



The Geology of the Carolina Terrane in Chatham County, North Carolina

Results of New Geologic Mapping by the NC Geological Survey

Philip J. Bradley, NC Geological Survey



Carolina Geological Society
Annual Meeting
October 27-29, 2023
Chatham County, North Carolina



Carolina Geological Society

2023 Board of Directors

President

Craig Kennedy
Applied Science and Engineering
Jacksonville, FL

Vice President

Jeff Chaumba
UNC – Pembroke
Pembroke, NC

Secretary

Ruth Tull
Mid-Atlantic Associates
Raleigh, NC
carolinageologicalsociety@gmail.com

Treasurer

Cheryl Waters-Tormey
Western Carolina University – Cullowhee

Past President

Heather Hanna
NC Geological Survey
Raleigh, NC

Board Member

Kenneth Taylor
NC Geological Survey
Raleigh, NC

2023 CGS Field Trip Committee

Heather Hanna, Cheryl Waters-Tormey, Craig Kennedy, Ken Gillon, Ruth Tull, Diane Willis, Paula LaPoint, Mark Durway, Jim Chapman and Chris Capps

ON THE COVER

Outcrop of conglomerate in the Aaron Formation with Emily Michael (NCGS 2021-2023) –

Stop 6.

IN MEMORIAM



Aaron Kevin Rice
1981 – 2021

Aaron K. Rice was a significant contributor to the geologic mapping in Chatham County. He was the primary author for the Goldston geologic map and contributing author to five additional geologic maps in Chatham County including:

- Rice, A.K.**, Bradley, P.J., Grimley, D.A., and Blocher, W.B., 2020, Geologic map of the Goldston 7.5-Minute Quadrangle: North Carolina Geological Survey Open-File Report 2020-06, scale 1:24,000, in color.
- Bradley, P.J., **Rice, A.K.**, and Peach, B.T., 2019, Geologic map of the eastern portion of the Bennett 7.5-Minute Quadrangle: North Carolina Geological Survey Open-File Report 2019-05, scale 1:24,000, in color.
- Bradley, P.J., **Rice, A.K.**, and Peach, B.T., 2019, Geologic map of the Bear Creek 7.5-Minute Quadrangle: North Carolina Geological Survey Open-File Report 2019-06, scale 1:24,000, in color.
- Bradley, P.J., **Rice, A.K.**, Grimley, D.A., and Blocher, W.B., 2020, Geologic map of the Colon 7.5-Minute Quadrangle. North Carolina Geological Survey Open-File Report 2020-04, scale 1:24,000, in color.
- Bradley, P.J., **Rice, A.K.**, and Grimley, D.A., 2021, Geologic map of the Moncure 7.5-Minute Quadrangle, Lee and Chatham Counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-01 scale 1:24,000, in color.
- Bradley, P.J., **Rice, A.K.**, Grimley, D.A., Hanna, H.D. and Malaska, M.J., 2021, Geologic map of the of the Merry Oaks 7.5-Minute Quadrangle, Chatham and Lee Counties, North Carolina: North Carolina Geological Survey Open-File Report 2021-02, scale 1:24,000, in color (Supersedes Open-file Report 2012-02).

Aaron was a Sergeant in the U.S. Army Reserves serving in Kuwait as a medic in 2002, and then a Surgical Technician in Massachusetts where he graduated in 2014 from Salem State University with a B.S. in Geological Sciences. Aaron completed his M.S. in Geosciences from UNCW in April of 2021. There he was awarded both the Patricia Kelley Teaching Award in the Department of Earth and Ocean Sciences and the UNCW Outstanding Teaching Assistant Award in 2018. In addition to his NCGS publications, Aaron was also the author or co-author of multiple Geological Society of America presentations and publications. On May 16, 2021, Aaron passed away unexpectedly after an accidental fall in Raleigh. His infectious smile, positive attitude, comradery, and enthusiasm for geology are deeply missed. To honor his memory and geological legacy, Aaron's parents, Kevin and Juanita Rice, have established the Aaron K. Rice '21 Applied Learning Award in Earth and Ocean Sciences at UNCW. This scholarship supports the future research of his fellow geology and geoscience graduate students for whom he cared so much. Information about Aaron's scholarship and ways to donate to his memory may be found at <https://giving.uncw.edu/why-it-matters/donor-funded-scholarships>.

IN MEMORIAM



Norman Kennedy (Kenny) Gay

1953 - 2023

Kenny Gay contributed to the geologic understanding of North Carolina in many ways. He was a Coastal Plain mapper, Piedmont bedrock mapper and an expert on North Carolina minerals.

Kenny had over 40 years' experience as a geologist including time in the petroleum industry and the geotechnical sector. He worked for the NC Geological Survey since 1995. Kenny was a well-known mineral collector and held several leadership positions in area mineral clubs. In 2022, he was honored by having a new mineral named after him. Kenny passed away unexpectedly in April 2023.

According to his son Brian, Kenny used to say, "If you do what you love you never work a day in your life." Kenny never worked a day in his life!

Link to Mindat.org page for [Kennygayite](https://www.mindat.org/Kennygayite).

Papers

Contents

Geology of Chatham County and Surrounding Areas, North Carolina	1
Updated Compiled Structural Data for Chatham County, North Carolina – Utilizing GIS to Unravel Structural Geology Problems.....	27
Preliminary Detrital Zircon Data from Chatham County, NC.....	41
Absolute Age Determination of the Parks Crossroads Granodiorite of the Carolina Terrane	47
Assessment of the timing of the Virgilina deformation with U-Pb ages of plutonic and volcanic rocks in the Carolina terrane	57
Quaternary Terraces and Deposits in the Chatham County area, North Carolina.....	77
Susceptibility Maps of Geogenic Contaminants in Chatham County, NC	88
Introduction to: The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and metallogenic analysis with an alternative model	101
Introduction to: A geologic analysis of the Charlotte terrane from a metallogenic perspective and a proposed first-order stratigraphy.....	113
Is a Large Complex Impact Crater Hiding in Plain Sight in Central North Carolina?*	120
Inquiry Based Field Trip – Investigations of Two Contrasting Sites at Jordan Lake, North Carolina.....	123
Carolina Geological Society 2023 Field Guide to Stops	142

Supplemental Contributions

Contributions to the field trip include large papers presented in two supplemental volumes available as digital downloads only.

Supplemental Papers 1 include:

https://carolinageologicalsociety.org/2020s_files/Supplemental_Papers1_CGS2023.pdf

Moye, R.J., 2023, The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and metallogenic analysis with an alternative model, *in* Supplemental Papers 1, Carolina Geological Society Annual Meeting 2023, p. 1-82.

and

Moye, R.J., 2023, A geologic analysis of the Charlotte terrane from a metallogenic perspective and a proposed first-order stratigraphy, *in* Supplemental Papers 1, Carolina Geological Society Annual Meeting 2023, p. 83-165.

Supplemental Papers 2 include:

https://carolinageologicalsociety.org/2020s_files/Supplemental_Papers2_Impact_Crater_CGS2023.pdf

McDaniel, R.D., Stoddard, E.F., Lumpkin, B.L., Powers, J.A., Capps, R.C., 2023, Is a large complex impact crater hiding in plain sight in central North Carolina?, *in* Supplemental Papers 2, Carolina Geological Society Annual Meeting 2023, 40p.

Geology of Chatham County and Surrounding Areas, North Carolina

by Philip J. Bradley, Piedmont Geologist, NC Geological Survey, pbradley@deq.nc.gov

Contributions to geologic mapping in alphabetical order by: Randy Bechtel, William B. Blocher, Philip J. Bradley, J. Robert Butler, Timothy W. Clark, Norman K. Gay, David A. Grimley, Heather D. Hanna, Michael J. Malaska, Brandon T. Peach, Aaron K. Rice, Edward F. Stoddard, and Mary E. Watson.

Introduction

The Carolina Geological Society (CGS) annual field trip visited portions of Chatham and adjacent counties in 2011 and 1964. In 2011, CGS visited several locations within the Deep River Triassic basin and an active pyrophyllite mine within the Carolina terrane in Moore County (Clark et al., 2011). In 1964, CGS visited stops in the “Carolina slate belt” in Chatham, Randolph and Orange counties (Bain et al., 1964). The goal of this 2023 CGS trip is to present the findings of detailed geologic mapping within Chatham and adjacent counties by the North Carolina Geological Survey. Detailed mapping in the area has been partially supported by STATEMAP - a component of the US Geological Survey (USGS) National Cooperative Geologic Mapping Program. Chatham County and nearby counties (e.g. Wake and Durham counties) are some of the most rapidly growing parts of the state. This growth, centered in Wake County, is spreading outward into adjacent counties, including Chatham. Mapping in Chatham County is a natural outgrowth of continued mapping from the Raleigh area outward. Mapping within the Piedmont by NCGS staff has mainly concentrated on areas undergoing rapid land use change and population increase. Significant land-use changes are anticipated in Chatham County over the next few decades as two Mega-Sites are built out and the Chatham Park development brings more than 60,000 new residents to the area.

Past Work

In 2023, the North Carolina Geological Survey (NCGS) celebrates its 200th anniversary. It is fitting that the NCGS should host the CGS annual field trip in 2023 in Chatham County for it is the location of some of the first published geologic research in North Carolina. In 1820, Denison Olmsted, a professor at UNC Chapel Hill, published a letter that described sandstones and coal deposits in Chatham County (Olmsted, 1820). In 1823, Denison Olmsted established the first geological survey in the US – the North Carolina Geological Survey. The NCGS preceded the founding of the USGS by 54 years! In 1825, Olmsted published the nation’s “First State Geologic Map” identifying the *Triassic area* and the *Great Slate Formation* in Chatham County (Olmsted, 1825 and Clark, 1999).

The earliest geologic mapping in the county was by Emmons (1856) with his Map of the Deep River Coal Field. County wide reconnaissance-scale mapping and compilation work was by

Wilson and Carpenter (1975 and 1981). This county reconnaissance-scale mapping was later compiled for the 1985 State Geologic Map (NCGS, 1985). Several masters theses, PhD dissertations, independent research by academics, research by the NCGS and USGS staff and independent geologists have been carried out in the map area and include: Abdelzahir, 1978; Allen and Wilson, 1968; Babiker, 1978; Bain and Harvey, 1977; Bain and Brown, 1981; Berry, 1943; Black, 1977; Clark, 1998; Eligman, 1987; Green et al., 1982; Green, 1977; Hauck, 1977; Heckert et al., 2012; Hicks, 1982; Hughes, 1987; Moore, 1980; Nixon, 1954; Parker, 1979; Powers, 1985 and 1993; Ragland and Butler, 1972; Rapprecht, 2010; Reinemund, 1955; Schmidt et al., 2006; Stirewalt et al., 1981; Tingle, 1982; Wagener, 1964 and 1965; and Wilkinson, 1978.

The compiled geologic map of Chatham County (Figure 1 and Table 1) is a compilation of modified and edited data from portions of 19 previously published or manuscript 1:24,000-scale mapping.

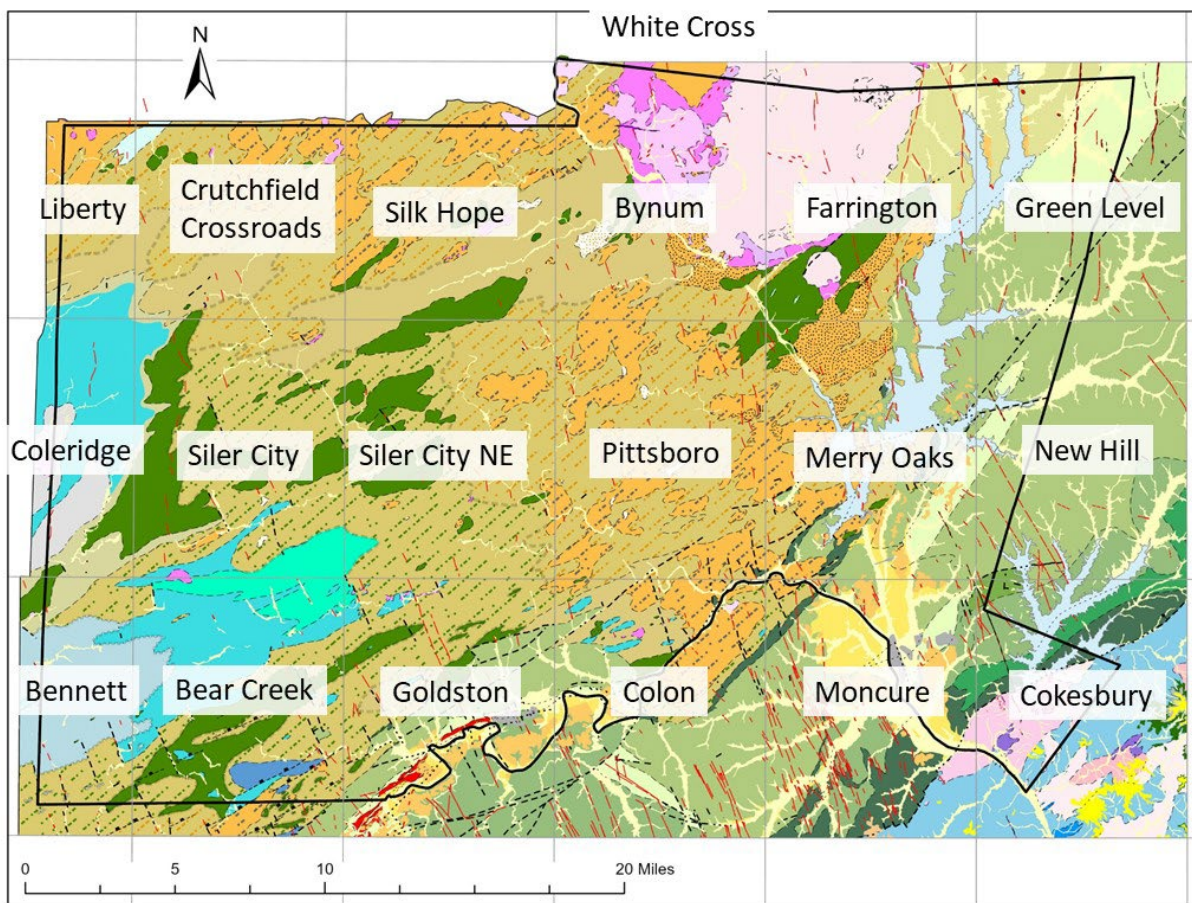


Figure 1: Index of 1:24,000-scale geologic maps of Chatham County. Base image is the compiled geologic map of Chatham County and surrounding areas (Bradley, 2022).

Reinemund (1955), is an important work, that has laid the foundation for the geology within the Sanford sub-basin of the Deep River Triassic basin. For this mapping effort, Reinemund's maps were georeferenced to a digital elevation model from Hillshade LiDAR. Geologic contacts

within the Triassic basin were digitized and modified, if needed. Most of the geology south of the Cape Fear and Deep rivers in the Goldston, Colon and Moncure quadrangles within the Triassic basin was digitized as presented by Reinemund.

Quadrangle	Reference
Liberty	Bradley, P.J, Peach, B.T. and Hanna, H.D., 2018, Geologic map of the Chatham County portion of the Liberty 7.5-minute Quadrangle, NCGS Open-file Report 2018-02, scale 1:24,000
Crutchfield Crossroads	Bradley, P.J., Hanna, H.D. and Peach, B.T., 2017, Geologic map of Chatham County portion of the Crutchfield Crossroads 7.5-Minute Quadrangle, NCGS Open-file Report 2017-10, scale 1:24,000
Silk Hope	Bradley, P.J., Hanna, H.D. and Michael, E.K., 2022, Geologic map of the Silk Hope 7.5-Minute Quadrangle, Chatham and Alamance counties, North Carolina, NCGS Open-file Report 2022-01, scale 1:24,000 (Supersedes NCGS Open-file Report 2014-02).
Bynum	Bradley, P.J., Hanna, H.D., Stoddard E.F., and Bechtel, R., 2013, Geologic map of the Bynum 7.5-minute quadrangle. NCGS Open-file Report 2013-03, scale 1:24,000
Farrington	Bradley, P.J., Gay, N.K., Bechtel, R. and Clark, T.W., 2007, Geologic map of the Farrington 7.5-minute quadrangle. NCGS Open-file Report 2007-03, scale 1:24,000
Green Level	Watson, M. E., 1998, Geology of the Green Level 7.5-minute quadrangle, Chatham, Durham, and Wake Counties, North Carolina, North Carolina Geological Survey Open-File Report 98-3, 28 p. Clark, T.W., Blake, D.E., Stoddard, E.F., Carpenter, P.A., III, and Carpenter, R.H., 2004, Preliminary bedrock geologic map of the Raleigh 30' x 60' quadrangle, North Carolina: North Carolina Geological Survey Open-file Report 2004-02, scale 1:100,000, in color.
Coleridge	Bradley, P.J, Peach, B.T. and Hanna, H.D., 2018, Geologic map of the Chatham County portion of the Coleridge 7.5-minute Quadrangle, NCGS Open-file Report 2018-03, scale 1:24,000
Siler City	Bradley, P.J., Peach, B.T. and Hanna, H.D., 2017, Geologic map of the Siler City 7.5-Minute Quadrangle, NCGS Open-file Report 2017-07, scale 1:24,000
Siler City NE	Hanna, H.D., Bradley, P.J., and Bechtel, R., 2015, Geologic Map of the Siler City NE 7.5 Minute Quadrangle, NCGS Open-file Report 2015-02, scale 1:24,000
Pittsboro	Bradley, P.J., Hanna, H.D., and Bechtel, R, 2014, Geologic map of the Pittsboro 7.5-minute quadrangle, Chatham County, NCGS Open-file Report 2014-01, scale 1:24,000
Merry Oaks	Bradley, P.J., Rice, A.K. Grimley, D.A., Hanna, H.D. and Malaska, M.J., 2021, Geologic map of the of the Merry Oaks 7.5-minute Quadrangle, Chatham and Lee Counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-02, scale 1:24,000, in color (Supersedes Open-file Report 2012-02)
New Hill	Clark, T.W., Manuscript geologic map of the New Hill 7.5-minute quadrangle, North Carolina: North Carolina Geological Survey, scale 1:24,000.

	Clark, T.W., Blake, D.E., Stoddard, E.F., Carpenter, P.A., III, and Carpenter, R.H., 2004, Preliminary bedrock geologic map of the Raleigh 30' x 60' quadrangle, North Carolina: North Carolina Geological Survey Open-file Report 2004-02, scale 1:100,000, in color.
Bennett	Bradley, P.J., Rice, A.K. and Peach, B.T., 2019, Geologic map of the eastern portion of the Bennett 7.5-Minute Quadrangle, NCGS Open-file Report 2019-05, scale 1:24,000
Bear Creek	Bradley, P.J., Rice, A.K. and Peach, B.T., 2019, Geologic map of the Bear Creek 7.5-Minute Quadrangle, NCGS Open-file Report 2019-06, scale 1:24,000
Goldston	Rice, A.K., Bradley, P.J., Grimley, D.A. and Blocher, W.B., 2020, Geologic map of the Goldston 7.5-Minute Quadrangle. NCGS Open-file Report 2020-06, scale 1:24,000
Colon	Bradley, P.J., Rice, A.K., Grimley, D.A. and Blocher, W.B., 2020, Geologic map of the Colon 7.5-Minute Quadrangle. NCGS Open-file Report 2020-04, scale 1:24,000
Moncure	Bradley, P.J., Rice, A.K., and Grimley, D.A., 2021, Geologic map of the Moncure 7.5-Minute Quadrangle, Lee and Chatham counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-01 scale 1:24,000, in color
Cokesbury	Butler, J.R., Clark, T.W. and Gay, N.K., 2016, Geologic map of the Cokesbury 7.5-minute quadrangle, NCGS Open-file Report 2016-22, scale 1:24,000
White Cross	Bradley, P.J., and Stoddard, E.F., 2008, Geologic map of the White Cross 7.5-minute quadrangle, NCGS Open-file Report 2008-01, scale 1:24,000
Compiled County Map Supersedes above maps	Bradley, P.J. (with contributions in alphabetical order from : Bechtel, R.; Blocher, W .B.; Butler, R.J.; Clark, T.W .; Gay, N.K.; Grimley, D.A.; Hanna, H.D.; Malaska, M .J.; Peach, B.T.; Rice , A.K.; Stoddard , E.F.; and Watson, M .E.), 2022, Compiled Geologic map of Chatham County and surrounding areas, North Carolina: North Carolina Geological Survey Open-file Report 2022-03, scale 1:50,000, in color. https://deq.nc.gov/energy-mineral-and-land-resources/geological-survey/ofrs-geological-survey/geologic-map-chatham-county-and-surrounding-areas-north-carolina

Table 1: List of published and manuscript maps that were compiled for the Chatham County map.

Geologic Setting

Chatham County and surrounding areas are underlain by four major geologic elements (Figure 2). They are, from west to east: Carolina terrane, Deep River Triassic basin, the easternmost Carolina terrane and small areas of Coastal Plain sediments. Coastal Plain sediments overlay units within the Deep River Triassic basin and the easternmost Carolina terrane. Older alluvium deposits are present along major drainages in addition to modern floodplain deposits.

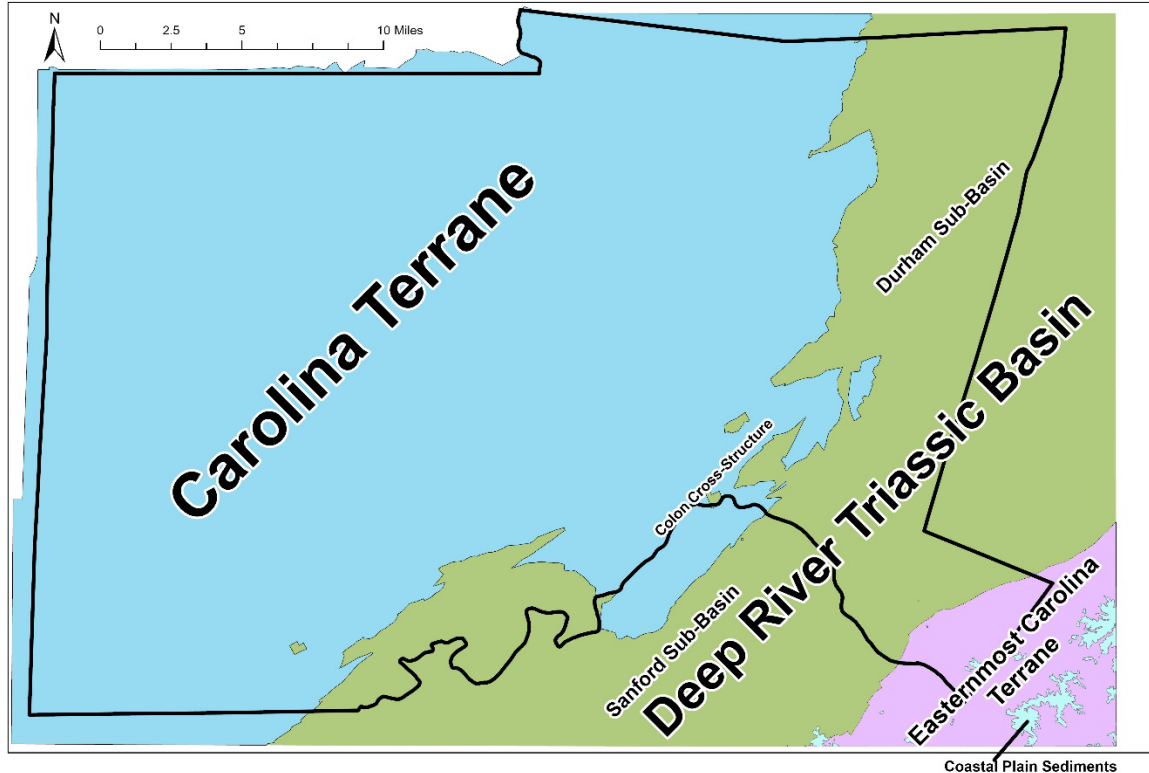


Figure 2: Major geologic elements present in Chatham County and surrounding areas: Carolina terrane, Deep River Triassic basin, Easternmost Carolina terrane and Coastal Plain sediments.

Carolina Terrane

The Carolina terrane underlies the western two-thirds of Chatham County and is the main subject of the 2023 CGS trip. The Carolina terrane is composed of Neoproterozoic to Cambrian metamorphosed volcanic, volcano-sedimentary, sedimentary and intrusive rocks (Hibbard et al., 2002; and Hibbard et al., 2006). The Carolina terrane is separated into three lithotectonic units: 1) the Hyco arc, 2) the Aaron Formation of the redefined Virgilina sequence (Hibbard et al., 2013) and 3) the Albemarle arc (Hibbard et al., 2013) (Figures 3 and 5). All three lithotectonic units are present in Chatham County.

Available Age Dates for the Carolina Terrane in Chatham County and Surrounding Areas

In Chatham County and adjacent areas, the Hyco Arc consists of the Hyco Formation which includes ca. 633 to 612 Ma (Wortman et al., 2000; Bowman, 2010; Bradley and Miller, 2011 and Bowman et al., 2013) metamorphosed layered volcanoclastic rocks and plutonic rocks. Dating by Barefoot (2015), indicates that magmatism in the lower portions of the Hyco Formation may be as old as ca. 650 Ma. Available age dates (Wortman et al., 2000; Bradley and Miller, 2011) indicate the Hyco Formation may tentatively be divided into lower (ca. 630 Ma) and upper (ca. 615 Ma) portions with an apparent intervening hiatus of magmatism (Figure 4).

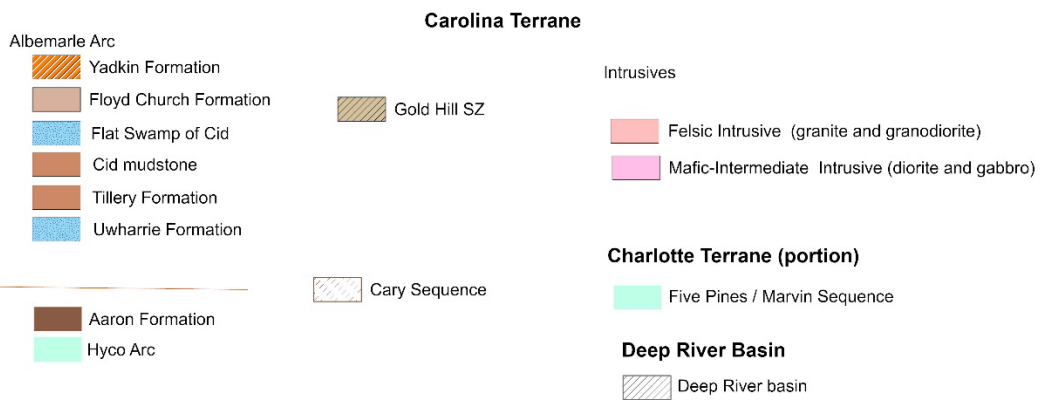
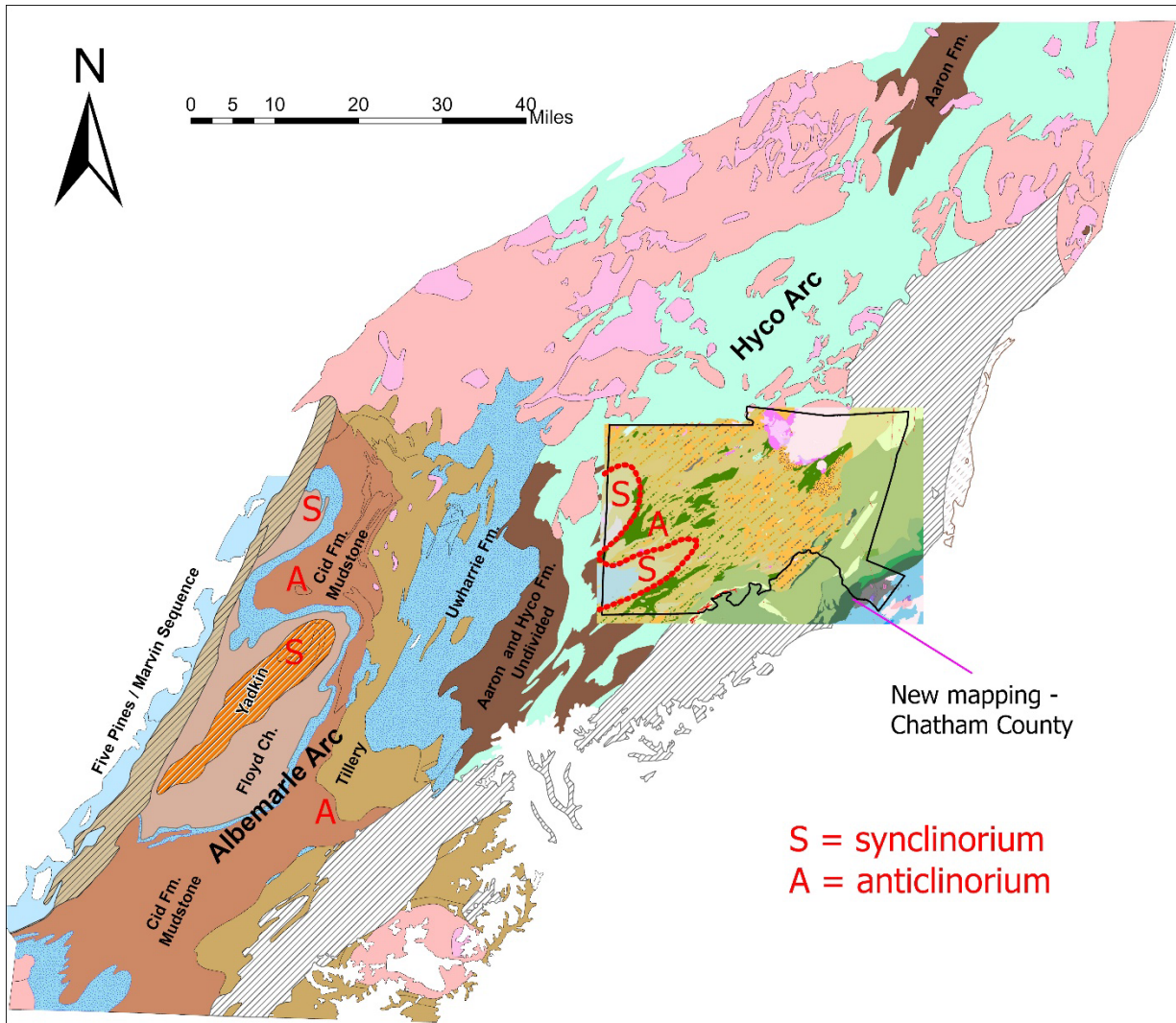


Figure 3: Major geologic formations and structures in North Carolina within the Carolina terrane and adjacent areas. New mapping in Chatham County is superimposed on map. Base map modified from NCGS (1985).

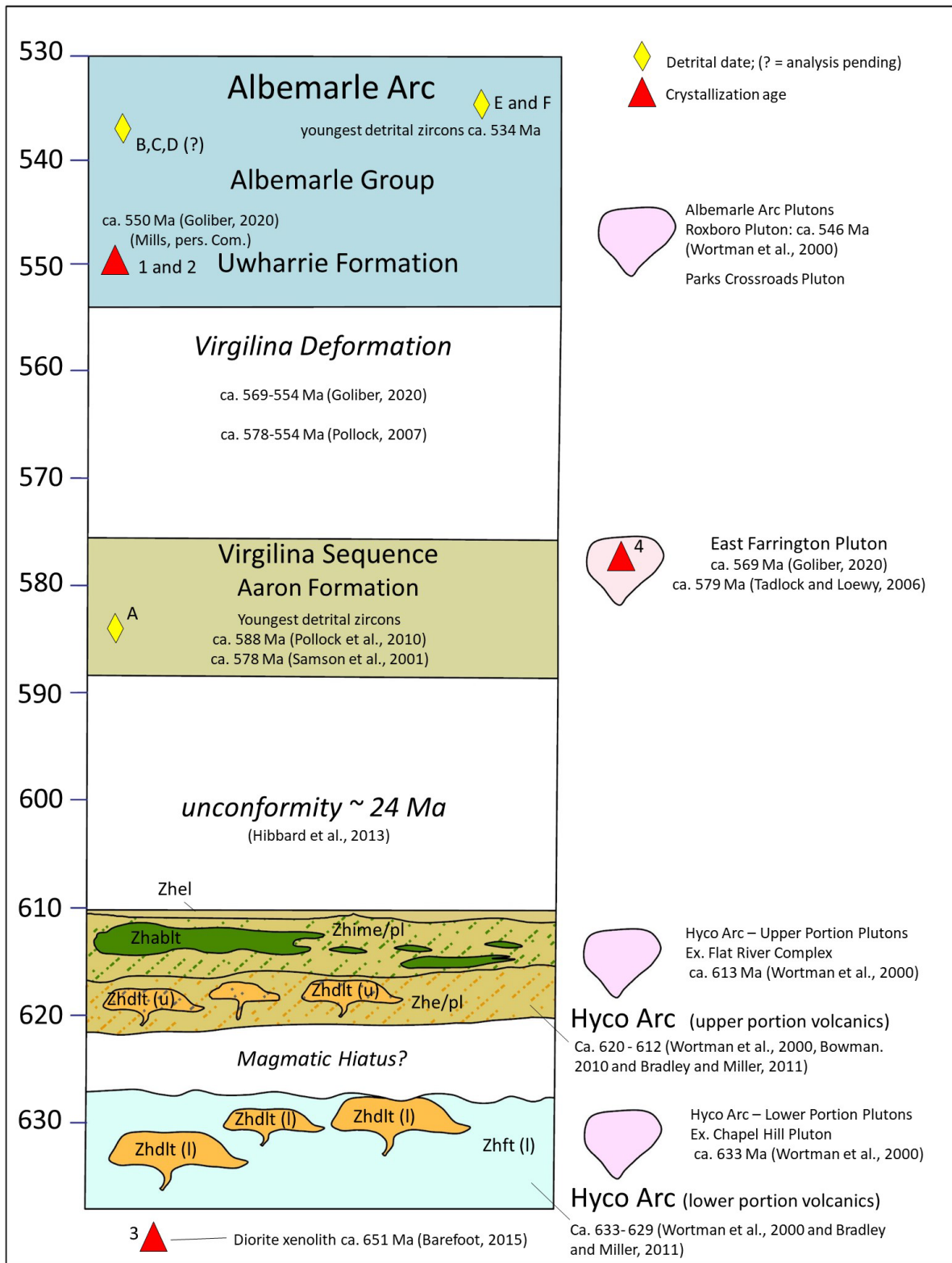


Figure 4: Generalized stratigraphy of major units and formations in Chatham County and nearby areas within the Carolina terrane.

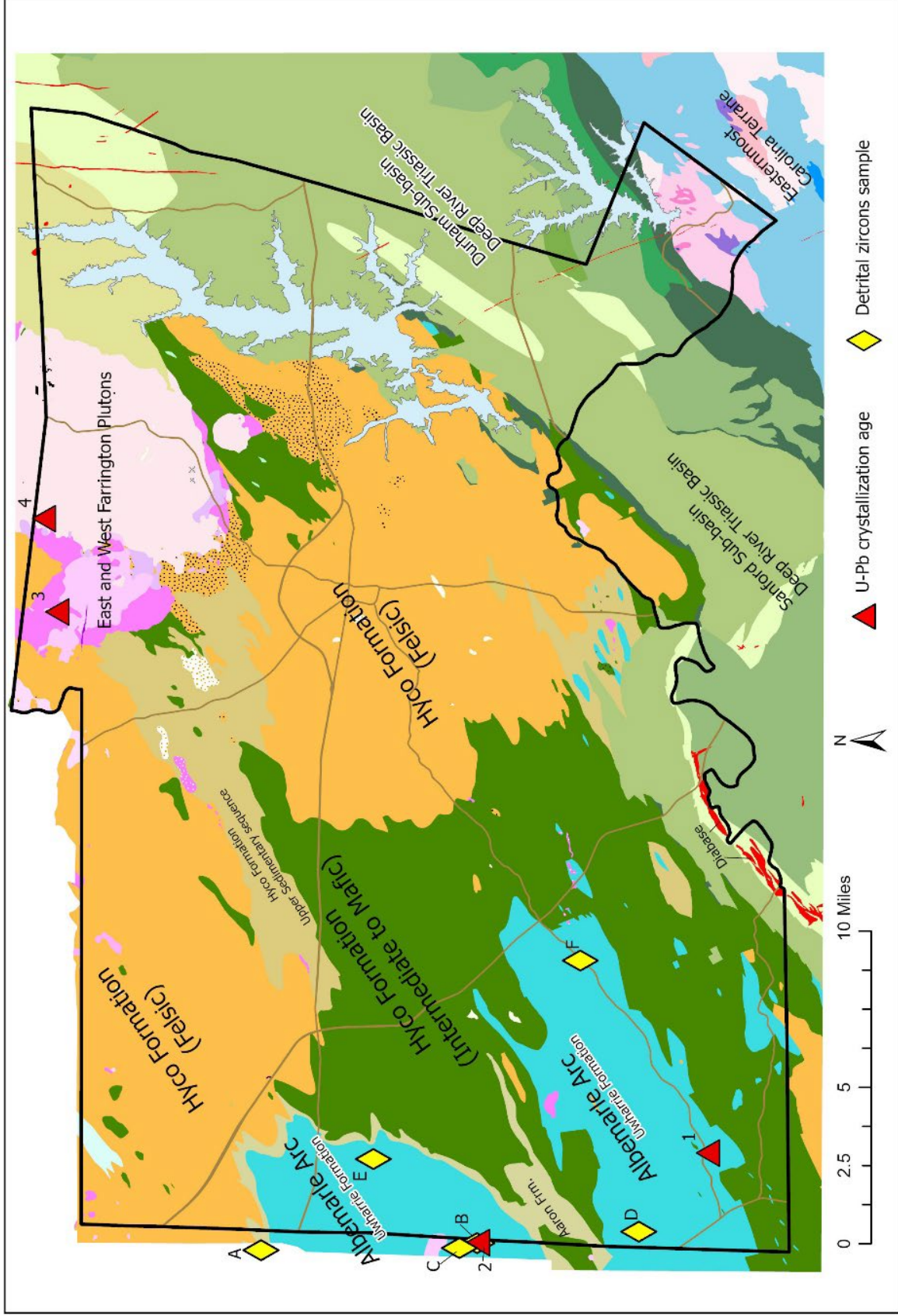


Figure 5: Age dates and generalized geologic map of major formations in Chatham County and nearby areas.

