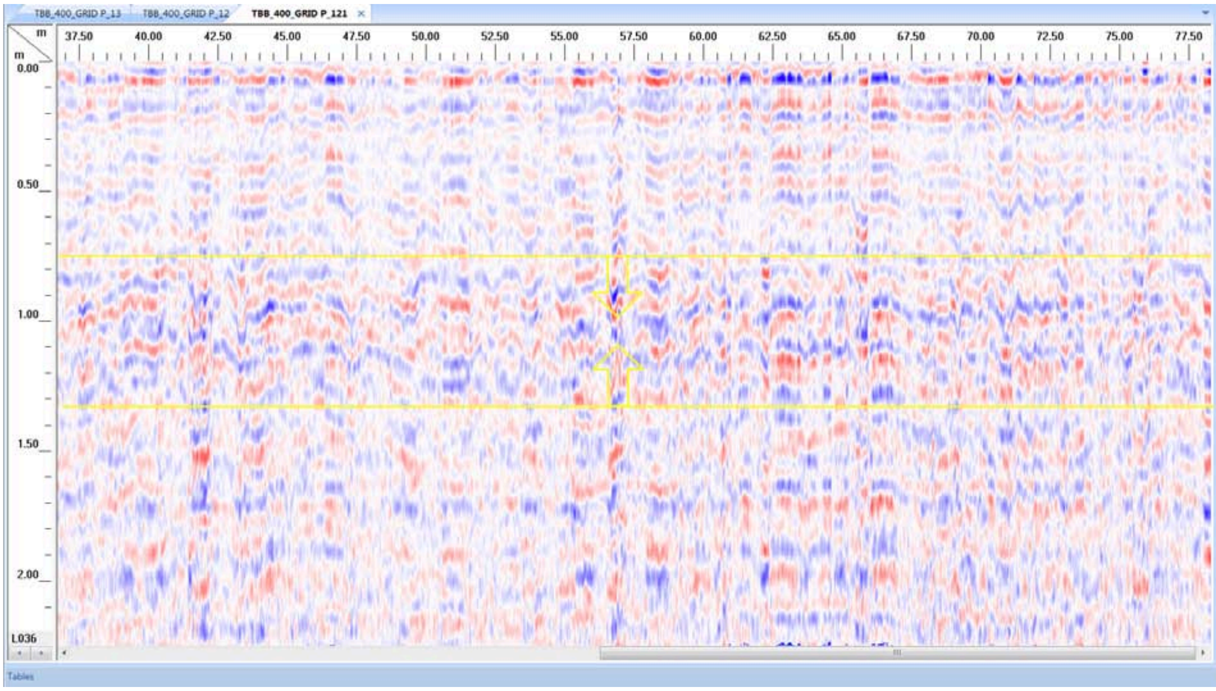

Figure 17. Profile from Survey 400-B with strath reflection. This profile from 400-B was processed by deconvolution to enhance the unconformity reflection and to remove some horizontal banding. The yellow lines and arrows enclose the unconformity package.