Label	Sample ID	Rock Type	Unit	Date	Source	Comments
1	NCGS Station Bennett-710	tuff	Uwharrie Formation	548.7 ± 1.1 Ma	U-Pb zircon date (Goliber, 2020)	
2	NCGS Station Coleridge-458	felsic tuff or dike	Uwharrie Formation	550.1 ± 2.4 Ma and 550.7 ± 1.3 Ma for two grains	U-Pb zircon date (R. Mills, personal com. 2018) UNC Chapel Hill sample NC-18-02	
3	UNC Chapel Hill Sample TC-14-01 Granodiorite	granodiorite	xenolith of older pluton in West Farrington Pluton	651.0 ± 3.4 Ma	U-Pb zircon date (Barefoot, 2015)	
4	UNC-Chapel Hill sample EF-19-01	granodiorite	East Farrington Pluton	569.0 ± 1.1 Ma	U-Pb zircon date (Goliber, 2020)	
A	Pollock et al. (2010) sample location	conglomerate	Aaron Formation (lower portion)	youngest detrital zircon of 588 ± 11 Ma	detrital zircon date (Pollock et al., 2010)	Distinctive conglomerate
B	NCGS Station Coleridge-8005	sandstone		analysis pending	detrital zircon date (pending USC-Columbia)	Analysis Pending
C	NCGS Station Coleridge-472	sandstone		analysis Pending	detrital zircon date (pending USC-Columbia)	Analysis Pending
D	NCGS Station Bennett-165	sandstone		analysis Pending	detrital zircon date (pending USC-Columbia)	Analysis Pending
E	NCGS Station Coleridge-3055	sandstone	Albemarle Arc	The four youngest detrital zircons are: ca. 534, 538, 538 and 538 Ma. (contemporary with Albemarle Group of Albemarle Arc)	detrital zircon date (AZ LaserChron)	Abundant quartz crystals
F	NCGS Station Bear Creek-626	sandstone	Albemarle Arc	The three youngest detrital zircons are: ca. 535, 535 and 536 Ma. (contemporary with Albemarle Group of Albemarle Arc)	detrital zircon date (AZ LaserChron)	No or sparse quartz crystals

Table 2: Summary of available age dates in Chatham County and surrounding areas. Refer to Figure 5 and Label number or letter for sample location.

In northeastern Chatham County, Hyc0 Formation units are intruded by the East Farrington pluton and associated West Farrington pluton. Two age dates are available for the East Farrington pluton: a recent date of 569.0 ± 1.1 Ma from Goliber (2020) and a previous date of ca. 579 Ma from Tadlock and Loewy (2006) in Orange County. The Aaron Formation consists of metamorphosed layered volcanoclastic rocks with youngest detrital zircons of ca. 588 and 578

Ma (Pollock et al., 2010 and Samson et al., 2001, respectively). Hibbard et al. (2013) interprets the presence of an at least 24 million year unconformity between the Aaron and underlying Hyco Formation. New detrital zircon data from lithologies previously mapped as belonging to the Aaron Formation indicate that the parts of the unit may be much younger than previously thought (to be discussed below).

Rocks interpreted to be part of the Albemarle arc in Chatham County include at least one map-scale volcanoclastic unit in the western portion of the county and intrusive rock types that cut Hyco and/or Aaron Formation units. A sample from the map scale unit (Zue/pl) yielded an U-Pb zircon age of ca. 549 Ma (Goliber, 2020).

Detrital Zircon Data

Pollock et al. (2010) reported detrital zircon data from an outcrop of conglomerate in the Aaron Formation located in northeast Randolph County - immediately west of the Chatham County line (Figure 5, Location A). Although not part of the new detailed mapping in Chatham County, the location is located adjacent to the contact of the Aaron and Hyco Formations and as such, likely represents the lowermost Aaron Formation. Pollock et al. (2010) reported a youngest U-Pb detrital zircon date of 588 ± 11 Ma. Samson et al. (2001) sampled sandstone and conglomerate from the Aaron Formation near the NC-VA line and reported a youngest U-Pb detrital zircon age of ca. 578 Ma. Prior to new detrital age dates, the Aaron Formation was interpreted to contain youngest detrital zircons of ca. 588 and 578 Ma (Pollock et al., 2010 and Samson et al., 2001, respectively).

New Detrital Zircon Data

In early 2022, two outcrops were sampled for detrital zircon analysis and analyzed by the University of Arizona LaserChron Center by LA-ICPMS: NCGS sample Coleridge-3055 and NCGS Sample Bear Creek-626 (Figure 5, Location E and F, respectively). Detailed plots are provided in Pelt and Bradley (2023, this volume).

Coleridge-3055: 312 zircon grains were analyzed, 264 zircons were between 90 – 110 % of concordia. Of these 264 grains, the $^{206}\text{Pb}/^{238}\text{U}$ ages range from 534.6 \pm 4.8 Ma to 2360.1 \pm 13.8 Ma. The four youngest detrital zircons are: ca. 534, 538, 538 and 538 Ma. 30 zircons are 554 Ma and younger (11%). 126 zircons are between 555 Ma and 610 Ma (48%). 72 zircons are between 610 and 650 Ma (27%). 36 zircons are between 651 – 2360 Ma. (14%).

Bear Creek-626: 316 zircon grains were analyzed, of those grains 212 fell within 90–110% of concordia. Of the 212 near concordia, the $^{206}\text{Pb}/^{238}\text{U}$ ages range from 535 \pm 3.7 Ma to 2671.1 \pm 12.7 Ma. The three youngest detrital zircons are: ca. 535, 535 and 536 Ma. 34 zircons are 554 Ma and younger (16%). 161 zircons are between 555 Ma and 610 Ma (76%). 13 zircons are between 610 and 650 MA (approx. 6%). 4 zircons are between 685 – 2671 Ma and are 685.7 \pm 5.0 Ma, 1255 \pm 12.51 Ma, 1420 \pm 10.1 Ma and 2671.1 \pm 12.7 Ma.

Prior to the new detrital zircon analysis, earlier NCGS mapping assigned NCGS sample Coleridge-3055 as part of the Aaron Formation (Bradley et al., 2018) and NCGS Sample Bear Creek-626 (Bradley et al., 2019b) as part of the uppermost Hyco Formation. Coleridge-3055 and similar rock types were assigned to the Aaron Formation because they match the descriptions of Harris (1984) for the Aaron Formation as quartz crystal bearing. Sample Bear Creek-626 and similar rocks were assigned to a distinct unit of the Hyco Formation and interpreted to likely represent the uppermost portion and youngest part of the Hyco Formation.

Based on the detrital zircon data, the earlier stratigraphic placement of these samples (as being part of the Hyco and Aaron Formations) needs to be revised. Both samples and the units they represent are likely related to distal sedimentation associated with the Albemarle arc. As part of the Chatham County compilation effort, both units have been re-assigned to the Uwharrie Formation due to textural similarities and their related detrital zircon dates as the Erect Member of the Uwharrie Formation (Pollock et al., 2010 and Hibbard et al., 2013).

Folds in the Carolina Terrane

The Hyco Arc and Aaron Formation lithologies were folded and subjected to low grade metamorphism during the ca. 578 to 554 Ma (Pollock, 2007; Pollock et al., 2010) Virgilina deformation (Glover and Sinha, 1973; Harris and Glover, 1985; Harris and Glover, 1988; and Hibbard and Samson, 1995). In the map area, original layering of Hyco and Aaron Formation lithologies is observed ranging from shallowly to steeply dipping. The range of structural attitude is interpreted to be a result of open to tight folds that are locally overturned. Sterograms and other structural data are provided in Thompson et al. (2023, this volume).

Rocks in the map area were also subjected to the ca. 450 Ma Cherokee deformation and low grade metamorphism (Hibbard et al., 2010 and 2012). Outcrop evidence of Cherokee deformation in the map area is scarce. Evidence is best exposed in area pyrophyllite mines where outcrop-scale folds deform an earlier foliation (see field trip stop 7 in Clark et al., 2011). This folding is associated with local deformation along several identified high-angle reverse faults in the map area (e.g. Glendon Fault).

Faults

Several terrane-internal ductile faults have been recognized in Chatham and adjacent Moore County within the Carolina terrane. The best known is the Glendon fault which has long been recognized by past workers (e.g. Stuckey, 1928 and Conley, 1962). The Glendon fault is a high angle reverse fault that is a locus of pyrophyllite alteration for a distance of over 30 km (18 miles) in northeast Moore County and into southern Chatham County. The Glendon fault is interpreted to be parallel to the axial surfaces of regional-scale overturned folds and disrupts an anticline near its crest (Green et al., 1982 and Klein, 1985). In general, the Glendon fault is a zone of intense deformation ranging from 10 to 50 meters wide with abundant small-scale folds, fractures and deformed and undeformed quartz veins indicating a complicated movement history (Klein, 1985). Quartz veins may be folded and high-strain foliations present within the fault

zone overprinting and/or transposing primary bedding and regional foliation. Main movement on the Glendon fault is speculated to be related to the Cherokee deformation.

Several other high-angle reverse faults with varying degrees of hydrothermal alteration were identified during mapping. Metamorphic foliation data indicate that the dip of the foliation progressively becomes more shallow to the southeast approaching the high-angle faults. In the immediate area of the faults, sericite (\pm pyrophyllite) phyllites and schistose phyllites with composite-like fabrics are common. It is interpreted that the older foliation has been transposed to a younger phyllonitic foliation within the fault zones.

The historic Clegg Copper Mine (Kerr and Hanna, 1893) located in the Colon Quadrangle is present within a quartz mineralized zone that is interpreted to have been a pre-metamorphic fault – the Copper Mine Fault (Babiker, 1978). The Copper Mine Fault is oriented parallel to later Mesozoic brittle faulting.

Abundant evidence of brittle faulting at the outcrop-scale and map-scale as well as large-scale lineaments (as interpreted from hillshade LiDAR data) are present in the map area. The brittle faulting and lineaments are interpreted to be associated with Mesozoic extension. Major named brittle normal faults include: the Jonesboro Fault, Bonsal-Morrisville Fault, Deep River Fault, Gulf Fault and Indian Creek Fault. The map area includes the Colon cross-structure that marks the transition between the Durham and Sanford sub-basins (Campbell and Kimball, 1923 and Reinemund, 1955) (Figure 2). Numerous map-scale relay ramps are present in this area. A fault-bounded block within the Carolina terrane along the Deep River (in the northwest corner of the Moncure Quadrangle and southwest corner of the Merry Oaks Quadrangle) has been identified with metamorphic foliations rotated up to 90 degrees clockwise. This rotation is speculated to be related to rotation of a breached relay ramp (see field trip stop 8a).

Rock Types and Rock Units of the Albemarle arc, Aaron and Hyco Formations of the Carolina Terrane in Chatham County

Albemarle Arc Units

In the western portion of Chatham County two major synclines (synclinoria) are present (Figure 3). Two samples with U-Pb crystallization ages of ca. 549 Ma (Goliber, 2020) and ca. 550 Ma (R. Mills, personal com. 2018) and two samples for detrital zircon analysis with youngest zircon of ca. 534 Ma have been collected. These dates are consistent with Albemarle arc available age dates (Hibbard et al., 2002; and Pollock et al., 2010).

Rock types associated with the Albemarle arc include metamorphosed tuffaceous sandstones, conglomeratic sandstones, siltstones with lesser amounts of fine- to coarse tuff, welded tuff and dacitic lavas. Fiamme-like shaped clasts are common in the conglomerates, sandstones and tuffs. Quartz and feldspar crystal fragments are common in the sedimentary components, tuffs and lavas.

Aaron Formation

NCGS mapping in Chatham County grouped rocks similar to those sampled for detrital zircon analysis by Pollock et al. (2010) and distinctive quartz-bearing sandstones and other interlayered sedimentary rocks as described by Harris (1984) into the Aaron Formation (Bradley et al., 2017 (Siler City); Bradley et al., 2018 (Coleridge); Bradley et al., 2019a (Bennett) and Bradley et al., 2019b (Bear Creek)). The results of the new detrital zircon data collected in 2022, required the re-evaluation of areas mapped as Aaron since large portions are much younger than previously interpreted. For the compiled Chatham County map (Bradley, 2022), conglomerates and related rocks proximal to the contact with the Hyco Formation and including the detrital zircon sample location of Pollock et al. (2010) were included in the newly revised Aaron Formation map unit.

The sandstones, pebbly sandstones and conglomerates of the Aaron are distinctive and commonly contain rounded to subrounded clasts of quartz ranging from sand- to gravel-sized. In the sandstones, feldspar is the most prominent mineral grain; quartz varies from sparse to abundant in hand sample. Lithic clasts are typically prominent and range from sand- to gravel-size.

Harris (1984) performed a detailed sedimentary study of the Aaron Formation to the immediate west of the map area (see Figure 23 in field trip stops, this volume). Harris (1984) interpreted the Aaron Formation to have been deposited by turbidity currents in a retrogradational submarine fan setting. Based on the results of the new detrital zircon data, a widespread re-evaluation of the Aaron Formation is needed. Harris and Glover (1988) identify significant areas west of Chatham County as being underlain by the Aaron Formation. These areas likely contain detritus of the Albemarle arc.

Hyco Formation

Generally, rock units of the Hyco Formation in Chatham County consist of packages of metamorphosed volcanic rocks and their volcanosedimentary detritus. The volcanic rocks and sedimentary rocks are quartz crystal *poor* or quartz is absent in hand sample. The differentiation of Hyco Formation volcanosediments from Aaron Formation volcanosediments was driven by the presence and/or absence of quartz while mapping in the field.

Map units of metavolcanic and metavolcaniclastic rocks include various lithologies that when grouped together are interpreted to indicate general environments of deposition. The dacitic lavas and tuffs unit is interpreted to represent dacitic domes and proximal pyroclastics. The andesitic to basaltic lavas (with tuffs or conglomerates) units are interpreted to represent eruption of intermediate to mafic lava flows and associated pyroclastic and/or epiclastic deposits. The epiclastic/pyroclastic units are interpreted to represent deposition from the erosion of dormant and active volcanic highlands. Deposition of the primary volcanics ranged from subaerial to subaqueous with concomitant deposition of various types and volumes of volcanic-derived

sediments. Some of the metavolcanic units within the map area display lithologic relationships similar to dated units present in northern Orange and Durham Counties. Due to these similarities, the metavolcanic and metavolcanic units have been tentatively separated into upper and lower portions of the Hyco Formation; geochronologic data in the map area is needed to confirm this interpretation.

Plutonic Rocks in Chatham County

Albemarle Arc Related Plutonic Rocks

A small satellite pluton of granodiorite, interpreted to be associated with the Parks Crossroads pluton, is present at the west central edge of the map and extends into Randolph County. Morrison and Coleman (2023, this volume) recently obtained a U-Pb age of ca. 552 Ma. from the main body of the Parks Crossroads pluton.

Also, a small pluton of diorite and gabbro is present in the southwestern portion of the county. Named Providence Church Road diorite (Zdi-pcr) (Bradley, 2022), it was described by Green et al. (1982) as a “roughly circular” pluton that cuts the surrounding unit. The apparent truncation of the surrounding units by both the satellite pluton of Parks Crossroads and the Providence Church Road diorite are problematic because detrital zircon data indicate the surrounding volcanosedimentary units contains detrital zircons as young as ca. 534 Ma.

Moye, 2023 a and b (this volume and supplemental paper), presents a new model of intra-arc rifting in the Carolina terrane. Generally, he proposes that Uwharrie magmatism was active ca. 554 – 551 Ma with rifting beginning ca. 547 Ma with the deposition of the Cid Formation. Rifting could have exhumed deeper plutonic rocks associated with the Uwharrie magmatic phase of the Albemarle arc (i.e. Parks Crossroads Pluton and the Providence Church road diorite) and disconformably deposited sediments with youngest detrital zircons of ca. 534 Ma.

Farrington Igneous Complex

The northeastern portion of Chatham County (and adjacent Orange County) is dominated by the Farrington igneous complex. The Farrington igneous complex consists of several map-scale plutons that are grouped into the East and West Farrington plutons. Wagener (1964 and 1965) conducted a study on the modal variation in the Farrington igneous complex. The East Farrington pluton is composed dominantly of granite to granodiorite with several map-scale facies with distinct mineral and textural characteristics. Two age dates are available for the East Farrington pluton: a recent date of 569.0 ± 1.1 Ma from Goliber (2020) and a previous date of ca. 579 Ma (Tadlock and Loewy, 2006) in Orange County. The West Farrington pluton is a gradationally zoned composite pluton (Ragland and Butler, 1972) that is characterized by diorite in the northern portions of the map, diorite to granodiorite along its southwestern margins, and leucogranodiorite in the central portions of the pluton.

The intrusive relationships between the different phases of the East and West Farrington plutons are not well understood. Additional information on the phases of the Farrington igneous complex can be found in the Bynum and Farrington geologic maps (Bradley et al., 2013 and Bradley et al., 2007, respectively).

Hyco Arc Plutons (?)

Plutonic rocks, ranging in composition from granite to diorite, that have been grouped with the Hyco arc are present in the northwestern part of the county (near the Town of Liberty). These plutonic rocks appear to cut Hyco Formation units and are texturally similar to dated rocks in Orange and Durham counties. Recent mapping (2022-2023) in central Alamance County has identified large areas underlain by diorites and gabbros that are grouped with Albemarle arc-aged plutonic rocks. Future revisions of the Chatham County geologic map may associate these plutonic rocks in the northwestern portion of the county with the Albemarle arc.

Easternmost Carolina Terrane in Chatham County

The southeastern corner of the map area is underlain by metamorphosed crystalline rocks of the Cary sequence (Parker, 1979; Farrar, 1985). The Cary sequence is interpreted to be part of the Carolina terrane but separated from the rest of the terrane by the Triassic basin (Hibbard et al., 2002). One of the main rock units is the Big Lake-Raven Rock schist. In the Cary Quadrangle, a sample from the unit yielded discordant $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages of 573, 574, and 579 Ma and an upper intercept age of 575 ± 12 Ma, interpreted as the time of crystallization (Goldberg, 1994). This is a similar age to parts of the Aaron Formation.

Deep River Triassic Basin in Chatham and Nearby Counties

Portions of the eastern and south-central areas of the map area are underlain by Triassic-aged sedimentary rocks of the Deep River Mesozoic basin. The basin is separated into three sub-basins (Durham, Sanford and Wadesboro). The Colon cross-structure (Campbell and Kimball, 1923 and Reinemund, 1955), located within Chatham and Lee counties, is a constriction zone in the basin characterized by crystalline rocks overprinted by complex brittle faulting (Figure 2). The Colon cross-structure marks the transition between the Durham and Sanford sub-basins.

Sanford and Durham Sub-basins Stratigraphy

The Merry Oaks and Moncure quadrangles are situated in the transition between the Sanford and Durham sub-basins. In the Sanford sub-basin, three stratigraphic units have been identified and formalized from oldest to youngest as the Pekin, Cumnock and Sanford Formations (Campbell and Kimball, 1923 and Reinemund, 1955). In the Durham sub-basin, this three-layer system is not recognized. Previous mapping by North Carolina Geological Survey staff separated the

Durham sub-basin into lithofacies associations using the nomenclature of Smoot et al. (1988). Hoffman and Gallagher (1989) began using the lithofacies association nomenclature and it was subsequently adopted for all mapping in the Durham sub-basin. The formation mapping of Reinemund (1955) in the Sanford sub-basin and the lithofacies association mapping in the Durham sub-basin are incompatible (Clark et al., 2001). These two methods of mapping meet in the Moncure and Merry Oaks quadrangles. The detailed investigation of the contrasting mapping methods and establishment of a unified stratigraphic nomenclature for the Sanford and Durham sub-basins was out of the scope of this mapping project. As such, the map units from the adjacent Cokesbury Quadrangle (Butler et al., 2016) were extended into the Moncure Quadrangle to rectify edge-match issues and mark the change of unit nomenclature from the Sanford sub-basin to the Durham sub-basin. Olsen et al. (2015, figure 12), indicates that Lithofacies Association II and III of the Durham sub-basin are younger than units in the Sanford sub-basin. Additional work is needed to establish a new stratigraphic nomenclature for the entire Deep River basin.

Post-Triassic Rock Units

Dikes of Jurassic diabase intrude the Triassic sedimentary and older crystalline rocks of the map area. Coastal Plain sediments are present in the southern portion of the map area. Quaternary alluvium is present in most modern river valleys, with at least two levels of fluvial terraces along the major drainages. These terraces, where preserved, likely mark the location and elevation of ancestral river systems, prior to incision to the modern floodplain levels (see Grimley, 2023 this volume).

Mineral Resources

The map area has many historic, abandoned, active and potential mineral resources, including: coal deposits; natural gas potential; historic iron, copper and gold mines/prospects; pyrophyllite deposits; crushed stone; and a long history of clay product mining. The location of individual mineral resources is provided on the compiled map of Chatham County. Refer to the individual 1:24K quadrangles for brief details about the mineral resources present in each quadrangle and specific references.

Discussion

Past mapping largely relied on textural characteristics of rock units while in the field. The presence/absence of certain minerals (e.g. quartz crystals), distinct rock types or assemblages of rock types, etc, drove geologic mapping and the assigning of geologic units. New detrital zircon data has brought into question multiple previously held interpretations of the Carolina terrane and has shed light on how little we actually know!

Supplemental Stop S.5 from the 2013 Carolina Geological Society field trip guidebook described an outcrop of the Erect Member from the base of the Uwharrie Formation (Hibbard et al., 2013). The stop is near the detrital zircon sample location for the Erect Member. Pollock et al. (2010) reported the sample contained a youngest detrital zircon grain with a date of 545 +/- 7 Ma. This age is similar to reported ages for the Flat Swamp Member of the Cid Formation (Hibbard et al., 2013). As part of a discussion for Supplemental Stop S.5 from the 2013 CGS guidebook, Hibbard et al. (2013) introduced the idea that portions of the Uwharrie Formation may be diachronous (occurring at different times), and areas currently mapped as Uwharrie Formation may be correlative to the Flat Swamp Member of the Cid Formation. If correct, then the stratigraphy of the Albemarle arc may need revision and/or a reassignment of map units is needed.

The map unit of one of the new detrital zircon samples in Chatham County (NCGS Sample Coleridge-3055), includes distinctive quartz-rich sandstones and is texturally similar to the Erect Member of the Uwharrie Formation (Pollock et al., 2010 and Hibbard et al., 2013). As such, the sample and unit are tentatively assigned to the Uwharrie Formation. Both new detrital zircon samples (NCGS sample Coleridge-3055 and NCGS Sample Bear Creek-626) contain populations of zircons ranging from ca. 545 to 534 Ma. These data suggest that deposition of both units were contemporaneous with the Flat Swamp Member of the Cid Formation. Should these units be assigned to the Uwharrie Formation or to the Cid Formation or to a new Formation? Perhaps Moyer (2023 a and b) may help with the long-term deciphering of the stratigraphy of the Carolina terrane.

Moyer, 2023 a and b (this volume and supplemental paper), presents a new model of intra-arc rifting in the Albemarle arc of the Carolina terrane. Generally, Moyer proposes that Uwharrie magmatism was active ca. 554 – 551 Ma with rifting beginning ca. 547 Ma with the deposition of the Cid Formation in an intra-arc basin. Additionally, Moyer (2023b) shows multiple rift zones throughout the Carolina terrane. These rift zones may have created sedimentary basins that filled with detritus as the surrounding older volcanic edifices eroded. Could the volcanosediments of western Chatham County be some of these sediments associated with a series of intra-arc basins?

Implications for Other Areas in the Carolina Terrane

Geologic compilation work in 2022-2023 in the type area of the Aaron Formation to the south of Virgilina, VA has noted the striking resemblance of the abundant quartz-bearing sandstones in the Aaron Formation to those in Chatham County. This is understandable inasmuch as Harris and Glover (1988) extended the Aaron Formation into Chatham and Randolph Counties. The new detrital zircon data from Chatham County have led to the reassignment of units identified as Aaron Formation to the Albemarle arc. Portions of the Aaron Formation in the type area of the Virgilina Synclorium may be Albemarle arc related. A sample of Aaron Formation from the Virgilina Synclorium was collected for detrital zircon analysis and forwarded to the University of Arizona LaserChron Center in August 2023 and is awaiting processing and analysis.

Acknowledgements

This geologic mapping was funded in part by the USGS National Cooperative Geologic Mapping Program under STATEMAP award numbers 01HQAG0061, 2001; 06HQAG0033, 2006; 07HQAG0140, 2007; G10AC00425, 2010; G11AC20296, 2011; G12AC20308, 2012; G13AC00204, 2013; G14AC00230, 2014; G15AC00237, 2015; G16AC00288, 2016; G17AC00264, 2017; G18AC00205, 2018; G19AC00235, 2019 and G20AC00249, 2020. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Thanks to Emily K. Michael, North Carolina Geological Survey Volunteer Intern, for field assistance during the 2020-2021 field session. Thanks to Michael J. Malaska for volunteer geologic mapping contributions in the Merry Oaks Quadrangle in 2012. Thanks for Skip Stoddard for review and comments to this manuscript.

References:

Abdelzahir, A.M., 1978, The geology of the Carolina slate belt, northern Moore County, North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina, 67 p.

Allen, E.P., and Wilson, W.F., 1968, Geology and mineral resources of Orange County, North Carolina: Division of Mineral Resources, North Carolina Department of Conservation and Development, Bulletin 81, 58 p.

Babiker, H.M., 1978, Geology of the Clegg Copper Mine and Vicinity, Lee and Chatham County, North Carolina: unpublished MS thesis, North Carolina State University, Raleigh, North Carolina, 67 p.

Bain, G.L., Allen, E.P., Wilson, W.F., and Butler, J.R., 1964, Road Log of the Chatham, Randolph and Orange County areas, North Carolina: Carolina Geological Society Field Trip Guidebook for the 1964 Annual Meeting, 10 p.

Bain, G.L., and Harvey, B.W., eds., 1977, Field guide to the geology of the Durham Triassic basin: Carolina Geological Society Fortieth Annual Meeting, 7-9 October 1977: North Carolina Department of Natural Resources and Community Development, Division of Earth Resources, Geology and Mineral Resources Section, 83 p.

Bain, G.L. and Brown, C.E., 1981, Evaluation of the Durham Triassic basin of North Carolina and techniques used to characterize its waste-storage potential: U.S. Geological Survey Open-File Report 80-1295, 133 p.

- Barefoot, J., 2015, Chronological and Mineralogical Comparison of Gold Prospect Host Rock with Known Gold Horizon Host Rock - Orange and Chatham Counties, North Carolina, unpublished senior thesis, University of North Carolina at Chapel Hill, 18 pages.
- Berry, E.W., 1943, The copper prospects of Chatham County: North Carolina Department of Conservation and Development, Division of Mineral Resources, Report of Investigation – The Copper Prospects of Chatham County, R.I. 43, 8p.
- Black, W.W., 1977, The geochronology and geochemistry of the Carolina Slate belt of north-central North Carolina, Ph.D. thesis, University of North Carolina, Chapel Hill, 118 p.
- Bowman, J.D., 2010, The Aaron Formation: Evidence for a New Lithotectonic Unit in Carolina, North Central North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina, 116 p.
- Bowman, J.D., Hibbard, J.P. and Miller, B.V. 2013, The Virgilina Sequence Redefined, North Central North Carolina, *in* Hibbard, J.P., and Pollock, J.C., eds., One arc, two arcs, old arc, new arc: the Carolina terrane in central North Carolina, Carolina Geological Society field trip guidebook, p. 127-138.
- Bradley, P.J., Gay, N.K., Bechtel, R. and Clark, T.W., 2007, Geologic map of the Farrington 7.5-minute quadrangle, Chatham, Orange and Durham Counties, North Carolina: North Carolina Geological Survey Open-file Report 2007-03, scale 1:24,000, in color.
- Bradley, P.J., and Miller, B.V., 2011, New geologic mapping and age constraints in the Hyco Arc of the Carolina terrane in Orange County, North Carolina: Geological Society of America Abstracts with Programs, Vol. 43, No. 2.
- Bradley, P.J., and Stoddard, E.F., 2008, Geologic map of the White Cross 7.5-minute quadrangle, NCGS Open-file Report 2008-01, scale 1:24,000
- Bradley, P.J., Hanna, H.D., Stoddard E.F., and Bechtel, R., 2013, Geologic map of the Bynum 7.5-minute quadrangle, Orange, Chatham and Alamance Counties, North Carolina: North Carolina Geological Survey Open-file Report 2013-03, scale 1:24,000, in color (supersedes NCGS OFR 2011-07).
- Bradley, P.J., Hanna, H.D., and Bechtel, R., 2014, Geologic map of the Pittsboro 7.5-minute quadrangle, Chatham County, North Carolina: North Carolina Geological Survey Open-file Report 2014-01, scale 1:24,000, in color. (supersedes NCGS OFR 2012-03)
- Bradley, P.J., Peach, B.T. and Hanna, H.D. 2017a, Geologic map of the Siler City 7.5-Minute Quadrangle, NCGS Open-file Report 2017-07, scale 1:24,000
- Bradley, P.J., Hanna, H.D. and Peach, B.T., 2017b, Geologic map of Chatham County portion of the Crutchfield Crossroads 7.5-Minute Quadrangle, NCGS Open-file Report 2017-10, scale 1:24,000
- Bradley, P.J., Peach, B.T. and Hanna, H.D., 2018a, Geologic map of the Chatham County portion of the Liberty 7.5-minute Quadrangle, NCGS Open-file Report 2018-02, scale 1:24,000

Bradley, P.J., Peach, B.T. and Hanna, H.D., 2018b, Geologic map of the Chatham County portion of the Coleridge 7.5-minute Quadrangle, NCGS Open-file Report 2018-03, scale 1:24,000

Bradley, P.J., Rice, A.K. and Peach, B.T., 2019a, Geologic map of the eastern portion of the Bennett 7.5-Minute Quadrangle, NCGS Open-file Report 2019-05, scale 1:24,000

Bradley, P.J., Rice, A.K. and Peach, B.T., 2019b, Geologic map of the Bear Creek 7.5-Minute Quadrangle, NCGS Open-file Report 2019-06, scale 1:24,000

Bradley, P.J., Rice, A.K., Grimley, D.A. and Blocher, W.B., 2020, Geologic map of the Colon 7.5-Minute Quadrangle, Chatham and Lee counties, North Carolina: North Carolina Geological Survey Open-file Report 2020-04, scale 1:24,000, in color.

Bradley, P.J., Rice, A.K., and Grimley, D.A., 2021a, Geologic map of the Moncure 7.5-Minute Quadrangle, Chatham and Lee counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-01, scale 1:24,000, in color.

Bradley, P.J., Rice, A.K. Grimley, D.A., Hanna, H.D. and Malaska, M.J., 2021b, Geologic map of the of the Merry Oaks 7.5-minute Quadrangle, Chatham and Lee Counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-02, scale 1:24,000, in color (Supersedes Open-file Report 2012-02).

Bradley, P.J. (with contributions in alphabetical order from : Bechtel, R.; Blocher, W .B.; Butler, R.J.; Clark, T.W .; Gay, N.K.; Grimley, D.A.; Hanna, H.D.; Malaska, M .J.; Peach, B.T.; Rice , A.K.; Stoddard , E.F.; and Watson, M.E.), 2022, Compiled Geologic map of Chatham County and surrounding areas, North Carolina: North Carolina Geological Survey Open-file Report 2022-03, scale 1:50,000, in color. <https://deg.nc.gov/energy-mineral-and-land-resources/geological-survey/ofrs-geological-survey/geologic-map-chatham-county-and-surrounding-areas-north-carolina>

Butler, J.R., Clark, T.W. and Gay, N.K., 2016, Geologic map of the Cokesbury 7.5-minute quadrangle, NCGS Open-file Report 2016-22, scale 1:24,000

Campbell, M.R., and Kimball, K.W., 1923, The Deep River coal field of North Carolina: North Carolina Geological and Economic Survey Bulletin 33, 95 p.

Clark, T.W., 1998, Fault-bend folding in the southern Durham Triassic basin, North Carolina, unpublished M.S. Thesis: Durham, North Carolina, Duke University, 84 p.

Clark, T.W., 1999, "America's First State Geologic Map" – poster celebrating the North Carolina Geological Survey's 175th Anniversary, North Carolina Geological Survey.

Clark, T.W., Gore, P.J., and Watson, M.E., 2001, Depositional and structural framework of the Deep River Triassic basin, North Carolina, *in* Hoffman, C.W., ed. Field Trip Guidebook for the 50th Annual Meeting of the Southeastern Section, Geological Society of America, Raleigh, North Carolina, p. 27-50. (re-printed in Carolina Geological Society Field Trip Guidebook 2011)

- Clark, T.W., Blake, D.E., Stoddard, E.F., Carpenter, P.A., III, and Carpenter, R.H., 2004, Preliminary bedrock geologic map of the Raleigh 30' x 60' quadrangle, North Carolina: North Carolina Geological Survey Open-file Report 2004-02, scale 1:100,000, in color.
- Clark, T.W., Taylor, K.B., Bradley, P.J., 2011, Geology, natural gas potential and mineral resources of Lee, Chatham and Moore counties, North Carolina, Carolina Geological Society field trip guidebook for 2011, 49 p.
- Conley, J.F., 1962, Geology and mineral resources of Moore County, North Carolina: Division of Mineral Resources, North Carolina Department of Conservation and Development, Bulletin 76, 40 p.
- Eligman, D., 1987, Volcanic stratigraphy in the Carolina slate belt near Chapel Hill, North Carolina, unpublished M.S. thesis, University of North Carolina at Chapel Hill, 51 p.
- Emmons, E., 1856, Geological Report of the Midland Counties of North Carolina: North Carolina Geological Survey, Miscellaneous Publication.
- Farrar, S.S., 1985, Stratigraphy of the northeastern North Carolina Piedmont: Southeastern Geology, v. 25, no. 3, p. 159-183.
- Goldberg, S. A., 1994, U-Pb geochronology of volcanogenic terranes of the eastern North Carolina Piedmont: preliminary results, *in* Stoddard, E.F. and Blake, D. E., eds., Geology and Field Trip Guide, Western Flank of the Raleigh metamorphic belt, North Carolina, Raleigh, North Carolina Geological Survey, Carolina Geological Society Guidebook for 1994, p. 13-17.
- Goliber, S.F.B., 2020, Assessment of the Timing of the Virgilina Deformation with U-Pb Ages of Plutonic and Volcanic Rocks in the Carolina Terrane (unpublished undergraduate thesis), University of North Carolina Chapel Hill, p. 14.
- Glover, L., and Sinha, A., 1973, The Virgilina deformation, a late Precambrian to Early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina, American Journal of Science, Cooper v. 273-A, pp. 234-251.
- Green, G., 1977, The geology of the slate belt rocks of the Goldston and Bear Creek quadrangles, North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina, 68 p.
- Green, G., Cavaroc, V., Stoddard, E., Abdelzahir, A., 1982, Volcanic and volcanoclastic facies in a part of the slate belt of North Carolina, In: Bearce, D., Black, W., Kish, S., Tull, J. (Eds.), Tectonic studies in the Talladega and Carolina slate belts, Southern Appalachian Orogen. Geological Society of America Special Paper, vol. 191, pp.109– 124.
- Grimley, D.A., 2023, Quaternary terraces and deposits in Chatham County area, North Carolina, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.
- Harris, C.W., 1984, Coarse-grained submarine-fan deposits of magmatic arc affinity in the late Precambrian Aaron Formation, North Carolina, U.S.A., Precambrian Research, 26, pp. 285-306.

Hanna, H.D., and Bradley, P.J., 2014, Geologic Map of the Chatham County Portion of the Silk Hope Quadrangle, NCGS Open-file Report 2014-02, scale 1:24,000

Hanna, H.D., Bradley, P.J., and Bechtel, R., 2015, Geologic Map of the Siler City NE 7.5 Minute Quadrangle, NCGS Open-file Report 2015-02, scale 1:24,000

Harris, C., and Glover, L., 1985, The Virgilina deformation: implications of stratigraphic correlation in the Carolina slate belt, Carolina Geological Society field trip guidebook, 36 p.

Harris, C., and Glover, 1988, The regional extent of the ca. 600 Ma Virgilina deformation: implications of stratigraphic correlation in the Carolina terrane, Geological Society of America Bulletin, v. 100, pp. 200-217.

Hauck, S.A., 1977, Geology and petrology of the northwest quarter of the Bynum quadrangle, Carolina slate belt, North Carolina, unpublished M.S. thesis, University of North Carolina at Chapel Hill, 146 p.

Heckert, A.B., Mitchell, J.S., Schneider, V.P., Olsen, P.E., 2012, Diverse New Microvertebrate Assemblage from the Upper Triassic Cumnock Formation, Sanford Subbasin, North Carolina, USA, *Journal of Paleontology* 2012; 86 (2): 368–390. doi: <https://doi.org/10.1666/11-098.1>

Hibbard, J., and Samson, S., 1995, Orogenesis exotic to the Iapetan cycle in the southern Appalachians, In, Hibbard, J., van Staal, C., Cawood, P. editors, *Current Perspectives in the Appalachian– Caledonian Orogen*. Geological Association of Canada Special Paper, v. 41, pp. 191–205.

Hibbard, J., Stoddard, E.F., Secor, D., Jr., and Dennis, A., 2002, The Carolina Zone: Overview of Neoproterozoic to early Paleozoic peri-Gondwanan terranes along the eastern flank of the southern Appalachians: *Earth Science Reviews*, v. 57, n. 3/4, p. 299-339.

Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian Orogen, Canada-United States of America, Geological Survey of Canada, Map-2096A. 1:1,500,000-scale.

Hibbard, J.P., van Staal, C.R., and Rankin, D.W., 2010, Comparative analysis of the geological evolution of the northern and southern Appalachian orogen: Late Ordovician-Permian: in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*: Geological Society of America Memoir 206, p. 51-69.

Hibbard, J.P., Miller, B.V., Allen, J.S., Standard, I.D., Hames, W.E., Lavallee, S.B., and Boland, I.B., 2012, Kinematics, U-Pb geochronology, and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of the Gold Hill shear zone, North Carolina: the Cherokee orogeny in Carolina, southern Appalachians. *Geological Society of America Bulletin*, v. 124, p.643-656.

Hibbard, J.P., Pollock, J.C., and Bradley, P.J., 2013, One arc, two arcs, old arc, new arc: An overview of the Carolina terrane in central North Carolina, Carolina Geological Society field trip guidebook, 265 p.

- Hicks, H.T., Jr., 1982, Geology and ore genesis of the Buckhorn District iron deposits, unpublished M.S. Thesis, Raleigh, North Carolina, North Carolina State University, 164p.
- Hoffman, C.W., and Gallagher, P.E., 1989, Geology of the Southeast and Southwest Durham 7.5 minute quadrangles, North Carolina: North Carolina Geological Survey Bulletin 92, 34 p.
- Hughes, E.H., 1987, The geology and hydrothermal alteration centers of the Snow Camp Mine-Major Hill area, central Carolina slate belt, Alamance and Chatham Counties, North Carolina: U.S. Geological Survey, Open-File Report OF-87-180, scale 1:24000.
- Kerr, W.C. and Hanna, G.B., 1893, Ores of North Carolina, North Carolina Geological Survey, Volume II, Chapter 2, 359 p.
- Klein, T.L., 1985, Glendon Pyrophyllite deposits – Stops 2-10, *in* Feiss, P.G., editor, Volcanic-hosted gold and high-alumina rocks of the Carolina slate belt, guidebook for the field trip held in conjunction with the 1985 fall meeting of the Society of Economic Geologists and the 1985 annual meeting of the Geological Society of America, Orlando, Florida, p. 48-72.
- Moore, B.R., 1980, Investigations of a felsic flow, northern Moore County, North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina 70 p.
- Morrison, D.J., and Coleman, D, 2023, Absolute age determination of the Parks Crossroads granodiorite of the Carolina terrane, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.
- Moye, R.J., 2023a, Introduction to: The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and metallogenic Analysis with an alternative model, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.
- Moye, R.J., 2023b, The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and metallogenic analysis with an alternative model, *in* Supplemental Papers, Carolina Geological Society Annual Meeting 2023, p. 1-82.
- North Carolina Geological Survey (NCGS), 1985, Geologic Map of North Carolina: Raleigh, North Carolina Department of Natural Resources and Community Development, Geological Survey Section, scale 1:500,000, in color.
- Nixon, E.C., 1954, Geology of the Harpers Crossroads area, southwestern Chatham County, North Carolina: Unpublished M.S. Thesis, North Carolina State College, Raleigh, 39 p.
- Olmsted, D., 1820, Red sandstone formation of North Carolina: American Journal of Science, 1st series, v. 2, n. 2, p. 175-176.
- Olmsted, D., 1825, Geological Map of North Carolina, in the North Carolina State Archives, <https://dc.lib.unc.edu/cdm/ref/collection/ncmaps/id/8417>

- Olsen, Paul E.; Reid, Jeffrey C.; Taylor, Kenneth B.; Whiteside, Jessica H.; Kent, Dennis V., 2015, Revised Stratigraphy of Late Triassic Age Strata of the Dan River Basin (Virginia and North Carolina, USA) Based on Drill Core and Outcrop Data, *Southeastern Geology*, V. 51, No. 1, p. 1-31.
- Parker, J.M., 1979, Geology and mineral resources of Wake County: North Carolina Geological Survey Bulletin 86, 122 p., 1:100,000-scale map.
- Pelt, K.E. and Bradley, P.J., 2023, Preliminary detrital zircon data from Chatham County, NC, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.
- Pollock, J. C., 2007, The Neoproterozoic-Early Paleozoic tectonic evolution of the peri-Gondwanan margin of the Appalachian orogen: an integrated geochronological, geochemical and isotopic study from North Carolina and Newfoundland. Unpublished PhD dissertation, North Carolina State University, 194 p.
- Pollock, J.C., Hibbard, J.P., and Sylvester, P.J., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina: in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 739-772.
- Powers, J.A., 1985, Mineralization and alteration associated with breccia pipe structures, Haw Branch Copper Deposit, Moore County, North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina, 105 p.
- Powers, J.A., 1993, Manuscript map of the Rodger's Creek project, Chatham and Moore Counties, Bear Creek 7.5 minute quadrangle, scale: 1 inch = 500 feet, unpublished data.
- Ragland, P.C. and Butler, J.R., 1972, Crystallization of the West Farrington pluton, North Carolina, U.S.A., *Journal of Petrology*, vol. 13, No. 3, pp. 381-404.
- Rapprecht, R.M., 2010, A study of Late-Proterozoic host rocks, the style of mineralization and alteration and their timing at the Deep River Gold Prospect, central North Carolina, unpublished M.S. thesis, University of North Carolina, Chapel Hill, North Carolina, 117 p.
- Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geol. Survey Prof. Paper 246, 159 p.
- Rice, A.K., Bradley, P.J., Grimley, D.A., and W.B. Blocher. 2020. Geologic Map of the Goldston 7.5-Minute Quadrangle, Chatham, Lee and Moore Counties, North Carolina, North Carolina Geological Survey Open File Report 2020-06.
- Samson, S.D., Secor, D.T, and Hamilton, M.A., 2001, Wandering Carolina: Tracking exotic terranes with detrital Zircons, *GSA Abstracts with Programs* Vol. 33, No. 6, p. A-263.

- Schmidt, R.G., Gumiel, P., and Payas, A., 2006, Geology and mineral deposits of the Snow Camp-Saxapahaw area, Central North Carolina: United States Geological Survey Open-file Report 2006-1259 (<http://pubs.usgs.gov/of/2006/1259/index.html>).
- Stirewalt, G.L., Harper, S.B. and Spruill, R., 1981, Mesoscopic structure and geochronology of the Buckhorn pluton and enveloping rocks of the Raleigh belt Chatham County, North Carolina - Evidence for late Paleozoic movement in the eastern Piedmont: Geological Society of America Abstracts with Programs, Southeastern Section, v.13, no.1, p.36.
- Stuckey, J.L., 1928, Pyrophyllite deposits of North Carolina: North Carolina Department of Conservation and Development, Bulletin 37, 62 p.
- Smoot, J.P., Froelich, A.J., and Luttrell, G.W., 1988, Uniform symbols for the Newark Supergroup, in Froelich, A.J., and Robinson, G.R., Jr., eds., Studies of the early Mesozoic basins of the eastern United States, US Geological Survey Professional Paper 1776, p. 1-6.
- Tadlock, K.A., and Loewy, S.L., 2006, Isotopic characterization of the Farrington pluton: constraining the Virgilina orogeny, in Bradley, P.J., and Clark, T.W., editors, The Geology of the Chapel Hill, Hillsborough and Efland 7.5-minute Quadrangles, Orange and Durham Counties, Carolina Terrane, North Carolina, Carolina Geological Society Field Trip Guidebook for the 2006 annual meeting, pp. 17-21.
- Thompson, G.J., Michael, E.K., Rice, A.K. and Bradley, P.J., 2023, Updated compiled structural data from Chatham County, North Carolina – Utilizing GIS to unravel structural geology problems, in Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.
- Tingle, T.N., 1982. Geology and geochronology of the Parks Crossroads granodiorite near Siler City, central North Carolina Piedmont. *Southeastern Geology*, vol. 23, p. 117- 122.
- Wagener, H.D., 1965, Areal modal variation in the Farrington igneous complex, Chatham and Orange Counties, North Carolina, *Southeastern Geology*, v. 6, no. 2, p. 49-77.
- Wagener, H.D., 1964, Areal modal variation in the Farrington igneous complex, Chatham and Orange counties, North Carolina, unpublished M.S. thesis, University of North Carolina at Chapel Hill, 51 p.
- Watson, M.E., 1998, Geologic map of Green Level 7.5-minute Quadrangle, Chatham, Wake and Durham Counties, North Carolina: North Carolina Geological Survey Open-file Report 98-3, scale 1:24,000, in color.
- Wilkinson, S.E., 1978, The geology of the northeast quarter of the Silk Hope quadrangle, Carolina Slate belt, North Carolina, unpublished M.S. thesis, University of North Carolina at Chapel Hill, 56 p.
- Wilson, W.F. and Carpenter, P.A., 1975 (updated 1981), Geologic Map of Region J (Chatham, Durham, Johnston, Lee, Orange and Wake counties, North Carolina): North Carolina Geological Survey, Open-File Report 81-5 and accompanying report of Regional Geology Series.

Wilson, W.F., and Carpenter, P.A., 1981, Geology and Land Use Chatham County, Including Geologic Map of Chatham County, scale 1:125,000, North Carolina Geological Survey Open file report 81-2.

Wortman, G.L., Samson, S.D., and Hibbard, J.P., 2000, Precise U-Pb zircon constraints on the earliest magmatic history of the Carolina terrane, *Journal of Geology*, v. 108, pp. 321-338.

Updated Compiled Structural Data for Chatham County, North Carolina – Utilizing GIS to Unravel Structural Geology Problems

Garett J. Thompson, Emily K. Michael, Aaron K. Rice, and Philip J. Bradley.
North Carolina Geological Survey, Raleigh, NC 27699-1620,
garett.thompson@deq.nc.gov and pbradley@deq.nc.gov

Background

The North Carolina Geological Survey (NCGS) recently concluded detailed geologic mapping in Chatham County, NC with partial support from STATEMAP. We have collected structural data from parts of 19 quadrangles by 12 geologists over a 25-year period. This data has been compiled into one GIS database currently consisting of 22,019 data points contained within Chatham County. This dataset includes over 759 primary features, 3,318 foliation measurements, and 5,253 joints. This data, used in conjunction with the detailed geology polygons, has great potential for various structural analyses over larger areas and provides the ability to easily share the dataset with collaborators. Versions of this dataset have been previously presented by Michael et al. (2023) and Rice and Bradley (2019). This paper presents an update to those works.

Geology

The Carolina terrane underlies the western two-thirds of Chatham County and is composed of Neoproterozoic to Cambrian metamorphosed volcanic, volcano-sedimentary, sedimentary, and intrusive rocks (Hibbard et al., 2002; and Hibbard et al., 2006) (Figure 1). The Carolina terrane is separated into three lithotectonic units: 1) the Hyco arc, 2) the Aaron Formation of the redefined Virgilina sequence (Hibbard et al., 2013) and 3) the Albemarle arc (Hibbard et al., 2013) (Figure 2). The southeastern corner of the county is underlain by metamorphosed crystalline rocks of the Easternmost Carolina terrane. The northeastern and south-central portions of the county are underlain by Triassic sedimentary rocks of the Deep River Triassic basin (Figures 1 and 2). Abundant evidence of brittle faulting at the outcrop scale and large-scale lineaments are present in the map area, both of which are interpreted to have originated from Mesozoic extension. Diabase dikes of Jurassic age intrude the crystalline rocks of the map area, some of them through these faults and lineaments.

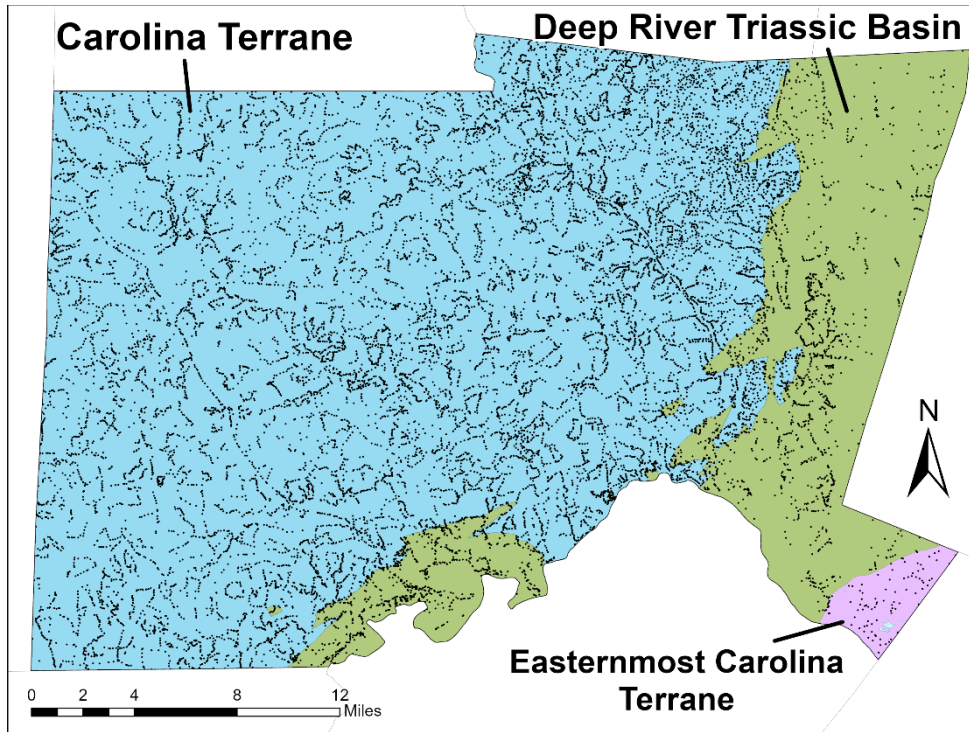


Figure 1: Location of 22,019 data points on a base map showing the major geologic elements in Chatham County. Points include float and outcrop with measurements of primary planar features, metamorphic features, and brittle features.

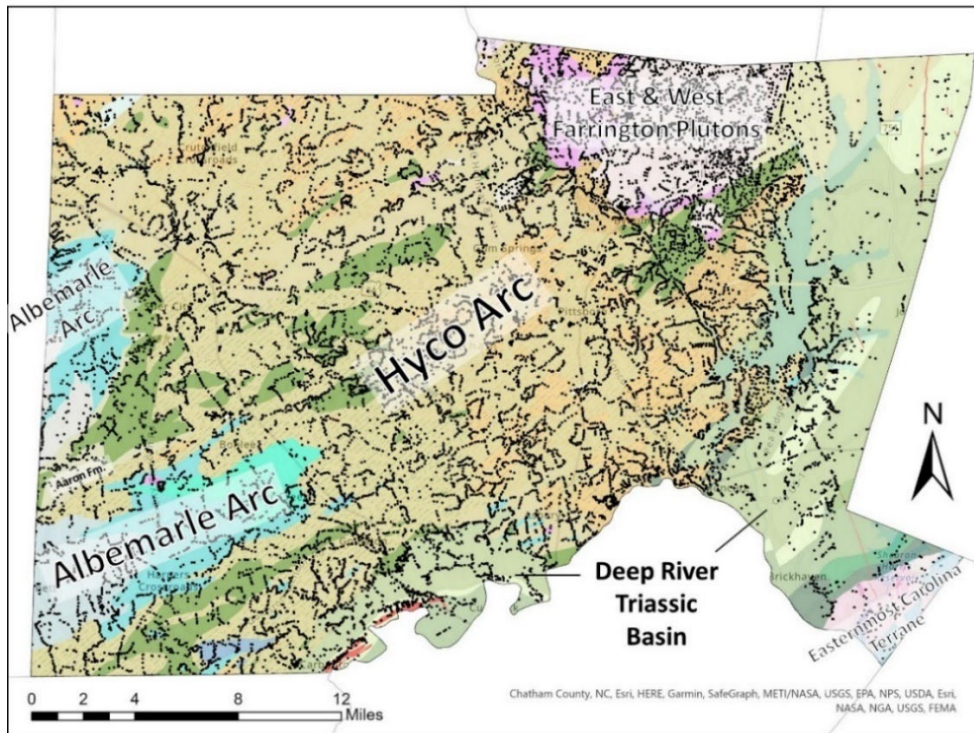


Figure 2: Location of 22,019 data points on a base map of the compiled geologic map of Chatham County. Major lithotectonic units of the Carolina terrane and other major geologic elements labeled.

Data Plots and General Observations

Multiple plots displaying primary features (ex. bedding, layering and compaction/welding foliation), metamorphic foliations, joint/fracture data and stereograms are provided (Figures 3 – 13). Generalized observations and comments gleaned from the plots are summarized in Table 1-3.

Table 1 – Primary Features - Summary of observations and comments

Figure	Observation	Comments
3	<p>Primary bedding and layering measurements are concentrated within volcanosedimentary units along the flanks of volcanic centers.</p> <p>Primary bedding and layering measurements are sparse to absent in the rock types interpreted as volcanic centers (i.e. areas dominated by lavas and tuffs).</p>	The occurrence of preserved primary features is in areas dominated by volcanosedimentary rocks.
4	<p>Most primary planar features dip steeply (61° to 89°). Five areas of note are identified in this plot with a concentration of dips ranging from 1° - 30°.</p> <p>20% of measurements fall between 1° to 30°; 30% of measurements fall between 31° to 60°; 49% of measurements fall between 61° to 89°.</p>	These areas are consistent with orientations expected in a folded terrane.
5	Most primary planar features dip toward the northwest and southeast with less features dipping toward the northeast and southwest.	Consistent with orientations expected in a folded terrane with plunging folds to the northeast and southwest.
6	Stereogram of 837 contoured poles to planes of primary features has a best fit great circle plane of 332,86 with an approximate fold axis of 242,4(right-hand rule).	This stereogram includes data outside Chatham County.
7	Stereogram of 950 contoured poles to planes of Triassic bedding measurements.	The data is consistent with shallowly, southeasterly dipping beds. This stereogram includes data outside Chatham County.

Table 2 – Metamorphic Features – Summary of observations and comments

Figure	Observations	Comments
8	Metamorphic planar feature measurements throughout Chatham County generally trend northeast to southwest with some local variation.	
9	Red- and yellow-colored points highlight areas of anomalously low dip and areas of structural complexity. Two zones of low dips are concentrated along the southern border of the Carolina terrane in the Glendon and Moncure areas.	<i>Glendon area-</i> Likely due to Glendon-style faulting, where the dip of the foliation becomes progressively shallower approaching high-angle reverse faults. <i>Moncure area-</i> Interpreted to be related to block rotation due to Mesozoic faulting. See field trip stop 8, this volume.
10	Most metamorphic planar features dip northwest and southeast. Three areas of note are identified in this plot with a concentration of measurements dipping to the northeast and southwest.	Possible reorientation of foliation due to brittle faulting?
11	Stereogram of 3,843 contoured poles to planes of metamorphic planar feature measurements in the Carolina terrane. Most measurements are steeply dipping ($>80^\circ$) and generally strike $\sim 220^\circ$.	Regionally, the foliation measurements in the rocks of the Carolina terrane strike approximately 220° and dip steeply. This stereogram includes data outside Chatham County.

Table 3 – Brittle Features – Summary of observations and comments

Figure	Observations	Comments
13	Generally, there are two major perpendicular joint sets trending northwest-southeast and northeast-southwest.	

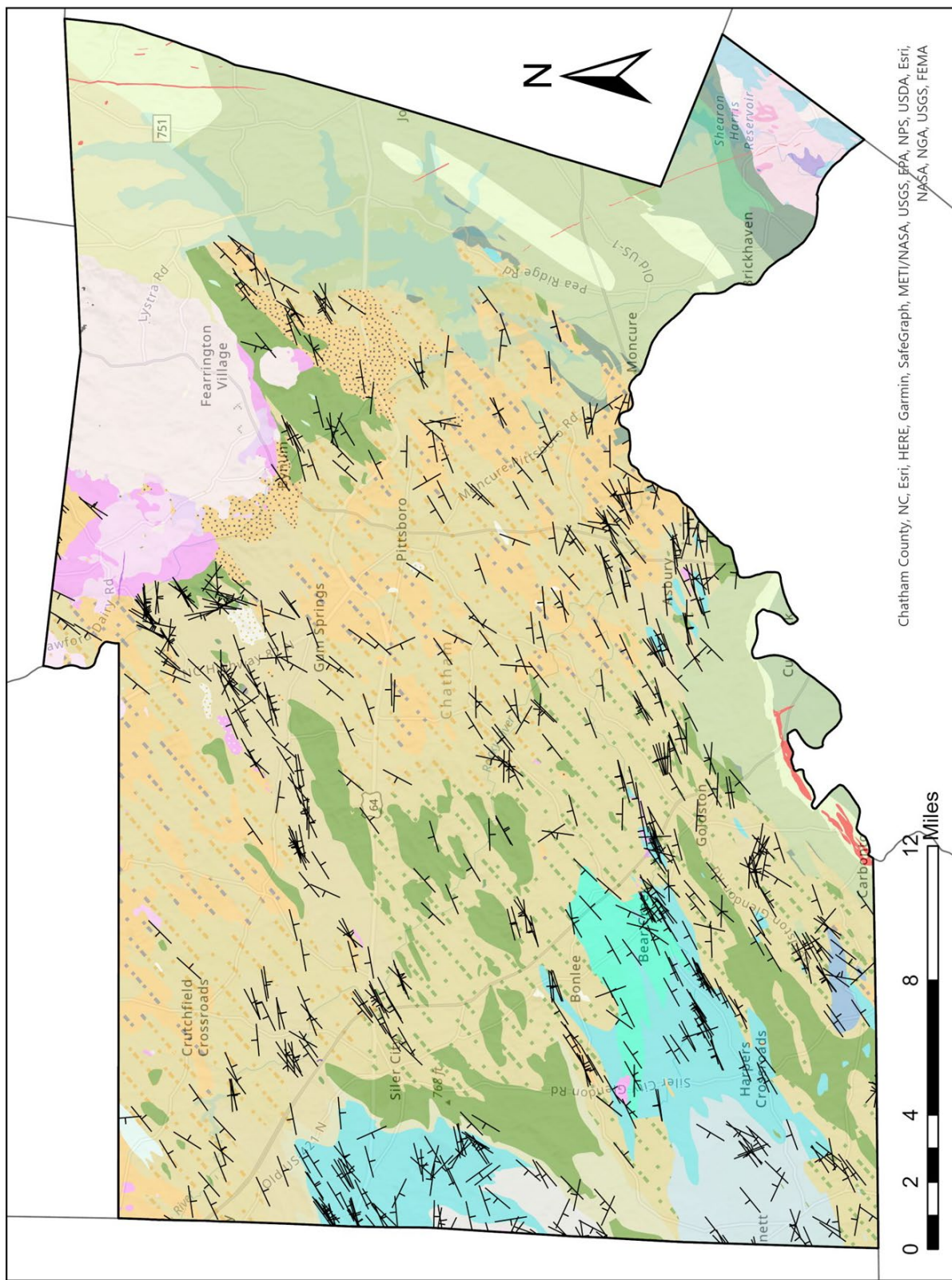


Figure 3: Orientation of 759 primary planar features that include bedding, layering, and welding/compaction foliation measurements. Bedding in the Triassic has been omitted.

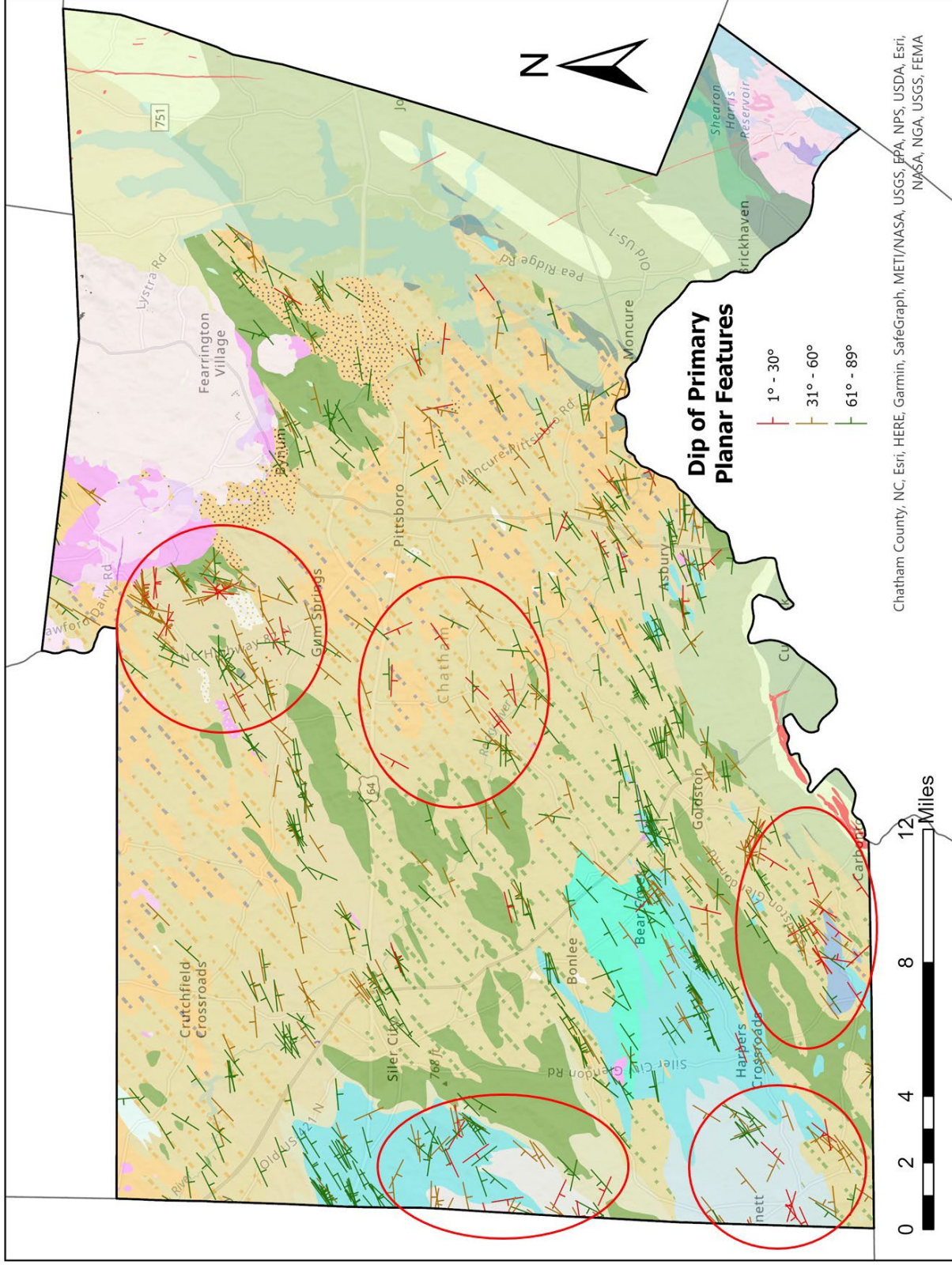


Figure 4: Orientation of 759 primary planar features that include bedding, layering, and welding/compaction foliation measurements color coded by the magnitude of the dip. 5 areas of low dips identified. Vertical dips (n=2) were not displayed.

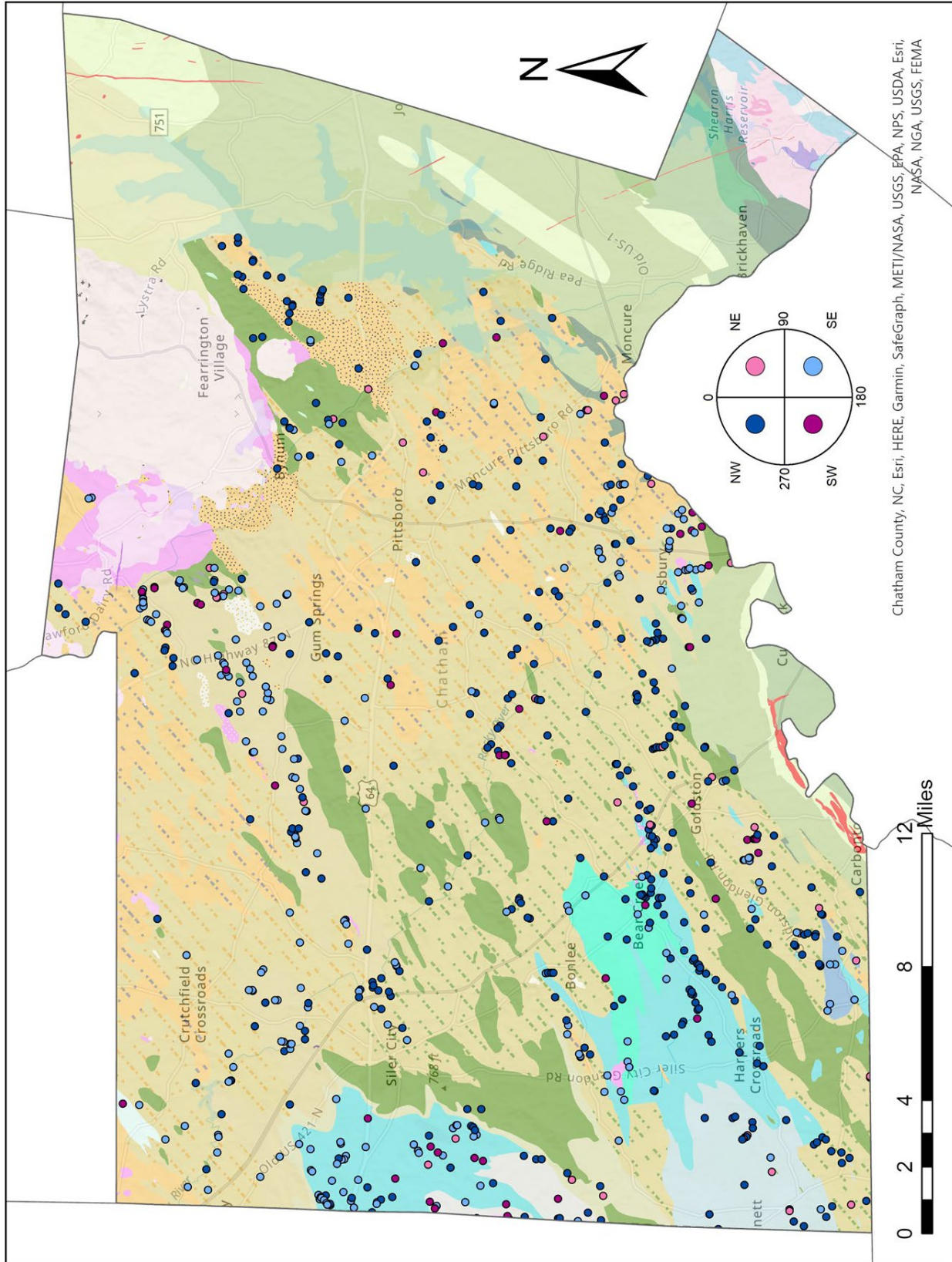


Figure 5: Point symbol map showing primary feature dip direction.

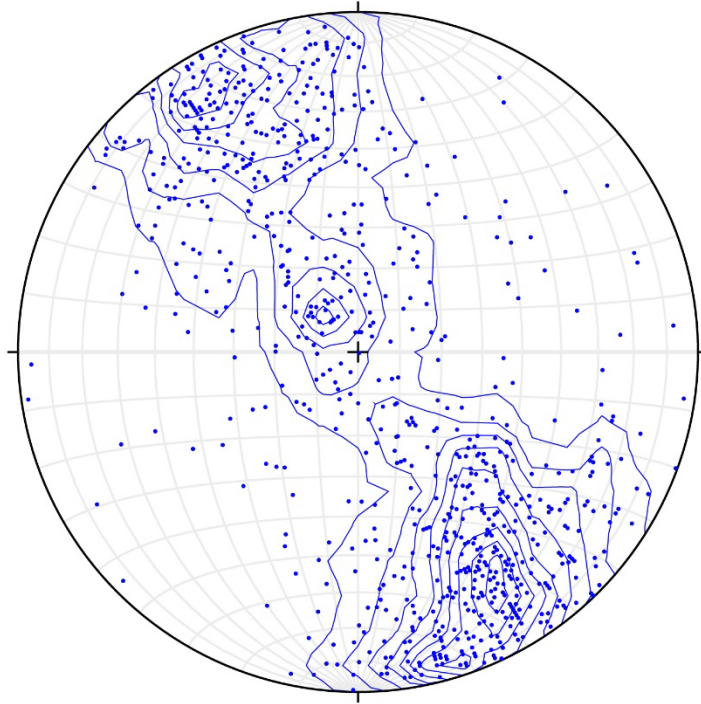


Figure 6: Equal area Schmidt net projection of contoured poles to primary planar features in the Carolina Terrane. Contour Interval = 2 sigma; N = 837.

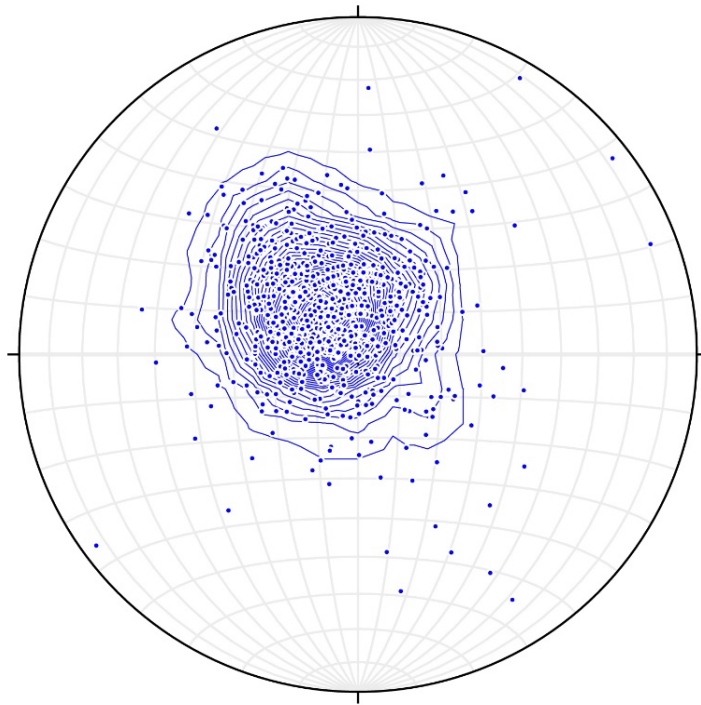


Figure 7: Equal area Schmidt net projection of contoured poles to primary planar features in the Deep River Triassic Basin. Contour Interval = 4 sigma; N = 950.

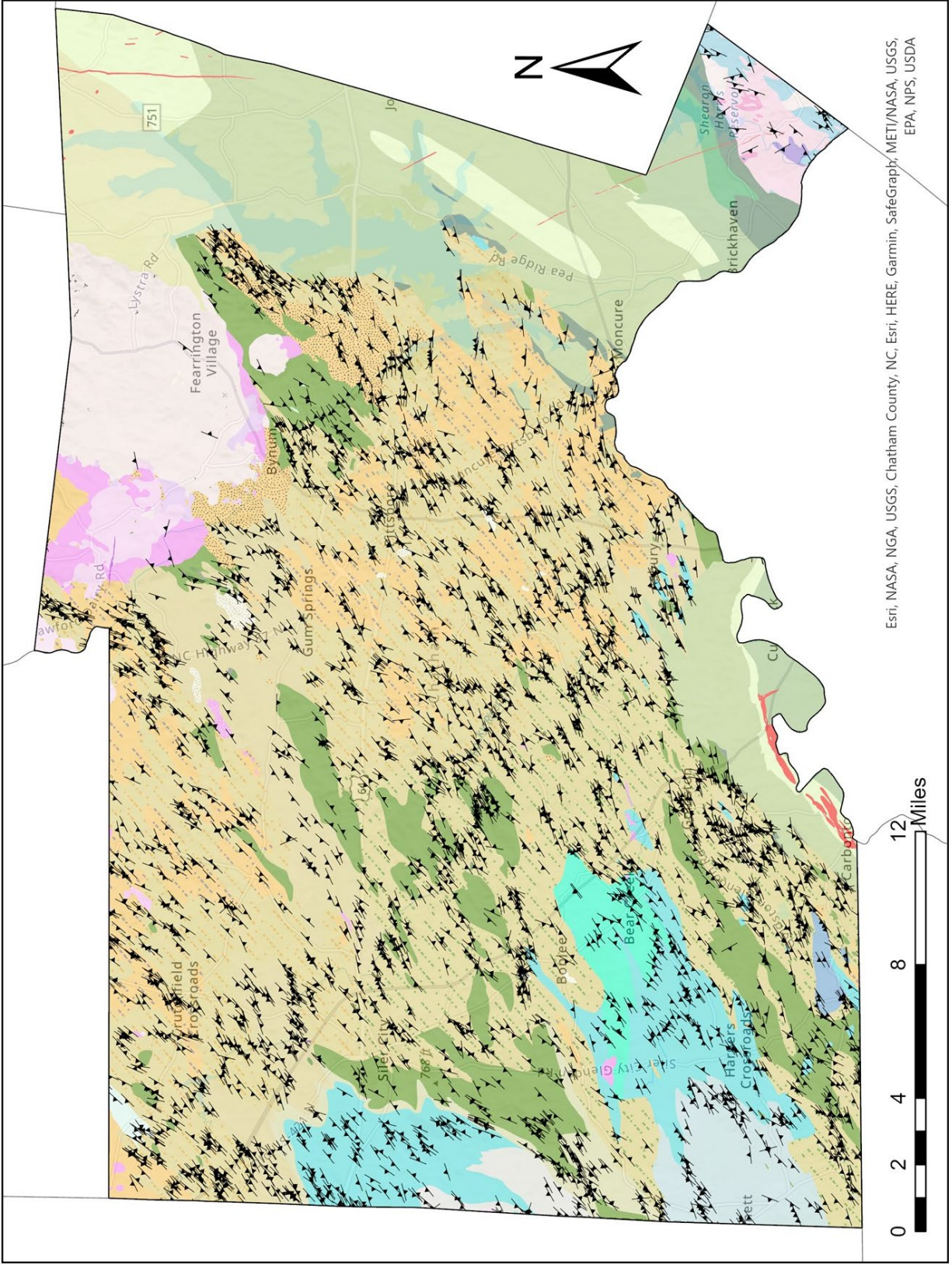


Figure 8: Orientation of 3,318 metamorphic planar features that include foliation, mylonitic foliation, and shear foliation.