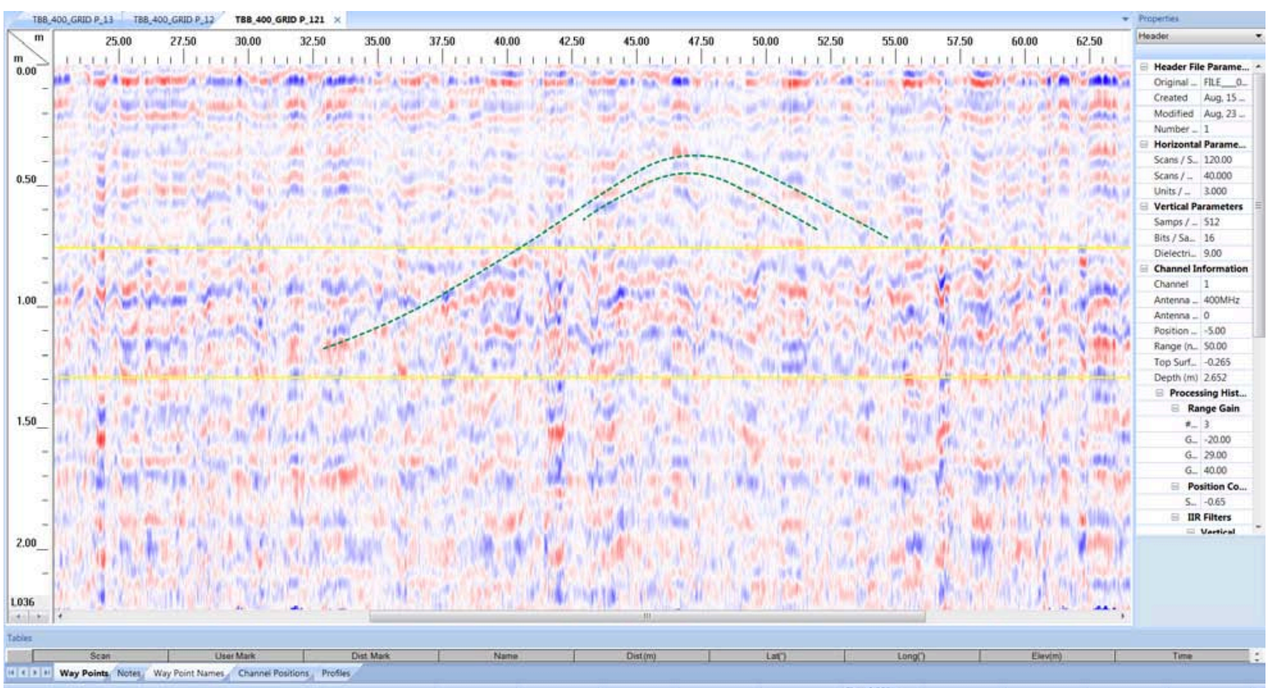

Figure 18. Domal reflections above and across strath reflection in Survey 400-B.

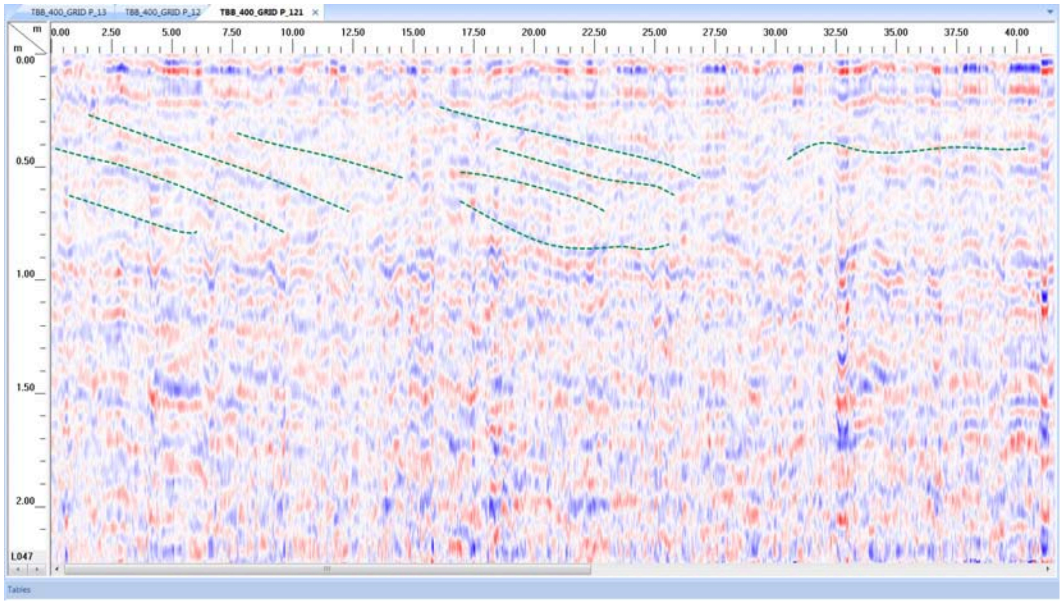

Figure 19. Inclined reflections within alluvial deposits, Survey 400-B. The inclined reflectors appear to terminate against the unconformity and the near-surface horizon. The profile is aligned N to S (left to right) and the inclined surfaces dip to the S.