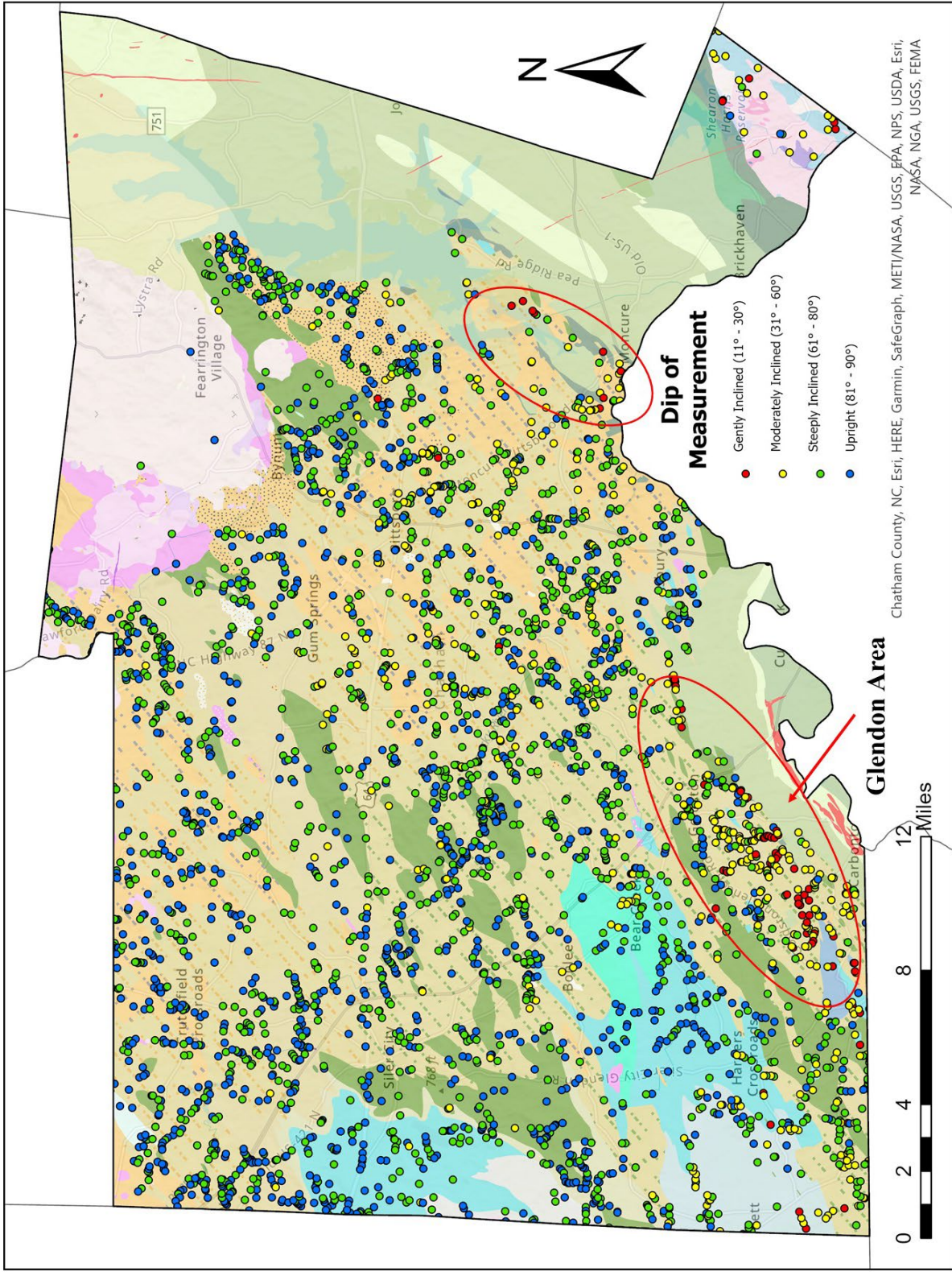


Figure 9: Point symbol map of metamorphic planar feature dip magnitudes. Classifications based on Fleuty (1964) fold axial surface orientation nomenclature.

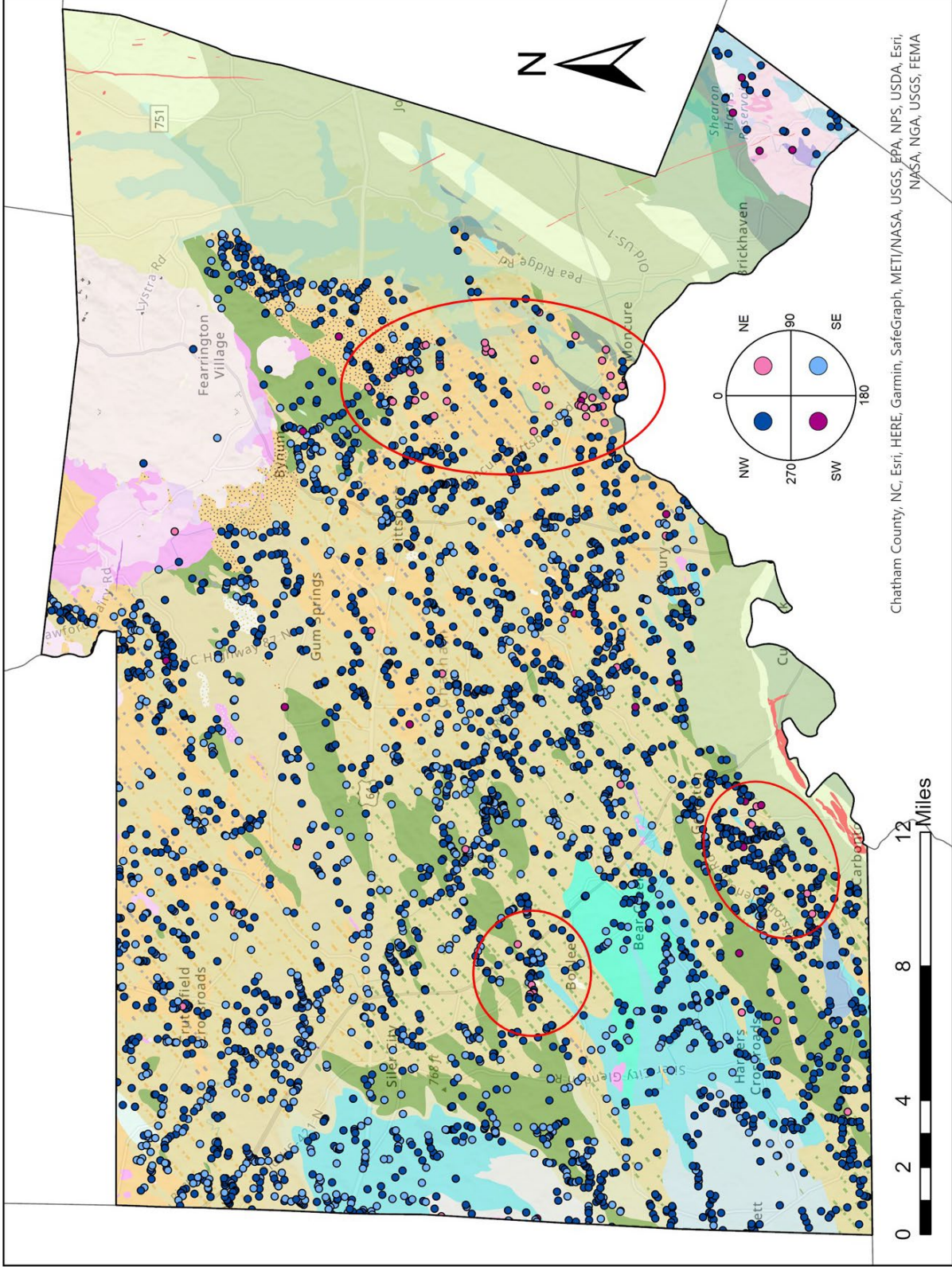


Figure 10: Point symbol map showing metamorphic feature dip direction. Three clusters of metamorphic features dipping northeast or southwest are identified.

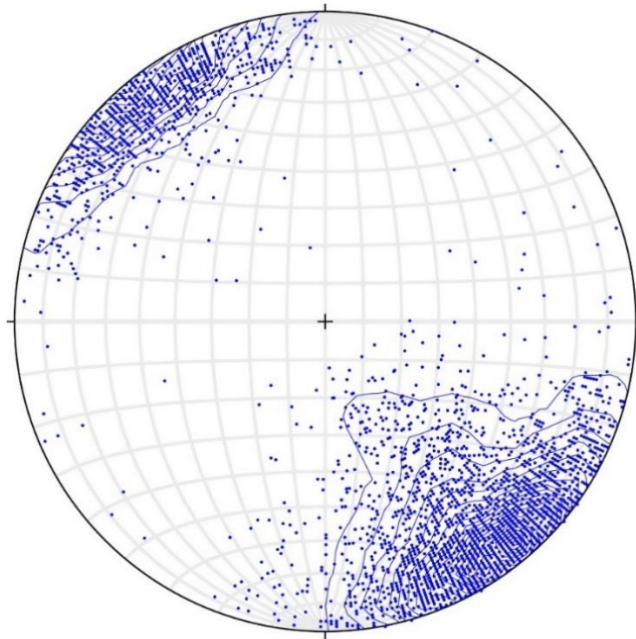


Figure 11: Equal area Schmidt net projection of contoured poles to metamorphic planar features in the Carolina Terrane. Contour Interval = 3 sigma; N = 3,843.

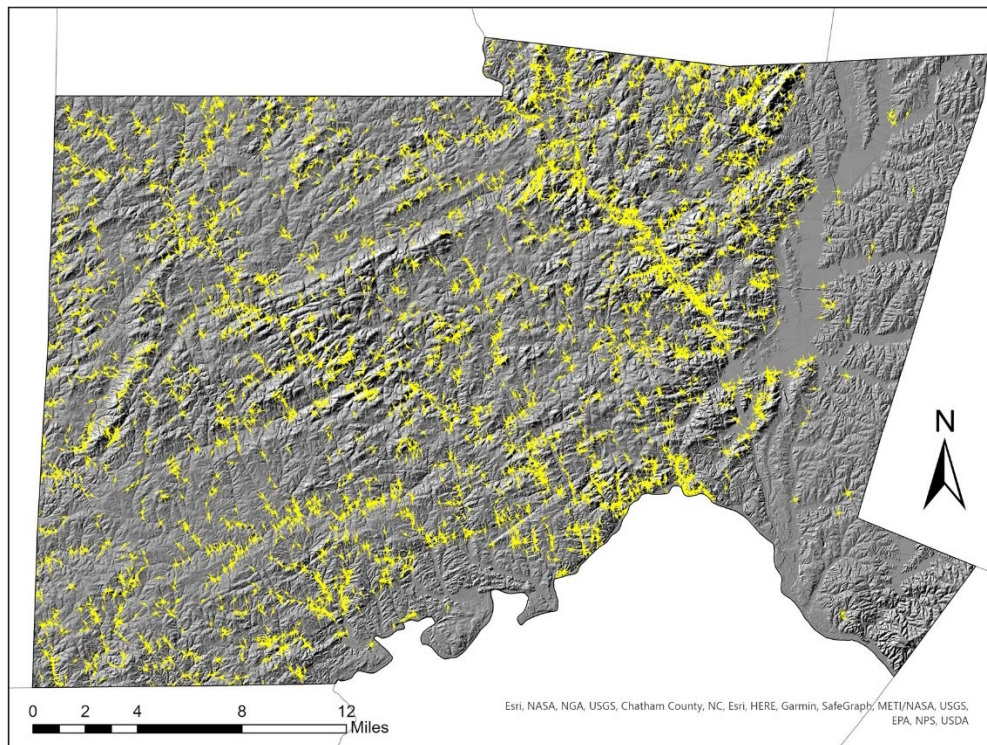


Figure 12: Orientation of 5,253 joint measurements.

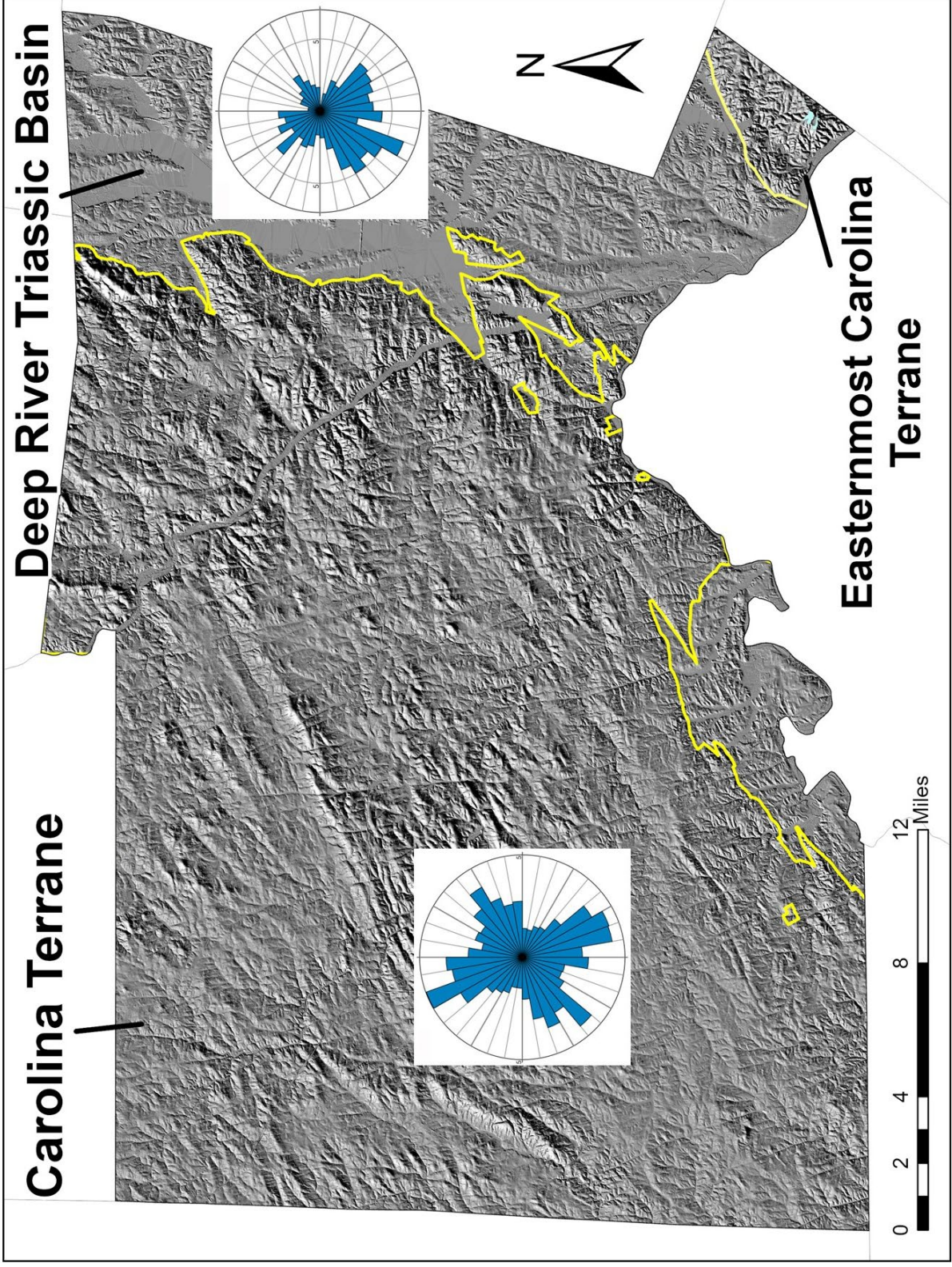


Figure 13: Hillshade LiDAR of Chatham County, NC with rose diagrams of joints in the Carolina and Easternmost Carolina terranes and the Triassic basin.

Acknowledgements

Stereogram plots and calculations were created using Stereonet v. 10.2.0 based on Allmendinger et al. (2013) and Cardozo and Allmendinger (2013). Color-coding of primary feature dip directions and metamorphic feature dip directions used in Figures 5 and 10 were inspired by Van Gool and Piazzolo (2006).

References

- Allmendinger, R. W., Cardozo, N. C., and Fisher, D., 2013, *Structural Geology Algorithms: Vectors and Tensors*: Cambridge, England, Cambridge University Press, 289 pp.
- Cardozo, N., and Allmendinger, R. W., 2013, Spherical projections with OSXStereonet: *Computers and Geosciences*, v. 51, no. 0, p. 193 - 205, doi: 10.1016/j.cageo.2012.07.021
- Fleuty, M.J., 1964, The description of folds. *Proc. Geol. Assoc.* 75: pg 461-492.
- Hibbard, J., Stoddard, E.F., Secor, D., Jr., and Dennis, A., 2002, The Carolina Zone: Overview of Neoproterozoic to early Paleozoic peri-Gondwanan terranes along the eastern flank of the southern Appalachians: *Earth Science Reviews*, v. 57, n. 3/4, p. 299-339.
- Hibbard, J. P., van Staal, C. R., Rankin, D. W., and Williams, H., 2006, Lithotectonic map of the Appalachian Orogen, Canada-United States of America, Geological Survey of Canada, Map-2096A. 1:1,500,000-scale.
- Hibbard, J.P., Pollock, J.C., and Bradley, P.J., 2013, One arc, two arcs, old arc, new arc: An overview of the Carolina terrane in central North Carolina, *Carolina Geological Society field trip guidebook*, 265 p.
- Michael, E.K., Rice, A.K., and Bradley, P.J., 2023, Compiled Structural data for Chatham County, NC – Utilizing GIS to unravel structural geology problems, *Geological Society of America Abstracts with Programs*. Vol. 55, No. 2, 2023 doi: 10.1130/abs/2023SE-385463 <https://gsa.confex.com/gsa/2023SE/meetingapp.cgi/Paper/385463>
- Rice, A.K. and Bradley, P.J., 2019, Compiled Structural data for Chatham County, NC – Utilizing GIS to unravel structural geology problems, *Geological Society of America Abstracts with Programs*, Vol. 51, No. 3, <https://gsa.confex.com/gsa/2019SE/meetingapp.cgi/Paper/326519>
- Van Gool, J. A., & Piazzolo, S., (2006), Presentation and interpretation of structural data from the Nagssugtoqidian orogen using a GIS platform: general trends and features, *GEUS Bulletin*, 11, 125–144, <https://doi.org/10.34194/geusb.v11.4921>

Preliminary Detrital Zircon Data from Chatham County, NC.

Katherine E. Pelt and Philip J. Bradley
North Carolina Geological Survey, Raleigh, NC 27699-1620,
kpelt@deq.nc.gov and pbradley@deq.nc.gov

Introduction

Staff from the North Carolina Geological Survey collected two samples for detrital zircon analysis in early 2022. The samples were forwarded to the Arizona LaserChron Center at the University of Arizona – Tucson, for processing and analysis by LA-ICPMS utilizing the methods from Gehrels and Ruiz (2008) and Gehrels and Pecha (2014).

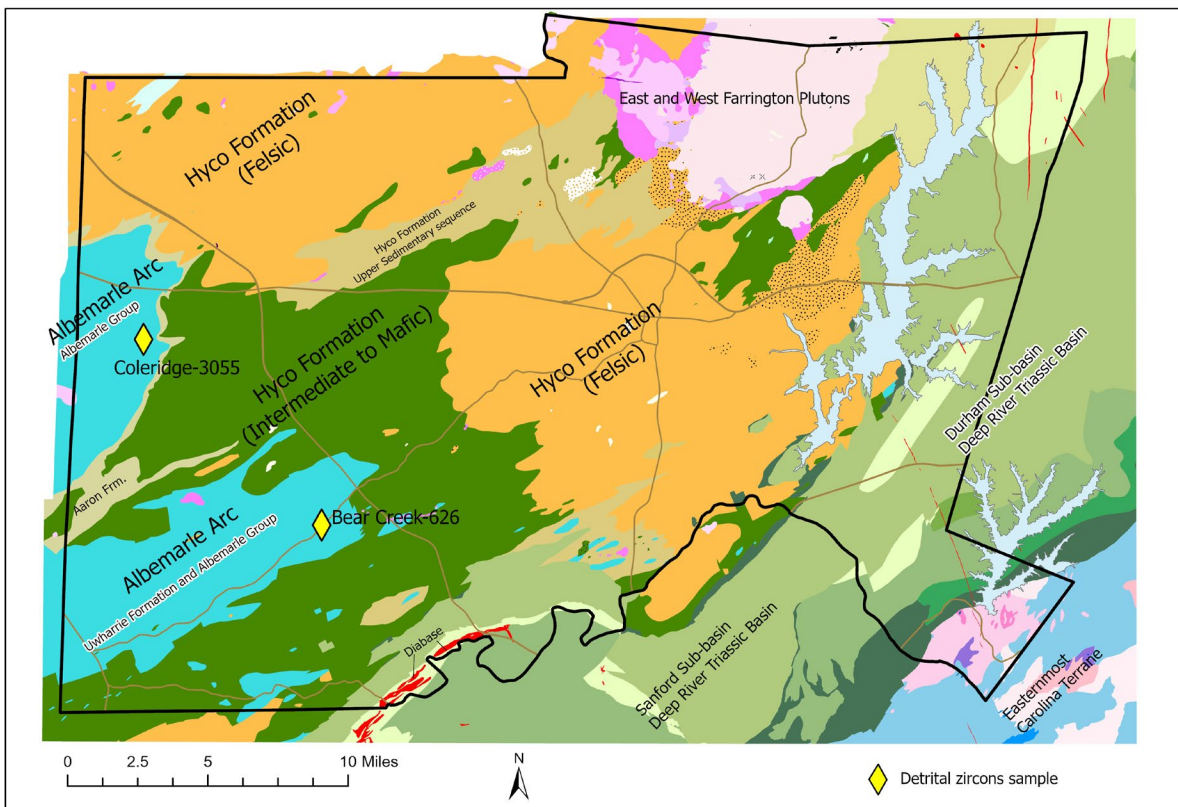


Figure 1: Location of detrital zircon samples and generalized geologic map of major formations in Chatham County and nearby areas.

Sample collection

Two samples, NCGS sample Coleridge-3055 (35.7081, -79.5044) and NCGS Sample Bear Creek-626 (35.6125, -79.39115) were collected (Figure 1). NCGS Sample Coleridge-3055 was sampled from an outcrop of metamorphosed tuffaceous sandstone with abundant plagioclase crystals and lesser amounts of quartz crystals adjacent to the Siler City airport within the Coleridge Quadrangle. NCGS Sample Bear Creek-626 was sampled from an outcrop of metamorphosed sandstone in a creek adjacent to Chatham Central High School in Bear Creek, NC within the Bear Creek Quadrangle.

Data

Coleridge-3055 contained 312 zircon grains. Of those 312 zircon grains that were analyzed, 264 zircons were between 90 – 110 % of concordia. Of the 264 grains within 10% of concordia, the $^{206}\text{Pb}/^{238}\text{U}$ ages range from 534.6 \pm 4.8 Ma to 2360.1 \pm 13.8 Ma. The four youngest detrital zircons were: ca. 534, 538, 538 and 538 Ma. Only 30 of the zircons were 554 Ma and younger (11%) and 126 zircons were between 555 Ma and 610 Ma (48%). Seventy-two (72) zircons were between 610 and 650 Ma (27%). Thirty-six (36) zircons were between 651 – 2360 Ma. (14%). Nineteen (19) zircons were less than 90% of concordance; 28 zircons were greater than 110% of concordance. One zircon within 92% concordance had a $^{206}\text{Pb}/^{238}\text{U}$ date of 304.8 \pm 1.8 Ma. These zircon results were not utilized in the data review.

Bear Creek-626 contained 316 zircon grains. Out of 316 grains, 212 fell within 90–110% of concordia. Of the 212 near concordia, the $^{206}\text{Pb}/^{238}\text{U}$ ages range from 535 \pm 3.7 Ma to 2671.1 \pm 12.7 Ma. From the zircon grains near concordia, the three youngest were: ca. 535, 535 and 536 Ma. Thirty-four (34) zircons were 554 Ma and younger (16%) and 161 zircons were between 555 Ma and 610 Ma (76%). Thirteen (13) zircons were between 610 and 650 MA (approx. 6%). Four (4) zircons were between 685 – 2671 Ma and were 685.7 \pm 5.0 Ma, 1255 \pm 12.51 Ma, 1420 \pm 10.1 Ma and 2671.1 \pm 12.7 Ma.

Eleven (11) zircons were less than 90% of concordance; 92 zircons were greater than 110% of concordance. These results were not utilized in the data review.

Detrital zircon plots using Microsoft Excel Spreadsheets

The detrital zircon data was graphically represented using the histogram tool within Microsoft Excel. Due to limitations of excel, a custom x-axis was created (Figure 2). The main intention of the plots is to show more refined resolution of data during the Hyco arc through the Albemarle arc time frames (ca. 633 to 530 Ma.). Accordingly, the plot of the NCGS sample Coleridge-3055 encompasses data spanning ca. 685 to 534 Ma, while the NCGS Sample Bear Creek-626 comprises data spanning ca. 686 to 535 Ma. Detrital zircon data older than 685 and 686 Ma (respectively) were not included in the plots.

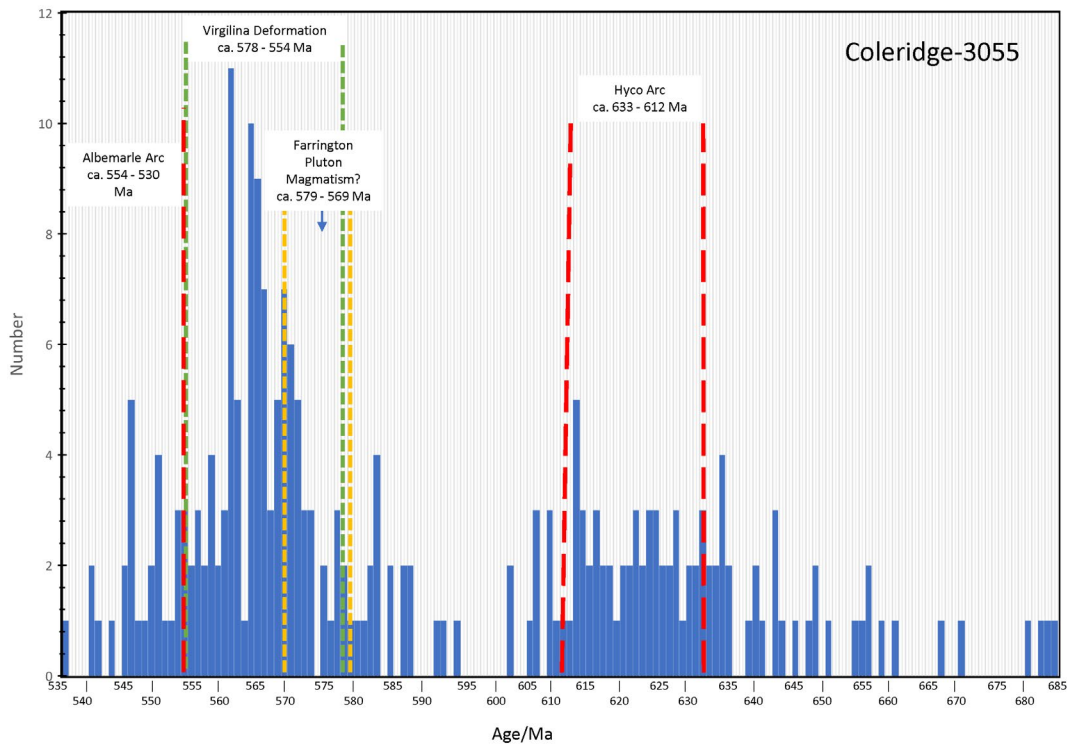
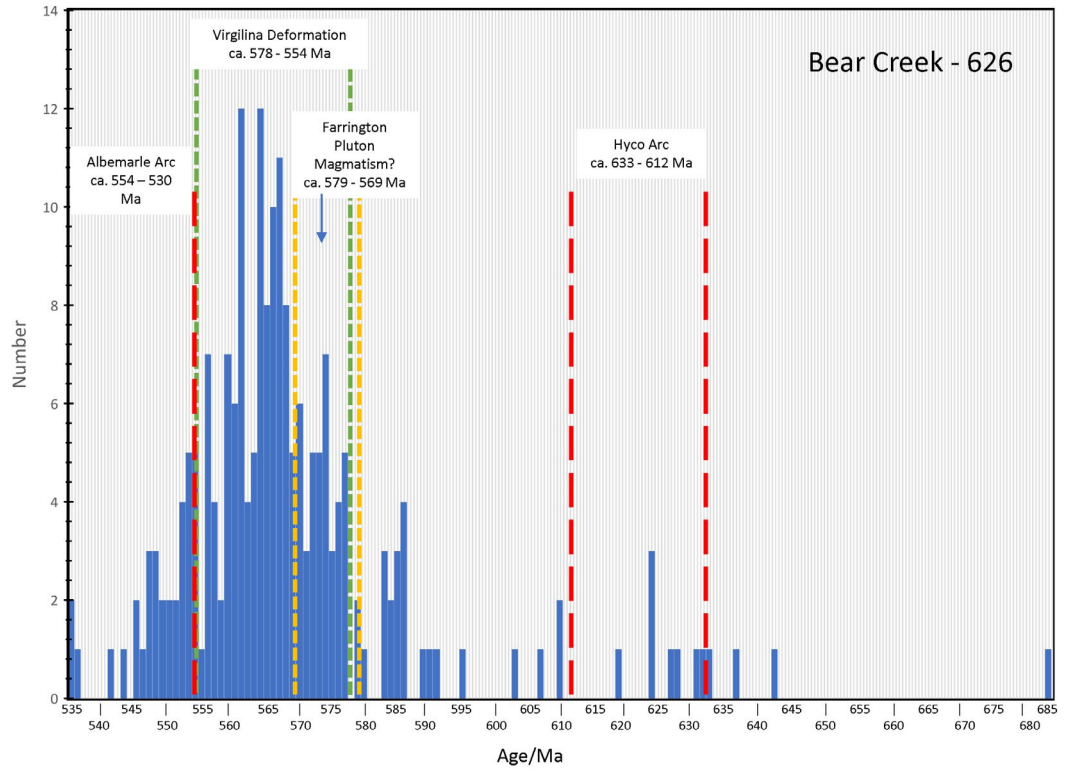


Figure 2: Detrital zircon plots for NCGS samples Coleridge-3055 and Bear Creek-626 with age ranges of the major arcs and/or magmatic and deformation events indicated.

The plots were annotated with reported age ranges of the major arcs and/or magmatic and deformation events and include: 1) the Hyco arc: ca. 633 - 612 Ma (Hibbard et al., 2013); 2) Farrington Pluton magmatism: ca. 579 Ma (Tadlock and Loewy, 2006) and ca. 569 Ma (Goliber, 2020); 3) Virgilina deformation: ca. 578 – 554 Ma (Pollock et al., 2010); and 4) Albemarle arc: ca. 554 – 530 Ma (Pollock et al., 2010).

Summary of plots

Coleridge-3055 results (includes zircons within 10% of concordia only)

28 zircons fell within Albemarle arc range (ca. 554 – 530 Ma)
25 zircons fell within Farrington pluton range (ca. 579 – 569 Ma)
99 zircons fell within Virgilina deformation range (ca. 578 – 554 Ma)
46 zircons fell within Hyco arc range (ca. 633 – 612 Ma)
32 zircons are older than 633 but younger than 686 Ma.
24 zircons are between 2361 – 686 Ma and are not on the plot

Bear Creek-626 results (includes zircons within 10% of concordia only)

29 zircons fell within Albemarle range (ca. 554 – 530 Ma)
44 zircons fell within Farrington pluton range (ca. 579 – 569 Ma)
145 zircons fell within Virgilina deformation range (ca. 578 – 554 Ma)
8 zircons fell within Hyco arc range (ca. 633 – 612 Ma)
4 zircons are older than 633 but younger than 686 Ma.
3 zircons are between 2672 – 686 Ma and are not on the plot

Discussion

Earlier NCGS mapping assigned NCGS sample Coleridge-3055 as part of the Aaron Formation (Bradley et al., 2018) and NCGS Sample Bear Creek-626 (Bradley et al., 2019) as part of the uppermost Hyco Formation. Upon analysis of the zircon data, the stratigraphic placement of these samples needs to be revised. Zircon data indicates that both samples and the units they represent are likely related to distal sedimentation associated with the Albemarle arc.

Major differences in the detrital zircon populations between NCGS samples Coleridge-3055 and Bear Creek-626 include the following: 1) a significant absence of zircons in the Hyco arc and older time frame in Bear Creek-626 and conversely 2) the presence of multiple zircons in the Hyco arc and older time frame in Coleridge-3055.

Figure 2 shows an apparent symmetrical peak of ca. 565 Ma near the middle of the zone identified as corresponding to the Virgilina deformation reported by Pollock et al. (2010).

Data Use

NCGS encourages other researchers to utilize this data. The raw data is available upon request. We ask that NCGS and STATEMAP are acknowledged if the data is published.

Acknowledgments

Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program under STATEMAP (Award 2021, G21AC10805). Thanks to Emily K. Michael for assistance with sample collection.

References

Bradley, P.J, Peach, B.T. and Hanna, H.D., 2018, Geologic map of the Chatham County portion of the Coleridge 7.5-minute Quadrangle, NCGS Open-file Report 2018-03, scale 1:24,000

Bradley, P.J., Rice, A.K. and Peach, B.T., 2019, Geologic map of the Bear Creek 7.5-Minute Quadrangle, NCGS Open-file Report 2019-06, scale 1:24,000

Gehrels, G.E., Valencia, V., Ruiz, J., 2008, Enhanced precision, accuracy, efficiency, and spatial resolution of U-Pb ages by laser ablation-multicollector-inductively coupled plasma-mass spectrometry: *Geochemistry, Geophysics, Geosystems*, v. 9, Q03017, doi:10.1029/2007GC001805.

Gehrels, G. and Pecha, M., 2014, Detrital zircon U-Pb geochronology and Hf isotope geochemistry of Paleozoic and Triassic passive margin strata of western North America: *Geosphere*, v. 10 (1), p. 49-65.

Goliber, S.F.B., 2020, Assessment of the Timing of the Virgilina Deformation with U-Pb Ages of Plutonic and Volcanic Rocks in the Carolina Terrane (unpublished undergraduate thesis), University of North Carolina Chapel Hill, p. 14.

Hibbard, J.P., Pollock, J.C., and Bradley, P.J., 2013, One arc, two arcs, old arc, new arc: An overview of the Carolina terrane in central North Carolina, *Carolina Geological Society field trip guidebook*, 265 p.

Pollock, J.C., Hibbard, J.P., and Sylvester, P.J., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina: in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206*, p. 739-772.

Tadlock, K.A., and Loewy, S.L., 2006, Isotopic characterization of the Farrington pluton: constraining the Virgilina orogeny, *in* Bradley, P.J., and Clark, T.W., editors, The Geology of the Chapel Hill, Hillsborough and Efland 7.5-minute Quadrangles, Orange and Durham Counties, Carolina Terrane, North Carolina, Carolina Geological Society Field Trip Guidebook for the 2006 annual meeting, pp. 17-21.

Absolute Age Determination of the Parks Crossroads Granodiorite of the Carolina Terrane

Dylan Jacob Morrison and Drew S. Coleman

Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, jacobmor@live.unc.edu and dcoleman@unc.edu

Abstract

New U-Pb zircon data for the Parks Crossroads pluton of the Carolina terrane yield a weighted mean age of 551.86 ± 0.88 Ma in good agreement with a previous Rb/Sr whole rock isochron age. This date suggests that the Parks Crossroads belongs to the Uwharrie Formation of the Albemarle arc. Moreover, the Parks Crossroads pluton is older than the surrounding sedimentary rocks that have a maximum depositional age of 534 Ma (Pelt and Bradley, 2023). Thus, the sedimentary unit has a disconformable depositional contact with the pluton, rather than an intrusive contact, as previously interpreted. This suggests that the sedimentary unit has affinity to the Albemarle arc.

Introduction

The Carolina terrane is an exotic superterrane thought to have formed as a volcanic island arc system that accreted with Laurentia in the Late Cambrian to Early Ordovician. Today, its arc rocks are exposed across North and South Carolina, extending into Georgia and Virginia. Major lithotectonic elements of the Carolina terrane include the Hyco arc, Virgilina sequence, and Albemarle arc. The Hyco arc is the older of the two magmatic arc sequences of this terrane. Formation of the Hyco arc and the younger Albemarle arc are interpreted to have been chronologically separated by the deposition of the dominantly sedimentary Virgilina sequence (including the sedimentary Aaron Formation and Virgilina Formation volcanic member), and an associated deformational event (Bowman et al., 2013). The oldest rocks in the Albemarle arc cut deformed rocks of the Virgilina sequence. The Uwharrie Formation, including volcanic and plutonic rocks, is the oldest formation of the Albemarle sequence (Hibbard et al., 2002).

Poor outcrop in eastern North Carolina often presents challenges to interpretation of geologic contacts and therefore, to interpretation of the geologic history of the region. An example of this ambiguity is the relationship of sedimentary rocks mapped as part of the Aaron Formation and the Parks Crossroads granodiorite, that is thought to be part of the younger Uwharrie Formation. As such, the Aaron Formation rocks are mapped as wall rocks to the younger Parks Crossroads pluton. This interpretation is complicated by the recent identification of detrital zircons from the rocks mapped as Aaron Formation that require them to be younger than the Uwharrie rocks (Pelt and Bradley, 2023). Specifically, detrital zircon U-Pb ages suggest a maximum depositional age of 534 Ma. Thus, if the Parks Crossroads granodiorite is a Uwharrie pluton, and the detrital zircon geochronology stands to further scrutiny, it is more likely that the sedimentary rocks are

part of a previously unrecognized unit that was deposited unconformably on the pluton. To test this hypothesis, we obtained a modern, thermal-annealing, chemical-abrasion, isotope dilution, thermal ionization mass spectrometry (TA-CA-ID-TIMS) U-Pb date for the Parks Crossroads granodiorite.

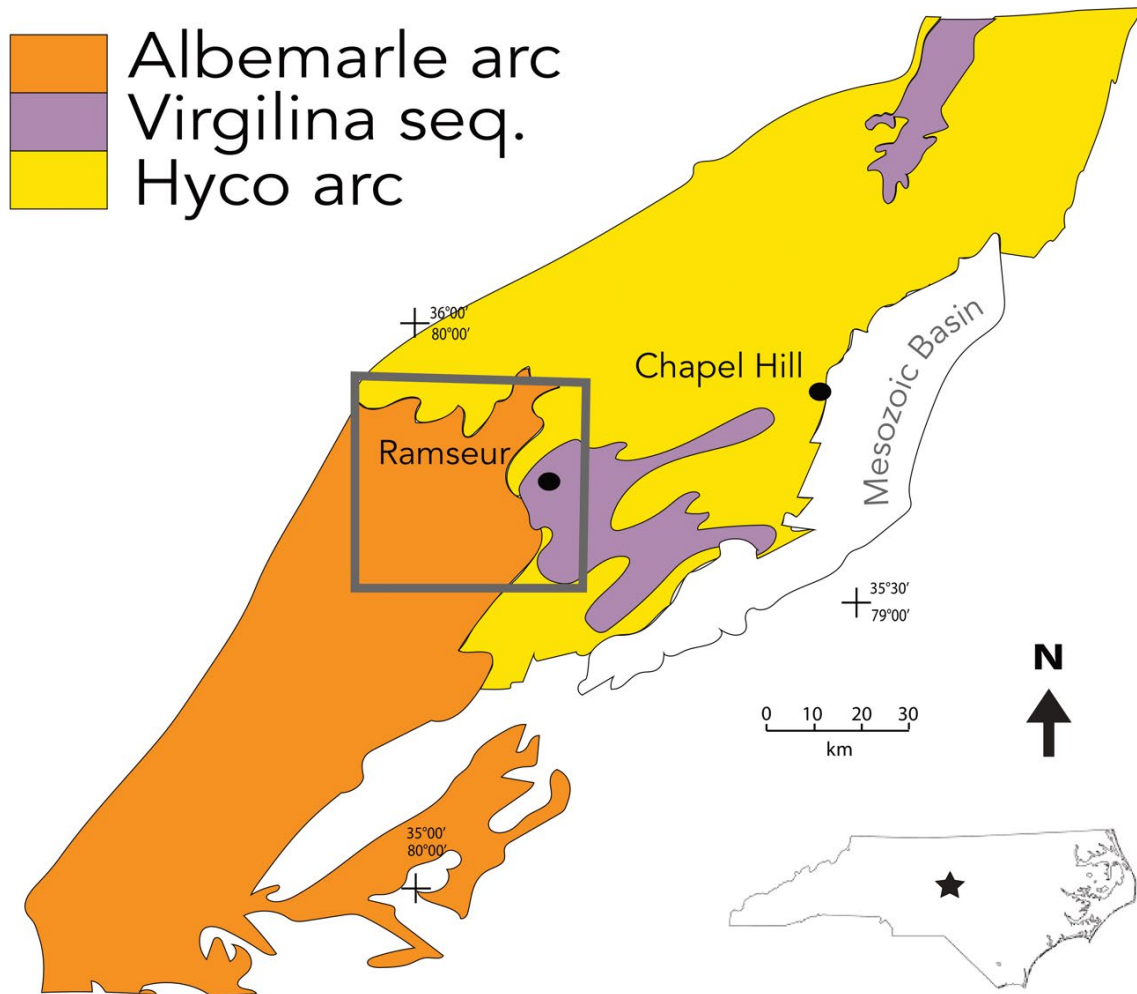


Figure 1. The major lithotectonic components of the Carolina Terrane. Outlined in gray is Randolph County, that includes the town of Ramseur where the Parks Crossroads pluton crops out. Inset shows the location of this field area within the state of North Carolina. Modified from Hibbard (2002).

Geologic Background

The Hyco and Albemarle sequences include magmatic arc rocks that are dominant components of the Carolina terrane (Fig. 1). The older Hyco arc (ca. 615 to 620 Ma) is a magmatic system

composed of primarily pyroclastic and volcanic rocks originally deposited in a shallow marine environment (Wortman et al., 2000). The Virgilina sequence is a stratigraphic sequence that includes the Aaron Formation (metasedimentary) then the Virgilina Formation (volcanic/pyroclastic). The Hyco arc, Aaron Formation, and Virgilina Formation were all deformed during the Virgilina deformational event after deposition. The age of deformation is bracketed between 588 Ma to 569 Ma (Goliber, 2020). The youngest of the major sequences in the Carolina terrane is the Albemarle arc, including the base sequence known as the Uwharrie Formation (~550 Ma) (Goliber, 2020), that is overlain by the sedimentary and volcanic rocks of the Albemarle Group (ca. 552-528 Ma) (Hibbard et al., 2013). The Uwharrie Formation is dominated by felsic volcanic rocks but also includes plutonic and sedimentary rocks. The Uwharrie Formation unconformably overlies the Aaron Formation (578 Ma to 588 Ma) (Pollock et al., 2010). The Parks Crossroads pluton (Fig. 2) is part of the Uwharrie Formation. Younger stratigraphic units of the Albemarle arc are (from oldest to youngest) the Tillery, Cid, Floyd Church and Yadkin Formations.

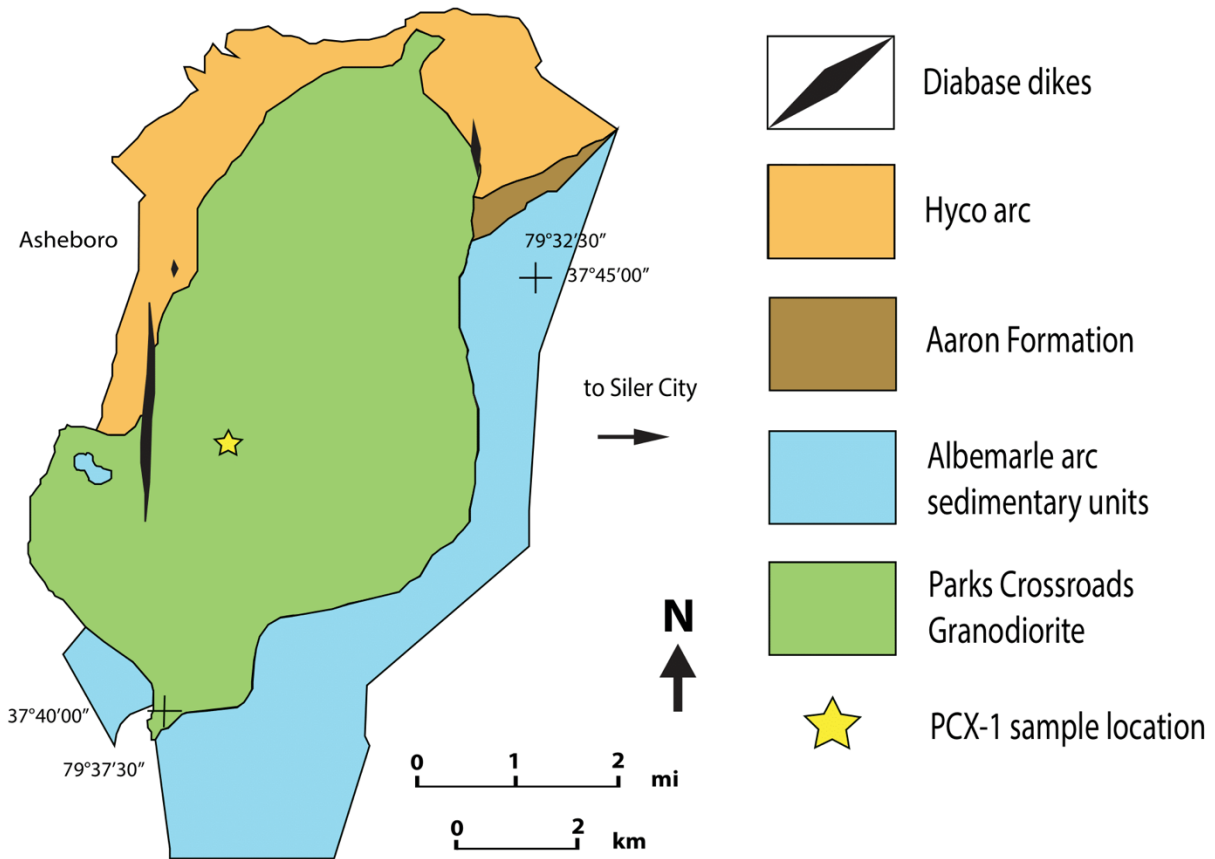


Figure 2. Modified from Tingle (1982). Simplified geologic map of the Parks Crossroads Pluton. Yellow star indicates approximate location of sampling for the work done in this study.

Methods

Bulk rock samples of the Parks Crossroads granodiorite (35.7180, -79.6116) were collected from an abandoned quarry that provided sufficient exposure of the pluton (Fig. 3 and 4). This sample location matches one of the sites used in previous work by Tingle (1982). Collected bulk rock samples were processed through the current U-Pb zircon geochronology methods at the University of North Carolina at Chapel Hill. Mineral separation techniques include crushing, magnetic, and specific gravity separation to aid in the isolation of zircon grains. Instruments used for the processing of this sample include a Bico Braun “Chipmunk” Jawcrusher, discmill, water table, hand magnet, methylene iodide (heavy liquid separation), and Frantz isodynamic magnetic separator.



Figure 3. Left photograph: Image of Parks Crossroads Granodiorite sampled from field area in Ramseur, NC.

Figure 4. Right photograph: Image of representative hand sample of the Parks Crossroads Granodiorite. This rock is a medium-grained, equigranular hornblende granodiorite with epidote veining and plagioclase saussuritization (hydrothermal alteration product of anorthite) (Tingle, 1982).

After isolation of zircon, approximately 30-40 inclusion-poor, euhedral zircon grains were hand-picked from the remaining sample. These zircon grains were then transferred to quartz crucibles and thermally annealed at 900°C for 72 hours in a Fisher Scientific Isotemp Muffle Furnace.

Annealed zircon grains were individually transferred to a Savillex Teflon beaker along with HF and HNO₃. The beaker containing the thermally annealed zircons was loaded into a Teflon insert and then a Parr bomb jacket for chemical abrasion at 220°C for 12 hours. Chemically abraded zircons were subjected to an ultrasonic cleaning sequence and intermittently rinsed with HNO₃ and MilliQ water. Individual zircons were then spiked with a ²⁰⁵Pb-²³³U-²³⁶U tracer (UNC GS-1 tracer) and dissolved in HF + HNO₃ in Parr bombs at 220°C for 48 hours. Dissolved zircon fractions were dried down into a nitrate salt and fluxed with 6N HCL to produce a chloride salt. This chloride salt was dissolved in 3N HCL for approximately 12 hours before proceeding with elemental separation through ion-exchange column chromatography to isolate U and Pb. Uranium and Pb were analyzed with an IsotopX Phoenix-X62 thermal ionization mass spectrometer (TIMS). Separate aliquots were prepared for sample U and Pb. Samples were loaded along with an NBS-981 common Pb standard and analyzed in single-collector mode with peak-switching on a Daly detector. In-run U fractionation was corrected assuming linear fractionation behavior and the ²³³U/²³⁶U ratio of the tracer. Replicate analyses of the Pb standard yield a fractionation correction of 0.14%/amu for this analysis.

Results

Three zircon crystals yielded concordant ²⁰⁶Pb/²³⁸U ages (Fig. 5 and 6) between 549.3 Ma to 552.6 Ma with a Th-corrected (initial of Th/U = 3.5 used for correction) weighted mean age of 551.86 ± 0.88 Ma (2σ uncertainty).

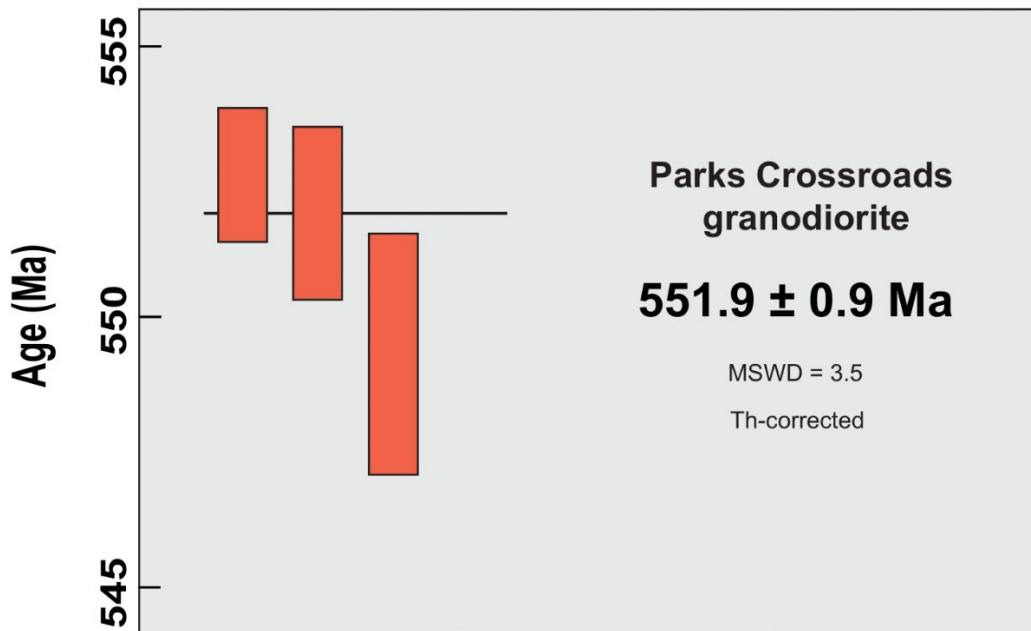


Figure 5. Rank-order plot of ages and respective uncertainties shown for three concordant zircon fractions from the Parks Crossroads pluton.

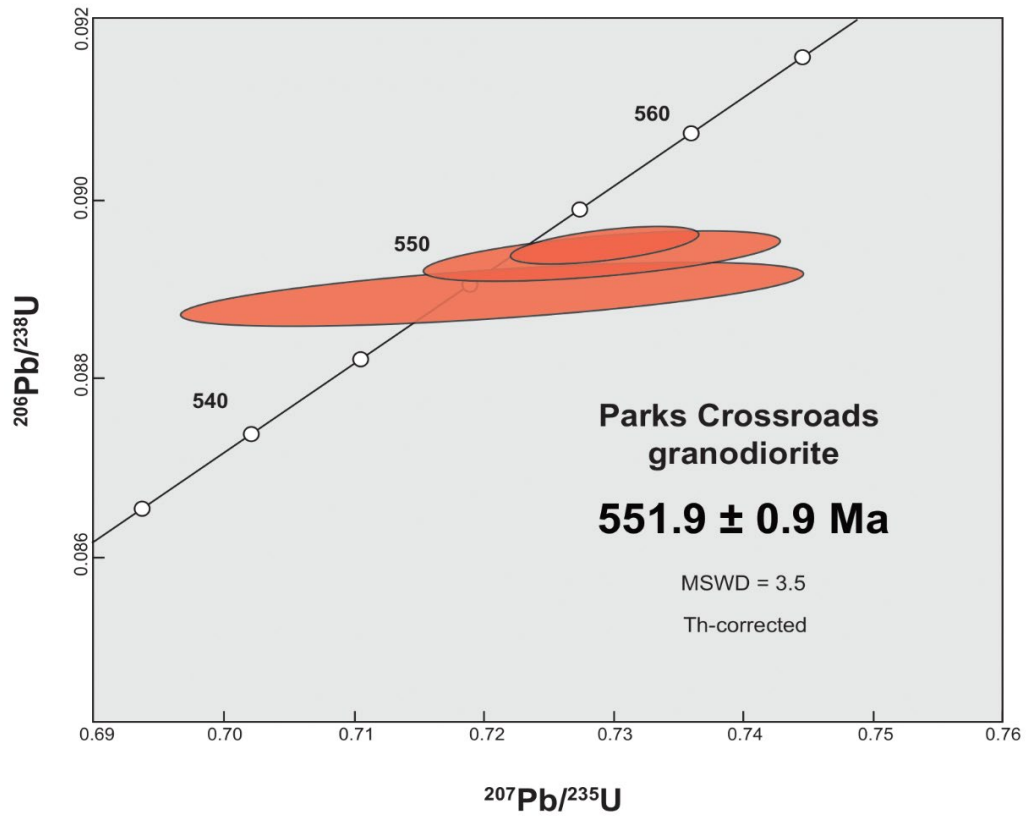


Figure 6. Concordia diagram of ages and respective uncertainties shown for three concordant zircon fractions from the Parks Crossroads pluton.

TABLE 1. Uranium-Lead Zircon Data for Parks Crossroads Granodiorite of the Carolina Terrane in North Carolina

fraction	Composition				Ages										
	U (ng)	Pb* (pg)	common Pb (pg)	Th/U [†]	²⁰⁶ Pb/ ²³⁸ U [‡]	²⁰⁶ Pb/ ²³⁵ U [‡]	error (2σ%)	²⁰⁷ Pb/ ²³⁵ U [‡]	error (2σ%)	²⁰⁶ Pb/ ²³⁸ U [∅]	error (Ma)	²⁰⁷ Pb/ ²³⁵ U ^Δ	correlation coefficient		
F-4	0.250	25.8	1.41	0.90	1029	0.08949	0.23	0.7292	0.99	0.05910	0.88	552.6	1.2	556.1	0.598
F-7	0.0853	8.29	1.72	0.68	300	0.08893	0.42	0.721	3.3	0.0588	3.1	549.3	2.2	551	0.603
F-9	0.104	10.1	1.21	0.68	507	0.08937	0.31	0.729	1.9	0.0592	1.7	551.9	1.6	556.0	0.575

* radiogenic Pb

† Th contents calculated from radiogenic ²⁰⁸Pb and ²³⁰Th-corrected ²⁰⁶Pb/²³⁸U date of the sample

‡ measured ratio corrected for fractionation and spike only

measured ratios corrected for fractionation, tracer, and blank

∅ corrected for initial Th/U disequilibrium using radiogenic ²⁰⁸Pb and Th/U [magma] = 3.5

Δ isotopic dates calculated using λ²³⁸U = 1.55125E-10 and λ²³⁵U = 9.8485E-10 values from Jaffey et al. 1971

Discussion

Age of the Parks Crossroads Granodiorite

Tingle (1982) dated the Parks Crossroads pluton using the Rb/Sr system and obtained an age of 566 ± 46 Ma. That age overlaps the weighted mean age of the zircons in this study. Because the zircons are concordant and their ages overlap within uncertainty, we suggest that the crystallization age of the Parks Crossroads granodiorite is 551.86 ± 0.88 Ma. The reduced uncertainty (Table 1) achieved from the U/Pb zircon age determined by this study for the granodiorite supports its affinity to the Uwharrie Formation (~550 Ma) of the Albemarle arc. This is consistent with the observation that the granodiorite is undeformed, and therefore, younger than deformation associated with the Virgilina that is thought to have ended by 569 Ma (Goliber, 2020).

Relation of the Parks Crossroads Granodiorite to the Adjacent Sedimentary Rocks

The new age for the Parks Crossroads Pluton (551.86 ± 0.88 Ma) and the maximum depositional age for the sedimentary rocks of 534 Ma clarify the nature of the contact between them. Independent of the affinity of the sedimentary rocks, the age relationship requires them to be an erosional remnant disconformably-deposited on the Parks Crossroads pluton. Poor exposure, typical of the Carolina Piedmont, can account for the misinterpretation of the contact as an intrusive contact. This study highlights the importance of high-precision geochronology ages to clarify rock relations in the region.

Exposure of the Parks Crossroads Granodiorite

Although there are no emplacement depth estimates available for the Parks Crossroads granodiorite, it is possible to evaluate whether the geologic relationship between the granodiorite and the sedimentary rocks is geologically possible by making some reasonable estimates for that depth and the maximum age of the sedimentary rocks. The Al-hornblende geobarometer allows for approximations of the depth of emplacement to be made for plutons based on the amount of tetrahedrally-coordinated aluminum in hornblende (Hammarstrom and Zen, 1986). Amphibole barometry has been applied to granitic plutons like the Parks Crossroads pluton and suggest a typical depth of emplacement to be approximately 4-7 kilometers depth. (Noury et al., 2021).

Given the age of the pluton (552 Ma) and the maximum depositional age of the sedimentary rocks (534 Ma), a maximum exhumation rate can be estimated. Assuming the depth of intrusion was 4-7 km and the pluton had to be brought to the surface and exposed in a minimum of 18 Ma (552-534 Ma) yields an erosion rate of approximately 0.22-0.39 km/Ma. This erosion rate is notably rapid, however the analogous St. Martin granodioritic pluton located in the Northern Lesser Antilles has been interpreted to have experienced exhumation rates up to 0.6 km/Ma in a transtensional subduction setting (Noury et al., 2021).

It is important to note that this is a maximum estimate of an exhumation rate for the Parks Crossroads granodiorite. It is likely that the sedimentary unit is significantly younger than the age of its youngest sampled zircon grain, which would result in a larger age disparity between it and the Parks Crossroads granodiorite and allow for relatively slower exhumation rates. It has

been suggested that the exhumation of the Parks Crossroads pluton may have been supplemented by displacement from intra-arc transtensional faulting, however such regional mechanisms are uncertain and are under current investigation (Moye, 2023). Mechanisms supplementing exhumation are not thoroughly considered in this study, and true exhumation of the Parks Crossroads granodiorite could be highly variable. Future isotope research could provide a more comprehensive thermal history of the Parks Crossroads pluton.

Conclusions

The age of 551.86 ± 0.88 Ma determined for the Parks Crossroads granodiorite is concordant with the existing, imprecise age estimate for the pluton of 566 ± 46 Ma determined by Rb/Sr (Tingle, 1982). This supports the interpretation that it is a Uwharrie pluton that post-dates the Virgilina deformational event that ended by 569 Ma. The age of the granodiorite combined with newly determined 534 Ma maximum depositional zircon age for a sedimentary unit in contact with the pluton indicate the unit contact between them is not intrusive, as previously suggested. Rather, it is a disconformable-depositional contact, and the sedimentary unit is interpreted to be part of the Albemarle arc. Using reasonable estimates for the depth of intrusion of the Parks Crossroads granodiorite yields a maximum erosion rate of 0.39 km/Ma. Given the inferred tectonic setting, this is a reasonable rate, even though it is a maximum estimate. The Carolina terrane has a complex history that must be inferred from poor exposure. This study demonstrates that the precision and accuracy of absolute ages derived from U-Pb zircon geochronology are invaluable supplements to field geologic interpretations.

Acknowledgements

The authors thank Phil Bradley of the NCGS for his help with sample collection and geologic interpretation. This manuscript benefitted tremendously from reviews by Dr. Josh Rosera and Dr. Brent Miller. We also thank Alexis Lopez, Michael Sandstrom, Ryan Mills and Anna Strickland for assistance in sample preparation, data analysis and interpretation.

References Cited

- Goliber S.F.B., 2020, Assessment of the Timing of the Virgilina Deformation with U-Pb Ages of Plutonic and Volcanic Rocks in the Carolina Terrane: UNC Carolina Digital Repository, <https://doi.org/10.17615/va5e-c616>.
- Harris, C.W., and Glover III, L., 1988, The Regional Extent of the Ca. 600 Ma Virgilina Deformation: Implications for Stratigraphic Correlation in the Carolina Terrane: Geological Society of America Bulletin, vol. 100, no. 2, 1988, pp. 200–217., [https://doi.org/10.1130/0016-7606\(1988\)100%3C0200:TREOTC%3E2.3.CO;2](https://doi.org/10.1130/0016-7606(1988)100%3C0200:TREOTC%3E2.3.CO;2).
- Hammarstrom, J. M., and Zen, E., 1986, Aluminum in hornblende: An empirical igneous geobarometer: Mineralogical Society of America, 71: 1297-1313.

- Hibbard, J. P., Stoddard, E.F., Dennis, A.J., 2002, The Carolina Zone: Overview of Neoproterozoic to Early Paleozoic Peri-Gondwanan Terranes along the Eastern Flank of the Southern Appalachians: *Earth-Science Reviews*, vol. 57, no. 3-4, 2002, pp. 299–339., [https://doi.org/10.1016/s0012-8252\(01\)00079-4](https://doi.org/10.1016/s0012-8252(01)00079-4).
- Hibbard, J., Pollock, J., & Bradley, P., 2013, One Arc, Two Arcs, Old Arc, New Arc: An overview of the Carolina Terrane in Central North Carolina in *Carolina Geological Society Annual Meeting and Field Trip, November 8-10, 2013: Carolina Geological Society*, p. 35-61
- Moye, R.J., 2023, The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and Metallogenic Analysis with an alternative model, in *Supplemental Papers, Carolina Geological Society Annual Meeting 2023*, p. 1-82.
- Noury, M., Philippon, M., Cornée, J.J., Bernet, M., Bruguier, O., Montheil, L., Legendre, L., Dugamin, E., Bonno, M., Münch, P., 2021, Evolution of a Shallow Volcanic Arc Pluton during Arc Migration: A Tectono-Thermal Integrated Study of the St. Martin Granodiorites (Northern Lesser Antilles): *Geochemistry, Geophysics, Geosystems*, vol. 22, no. 12, 2021, <https://doi.org/10.1029/2020gc009627>.
- Pelt, K.E. and Bradley, P.J., 2023, Preliminary detrital zircon data from Chatham County, NC, *in* Bradley, P.J., ed., *The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023*.
- Pollock, J.C., Hibbard, J.P., and Sylvester, P.J., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina: in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206*, p. 739-772
- Stromquist, A.A., Sundelius, H.W., 1969, Stratigraphy of the Albemarle Group of the Carolina Slate Belt in Central North Carolina: U.S. Govt. Print. Off., *Geological Survey Bulletin 1274-B*, <https://doi.org/10.3133/b1274b>.
- Tingle, T.N., 1982, Geology and geochronology of the Parks Crossroads Granodiorite, near Siler City, central North Carolina Piedmont: *Southeastern Geology*, v. 23, no. 2, p. 117-122.
- Vick, H.K., Channell, J.E.T., and Opdyke, N.D., 1987, Ordovician docking of the Carolina slate belt: Paleomagnetic data: *Tectonics*, v. 6, p. 573–583, <https://doi.org/10.1029/TC006i005p00573>.
- Wortman, G.L., Samson, S.D., Hibbard, J.P., 2000, Precise u-pb zircon constraints on the earliest magmatic history of the Carolina terrane: *The Journal of Geology*, 108:321–338, <https://doi.org/10.1086/314401>.

Assessment of the timing of the Virgilina deformation with U-Pb ages of plutonic and volcanic rocks in the Carolina terrane

Skylar Fay Beadle Goliber and Drew S. Coleman

Department of Earth, Marine and Environmental Sciences, University of North Carolina at Chapel Hill, skylar.beadle.goliber@gmail.com and dcoleman@unc.edu

ABSTRACT

The undeformed Farrington pluton in the Carolina Terrane of North Carolina was previously interpreted to be contemporaneous with nearby volcanic rocks, mapped as the deformed Virgilina Sequence, and hypothesized to be diagnostic of the timing and duration of the Virgilina deformation event. New U-Pb zircon ages for the Farrington pluton and the volcanic unit presumed to be a part of the Virgilina sequence demonstrate that the correlation is incorrect. Nine concordant U-Pb analyses of zircon from the East Farrington pluton yielded a weighted mean age of 569.0 ± 1.1 Ma. Three concordant U-Pb analyses of zircons from rocks mapped as the Virgilina Sequence yielded a weighted mean age of 548.7 ± 1.1 Ma. These data suggest that the Farrington pluton is younger than previously assumed (~ 569 Ma vs. ~ 579 Ma). Moreover, the new date for volcanic rocks suggests they belong to the much younger Uwharrie Formation, a volcanic portion of the more recent Albemarle Arc, extending exposure of the arc much farther northeast than previously recognized. The new geochronologic data also indicate that the Virgilina deformation likely occurred between the deposition of the Aaron Formation (~ 588 Ma) and the intrusion of the Farrington pluton (~ 569 Ma).

INTRODUCTION

The Carolina terrane is an assemblage of rocks exotic to Laurentia, centrally located on the east coast of the US from Virginia to Georgia (Secor, 1983). It generally follows the NE-striking trend of the Appalachian orogen (Figure 1; e.g., Hibbard et al., 2006; Hibbard et al., 2013). In North Carolina, the terrane is bound in the west by the Charlotte and Piedmont terranes and to the east by fragments of terranes that are not well understood (Hibbard et al., 2013). Overall the Carolina terrane is composed of juvenile arcs and continental fragments that formed in the Neoproterozoic and consolidated in the early Paleozoic, prior to colliding with Laurentia (Hibbard et al., 2002).

As a historical source of gold in the Carolinas, the Carolina terrane is of particular interest for studying the origins and distribution of gold and other metallic deposits in the area (e.g., Pardee and Park, 1948; Hibbard et al., 2013; Alarifi et al., 2021). The Carolina terrane is also important for understanding the amalgamation of Pangea and the mechanisms involved in the Appalachian orogeny (e.g., Secor et al., 1984; Dennis and Wright, 1997; Tadlock and Lowey, 2006). Recent studies on stratigraphy and tectonic histories have helped to revise the tectonic model used to understand the formation of the Carolina terrane (e.g., Hibbard et al., 2013). This manuscript seeks to provide new insights into the ages and relationships between intrusive and extrusive igneous rocks that crystallized before the terrane's collision with Laurentia. Better defining this relationship could aid in understanding the timing of the Virgilina Orogen (Tadlock and Lowey, 2006), continental amalgamation of Laurentia, and better evaluating the significance of other plutons within the terrane.

Presented here are new zircon U-Pb geochronologic data from the undeformed Farrington Pluton and the deformed Virgilina Volcanic Member, to aid in determining the timing and duration of the Virgilina deformation and investigate potential connections between intrusive and

extrusive magmatism in the early history of the Carolina terrane. While previous geochronology exists for some units of the Carolina terrane, these new data were generated using chemical abrasion-isotope dilution-thermal ionization mass spectrometry (CA-ID-TIMS) of single zircon crystals, which allows for higher temporal precision, mitigation of Pb-loss and evaluation of multicomponent mixing within zircon age domains (e.g., Schaltegger et al., 2015; Widemann et al., 2019; Gaynor et al., 2022). This is particularly relevant in regions that have gone through tectonic deformation or fluid alteration associated with economic mineralization (e.g., Chelle-Michou et al., 2014; Rosera et al., 2021; Ruiz et al., 2022), both of which have occurred in the post-collisional history of the Carolina terrane (e.g., Bell et al., 1974; Foley et al., 2001; Alarifi et al., 2021). As a result, these new results reveal significant geologic complications previously obscured by either geologically inaccurate or imprecise data, and emphasize the need for similar studies moving forward.

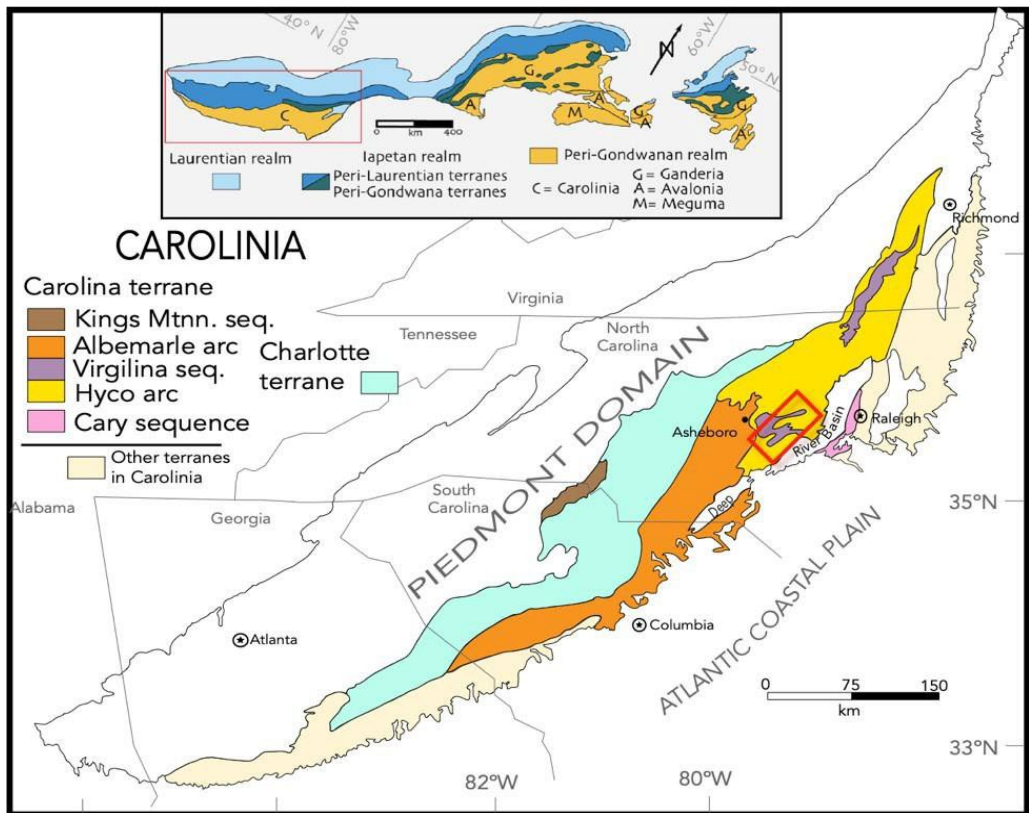


Figure 1: Regional, simplified geologic map of the southern eastern USA, showing the region studied as a part of this study, modified from Harris and Glover (1985) and Hibbard et al. (2013); inset shows major tectonic components of the Appalachian peri-Gondwanan realm from Hibbard et al. (2006). Red box shows approximate study area.

GEOLOGIC BACKGROUND

In North Carolina, the Carolina terrane includes three major lithotectonic units - the Hyco, Virgilina, and Albemarle sequences (Figure 2; Bowman et al., 2013; Hibbard et al., 2013). The Hyco and Albemarle sequences are igneous rocks representative of former large magmatic arc systems, stratigraphically positioned between the largely sedimentary Virgilina sequence. The oldest of the terrane's constituents, termed the Hyco arc, consists of subaqueous pyroclastic rocks and felsic to intermediate volcanic rocks associated with volcanic arc formation, eruption and accretion, and are isotopically juvenile (e.g., Laney, 1917; Samson et al., 1995; Fullagar et al., 1997). These data have been interpreted to reflect a mantle-derived source for magmatism within the Hyco arc, and that much of the exposed volcanic section was deposited in shallow water (Hibbard et al., 2013). Wortman et al. (2000) analyzed multigrain-zircon fractions using thermal ionization mass spectrometry (TIMS) from two different rocks of the Hyco arc, and reported normally discordant data with upper intercept U-Pb ages of $619.9 \pm 4.5/-3$ Ma and $615.7 \pm 3.7/-1.9$ Ma, which has been interpreted as the age of igneous crystallization within the block.

The next oldest main lithotectonic element of the Carolina terrane, the Virgilina sequence, includes the sedimentary Aaron Formation and a volcanic member (Bowman et al., 2013). The Hyco and Virgilina sequences were traditionally considered to be the same sequence, but recent geochronology studies determined the tuff and volcanoclastic rocks in the upper portion of the Hyco arc in contact with the Aaron Formation to be approximately 616 Ma (Bowman, 2013). This age discrepancy indicated that the Hyco and Virgilina sequences are separated by at least 24-37 Ma and are two independent portions of the Carolina terrane (Bowman, 2013).

The Aaron formation is composed of lightly metamorphosed epiclastic sedimentary rocks and conglomerates (Hibbard et al., 2013). Detrital zircon ages indicate that clastic deposition of

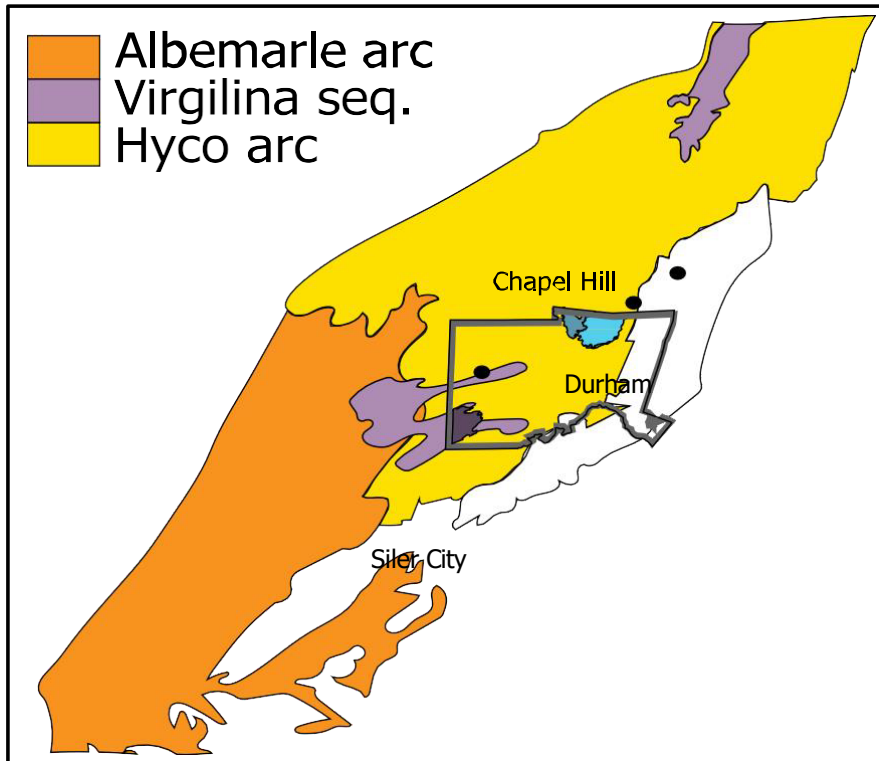


Figure 2: Regional setting of the Farrington pluton, showing the general setting of the intrusion within other peri-Gondwanan terrane components, modified from Bowman et al. (2013). The region has three major lithotectonic elements of the Carolina terrane in North Carolina, the location of the Farrington pluton in blue, and the location of the Virgilina Volcanic Member in dark purple. The outline of Chatham Co., NC is in dark gray.

the Aaron Formation must have predated approximately 578 Ma (Samson et al., 2001), and may be as old as about 588 Ma (Pollock et al., 2010). The Virgilina Member was previously undated but expected to be similar in age to the Aaron Formation, and was significantly metamorphosed following deposition (e.g., Bradley et al., 2006).

Both the Hyco Sequence and the Aaron Formation (including the Virgilina Member) were deformed by the Virgilina event (Bowman, 2010), which was recorded by upper crustal folding, foliation formation, and faulting. It is interpreted to have occurred between approximately 578 and 544 Ma, based on existing geochronology (Hibbard et al., 2013). The timing of this deformation event is not well understood, in part due to the undeformed Farrington

Pluton Complex, which intrudes the deformed Hyco and Virgilina sequences (e.g., Hibbard and Samson, 1995; Wortman et al., 2000; Tadlock and Lowey 2006). Therefore, its age should provide better understanding of the timing of the Virgilina deformation. Previous multigrain-zircon U-Pb geochronology from samples on the eastern portion of the Farrington pluton yielded a discordant upper intercept age of 578.7 ± 5.5 Ma, which was interpreted to reflect crystallization of the pluton (Tadlock and Lowey, 2006).