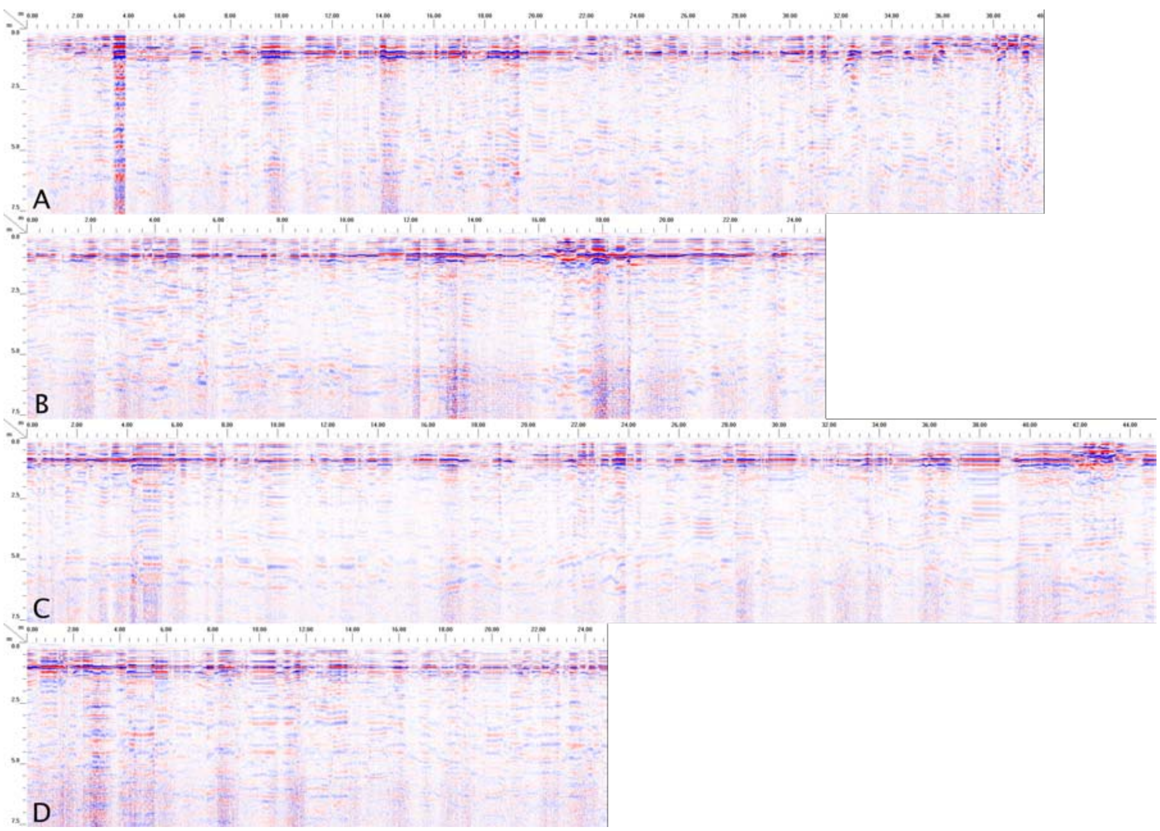

Figure 20. TBB Profiles from Survey 100. These profiles all received the same processing workflow. Because the profiles were collected in time mode, and because the rates of travel varied widely among profiles, the present horizontal scales do not agree, They have not been co-normalized. (A) Profile 100-A. (B) Profile 100-B. (C) Profile 100-C. (D) Profile 100-D.

For Line 100-D, which extends north from 100-A, the depth is 1.2 m at 100-A and 1.3 m at the end of the line. These depth and thickness ranges are consistent with the terrace deposits thickening slightly toward the Uwharrie River and toward the next terrace to the south.

There are a few notable features along these four profiles. 32.5 m from the beginning of 100-A, a well-formed hyperbola is present at a nominal depth of 1.3 m. That places the reflecting object right at the unconformity. There is a low velocity band in the profile immediately under the hyperbola. This pattern often denotes a void. If the object is enclosed by alluvium, it could be, for example, the remains of a tree. On the other hand, this pattern may be a fortuitous coincidence of the hyperbola in a section along the profile where the antenna became decoupled briefly during the survey. During excavation of a trench about 15 m south of here, a cluster of cobbles was recovered from the unconformity surface. It is possible that those deposits represent lag gravels on the strath surface at the base of the alluvium and that the reflections in 100-A are from similar deposits. Line 100-B crossed the closed trench at profile distance 18 m (Fig. 20).

SUMMARY

For the TBB area, low- and high-frequency GPR surveys proved useful because (a) the strath at the base of the terrace deposits falls within the effective range of a 400 MHz antenna, and (b) internal radar characteristics within terrace deposits and within bedrock are sufficiently different that the contact is clearly evident. The alluvial sequence is a flat sheet within the survey area. Thus far, cultural artifacts seem limited to less than 1 m depth. There are a large number of radar reflections of possible human origin in TBB, and many merit investigation by excavation because they are relatively shallow. To resolve fine details in geology or archaeology with GPR surveying at TBB it will be necessary to groom the ground surface to be much smoother and /or to conduct point surveys across critical areas.

ACKNOWLEDGMENTS

The Uwharrie Ranger District, Uwharrie /Croatan National Forests provided logistic and financial support for this research including clear-cutting TBB and the backhoe for trenching. Students in the Spring, 2012 Applied Geophysics class at UNC Charlotte participated in collecting GPR data for Survey 400-A. The authors gratefully acknowledge all assistance and support.