The tectonic evolution of the Carolina terrane has previously been interpreted as a complex sequence of magmatism and deformation (Fig. 3; e.g., Golver and Sinha, 1973; Wright and Seiders, 1980; Tadlock and Loewy, 2006). Noteworthy is that, whereas the previously interpreted 579 Ma crystallization of the Farrington pluton was not apparently deformed by the Virgilina or later deformational episodes, the Virgilina Member, presumed to be the volcanic equivalent, is deformed. This is significant because the Virgilina deformation the pluton would have experienced more focused and local amounts of stress. The Farrington pluton has been interpreted to not reflect these deformation events, either because the Virgilina deformation was heterogeneous (Bowman 2010), or because the pluton was exceptionally rheologically strong or mineralogically inconducive to alteration (Schaltegger et al., 2021).

The Farrington Pluton

The Farrington pluton has been subdivided into eastern and western facies (the East and West Farrington plutons, respectively), based on more recent geologic mapping and differences in hand sample composition (e.g., Bradley et al., 2006). In the Bynum Quadrangle, the East Farrington pluton includes a range of amphibole granite to granodiorites, but the pluton also displays areas of gray granitoids and monzodiorite porphyries (Hauck, 1977). The grain size ranges from medium- to coarse-grained, with medium-grained textures present along the pluton

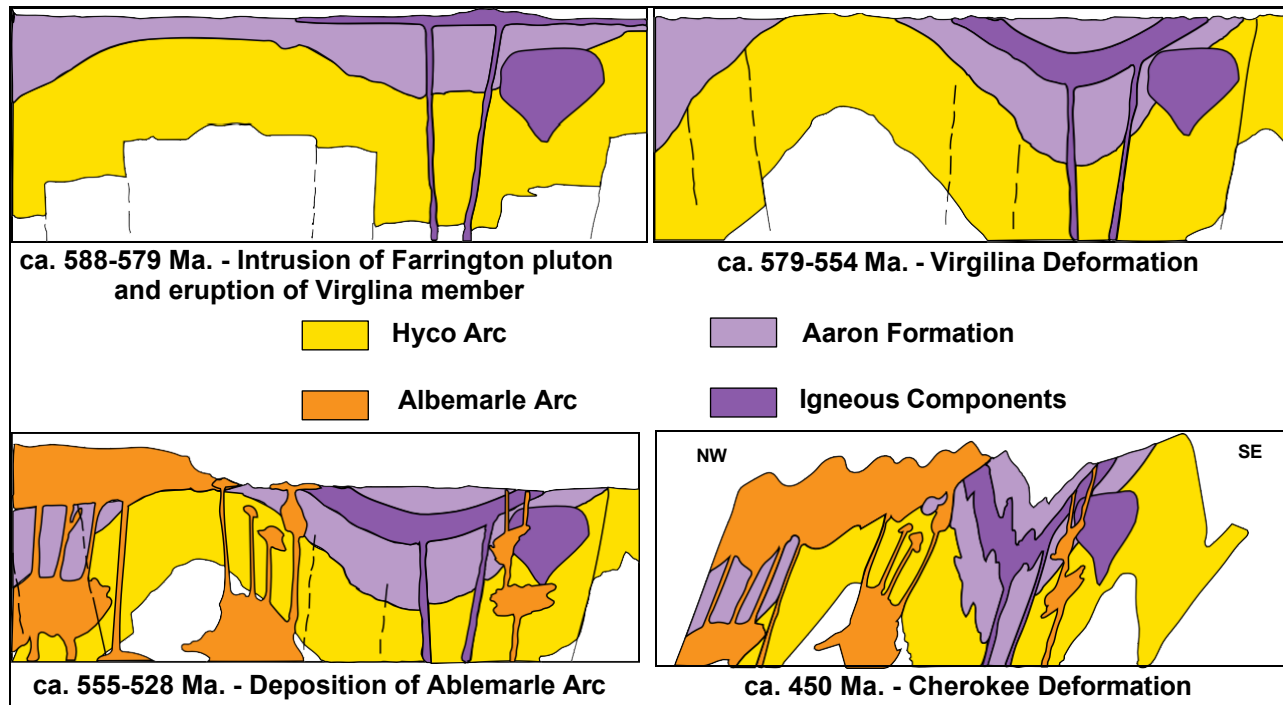


Figure 3: Simplified geological interpretation of the tectonic evolution for the Carolina terrane, modified from Hibbard et al. (2013), based on an interpreted tectonic evolution of the Carolina terrane along a cross section that now lies from the northwest to the southeast of north central North Carolina. The timing and duration of the Virgilia deformation based on absolute ages of the Hyco Arc and a post-Virgilia pluton, analyzed by Wortman et al. (2000), and the emplacement of the Farrington pluton at about 579 Ma. Including the more recent Alleghenian deformation, this model displays a pluton that is not greatly affected by three large deformation events.

edge, where enclaves are larger and more frequent. The most common rocks exposed within the region mapped as the East Farrington pluton are leucocratic and orange pink to pinkish-gray in color (Figure 4). They contain 5-10% amphibole by volume, which are dark green, elongate crystals, occasionally intergrown with quartz and feldspar. The main facies is characterized by orthoclase and plagioclase phenocrysts within an orthoclase, plagioclase, and quartz matrix. The areas described as monzodiorite porphyries have a medium- to fine-grained groundmass, with plagioclase phenocrysts up to 8 mm (Bradley et al., 2013).

The West Farrington pluton hosts a range of medium- to coarse- grained diorites that are largely unfoliated (Figure 5). The northern-most exposure is a dominantly equigranular



Figure 4: Photo of hand sample from the main facies of the East Farrington.



Figure 5: Photo of hand sample from the main facies of the West Farrington.

mesocratic diorite, with dark green amphibole crystals and small enclaves of darker microdiorite and hornfelsed country rocks. The largest exposed component of the West Farrington pluton is a leucogranodiorite, which is biotite-bearing with dark green amphiboles and varying quartz content (Bradley et al., 2013).

The Virgilina Volcanic Member

The Virgilina Member in the Bennett Quadrangle is composed of a variety of epiclastic and pyroclastic rocks, along with a suite of dacitic lavas. The current exposure of this unit is dominated by metamorphosed tuffaceous sandstones and conglomeratic sandstones and siltstones, with lesser amounts of fine- to coarse tuff and welded tuff. Fiamme-like clasts and quartz and feldspar crystals are common in all three rock types. Locally present are also occurrences of quartz with adularia and silicified and/or sericitized altered rock (Bradley, 2019).

METHODS

One sample of the leucocratic East Farrington pluton and one sample mapped as the Virgilina Member of the Aaron Formation were processed for U-Pb isotope geochronology. Zircon were separated from bulk rocks through standard mineral separation techniques, including crushing, magnetic, and gravitational extraction methods using a Bico Braun “Chipmunk” Jawcrusher, discmill, water table, methylene iodide, handmagnet, and Frantz isodynamic separator. Approximately 100 euhedral and inclusion-poor zircons per sample were then selected using a binocular microscope, transferred to quartz crucibles, loaded in a muffle furnace, and annealed at 900° C for 48 hours.

The zircons were transferred individually to 3mL Teflon beakers, rinsed in 6 N HCl and Milli-Q® (MQ) H₂O and fluxed in 6 N HCl at 100° C on a hot plate for 30 minutes, after which they were each loaded into a 200 µl Savillex™ microcapsule with 100 µl of 29 M HF and 15 of µl 3 N HNO₃. These microcapsules were then loaded into high-pressure Parr™ bombs for chemical abrasion at 220 °C for 8 hours, in order to remove portions of the crystal affected by radiation damage and non-zircon mineral inclusions (e.g., Mattinson, 2005; Widemann et al., 2019; McKanna et al., 2023). The zircon grains were rinsed after chemical abrasion, with a sequence of 6 N HCl, MQ H₂O, and 3 N HNO₃, and then spiked with an in-house ²⁰⁵Pb-²³³U-²³⁶U tracer (GS-1). The zircons were dissolved in Parr™ bombs at 220 °C for 48 hours, dried down, and redissolved in 100 µl of 6 N HCl to be converted to chlorides at 100 °C for 48 hours. This solution was evaporated to dryness and brought back up in 3 N HCl for the isolation of U and Pb, using HCl anion exchange chromatography following the methods outlined in Gaynor et al. (2019a).

Individually separated aliquots of U and Pb from each zircon crystal were analyzed for their isotopic composition using an IsotopX Phoenix-X62 thermal ionization mass spectrometer

(TIMS) at the University of North Carolina at Chapel Hill (UNC-CH). Separated U and Pb aliquots were both loaded onto different zone-refined Re ribbon filaments with a silica gel emitter solution, and the Pb onto a single zone-refined Re filament between two degassed Re filaments. Both U and Pb aliquots were analyzed in single-collector, peak-switching mode using a Daly-ion counting system, and U isotopes were measured as an oxide (UO₂). The mass-fractionation U samples was calculated based upon the ²³³U/²³⁶U measured value, and the abundance of U was calculated using a sample composition ²³⁸U/²³⁵U ratio of 137.818 ± 0.045 (2σ; Hiess et al., 2012). The in-run mass fractionation of Pb was estimated to be 0.15%/amu based on the replicate analysis of the NBS-981 common Pb standard. All common Pb was considered laboratory blank and was corrected using the long-term isotopic composition of the Pb blanks of the UNC-CH U-Pb lab. The Tripoli and U-Pb Redux applications were used for all data reduction (Bowring et al., 2011; McLean et al., 2011). All ²⁰⁶Pb/²³⁸U ages were corrected for initial ²³⁰Th disequilibrium in the melt using a U/Th ratio of the respective magmas of 3.5 (Table 1).

RESULTS

In total, we report 10 individual zircons from the East Farrington pluton analyzed using CA-ID-TIMS for U-Pb geochronology, of which nine analyses yielded concordant data. These analyses yielded ²⁰⁶Pb/²³⁸U dates that span from 521.3 ± 8.1 Ma to 681.6 ± 12.7 Ma, with a plateau of dates at approximately centered around ~570 Ma (Figure 6). The oldest analysis from this sample is normally discordant.

Three zircon grains from the unit mapped as the Virgilina volcanic Member were also analyzed using CA-ID-TIMS for U-Pb geochronology, all of which yielded concordant data. These dates all overlap within uncertainty, ranging from 548.3 ± 1.59 Ma to 549.3 ± 2.05 Ma (Figure 6).

TABLE 1. URANIUM-LEAD DATA FOR INTRUSIVE AND EXTRUSIVE ROCKS IN THE CAROLINA TERRANE, NORTH-CENTRAL NORTH CAROLINA

ID	U		Pb* (pg)	Th† U	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	error (2 σ %)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	error (2 σ %)	$\frac{^{207}\text{Pb}}{^{209}\text{Pb}}$	error (2 σ %)	$\frac{^{206}\text{Pb}}{^{238}\text{U}}$	error (Ma)	$\frac{^{207}\text{Pb}}{^{235}\text{U}}$	correlation coefficient	total common Pb (pg)
	(ng)	(pg)														
EF19-01: East Farrington pluton																
F-1	0.1040	12.16	1.335		0.092247	0.590	0.7337	3.55	0.0577	3.25	568.9	568.9	3.21	558.7	0.568	1.44
F-3	0.0738	11.30	2.839		0.091479	0.669	0.7586	4.19	0.0601	3.89	564.3	564.3	3.62	573.2	0.516	2.06
F-5	0.0744	9.159	1.694		0.090164	0.743	0.7384	9.09	0.0594	8.56	556.6	556.6	3.96	561.5	0.734	4.35
F-8	0.2124	25.09	1.311		0.093502	0.457	0.7743	2.38	0.0601	2.17	576.3	576.3	2.52	582.2	0.524	3.35
F-9	0.0625	7.453	1.442		0.091684	1.38	0.7769	7.00	0.0615	6.45	565.5	565.5	7.48	583.7	0.478	2.97
F-11	0.0666	7.165	1.364		0.084208	1.61	0.6786	13.3	0.0584	12.5	521.3	521.3	8.05	525.9	0.542	5.28
F-14	0.0254	3.000	1.432		0.091008	1.44	0.7757	16.8	0.0618	15.8	561.6	561.6	7.72	583.0	0.707	13.0
F-15	0.0456	5.283	1.317		0.091463	1.31	0.7625	18.6	0.0605	17.5	564.2	564.2	7.10	575.5	0.808	2.95
F-18	0.1684	21.00	1.632		0.092451	0.326	0.7501	2.69	0.0588	2.48	570.1	570.1	1.78	568.3	0.660	2.68
BI-710: Virailina volcanic member																
F-1	0.1058	10.10	0.6119		0.088812	0.432	0.7253	4.29	0.0592	4.03	548.6	548.6	2.27	553.8	0.639	2.96
F-3	0.2153	20.57	0.6097		0.088943	0.390	0.7229	4.41	0.0589	4.15	549.4	549.4	2.05	552.4	0.687	6.14
F-5	0.1745	16.76	0.6434		0.088767	0.302	0.7105	2.24	0.0580	2.08	548.3	548.3	1.59	545.0	0.568	6.87

* radiogenic Pb

† Th contents calculated from radiogenic ^{206}Pb and ^{230}Th -corrected $^{206}\text{Pb}/^{238}\text{U}$ date of the sample, assuming concordance between U/Pb Th/Pb systems.

‡ measured ratio corrected for fractionation and spike contribution only

measured ratios corrected for fractionation, tracer and blank.

‡ corrected for initial Th/U disequilibrium using radiogenic ^{206}Pb and Th/U(magma) = 3.5

* isotopic dates calculated using $\lambda_{238}\text{U} = 1.55125\text{E}^{-10}$ (Jaffey et al. 1971) and $\lambda_{235}\text{U} = 9.8485\text{E}^{-10}$ (Jaffey et al. 1971).

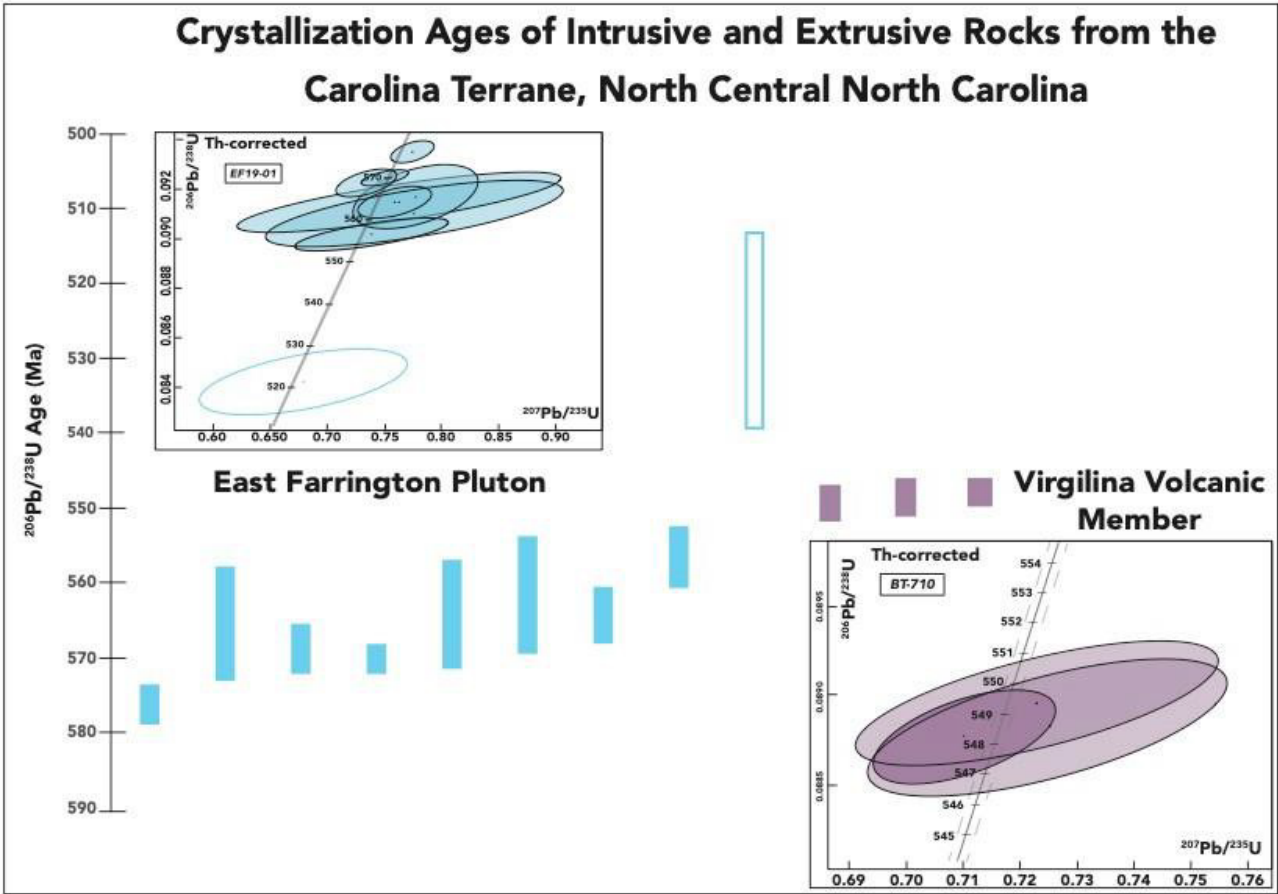


Figure 6: Plot of the U-Pb data from the Farrington pluton and volcanic unit mapped as the Virgilina Volcanic Member, with a rank order plot of the $^{206}\text{Pb}/^{238}\text{U}$ dates of individual zircons, with insets of concordia plots from both samples.

DISCUSSION

Interpreting Ages for the Farrington Pluton & Virgilina Volcanic Member

As technical advancements in U-Pb zircon geochronology have progressed, decreases in precision have revealed increasingly dispersed age spectra, requiring interpretation to yield geologically meaningful ages from high-precision CA-ID-TIMS data sets (e.g., Samperton et al., 2015; Szymanowski et al., 2019; Gaynor et al., 2023). The sample of the Virgilina volcanic member yielded a series of dates that overlapped within uncertainty and statistically represent an individual population (Wendt and Carl, 1991), and therefore, we interpret a weighted mean of all analyzed dates to reflect deposition of this volcanic unit at 548.7 ± 1.1 Ma, based on the

weighted mean Th-corrected $^{206}\text{Pb}/^{238}\text{U}$ weighted mean value of all analyses ($n = 3$; Figure 6). However, there is significant dispersion between the zircon dates of the Farrington pluton, and therefore resolving a geologically accurate age from these values requires additional interpretation.

Zircon dates from the Farrington pluton have a range significantly longer than anticipated from plutonic crystallization (e.g., Annen et al., 2006; Barboni and Schoene, 2014), and therefore it is unlikely that the entire spectra reflects igneous crystallization of the intrusion. Clusters, or plateaus, of data on rank order plots with an outlier are usually an indication of a geologically meaningful age (the plateau) and inheritance (ages older than the plateau), or Pb-loss (ages younger than the plateau). In such cases, the weighted mean of the cluster is taken as geologically significant. One grain yielded a $^{206}\text{Pb}/^{238}\text{U}$ date of 681.6 ± 12.7 Ma, significantly older than the cluster of grains for the Farrington pluton sample (Table 1), and is interpreted to reflect inheritance. We interpret also the youngest grain from the East Farrington pluton reflects unmitigated Pb-loss, and therefore does not reflect a geologically accurate date for the crystallization of the Farrington pluton.

Mapping & Tectonic Implications of New Ages for the Farrington Pluton & Virgilina Volcanic Member

Tadlock and Lowey (2006) dated a different sample from the East Farrington pluton using multi-grain zircon fractions. They interpreted that it was emplaced at approximately 579 Ma, significantly older than suggested here. This may be in part due to inheritance, as well as the normal discordance observed in all aliquots analyzed in that study. In a multi-zircon grain analyses, the measured U/Pb composition is an average of the composition of all grains within the aliquot, weighted by the relative abundance of U and Pb in each crystal; therefore, allowing

for more subtle incorporation of inherited U-Pb components, complicating the ability to identify inherited grains. The occurrence of inherited U-Pb components in this study supports that interpretation. Furthermore, all of the analyses of that study yielded normally discordant data, and therefore complicates the ability to assess closed system U-Pb behavior (e.g., Schoene, 2014; Gaynor et al., 2022). Alternatively, the age discrepancy between the two studies could be because that the Farrington pluton was assembled incrementally over at least 10 Ma, similar to the total duration of many well dated intrusive suites (e.g., Coleman et al., 2004; Frazer et al., 2014; Samperton et al., 2016; Gaynor et al., 2019b). However, this would suggest an incredibly low magma flux throughout emplacement based on the current exposure of the pluton, and because the Tadlock and Lowey (2006) date is an upper intercept age derived from discordant analyses, we prefer the interpretation that their fractions include unresolved inheritance and therefore do not represent an accurate age for emplacement of the pluton. Further research is needed to better determine the total duration of the emplacement of the Farrington pluton.

The weighted mean of 569.0 ± 1.1 Ma for the Farrington pluton is about 10 Ma younger than previously reported. This age indicates that intrusion of the pluton postdates deposition of the Aaron formation and the emplacement of the volcanic Virgilina Member. Because the zircon geochronology indicates the pluton is younger than the Virgilina volcanic rocks, it indicates it also predates Virgilina deformation (Figure 7). This brackets the Virgilina deformation to between the cessation of the earliest estimates of the deposition of the Aaron Formation at approximately 588 Ma and 569.0 ± 1.1 Ma. Previously, the best estimate for the end of Virgilina deformation was the age of the undeformed, 546 Ma Roxboro pluton (Wortman, 2000). Alternatively, the Farrington pluton could be interpreted to have experienced three significant deformation events – the Virgilina, the Cherokee, and the Alleghenian – without developing

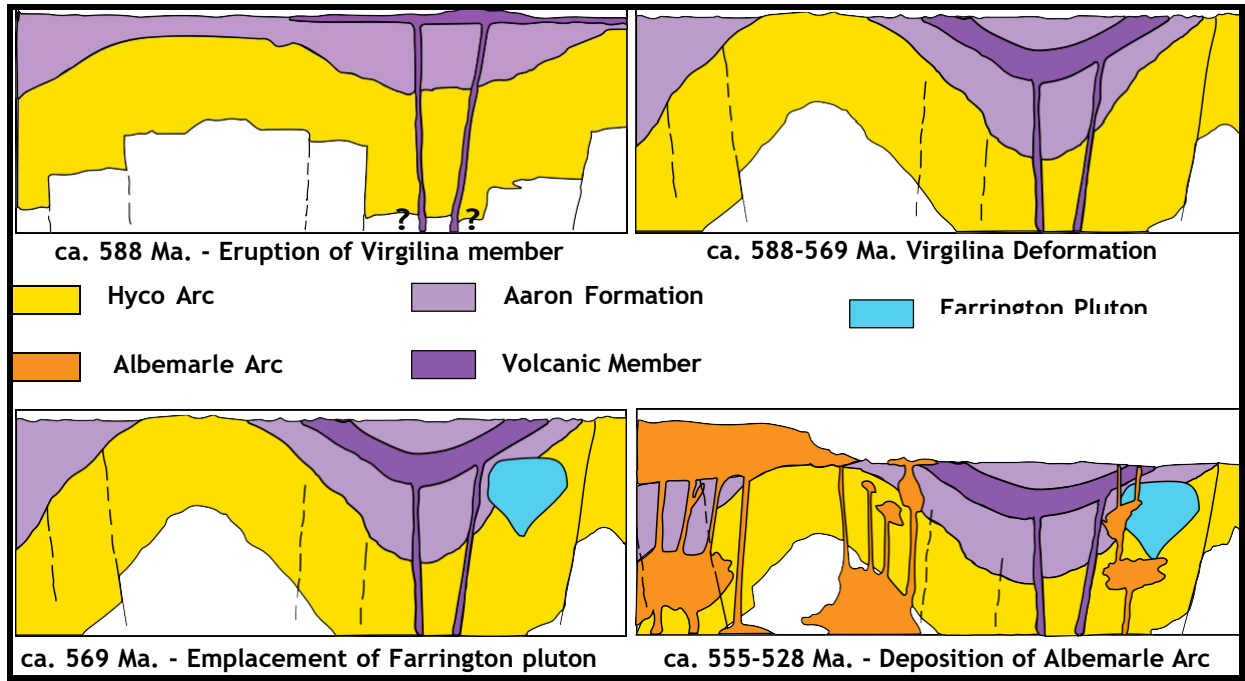


Figure 7: Modified from Hibbard et al. (2013); shows emplacement of the Farrington pluton after the deposition of the entire Virgilina sequence and the Virgilina deformation event.

significant observable indications of deformation. This model seems less feasible because it does not provide an explanation as to why the granites of the Farrington pluton would be so much more resistant to deformation relative to other similar granites emplaced in the region.

The volcanic rocks analyzed yielded a mean weighted age of 548.7 ± 1.1 Ma. Unlike the sample from the East Farrington pluton, these data did not yield complicated age spectra, and therefore there are not significant concerns over issues such as inheritance or Pb- loss, the age interpretation is fairly unambiguous. This age is about 20 million years younger than expected, if the rocks belong to the Virgilina Member as mapped, suggesting that the volcanic rocks in southwestern Chatham county do not belong to the Virgilina Sequence. Instead, this age indicates that they are part of the Uwharrie Formation, a component of the younger Albemarle Arc. If this interpretation is correct, the Uwharrie Formation now extends significantly farther

north and east than previously recognized. The correlation with the Uwharrie Formation should be further tested by dating additional volcanic rocks in the area.

CONCLUSIONS

The timing and duration of the Virgilina deformation within the Carolina terrane has been unclear, because the deformed Aaron Formation has been previously correlated with the undeformed Farrington pluton. This study determined a zircon crystallization age of 569.0 ± 1.1 Ma for the East Farrington pluton, approximately 10 Ma younger than previously reported. This new, younger age demonstrates that there was not a magmatic link between the older Virgilina sequence and the Farrington pluton. The age also allows the possibility that the Farrington pluton post-dates Virgilina deformation, bracketing that event to have occurred between approximately 588 Ma and 569 Ma. The age of volcanic rocks previously correlated with the Virgilina Member exposed in the southwestern portion of Chatham County, NC is about 20 Ma too young (548.7 Ma) for this correlation to be correct. Instead, the sampled unit likely belongs to the Uwharrie Formation, the volcanic component of the younger Albemarle Arc. These data indicate that the remnants of the Albemarle Arc may not be as well constrained as previously interpreted, and indicates that future geochronology studies will significantly aid in understanding the amalgamation of eastern Laurentia.

ACKNOWLEDGEMENTS

We thank Phil Bradley for samples and valuable insights into the rocks of North Carolina. Finally, we recognize the support of everyone in the geochemistry lab at UNC-CH, especially Benjamin Thyer, Kyle Krajewski, Molly Paul, and Josh Rosera. Special thanks to our reviewers, Sean Gaynor and Brent Miller.

REFERENCES CITED

- Alarifi, S.S., Kellogg, J., Ibrahim, E., 2021, Geophysical study of gold mineralized zones in the Carolina Terrane of South Carolina: *Economic Geology*, v. 116, p. 1309-1327
- Annen, C., Blundy, J.D., Sparks, R.J., 2006, The genesis of intermediate and silicic magmas in deep crustal hot zones: *Journal of Petrology*, v. 47 p. 505-539
- Barboni, M., Schoene, B., 2014, Short eruption window revealed by absolute crystal growth rates in a granitic magma: *Nature Geosciences*, v. 7, p. 524-528
- Bradley, P.J., Gay, K., Clark, T.W., 2006, An overview of new geologic mapping of the Chapel Hill, Hillsborough and Efland 7.5-Minute quadrangles, Carolina Terrane, North Carolina: *Carolina Geological Society Field Trip Guide*, p. 1-16
- Bradley, P.J., Hanna, H.D., Stoddard, E.F., Bechtel, R., 2013, Geologic map of the Bynum 7.5-minute quadrangle, Orange, Chatham, and Alamance Counties: North Carolina Geological Survey, scale 1:24,000
- Bradley, P.J., 2013, The Carolina Terrane on The West Flank of The Deep River Triassic Basin in The Northern Piedmont of North Carolina – A Status Report *in* Carolina Geological Society Annual Meeting and Field Trip, November 8-10 2013: Carolina Geological Society, p. 139-151
- Bradley, P.J., Rice, A.K., Peach, B.T., 2019, Geologic Map of the Chatham County portion of the Bennett 7.5-Minute Quadrangle, Chatham, Randolph, and Moore Counties, North Carolina: North Carolina Geological Survey, scale 1:24,000
- Bowman, J.D., 2010, The Aaron Formation: Evidence for a New Lithotectonic Unit in Carolina, North Central North Carolina: North Carolina State University, p. 87
- Bowman, J.D., Hibbard, J.P., Miller, B.V., 2013, The Virgilina sequence redefined, North Central North Carolina *in* Carolina Geological Society Annual Meeting and Field Trip, November 8-10 2013: Carolina Geological Society, p. 127-138
- Chelle-Michou, C., Chiaradia, M., Ovtcharova, M., Ulianov, A., Wotzlav, J.F., 2014, Zircon petrochronology reveals the temporal link between porphyry systems and the magmatic evolution of their hidden plutonic roots (the Eocene Corocochuayco deposit, Peru): *Lithos*, v. 198, p. 129-140
- Coleman, D.S., Gray, W., Glazner, A.F., 2004, Rethinking the emplacement and evolution of zoned plutons: Geochronologic evidence for incremental assembly of the Tuolumne Intrusive Suite, California: *Geology*, v. 32 (5), p. 433-436
- Dennis, A.J., Wright, J.E., 1997, The Carolina terrane in northwestern South Carolina, U.S.A.: Late Precambrian-Cambrian deformation and metamorphism in a peri-Gondwanan oceanic arc: *Tectonics*, v. 16, p. 460-473.

- Foley, N., Ayuso, R., Seal, R. II, 2001, Remnant colloform pyrite at the Haile gold deposit, South Carolina: A textural key to genesis: *Economic Geology*, v. 69, p. 891-902
- Frazer, R.E., Coleman, D.S., Mills, R.D., 2014, Zircon U-Pb geochronology of the Mount Givens Granodiorite: Implications for the genesis of large volumes of eruptible magma: *Journal of Geophysical Research: Solid Earth*, v. 119, p. 2907-2924
- Fullagar, P., Goldberg, S., Butler, R., 1997, Nd and Sr isotopic characterization of crystalline rocks from the southern Appalachian Piedmont and Blue Ridge, North Carolina and South Carolina: *in* Sinha, K., Whalen, J., Hogan, J., *eds.*, *The Nature of Magmatism in the Appalachian Orogen*: Geological Society of America Memoir 191, p. 165-179
- Gaynor, S.P., Rosera, J.M., Coleman, D.S., 2019a, Intrusive history of the Oligocene Questa porphyry molybdenum deposit, New Mexico: *Geosphere*, v. 15, p. 6-8
- Gaynor, S.P., Coleman, D.S., Rosera, J.M., Tappa, M.J., 2019b, Geochronology of a Bouguer Gravity Low: *Journal of Geophysical Research: Solid Earth*, v., 124, p. 2457-2468
- Gaynor, S.P., Ruiz, M., Schaltegger, U., 2022, The importance of high precision in the evaluation of U-Pb zircon age spectra: *Chemical Geology*, v. 603, 120913
- Gaynor, S.P., Smith, T.M., Schaltegger, U., 2023, Tracing magmatic genesis and evolution through single zircon crystals from successive supereruptions from the Socorro Caldera Complex, USA: *Earth and Planetary Science Letters*, v. 616, 118236
- Glover, L., III, Sinha, A.K., 1973, The Virgilina deformation, a late Precambrian to early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina: *American Journal of Science*, v. 273, p. 234-251
- Harris, C., Glover, L., 1985, The Virgilina deformation: implications of stratigraphic correlation in the Carolina slate belt: *Carolina Geological Society Field Guidebook*, 58 p.
- Hauck, S.A., 1977, Geology and petrology of the northwest quarter of the Bynum quadrangle, Carolina slate belt, North Carolina: *unpublished M.S. thesis*, University of North Carolina at Chapel Hill, 146 p.
- Hibbard, J.P., Samson, S.D., 1995, Orogenesis exotic to the Iapetan cycle in the southern Appalachians *in* Hibbard, J.P., van Staal, C.R., Cawood, P.A., *eds.*, *Current Perspectives in the Appalachian-Caledonian Orogen*: Geological Association of Canada, Special Paper 41, p. 191-205
- Hibbard, J.P., Stoddard, E.F., Dennis, A.J., 2002, The Carolina Zone: overview of Neoproterozoic to Early Paleozoic peri-Gondwanan terranes along the eastern Flank of the southern Appalachians: *Earth-Science Reviews*, v. 57, pp. 299-339
- Hibbard, J., Pollock, J., & Bradley, P., 2013, One Arc, Two Arcs, Old Arc, New Arc: An overview of the Carolina Terrane in Central North Carolina *in* Carolina Geological Society Annual Meeting and Field Trip, November 8-10 2013: Carolina Geological

Society, p. 35-61

- Ingle, S., Mueller, P., Heatherington, A., Kozuch, M., 2003, Isotopic evidence for the magmatic and tectonic histories of the Carolina terrane: implications for stratigraphy and terrane affiliation: *Tectonophysics*, v. 371, p. 187-211
- Laney, F., 1917, The geology and ore deposits of the Virgilina district of Virginia and North Carolina: *Virginia Geological Survey Bulletin* 14, 176 p.
- Mattinson, J.M., 2005, Zircon U-Pb chemical abrasion (“CA-TIMS”) method: combining annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages: *Chemical Geology*, v. 220, p. 47-66
- McKanna, A.J., Koran, I., Schoene, B., Ketcham, R.A., 2023, Chemical abrasion: the mechanics of zircon dissolution: *Geochronology*, v. 5, p. 127-151
- Pardee, J.R., Park, C.F. Jr., 1948, Gold deposits of the southern piedmont: U.S. Geological Survey Professional Paper 213, 156 p.
- Pollock, J.C., Hibbard, J.P., and Sylvester, P.J., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina: in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*: Geological Society of America Memoir 206, p. 739-772
- Rosera, J.M., Gaynor, S.P., Coleman, D.S., 2021, Spatio-temporal shifts in magmatism and mineralization in northern Colorado beginning in the Late Eocene: *Economic Geology*, v. 116, p. 987-1010
- Ruiz, M., Schaltegger, U., Gaynor, S.P., Chiaradia, M., Abrecht, J., Gisler, C., Giovanoli, F., Widerkehr, M., 2022, Reassessing the intrusive tempo and magma genesis of the late Variscan Aar batholith: U-Pb geochronology, trace element and initial Hf isotope composition of zircon: *Swiss Journal of Geosciences*, v. 115
- Samperton, K.M., Schoene, B., Cottle, J.M., Keller, C.B., Crowley, J.L., Schmitz, M.D., 2015, Magma emplacement, differentiation and cooling in the middle crust: Integrated zircon geochronological-geochemical constraints from the Bergell Intrusion, Central Alps: *Chemical Geology*, v. 417, p. 325-326
- Samson, S., Hibbard, J., Wortman, G., 1995, Nd isotopic evidence for juvenile crust in the Carolina terrane, southern Appalachians: *Contributions to Mineralogy and Petrology*, v. 121, p. 171-184
- Samson, S.D., Secor, D.T., and Hamilton, M.A., 2001, Wandering Carolina: tracking exotic terranes with detrital zircons: *Geological Society of America Abstract with Programs*, v. 33, no. 2, p. A-263.
- Schaltegger, U., Schmitt, A.K., Horstwood, M.S.A., 2015, U-Th-Pb zircon geochronology by ID-

- TIMS, SIMS and laser ablation ICP-MS: Recipes, interpretations and opportunities: *Chemical Geology*, v. 402, p. 89-110
- Szymanowski, D., Ellis, B.S., Wotzlaw, J.F., Bachmann, O., 2019, Maturation and rejuvenation of a silicic magma reservoir: High-resolution chronology of the Kneeling Nun Tuff: *Earth and Planetary Science Letters*, v. 510, p. 103-115.
- Secor, D.T., Samson, S.L., Snoke, A.W., and Palmer, A.R., 1983, Confirmation of the Carolina Slate Belt as an Exotic Terrane: *Science*, v. 221, p. 649-651.
- Tadlock, K.A., Lowey, S.L., 2006, Isotopic Characterization of the Farrington Pluton: Constraining the Virginia Orogeny: The University of North Carolina at Chapel Hill
- Wendt, I., Carl, C., 1991, The statistical distribution of the mean squared weighted deviation: *Chemical Geology: Isotope Geoscience Section*, v. 86, p. 275-285
- Wortman, G.L., Samson, S.D., Hibbard, J.P., 2000, Precise U-Pb zircon constraints on the earliest magmatic history of the Carolina terrane: *The Journal of Geology*, v. 108, p. 321- 338
- Widmann, P., Davies, J.H.F.L., Schaltegger, U., 2019, Calibrating chemical abrasion: its effects on zircon crystal structure, chemical composition and U-Pb age: *Chemical Geology*, v. 511, p. 1-10
- Wright, J.E., Seiders, V.M., 1980, Age of zircon and volcanic rocks of the central North Carolina Piedmont and tectonic implications fo the Carolina volcanic slate belt: *Geological Society of America Bulletin*, v. 91, p. 287-294

Quaternary Terraces and Deposits in the Chatham County area, North Carolina

David A. Grimley*, 2023

* Illinois State Geological Survey, University of Illinois (affiliated w/NCGS and NCSU)

Introduction

This section reports on recent mapping of Quaternary deposits and terraces in Chatham County and northern Lee County. We will not visit terrace sites on this field trip, but may cross some of these landforms en route to other locations. The study area is located in the east-central Piedmont of North Carolina and is geologically mostly within the Deep River (Mesozoic) Basin. This basin includes Triassic sedimentary rocks and Jurassic diabase dikes (Clark et al., 2001), that are overlain by Quaternary sediments in the major valleys (Reinemund, 1955). The Cape Fear River and Deep River border much of the southern edge of Chatham County. The Haw River extends across the east-central part of the county and joins with the Deep River; below this confluence it is called the Cape Fear River. Jordan Lake (or B. Everett Jordan Lake), in the eastern part of the county, was created by the U.S. Army Corps of Engineers primarily for water supply and flood control; the dam was completed in 1974 and impounded the Haw River and New Hope River (flooding valleys and low terraces). Prior to construction of the dam, the New Hope River joined the Haw River upstream of its confluence with the Deep River (Fig. 1). Jordan Lake's current mean water level of 216 ft (66 m) above sea level was reached in 1983, with a record level of 233.8 ft (71 m) in 2003.

Quaternary terraces, and associated fluvial deposits, occur along the Deep River, Haw River, and Cape Fear River valleys (Fig. 1; Reinemund, 1955; Bradley et al., 2020, 2021a, 2021b; Rice et al., 2020). Terraces also occur, to a more limited extent, adjacent to Jordan Lake and are associated with the now inundated New Hope River valley (New Hope Creek today flows between Durham and Chapel Hill and drains into northern Jordan Lake). Terraces (mapped as Qtl and Qth in Fig. 1) are mostly preserved today in the broader areas of major river valleys, which occur nearly exclusively in areas of soft sedimentary bedrock of the Deep River (Mesozoic) Basin. In areas of crystalline bedrock, the creeks and rivers are more deeply incised and the valleys are narrow; thus, terrace landforms are not preserved or are very limited in extent. Terrace deposits in the study area, described in more detail below, typically range from 2 to 20 feet thick, but may locally be as thick as 30 feet. In many areas, the deposits consist of only a thin lag of gravelly sand to loamy fine sand on weathered Triassic bedrock (strath terraces). Deposits less than 1.5 feet thick were generally not mapped, as they are of limited practical significance and could not be clearly distinguished from pedogenically altered Triassic sedimentary sequences in the modern soil profile.

Quaternary deposits in Chatham and northern Lee counties, North Carolina

David A. Grimley; Sept. 2023

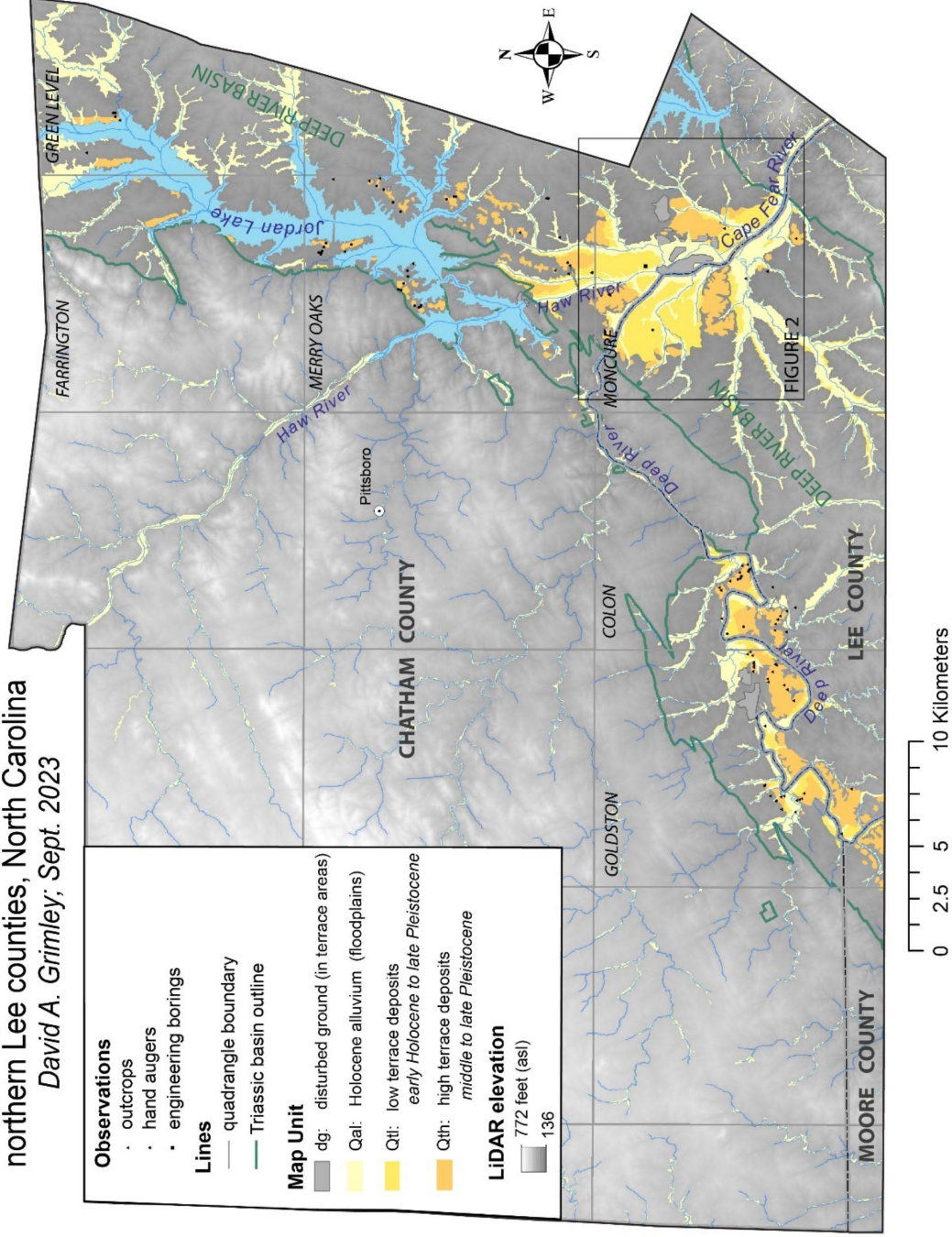


Figure 1. Quaternary deposits in Chatham and northern Lee counties, North Carolina; compiled (and modified in some cases) from recent Quaternary mapping in the Goldston, Colon, Moncure, Merry Oaks, Farrington, and Green Level 1:24,000-scale quadrangles. Terrace deposits predominantly occur within the Triassic Basin (outlined in green). The location of Figure 2 is shown by black outline.

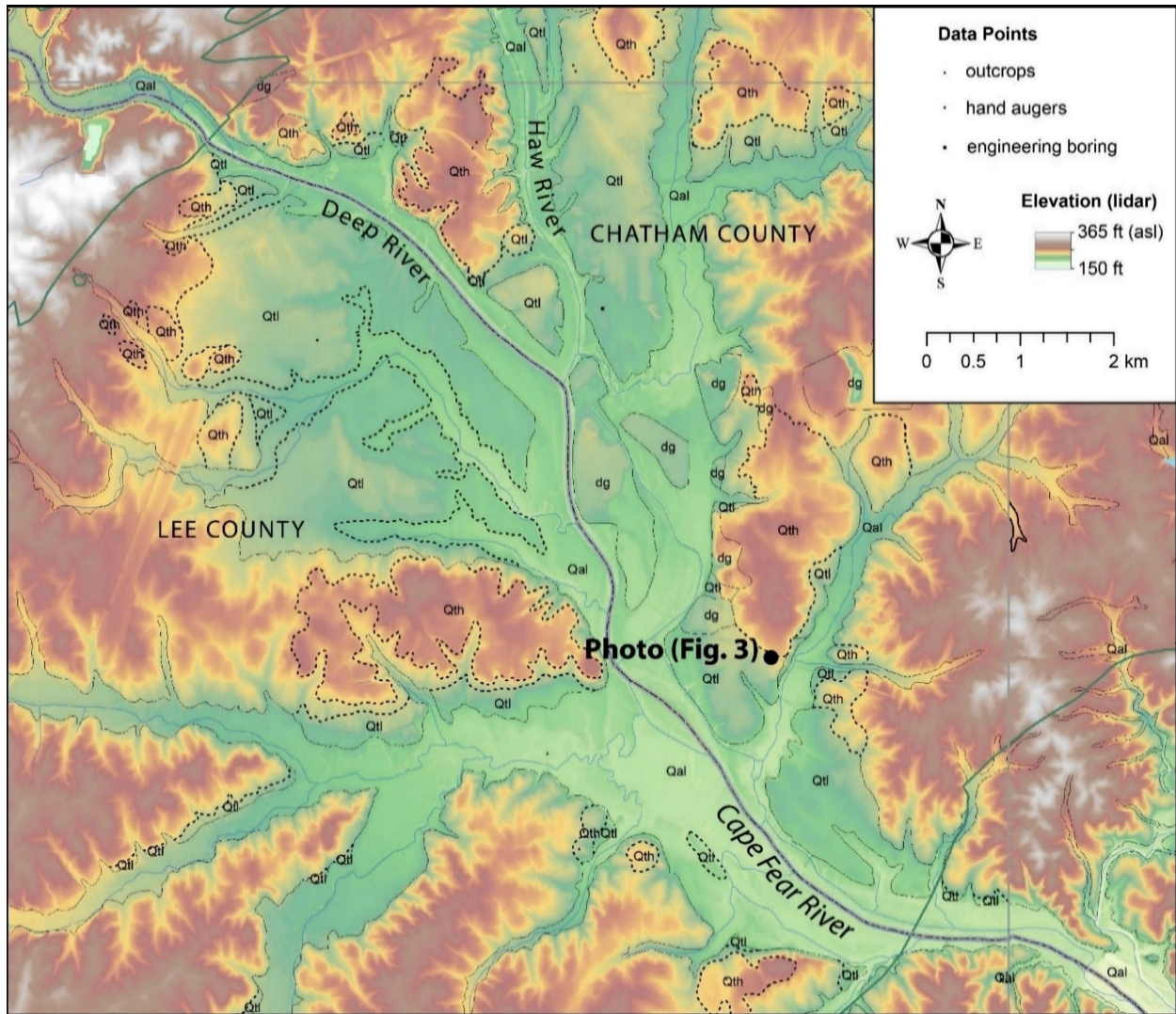


Figure 2. Mapping of Quaternary deposits in the northern Moncure Quadrangle (Bradley et al, 2021b), and adjacent areas, in the confluence area of the Deep and Haw Rivers. Unit contacts are overlain on a lidar surface elevation map. The mapped units consist of Qth (high terrace deposits), Qtl (low terrace deposits), Qal (Holocene alluvium in modern floodplain), and dg (disturbed ground). Areas of higher elevation that are not labelled are underlain by Triassic sedimentary rocks (mostly) or crystalline rocks (in the NW and SW corners of the map). The location of the Figure 3 photograph is shown.

Previously, in the study area, four Quaternary terrace levels had been mapped by Reinemund (1955) along the Deep River and Cape Fear River valleys. In the lower Cape Fear River valley, up to five terraces were suggested to range in age from late Pliocene to late Pleistocene (Soller, 1988). In another part of the Cape Fear River Basin (Little River Basin in the Sandhills of North Carolina), Suther et al. (2011) mapped five terrace levels that were up to 30 m above the modern river level. Luminescence ages and weathering indices suggest these terraces are late Pleistocene to Holocene in age (Suther et al., 2022). However, luminescence ages that approach 100 ka can

be difficult to assess, have significant error, and may provide only minimum ages. Although more than two terrace levels could potentially be mapped in Chatham and northern Lee counties, from a practical standpoint it was decided to map only two terrace levels above the floodplain in recent geologic mapping of 2020-2021 (D. Grimley in the Goldston, Colon, Moncure, and Merry Oaks quadrangles). These mapped terraces (and their associated deposits) can likely be split further given more study, subsurface investigations, and geochronology data. Based on new observations, previously mapped undifferentiated Cretaceous-Tertiary deposits (KTu or TKu) in the Green Level Quadrangle (Watson, 2001) and Farrington Quadrangle (Bradley et al., 2007) have been revised and remapped as Qth deposits where fluvial sediments occur and are > 1.5 feet thick. Some unconsolidated loamy sands to sandy clay previously mapped as KTu at higher elevations have been shown to be a product of in-situ alteration of Triassic sandstone and mudstone. In other areas (such as Field Trip Stop #4 of Clark et al., 2001), the deposits and terraces are clearly post-Triassic but are now interpreted as Pleistocene in age based on degree of pedogenic alteration, elevation, confinement to near river valleys, and degree of dissection.

Methods / Data Sources

The study area included eastern Chatham, northern Lee, and a small part of northeastern Moore County. Natural exposures of unconsolidated (presumably Quaternary or Cenozoic) sediments were examined from more than 75 exposures along stream banks, eroded hillslopes, road cuts, and railroad cuts. Samples from more than 35 hand augered borings to depths of 2 to 13 feet, were also acquired. Hand augers were conducted primarily in the recently mapped Goldston, Colon, Moncure, and Merry Oaks quadrangles (Bradley et al., 2020, 2021a, 2021b; Rice et al., 2020) but also in northeastern Chatham County where terrace deposits were previously mapped as KTu. In addition to exposures and hand augers, subsurface boring records from Reinemund (1955), an EPA Superfund Site (Reichhold Chemical site), and the former Cape Fear Power Plant site (Synterra, 2015) were examined.

Quaternary deposits in parts of southern Chatham County had been previously mapped by Reinemund (1955), who also mapped the bedrock and coal resources. However, this mapping was conducted prior to the availability of 1:24,000 topographic maps, detailed USDA soils mapping, and lidar data. Surficial (Quaternary) deposit mapping in 2020-2021 by D. Grimley, in collaboration with NCGS geologists for four 7.5-minute quadrangles, utilized digital county soil survey parent material maps (Soil Survey Staff, 2019), high resolution lidar surface topography, data from Reinemund (1955), new field observations (outcrops and hand augers), and subsurface boring records.

Quaternary Deposits and Landforms (terraces)

Quaternary fluvial sediments in southern Chatham County (and nearby areas) were previously divided by Reinemund (1955) into five map units (modern floodplain and four terrace levels). However, based on LiDAR and soil survey mapping, the lowest terrace level of Reinemund

occurs in large part on the modern floodplain. The upper terrace levels were also difficult to consistently distinguish and the deposits contained a similar lithology. Thus, due to practical considerations and mappability at the 1:24,000 scale, we chose to map only two terrace levels (Qth and Qtl) in the Goldston, Colon, Moncure and Merry Oaks quadrangles (Bradley et al., 2020, 2021a, 2021b; Rice et al., 2020). Mapping of the two terrace levels and the Holocene alluvium (Qal) in the northern Moncure Quadrangle is highlighted in Figure 2.

High Terrace Deposits (Qth)

The oldest and highest terrace deposits (Qth) contain fluvial sequences in ancestral Haw, Deep, New Hope, and Cape Fear River systems that have since incised to their present level. The elevation of this terrace is 250–350 feet asl in the Goldston Quadrangle, 240–305 feet asl in the Colon Quadrangle, 200–280 feet asl in the Merry Oaks Quadrangle, and 190–265 feet asl in the Moncure Quadrangle (Figure 2). As the modern valleys also slope downgradient, the Qth terraces are typically about 30–100 feet above the modern (or preexisting) floodplains of the Deep, Haw, New Hope, and Cape Fear Rivers. There are likely multiple terrace levels within this map unit that we chose not to differentiate because of the high degree of dissection and fragmentary record, and because lithological differences were not readily observed.

Deposits of Qth range up to 20 feet thick and consist of silt loam to sandy clay loam to gravelly loamy sand to gravelly sand (up to 40 % gravel). The matrix color is typically yellowish brown to reddish brown, with gravel consisting primarily of white, rounded to subrounded quartz pebbles, and rare cobbles. The fluvial sequence generally fines upwards, with gravelly zones typically revealed along eroding slopes. Surficial deposits contain the E and Bt horizons of an Ultisol soil profile, with significant alteration extending several feet into the unit. Crude stratification or cross-bedding is locally observed at depths generally below 10 ft, where deposits are this thick. Areas with thin Qth deposits < 1.5 ft (0.5 m) are not mapped and may occur in strath terraces underlain by Triassic residuum (often reddish and clayey) and bedrock. In some areas, in-situ weathering of Triassic sandstone or conglomerate can result in soil profiles with loamy sand or gravelly sand textures that resemble terrace deposits (terrace deposits themselves are in part reworked from weathered Triassic bedrock). Thus, differentiation of these materials can be difficult within the soil profile, but may be based on the sharpness of the contact, the presence of a basal gravel lag, or an unconformity.

Low Terrace Deposits (Qtl)

The low terrace deposits (Qtl) contain younger Cape Fear River Basin fluvial deposits, with terrace elevations ranging from 225–255 feet asl in the Goldston Quadrangle, 220–240 feet asl in the Colon Quadrangle, 180–220 feet asl in the Merry Oaks Quadrangle, and 170–210 feet asl in the Moncure Quadrangle (Figure 2). The elevation of this terrace is typically about 10 to 30 feet above the local modern floodplain of the Deep, Haw, New Hope or Cape Fear rivers. Mapped deposits of the low terrace (Qtl) are generally more fine-grained than Qth (high terrace) deposits

and can range from 2 feet to at least 25 feet thick. Deposits are yellowish brown to brown to light gray and range in texture from silt loam to clay loam to sand. The Qtl unit generally does not contain gravel, but may contain a thin zone or lag of gravel near the unit base. From subsurface boring records, at least 20 feet of fine-grained (silty clay, silt and fine sand) deposits occur underneath the low terrace east of the Haw River, along Corinth Road where a Reichhold Chemical Superfund site was located. In some areas, it is difficult to differentiate areas of Qtl from high levels of the modern floodplain (Qal). Some mapped areas are strath terraces with thin deposits above Triassic bedrock.

Holocene alluvium in modern floodplain (Qal)

Alluvial deposits on the modern (Holocene) floodplain (Qal) in the Deep River (Mesozoic) Basin study area consist mainly of silt loam to silty clay loam, with fine to medium sand in point bar and channel deposits. Fine sand to gravelly sand alluvium also occurs along smaller creeks in crystalline terrain and likely at depth from reworking of Pleistocene and older sediments. Holocene alluvium in floodplains (Qal) ranges from brown to reddish brown to grayish brown, is soft, and ranges from massive to crudely stratified. It has been observed to be up to 10 feet thick in cutbank exposures along the Deep River, but the maximum thickness in the subsurface is unknown without drilling. This relatively young deposit contains weak to moderately developed soil profiles (Soil Survey Staff, 2019). In areas of the mapped terraces of the study area along the Deep, Haw, and Cape Fear River valleys, the modern floodplain ranges in elevation from about 240 feet asl (Deep River valley in Goldston Quadrangle) to 160 feet asl (Cape Fear River valley on eastern edge of Moncure quadrangle). Holocene alluvial deposits (up to 190 feet asl elevation in Merry Oaks Quadrangle) in much of the New Hope River valley have been inundated by Jordan Lake since the 1980s. The Qal map unit likely also includes very low terraces which are blanketed by modern overbank flood deposits from periodic high-level floods.

Disturbed Ground (dg)

Mapped areas of disturbed ground consist of fill in highway embankments, railway embankments, Jordan Lake Dam, industrial areas and mine spoil piles, as well as areas of moved earth in mined-out-areas (clay pits) and coal ash ponds. Areas of fill or removed earth were mapped only in quadrangles with mapped terraces, such as Moncure Quadrangle (Figure 2).

Key Sites and Field Observations of Terrace Deposits

- Carbonton Railroad Cut in Goldston Quadrangle (35.536 °N, 79.328 °W): located ~ 2.5 km northeast of town of Carbonton and ~ 1 km west of Deep River. Good exposure of Qth deposits on SE side of railway. About 8 feet of weathered loamy sand (as red as 2 YR color); over 6 feet of stratified gravelly sand (7.5YR 5/6; strong brown) over Triassic bedrock (exposed in gully below railroad level). The Qth fluvial deposits include rounded white quartz pebbles up to several cm diameter. Section top at ~268 feet elevation asl.

- Brickhaven Railroad Cut in Moncure Quadrangle (35.570 °N, 79.028 °W): located east of Corinth Road and ~0.5 km south of Brickhaven (section top ~ 218 ft elev.). Exposure of ~6 feet of Qtl fluvial deposits over > 6 feet Qth fluvial deposits on north side of railroad. The low terrace deposits consist of yellowish brown loamy sand and coarsens somewhat with depth, containing a thin basal layer of rounded quartz gravel. Qtl deposits overlie a likely paleosol developed into Qth deposits (Figure 3). Qth deposits are more reddish (Bt horizon), more altered, and finer-grained in the upper few feet and become more coarser, less altered and stratified in lower portions (unit base not well exposed).
- Haywood Railroad Cut in Moncure Quadrangle (35.619 °N, 79.063 °W): located NE of railroad and south of Old U.S. Route 1; exposed in gullies (section top ~230 feet elev.). Outcrop contains 7 feet sandy clay loam (weathered, mottled) over 2 feet planar-bedded to cross-bedded loamy sand over 2 feet loamy sand to rounded gravelly sand (basal part not well exposed). Triassic bedrock likely < 5 feet below, based on ponded water.
- Jordan Lake Bluff in Green Level Quadrangle (35.830 °N, 78.971 °W): This site includes south- and west-facing bluff exposures for 50 m or more laterally along Jordan Lake (~0.6 km west of NC route 751); is easily accessible at normal or low water levels. This site, in Jordan Lake Game Lands, was Stop #4 of a prior field trip (Clark et al., 2001). Exposures consist of up to 8 feet of unconsolidated fluvial deposits (interpreted as Qth) unconformably overlying dipping beds of Triassic sandstone and mudstone. Qth deposits (formerly mapped as KT_u) are mottled strong brown to light gray sandy loam to gravelly sand, with some rounded quartz pebbles at the basal contact. Fragments of likely Jurassic diabase have been observed in the alluvium. The upper few feet is altered and mottled in the modern Bt horizon with sandy loam to sandy clay loam and pedogenic clay skins on fracture faces. Section top at ~230 feet elevation asl.

Inferred Age and Origin of Terraces

At least two levels of fluvial terraces, above the modern floodplain, are found within broad portions of the Haw, Deep, New Hope, and Cape Fear River valleys in the area of the Deep River Basin. These terraces, where preserved, mark the location and elevation of ancestral river systems, prior to incision to the modern floodplain levels. The age of deposits within the high terrace unit (Qth) are speculatively middle to late Pleistocene based on the terrace height above the modern floodplain (Mills, 2000), degree of dissection, and weathering characteristics (Suther et al., 2011). The age of deposits within the low terrace unit (Qtl) are speculatively late Pleistocene to early Holocene based on the terrace height above the modern floodplain (Mills, 2000; Suther et al., 2011).

Slow rates of neotectonic uplift in the southern Piedmont region during the Quaternary are generally accepted to be the reason for older Pleistocene fluvial terraces occurring at higher elevations (Soller, 1988; Mills, 2000; Leigh, 2008; Suther et al., 2011). Rates of uplift in the Carolinas during the late Pleistocene are estimated to have ranged from 0.02–1.8 mm/yr, and

may have varied spatially (Marple and Talwani, 2000; Suther et al., 2011). Yet, in order to explain multiple cycles of river incision and aggradation that formed the terraces, another driver must have been superimposed on long-term tectonic uplift. Possible drivers of such cycles during the Quaternary include climatic effects, vegetation changes, eustatic sea level changes, and glacial isostatic adjustments (forebulge of Laurentide Ice Sheet). All such potential drivers have a likely relation to glacial-interglacial cycles of the Quaternary.

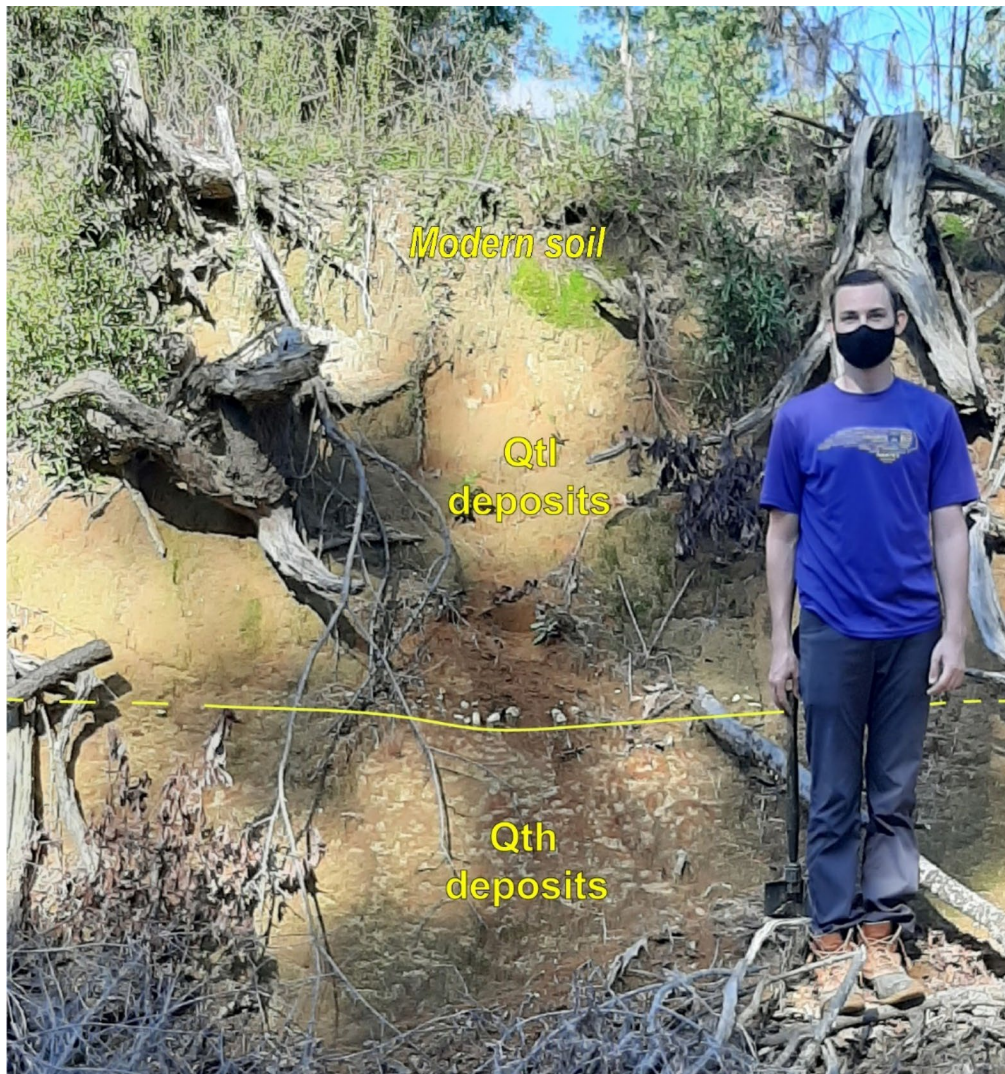


Figure 3. Exposure in Moncure Quadrangle, near Brickhaven, along railroad cut that reveals 6 feet of fine loamy sand deposits of the lower terrace (QtI) above older deposits that laterally underlie the upper terrace (Qth). A gravelly stone lag (mainly white quartz) occurs in basal QtI deposits, just above contact with Qth deposits. The upper 1 to 2 m of Qth deposits are highly altered and mottled (paleosol). Both sequences are coarser-grained (more sandy) and stratified in basal portions and finer-grained and more altered in upper portions. Geologist shown is Colby Brown (formerly NCGS, currently USACE).

Reinemund (1955) had speculated that the fluvial terraces in the upper Cape Fear River Basin may reflect changes in eustatic sea level during Pleistocene glacial-interglacial cycles. However, more current evidence suggests that eustatic effects, from sea level drop during the last glaciation, did not propagate more than 80 km upriver from the current shoreline in the southeastern Atlantic Coastal Plain (Marple and Talwani, 2000; Leigh, 2008) and knickpoints may have existed in the now-submerged continental slope. Climate-induced terrestrial sediment supply increases are now suspected to have overwhelmed effects of sea-level change. Leigh (2008) notes that during the peak of the last glaciation (~30,000 to 16,000 years ago), braided river channels were common in the Carolinas as a result of higher sediment yields during colder and drier conditions. Higher sediment yields during cold glacial periods may reflect sparser (and savanna-like) vegetation, increased eolian sand activity, and higher frequency of freeze-thaw cycles, river ice-jam floods, desiccation cycles, and mass wasting processes (Chassiot et al., 2020). River bank stability would also have been lower, with reduced vegetation, and steeper river gradients; thus, fluvial sediments would have tended towards coarser particle size compared with interglacial meandering stream systems. The braided river systems shifted to meandering river systems after ~16,000 years ago as the climate warmed and a moister forested environment replaced cold-dry savanna conditions (Leigh, 2008). As sediment yields decreased, rivers likely began to incise. Later changes in the meandering river system in the past 16,000 years were likely driven by more moderate changes in vegetation and precipitation. Overall, the cycles of river incision and aggradation in the southeastern USA can be explained by changes in climate (notably precipitation) and vegetation cover in drainage basins. Radiocarbon and luminescence ages support this idea with many terrace deposits recording times of braided stream aggradation during colder, drier, and more sparsely vegetated periods of the last glaciation (Suther et al., 2011, 2022).

Another possible (or additional) factor that may have influenced river incision and aggradation and terrace formation was glacial isostatic adjustments (including a peripheral forebulge) during the Quaternary. During glaciations, a peripheral bulge (or forebulge) south of the Laurentide Ice Sheet (in contrast to glacial subsidence beneath the ice sheet) likely affected stream gradients, stream power, and pathways of several rivers in the mid-Atlantic region (Reusser et al., 2004, Pico et al., 2019). According to Pico et al. (2019), a glacial forebulge in the Eastern USA extended from Pennsylvania and New Jersey (near the ice margin) to the Carolinas, generally decreasing in effect southward but still significant. Along the Potomac and Susquehanna Rivers, 10 to 20 m deep gorges that formed ~35,000 years ago may result in part from the Laurentide Ice Sheet forebulge (Reusser et al., 2004). Significant fluvial and coastal responses to the Laurentide Ice Sheet's peripheral forebulge have also been noted along the Mississippi River valley (Wickert et al., 2019) and in the Virginia Coastal Plain (Scott et al., 2010).

Preliminary results from a numerical model of the Laurentide Ice Sheet isostatic effects indicate as much as 8 mm/yr of uplift in the White Pines area of the Deep River during the last glaciation ~26,000 years ago (Tamara Pico, personal communication 2022). However, terrace formation would require an upstream-downstream differential in the forebulge uplift rate, with the orientation of river valleys with respect to isostatic gradients being an important consideration (Pico et al., 2019). Although a glacial forebulge may be a contributing factor, it seems unlikely that it can explain the location of all terraces in the North Carolina Piedmont study area on valleys with various orientations. Thus, more study is still needed. In the future, we plan to age date fluvial sediment from the terraces (using luminescence methods) to help constrain timing of aggradation and incision and perhaps test the forebulge hypothesis. Although long term uplift of the region over the Pleistocene is well accepted, the exact cause of cyclical aggradation and incision of Piedmont rivers remains somewhat uncertain. It seems likely, however, that they are related to glacial-interglacial cycles of the Quaternary Period, through their impact on climatic oscillations, vegetation cover, and/or peripheral glacial isostatic adjustments during the Quaternary Period.

References

- Bradley PJ, Gay NK, Bechtel R, and Clark TW. 2007. Geologic map of the Farrington 7.5-Minute Quadrangle, Chatham, Orange, and Durham counties, North Carolina: North Carolina Geological Survey Open-file Report 2007-03, 1:24,000.
- Bradley, P.J., Rice, A.K., Grimley, D.A. and Blocher, W.B., 2020, Geologic map of the Colon 7.5-Minute Quadrangle, Chatham and Lee counties, North Carolina: North Carolina Geological Survey Open-file Report 2020-04, 1:24,000.
- Bradley PJ, Rice AK, Grimley DA, Hanna HD, Malaska MJ. 2021a. Geologic Map of the Merry Oaks 7.5-Minute Quadrangle, Chatham and Lee Counties, North Carolina, North Carolina Geological Survey Open File Report 2021-02, 1:24,000.
- Bradley PJ, Rice AK, Grimley DA. 2021b. Geologic Map of the Moncure 7.5-Minute Quadrangle, Lee and Chatham Counties, North Carolina, North Carolina Geological Survey Open File Report 2021-01, 1:24,000.
- Chassiot, L., Lajeunesse, P. and Bernier, J.F., 2020. Riverbank erosion in cold environments: Review and outlook. *Earth-Science Reviews*, 207, p.103231.
- Clark, T.W., Gore, P.J., and Watson, M.E., 2001, Depositional and structural framework of the Deep River Triassic basin, North Carolina, *in* Hoffman, C.W., ed. Field Trip Guidebook for the 50th Annual Meeting of the Southeastern Section, Geological Society of America, Raleigh, North Carolina, p. 27-50. (re-printed in Carolina Geological Society Field Trip Guidebook 2011)
- Leigh, D.S., 2008. Late Quaternary climates and river channels of the Atlantic Coastal Plain, Southeastern USA. *Geomorphology*, 101(1-2), pp.90-108.

- Marple, R.T. and Talwani, P., 2000. Evidence for a buried fault system in the Coastal Plain of the Carolinas and Virginia—implications for neotectonics in the southeastern United States. *Geological Society of America Bulletin*, 112, pp.200-220.
- Mills, H.H., 2000, Apparent increasing rates of stream incision in the eastern United States during the late Cenozoic. *Geology*, v. 28; no. 10; p. 955–957.
- Pico, T., Mitrovica, J.X., Perron, J.T., Ferrier, K.L. and Braun, J., 2019. Influence of glacial isostatic adjustment on river evolution along the US mid-Atlantic coast. *Earth and Planetary Science Letters*, 522, pp.176-185.
- Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geol. Survey Prof. Paper 246, 159 p.
- Rice, A.K., Bradley, P.J., Grimley, D.A., and W.B. Blocher. 2020. Geologic Map of the Goldston 7.5-Minute Quadrangle, Chatham, Lee and Moore Counties, North Carolina, North Carolina Geological Survey Open File Report 2020-06.
- Scott, T.W., Swift, D.J., Whittecar, G.R. and Brook, G.A., 2010. Glacioisostatic influences on Virginia's late Pleistocene coastal plain deposits. *Geomorphology* 116, pp.175-188.
- Soil Survey Staff, 2019, Natural Resources Conservation Service, United States Department of Agriculture. Soil Survey Geographic (SSURGO) Database for Chatham, Lee, and Moore Counties, North Carolina. Available online. Accessed December 2019.
- Soller, D.R., 1988. Geology and Tectonic History of the Lower Cape Fear River Valley, Southeastern North Carolina. U.S. Geological Survey Professional Paper 1466–A
- Suther, B.E., Leigh D.S., and G.A. Brook, 2011. Fluvial terraces of the Little River Valley, Atlantic Coastal Plain, North Carolina. *Southeastern Geology*, v. 48, no.2, p. 73-93.
- Suther, B.E., Leigh D.S., and West L.T., 2022. Soil Chemistry and Clay Mineralogy of an Alluvial Chronosequence from the North Carolina Sandhills of the Upper Coastal Plain, USA.
- SynTerra, 2015, Comprehensive Site Assessment Report – Cape Fear Steam Electric Plant, pages 1010. Accessed from NC Department of Environmental Quality, Division of Water Resources online document library in 2020.

Acknowledgments

This work was supported in part by the Illinois State Geological Survey, Prairie Research Institute, University of Illinois. Thanks to Colby W. Brown, North Carolina Geological Survey (currently U.S. Army Corps of Engineers) for field assistance with hand augering. Discussions in the field with Aaron Rice and Phil Bradley (NCGS) were helpful in formulating mapping strategies and map unit delineations. Phil and Aaron also helped to locate and examine several sites with Quaternary deposits. Field discussions with Mike Vepraskas (NC State University) are also appreciated.

Susceptibility Maps of Geogenic Contaminants in Chatham County, NC

Owen W. Duckworth,^a Robert E. Austin,^{a,*} Taylor R. Alvarado,^a Philip J. Bradley^b

^aDepartment of Crop and Soil Sciences, North Carolina State University, Raleigh, North Carolina 26795, United States

^bNorth Carolina Geological Survey, 512 North Salisbury Street, Raleigh, North Carolina 27604, United States

1. Introduction

Approximately 144 million Americans rely on groundwater as their primary source of domestic water (Johnson et al., 2022). Unfortunately, groundwater is vulnerable to contamination from a variety of potentially toxic elements. In most cases, this contamination results from naturally occurring interactions between water and geomaterials, with >30 million Americans estimated to consume water contaminated by arsenic (As), fluoride (F), manganese (Mn), molybdenum (Mo), uranium (U), and others (Belitz et al., 2022). In North Carolina, geogenic contamination by As, chromium (Cr), Mn, radium (Ra), radon (Rd), vanadium (V), and U has been determined to be frequently present in well water within specific geographic areas (Alvarado et al., 2023; Ayotte et al., 2017; Coyte and Vengosh, 2020; Dinwiddie and Liu, 2018; Eaves et al., 2022; Gillispie et al., 2016; Kim et al., 2011; McMahan et al., 2019; Messier et al., 2015; Owusu et al., 2021; Pippin et al., 2003; Vinson et al., 2009).

The majority of geogenic contamination of groundwater by As, Cr, and Mn in North Carolina is thought to occur in the Carolina terrane (also known as the Carolina Slate belt) of the Piedmont physiographic region, although contamination can be found elsewhere (Alvarado et al., 2023; Ayotte et al., 2017; Coyte and Vengosh, 2020; Eaves et al., 2022; Gillispie et al., 2016; McMahan et al., 2019; Pippin et al., 2003). Within the Carolina terrane, it has been shown that specific geologic units with high frequencies of contamination may be located adjacent to geologic

units that have lesser contamination frequencies (Alvarado et al., 2023; Pippin et al., 2003). For example, within Union county (NC), the percentage of wells exceeding the As maximum contaminant level (MCL) in individual units was found to vary by 110-fold (Alvarado et al., 2023). It is thus critical to identify areas that contain greater probability of groundwater contamination to better target public health interventions, guide development and infrastructure decisions, and set realistic remediation and mitigation goals. This is particularly critical in areas that are experiencing rapid population growth and accompanying changes in land and water use. One such area is Chatham County, NC, which is predicted to grow in population by >40% by 2050 (NCOSBM, 2022).

Susceptibility maps (Bradley et al., 2017) have proven to be a useful tool to communicate risk of geogenic contamination to stakeholders. These maps generally aim to identify broad areas with defined levels of susceptibility of contamination by a specific element or chemical of concern. In this report, we create susceptibility maps of Chatham County for the common geogenic contaminants As, Cr, and Mn. To do so, we leverage a large recently published water quality database (Eaves et al., 2022) and a newly created 1:50,000 scale geologic map (Bradley, 2022) to better understand and communicate the potential for groundwater contamination. The results are discussed both in terms of regional geology and management implications.

2. Methods

2.1 NCWELL database. The well water database that was used for this analysis (NCWELL (Eaves et al., 2022)) was constructed from NC Department of Health and Human Services State Laboratory for Public Health well water tests from October 19, 1998, to May 20, 2019, resulting in a dataset with >60,000 individual measurements for the elements of interest. Within Chatham

County, there were 3130, 2065, and 3129 wells with concentration data for As, Cr, and Mn, respectively. This equates to one data point per 0.56–0.86 km² of land area. Details about well testing, as well as the geocoding and cleaning of the dataset, are presented in Eaves et al. (2022). Reporting limits were variable but were 1–10 µg/L for As and Cr, and 1–30 µg/L for Mn.