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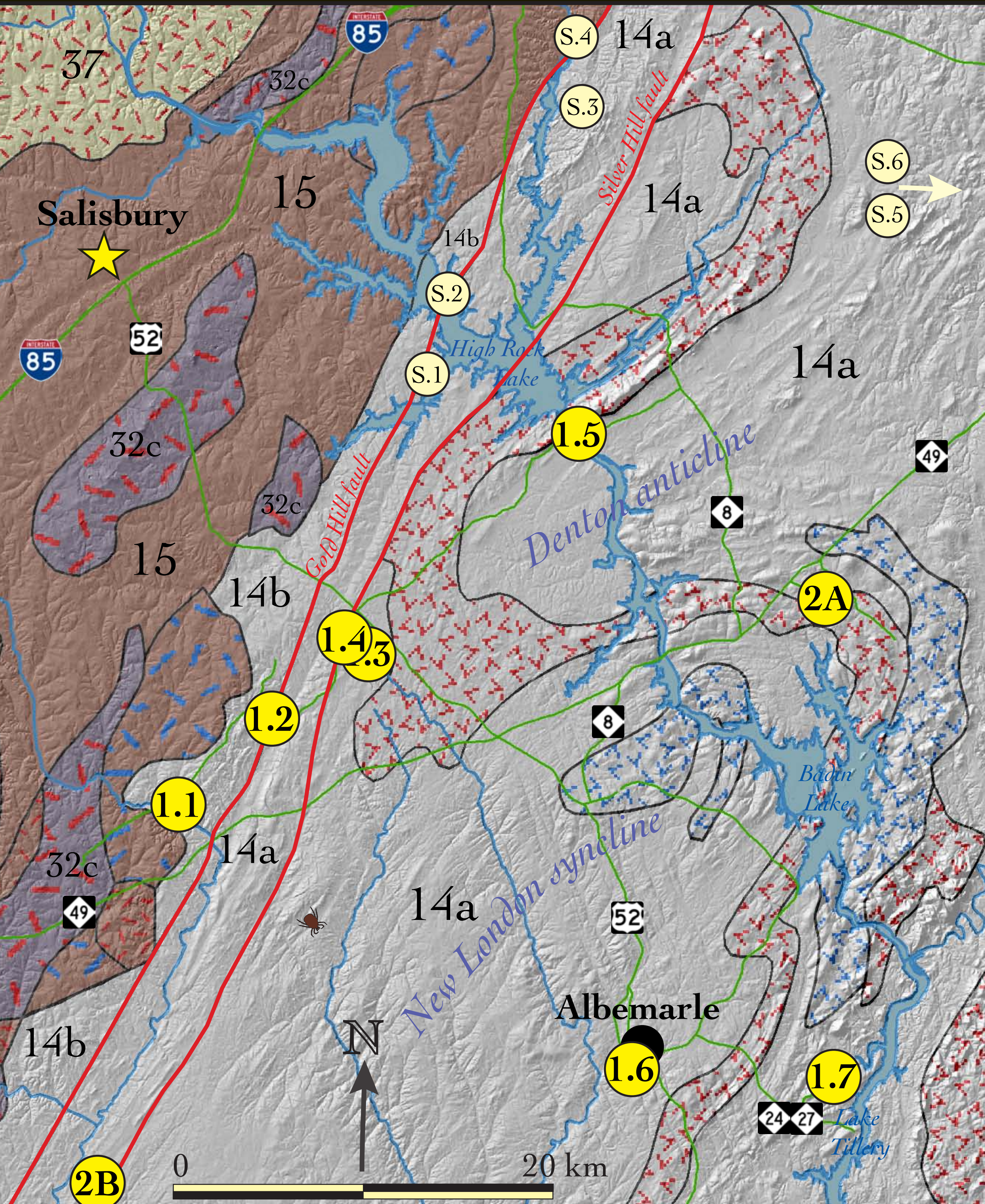

2013 CAROLINA GEOLOGICAL SOCIETY FIELD STOP MAP

37	**Carboniferous to Permian plutonic rocks**
32c	**CONCORD-SALISBURY INTRUSIVE SUITES:** Late Silurian to Early Devonian plutonic rocks confined to Carolinia
15	**CHARLOTTE TERRANE:** unseparated metavolcanic and intrusive rocks: Neoproterozoic to Cambrian
14	**CAROLINA TERRANE:** 14a. Younger magmatic arc: Neoproterozoic to Cambrian 14b. Older magmatic arc: Neoproterozoic

Volcanic rocks (felsic/interm.-mafic)

Intrusive rocks (felsic/interm.-mafic)

1.1 Trip stop

S.1 Supplemental stop