2.2 Geologic analysis of water contamination. A recently produced 1:50,000 scale geologic map of Chatham County, NC (Bradley, 2022), serves as the basis for our spatial analysis. Geologic units deemed to be similar in origin and composition were combined to increase the number of well tests for each geologic environment (Figure 1). For each of Mn, As, and Cr, the percentage of wells exceeding a threshold concentration was determined to calculate an exceedance probability (Alvarado et al., 2023). For this analysis, the reporting limit was used as the threshold concentration for As and Cr. We used this approach because reporting limits are near health standards for As and Cr(VI) (Eaves et al., 2022), and thus maps represent an estimate of the susceptibility for detectable concentration for these elements. For Mn, the health advisory level (300 µg/L) was used as the threshold concentration (*vida infra*). Visualization of these frequencies was conducted using ArcGIS Pro version 2.292.

3. Results and discussion

3.1 Arsenic. Arsenic is a carcinogen, and chronic exposure to As is associated with a number of different health issues, including diabetes, skin lesions, and cardiovascular and respiratory disorders (Farkhondeh et al., 2019; Ravenscroft et al., 2009). Of the 3,130 wells in Chatham County in the NCWELL dataset, 422 reported dissolved As (13.5%), resulting in 59% of the land area mapped as medium susceptibility, and an additional 18% mapped as high susceptibility. This widespread distribution is in agreement with previous studies that found As to occur at detectable

concentrations frequently in groundwater in the region (Alvarado et al., 2023; Ayotte et al., 2017; Coyte and Vengosh, 2020; Dinwiddie and Liu, 2018; Eaves et al., 2022; Pippin et al., 2003).

The potential for As in groundwater varies significantly across the county (Figure 2). Low susceptibility areas are most commonly found in the eastern and northeastern part of the county in areas underlain by the Farrington pluton or Buckhorn Dam intrusive suite, which are granitic rocks expected to be of low susceptibility. In contrast, in the western parts the county, Carolina terrane geologic units associated with the metavolcanic rocks from Uwharrie Formation and within the Hyco arc have high susceptibility, which is consistent with As in groundwater being associated with volcanogenic material in many areas (Morales-Simfors et al., 2020; Smedley and Kinniburgh, 2002; Vinson et al., 2011; Welch et al., 2000). However, it is worth noting that in this area of elevated susceptibility there are also areas associated with lesser susceptibility, including a formation within the Hyco arc with similar rock type and age to a high susceptibility unit. Much of the rest of Chatham County is mapped as medium susceptibility.

3.2 Chromium. Chromium in its hexavalent form (Cr(VI)) is a carcinogen, teratogen, and mutagen, and its ingestion in water is associated with cellular damage and increased risk of cancer (Zhitkovich, 2011). In groundwater in the NC piedmont, Cr(IV) has been found to be the dominant form, thus making the presence of any Cr in water a potential concern (Vengosh et al., 2016). Of the 2065 wells in Chatham County in the NCWELL dataset, 29 contain Cr above the reporting limit (1.4%). Based on this analysis, >99% of the area in Chatham county is at low susceptibility for Cr (Figure 3).

Across the county, the only geologic unit in the medium susceptibility category is meta-granitoid rock of the Buckhorn Dam Intrusive, found in the southeastern corner of Chatham

County. Small pods of mafic and ultramafic rocks are present in the Buckhorn Dam Intrusive area and may be the source of the Cr. It is worth noting that there are a small number of data points located in this formation (only four wells with Cr concentration data, which is >9-fold less than other formations). We thus suggest this region necessitates additional sampling, including efforts targeting areas near the mafic and ultramafic rock types, to better determine the extent of Cr contamination associated with this formation.

3.3 Manganese. Ingestion of excess Mn is associated with central nervous system effects including neurotoxicity and developmental defects (USEPA, 2003). Of the 3,129 wells in Chatham County in the NCWELL dataset, 1,320 reported detectable Mn (42.2%). However, Mn is known to be ubiquitous in soil, sediment, and water (USEPA, 2003), and its toxicity is typically associated with concentrations significantly greater than reporting limits. Therefore, we used the USEPA health advisory level of 300 µg/L as the threshold value in our susceptibility map (Figure 4). This criterion reduced the number of wells containing Mn above the threshold value to 323 (10.3%). Nonetheless, almost 50% of Chatham County land area falls in the medium or high susceptibility category, in agreement with previous studies that have identified widespread Mn contamination in the NC Piedmont (Gillispie et al., 2016).

Manganese in groundwater shows both strong geographic and geologic trends in Chatham County (Figure 4). Low susceptibility areas are most commonly found in the eastern and northeastern part of the county in areas underlain by sedimentary units within the Triassic basin or granitic rocks of the Farrington pluton and the Buckhorn Dam intrusive suite. In contrast, the central and western parts the county contain co-located areas that vary from low to high

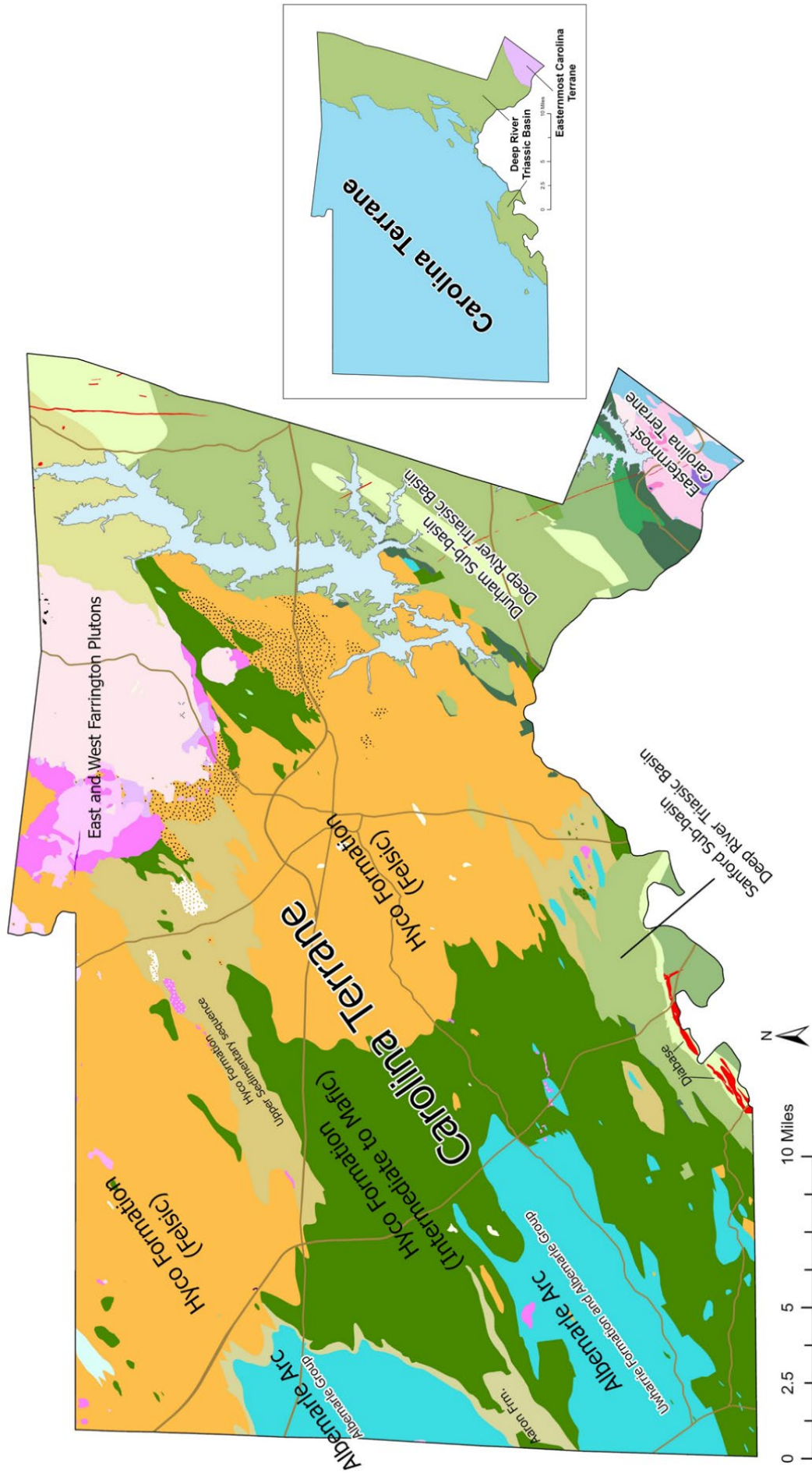


Figure 1. Maps showing generalized geology (main) and the boundaries of geologic terranes (inset) in Chatham County.

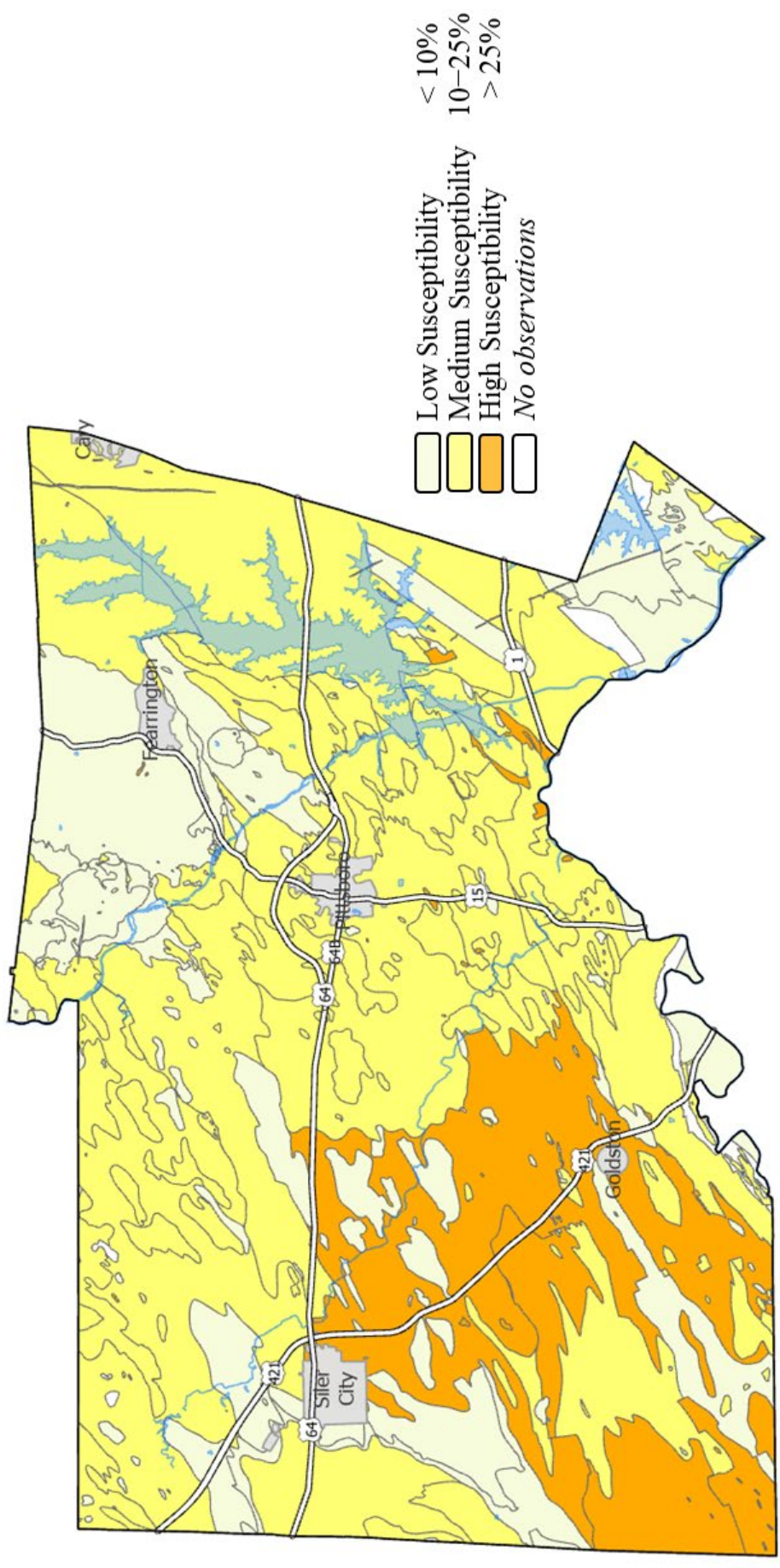


Figure 2. Arsenic susceptibility map based on percentage of wells exceeding As reporting limit (1–10 µg/L) within geologic units.

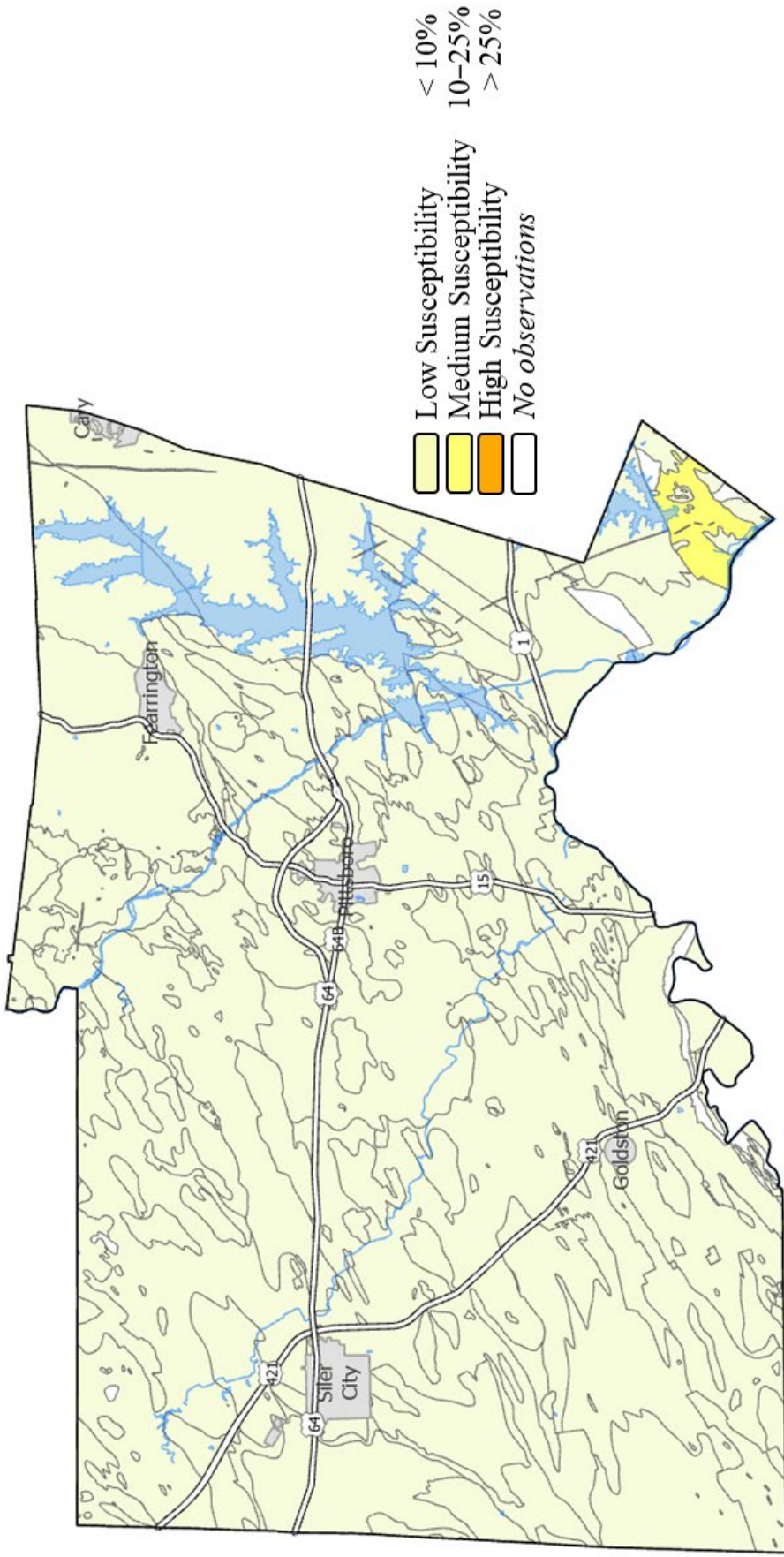


Figure 3. Chromium susceptibility map based on percentage of wells exceeding the Cr reporting limit (1–10 µg/L) within geologic units.

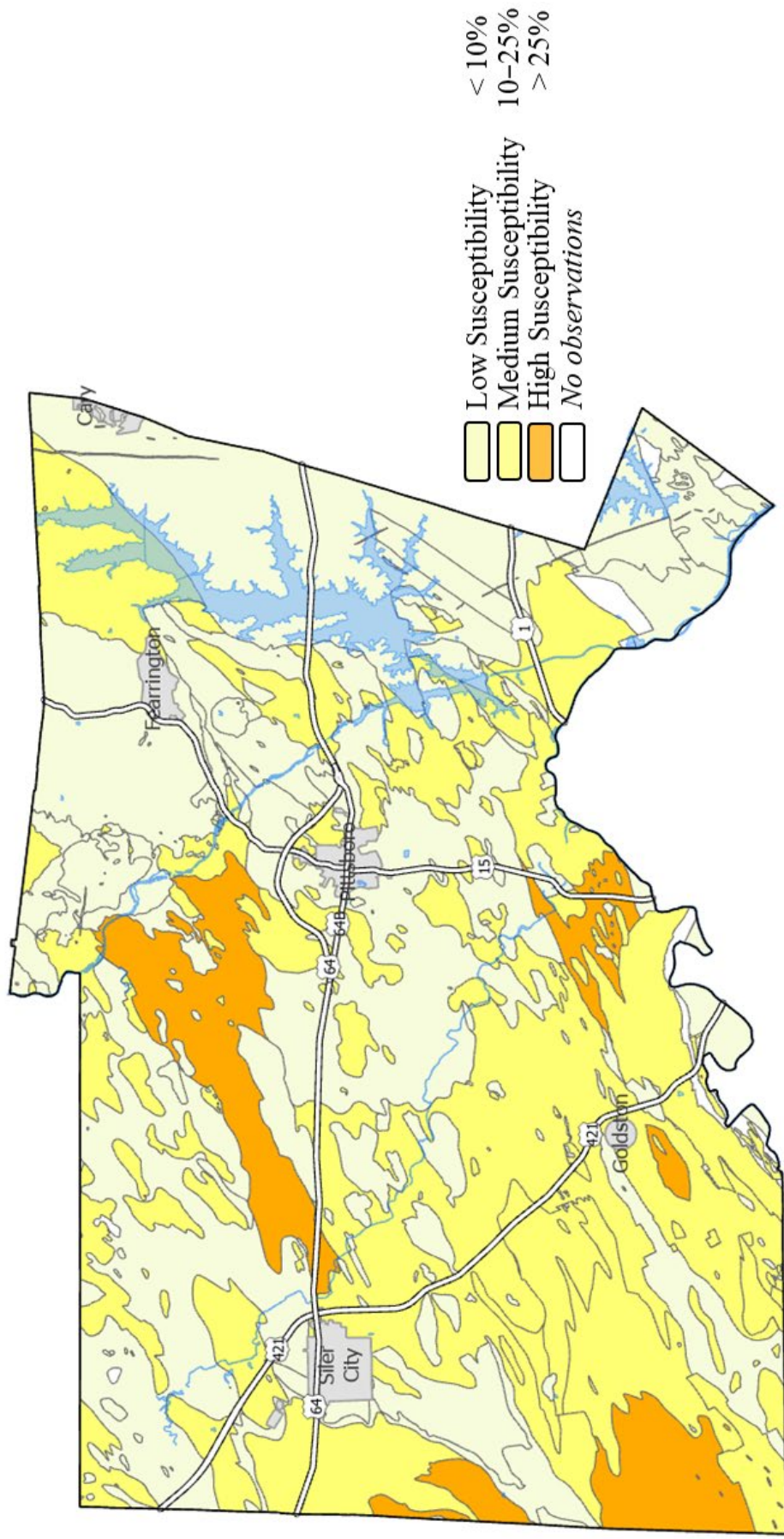


Figure 4. Manganese susceptibility map based on percentage of wells exceeding Mn health advisory level (300 µg/L) within geologic units.

susceptibility, with high susceptibility units associated with Carolina terrane metasedimentary and volcanic rocks from the Uwharrie Formation and from within the Hyco arc.

4. Conclusions

This study emphasizes the importance of geologic control on groundwater chemistry. In Chatham County, Cr had the least frequency of detection and consequently the greatest areas of low contamination susceptibility; in contrast, approximately $\frac{3}{4}$ of the county was classified as medium or high susceptibility for As. The potential for As and Mn in groundwater was widespread, with higher susceptibility predominantly associated with volcanogenic rocks in the Carolina terrane. Susceptibility for contamination by all elements was least in northeastern Chatham County in the area underlain by the Farrington pluton.

It is important to note that susceptibility maps herein only provide a probabilistic estimate of groundwater chemistry. Although the NCWELL database is quite extensive, in some geologic units estimates may be based on a low number of measurements and a small number of units contain insufficient data for analysis. Furthermore, hydrogeochemical factors can lead to pronounced differences in water chemistry over short distances, even within the same geologic unit (Alvarado et al., 2023). For private well uses, it must be emphasized that health authorities recommend well testing to determine the presence of potential hazards in domestic water (CDC, 2023).

Acknowledgements. This research was funded in part by a UNC Superfund Program grant from the National Institute of Environmental Health Sciences (P42ES031007). This work was supported

by the USDA National Institute of Food and Agriculture, Hatch project NC02713. This work was made possible by a US Department of Defense SMART Fellowship Program awarded to T.R.A. We thank Lauren Eaves for use of the NCWELL dataset. Geologic mapping by the North Carolina Geological Survey of Chatham County partially supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program under STATEMAP. We thank Matthew Polizzotto, David Vinson, and Hannah Peel for valuable discussion.

References

- Alvarado, T. R., Austin, R. E., Bradley, P. J., Eaves, L. A., Fry, R. C., George, A., Gray, K. M., Osborne, J. A., Stýblo, M., Vinson, D. S., and Duckworth, O. W., 2023, Geologic Predictors of Drinking Water Well Contamination in North Carolina: submitted.
- Ayotte, J. D., Medalie, L., Qi, S. L., Backer, L. C., and Nolan, B. T., 2017, Estimating the High-Arsenic Domestic-Well Population in the Conterminous United States: *Environmental Science & Technology*, v. 51, no. 21, p. 12443-12454.
- Belitz, K., Fram, M. S., Lindsey, B. D., Stackelberg, P. E., Bexfield, L. M., Johnson, T. D., Jurgens, B. C., Kingsbury, J. A., McMahon, P. B., and Dubrovsky, N. M., 2022, Quality of Groundwater Used for Public Supply in the Continental United States: A Comprehensive Assessment: *ACS ES&T Water*, v, 12, p. 2645–2656.
- Bradley, P.J., Marciniak, K.J., Caldwell, C., 2017, Groundwater Arsenic Susceptibility Map of Orange County: Coupling Detailed Geologic Data and Groundwater Quality Data to Model Arsenic Susceptibility: Geological Society of America Abstracts with Programs, Session No. 21, doi: 10.1130/abs/2017SE-289941
- Bradley, P.J. (with contributions in alphabetical order from : Bechtel, R.; Blocher, W .B.; Butler, R.J.; Clark, T.W .; Gay, N.K.; Grimley, D.A.; Hanna, H.D.; Malaska, M .J.; Peach, B.T.; Rice , A.K.; Stoddard , E.F.; and Watson, M .E.), 2022, Compiled Geologic map of Chatham County and surrounding areas, North Carolina: North Carolina Geological Survey Open-file Report 2022-03, scale 1:50,000, in color.
- CDC, 2023, Well Testing: Atlanta, Georgia, Center for Disease Control.
- Coyte, R. M., and Vengosh, A., 2020, Factors Controlling the Risks of Co-occurrence of the Redox-Sensitive Elements of Arsenic, Chromium, Vanadium, and Uranium in Groundwater from the Eastern United States: *Environmental Science & Technology*, v. 54, no. 7, p. 4367-4375.
- Dinwiddie, E., and Liu, X.-M., 2018, Examining the Geologic Link of Arsenic Contamination in Groundwater in Orange County, North Carolina: *Frontiers in Earth Science*, v. 6.
- Eaves, L. A., Keil, A. P., Rager, J. E., George, A., and Fry, R. C., 2022, Analysis of the novel NCWELL database highlights two decades of co-occurrence of toxic metals in North Carolina private well water: Public health and environmental justice implications: *Science of The Total Environment*, v. 812, p. 151479.

- Farkhondeh, T., Samarghandian, S., and Azimi-Nezhad, M., 2019, The role of arsenic in obesity and diabetes: *J Cell Physiol*, v. 234, no. 8, p. 12516-12529.
- Gillispie, E. C., Austin, R. E., Rivera, N. A., Bolich, R., Duckworth, O. W., Bradley, P., Amoozegar, A., Hesterberg, D., and Polizzotto, M. L., 2016, Soil Weathering as an Engine for Manganese Contamination of Well Water: *Environmental Science & Technology*, v. 50, no. 18, p. 9963-9971.
- Johnson, T. D., Belitz, K., Kauffman, L. J., Watson, E., and Wilson, J. T., 2022, Populations using public-supply groundwater in the conterminous U.S. 2010; Identifying the wells, hydrogeologic regions, and hydrogeologic mapping units: *Science of The Total Environment*, v. 806, p. 150618.
- Kim, D., Miranda, M. L., Tootoo, J., Bradley, P., and Gelfand, A. E., 2011, Spatial Modeling for Groundwater Arsenic Levels in North Carolina: *Environmental Science & Technology*, v. 45, no. 11, p. 4824-4831.
- McMahon, P. B., Belitz, K., Reddy, J. E., and Johnson, T. D., 2019, Elevated manganese concentrations in United States groundwater, role of land surface–soil–aquifer connections: *Environmental Science & Technology*, v. 53, no. 1, p. 29-38.
- Messier, K. P., Campbell, T., Bradley, P. J., and Serre, M. L., 2015, Estimation of Groundwater Radon in North Carolina Using Land Use Regression and Bayesian Maximum Entropy: *Environ Sci Technol*, v. 49, no. 16, p. 9817-9825.
- Morales-Simfors, N., Bundschuh, J., Herath, I., Inguaggiato, C., Caselli, A. T., Tapia, J., Choquehuayta, F. E. A., Armienta, M. A., Ormachea, M., Joseph, E., and López, D. L., 2020, Arsenic in Latin America: A critical overview on the geochemistry of arsenic originating from geothermal features and volcanic emissions for solving its environmental consequences: *Science of The Total Environment*, v. 716, p. 135564.
- NCOSBM, 2022, Standard Population Estimates, Vintage 2021 and Population Projections, Vintage 2022: North Carolina Office of State Budget and Management.
- Owusu, C., Silverman, G. S., Vinson, D. S., Bobyarchick, A., Paul, R., and Delmelle, E., 2021, A Spatial Autologistic Model to Predict the Presence of Arsenic in Private Wells Across Gaston County, North Carolina Using Geology, Well Depth, and pH: *Exposure and Health*, v. 13, no. 2, p. 195-206.
- Pippin, C. G., Butczynski, M. M., and Clayton, J. H., 2003, Distribution of total arsenic in groundwater of the North Carolina Piedmont province: North Carolina Department of Environmental Quality, Division of Water Resources.
- Ravenscroft, P., Brammer, H., and Richards, K., 2009, *Arsenic Pollution: A Global Synthesis*, Wiley.
- Smedley, P. L., and Kinniburgh, D. G., 2002, A review of the source, behaviour and distribution of arsenic in natural waters: *Applied Geochemistry*, v. 17, no. 5, p. 517-568.
- USEPA, 2003, Health Effects Support Document for Manganese: U.S. Environmental Protection Agency.
- Vengosh, A., Coyte, R., Karr, J., Harkness, J. S., Kondash, A. J., Ruhl, L. S., Merola, R. B., and Dywer, G. S., 2016, Origin of Hexavalent Chromium in Drinking Water Wells from the Piedmont Aquifers of North Carolina: *Environmental Science & Technology Letters*, v. 3, no. 12, p. 409-414.

- Vinson, D. S., McIntosh, J. C., Dwyer, G. S., and Vengosh, A., 2011, Arsenic and other oxyanion-forming trace elements in an alluvial basin aquifer: Evaluating sources and mobilization by isotopic tracers (Sr, B, S, O, H, Ra): *Applied Geochemistry*, v. 26, no. 8, p. 1364-1376.
- Vinson, D. S., Vengosh, A., Hirschfeld, D., and Dwyer, G. S., 2009, Relationships between radium and radon occurrence and hydrochemistry in fresh groundwater from fractured crystalline rocks, North Carolina (USA): *Chemical Geology*, v. 260, no. 3, p. 159-171.
- Welch, A. H., Westjohn, D. B., Helsel, D. R., and Wanty, R. B., 2000, Arsenic in Ground Water of the United States: Occurrence and Geochemistry: *Groundwater*, v. 38, no. 4, p. 589-604.
- Zhitkovich, A., 2011, Chromium in Drinking Water: Sources, Metabolism, and Cancer Risks: *Chemical Research in Toxicology*, v. 24, no. 10, p. 1617-1629.

Introduction to: The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and metallogenic analysis with an alternative model

ROBERT J. MOYE

5 Sunvale Avenue, Sandy Bay TAS 7005, Australia

rjimoje@gmail.com

This is an introduction to a synthesis and geologic analysis of the Albemarle sequence of the Carolina terrane from the perspective of precious and base metal sulfide exploration and ore deposit geology ([link to supplemental resources](#)). The Albemarle Sequence in south-central North Carolina is one of the most distinctive, most studied, and most widely mineralized components of the Carolina terrane. It consists of the basal Uwharrie Formation, a felsic-dominated Ediacaran volcanic arc, and the overlying Albemarle Group, accumulated in an Ediacaran-Cambrian arc-rift basin. Each is associated with distinctive styles of base and precious metal sulfide mineralization. This paper is a comprehensive compilation of information on the component formations of the sequence, a review of assumptions regarding their character, relationships, and associations and an analysis of their metallogenic potential.

Interpretations of petrologic and geochronologic studies published over the past decade (**Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**) have challenged the classic stratigraphic model of the Albemarle Sequence (**Stromquist and Sundelius, 1969**; **Stromquist *et al.*, 1971**; **Seiders, 1981**; **Milton, 1984**) and the character and timing of felsic and mafic magmatism associated with the Albemarle Group (**Pollock and Hibbard, 2010**; **Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**; **Boorman *et al.*, 2013**). These challenges are examined from a geologic and metallogenic perspective to better constrain and understand their implications and relevance to the distribution and timing of known precious and base metal sulfide mineralization in the Albemarle Sequence, as well as the potential for additional discoveries.

This analysis favors the classic stratigraphic model for the Albemarle Sequence, but with a radical reinterpretation of the character and timing of felsic magmatism associated with arc-rifting and deposition of the Albemarle Group formations. Felsic igneous units in the upper Uwharrie and Tillery formations and the Mudstone Member of the Cid Formation are interpreted as largely intrusive units of Morrow Mountain rhyodacite. Felsic volcanism associated with arc-rifting is largely restricted to the Flat Swamp member of the Cid Formation. This has important implications for the potential for additional discoveries of VMS styles of mineralization in the Albemarle Group.

A rift origin for the Albemarle Group was suggested in-house by the author when employed by Amselco Exploration, Inc. in the mid-1980s. Recognizing the potential of this environment for the occurrence of VMS deposits and other forms of sulfide mineralization

beyond the known deposits in the historic Cid and Gold Hill mining districts, a major program of geochemical reconnaissance was initiated across the entire sequence. Surprisingly, this effort failed to identify new areas of base metal sulfide mineralization. The absence of VMS-style mineralization from the thick sequence of marine sediments with apparently bimodal felsic-mafic volcanism in a rift basin was left unresolved.

A rifted-arc origin for the Albemarle Group is now well established (**Moye and Stoddard, 1987; Feiss *et al.*, 1993; Pollock *et al.*, 2010; Hibbard *et al.*, 2012; Hibbard *et al.*, 2013**) and is consistent with the presence of VMS-style mineralization. Volcanic-hosted polymetallic massive sulfide deposits (VMS) are among the more distinctive and historically economically significant styles of mineralization present in the Carolina terrane. The VMS deposits of the Cid and Gold Hill mining districts in central North Carolina are latest Ediacaran in age and hosted by the Flat Swamp Member of the Cid Formation of the Albemarle Group. These often small tonnage but extraordinarily high grade deposits appear to cluster locally, offering collective economic potential. The present study expands on Special Report 11 from the North Carolina Geological Survey (**Moye *et al.*, 2017**) to better constrain the occurrence and distribution of VMS deposits in the Albemarle Group and examine the potential for similar mineralization throughout the entire stratigraphic succession.

The potential for new metallic mineral deposit discoveries is also discussed in association with the Uwharrie Formation. Early Uwharrie magmatism was focused along a series of 20-40 kilometers long transtensional fault zones that host alignments of often F-rich advanced argillic epithermal alteration systems (AES) that are potentially epizonal manifestations of intrusion-centered porphyry Au-Cu-Mo deposits at depth (**Moye, 2013**). Represented by the type-example Pilot Mountain AES in Randolph County (**Klein and Schmidt, 1985**), there is significant potential for epithermal styles of mineralization near the surface and large tonnage porphyry mineralization at greater depths. This potential is consistent with discovery of the ca. 550 Ma Deep River Au-Cu-Mo porphyry prospect in northern Moore County (**Rapprecht *et al.*, 2013**).

Acknowledgements

The author is profoundly grateful to the North Carolina Geological Survey and the Carolina Geological Society for their encouragement and support in making this study available to a wider audience interested in the geology and mineral resources of the Carolina and Charlotte terranes of the Southeastern Piedmont. I am also greatly indebted to Dr. James Hibbard of NC State University for his outstanding contributions and his encouragement, advice, and patient explanations.

Background to this analysis

Mineral exploration programs focused primarily on gold and polymetallic massive sulfide deposits were active intermittently in the piedmont terranes of Virginia, the Carolinas, and Georgia from the 1950s through the early 1970s. Out of their experience with Bear Creek Mining Company, part of the Kennecott Copper Corporation, geologists Joe Worthington and Irv Kiff published the influential paper “*A suggested volcanogenic origin for certain gold deposits in the Slate Belt of the North Carolina piedmont*” in *Economic Geology* (**Worthington and Kiff, 1970**). This paper suggests the potential for large tonnage volcanogenic gold and base metal deposits in the Carolina terrane. Interest in this potential grew with the end of Federal regulation of the price of gold in 1972 and the subsequent rapid rise in value.

Worthington and Kiff controlled the historic Haile Gold Mine property and were exploring its economic potential at this time. Dr. William H. Spence of North Carolina State University was researching the epithermal origin of pyrophyllite deposits in the Carolina terrane in North Carolina. The chance meeting of these three at the Haile Mine on a 1974 Carolina Geological Society field trip resulted in a long-term collaboration that contributed directly to the discovery of the Kennecott Ridgeway gold deposit in South Carolina in 1979.

This precipitated a new gold rush to the Carolinas through the late 1970s and into the 1990s involving dozens of mining and exploration companies. The Haile and Ridgeway deposits were interpreted as the products of large seafloor hydrothermal vent sulfide systems that formed large tonnage low-grade stratabound gold deposits that were subsequently remobilized and recrystallized during regional deformation events (**Spence *et al.*, 1980; Feiss, 1982; Kiff and Spence, 1987; Spence *et al.*, 1987; Feiss *et al.*, 1993; Gillon *et al.*, 1995; Gillon *et al.*, 1998; Eager, 1997; Foley and Ayuso, 2012**).

This model was widely applied to metamorphosed auriferous hydrothermal alteration systems throughout the Carolina terrane and also in adjacent piedmont terranes. Large to moderate tonnage low-grade gold deposits characterized by disseminated pyrite hosted by silicic to phyllic alteration were interpreted as metamorphosed and deformed low sulfide precious metal-rich VMS deposits. This includes the historic Sawyer-Jones Keystone and Russell-Coggins groups of gold deposits hosted by the Albemarle Group in North Carolina (**Klein *et al.*, 2007**). This genetic model continued to hold dominance over minerals exploration program strategies and deposit evaluations in the region through the late 1990s and even into the mid-2010s.

Recognition of the dominance of structural controls and the epigenetic character of the Haile and Ridgeway gold deposits began in the late-1980s (**Tomkinson, 1988; Haywood, 1992; Maddy and Kilby, 1995; Berry *et al.*, 2015**) and evolved into their present classification as mesozonal orogenic gold deposits structurally linked to granitic magmatic reservoirs (**Moye, 2023; OceanaGold, 2022**) and dated to ca. 550 Ma (**Moye, 2023; Mobley**

et al., 2014). A review and analysis of the Sawyer-Jones Keystone and Russell-Coggins groups of gold deposits in central North Carolina concluded that they are also mesozonal orogenic gold deposits, but younger and formed during the late Ordovician-early Silurian Cherokee Orogeny without any apparent connection to felsic magmatism (Moye, 2018a, b).

The recognition that most of the gold deposits hosted by the Albemarle Group of the Carolina terrane, including the Sawyer-Jones Keystone and Russell-Coggins type, are various forms of mesozonal orogenic gold deposits of early Paleozoic age has profound implications for interpretations of the metallogenic associations and evolution of the sequence. This further constrains future natural resource assessments and exploration and evaluation strategies.

The volcanogenic massive sulfide (VMS) ore deposit model

Volcanogenic massive sulfide (VMS) deposits form in extensional tectonic regimes, typically in active rift environments. These include mid-ocean ridges, back-arc basins, intra-oceanic arc rifts, and continental arc rifts (e.g. Swinden, 1991; Hannington *et al.*, 1995; Scott, 1997; Syme *et al.*, 1999; Barrett *et al.*, 2001; Piercey *et al.*, 2001; Dusel-Bacon *et al.*, 2004). These deposits are characteristically associated with extensional and trans-tensional grabens, calderas, and synvolcanic and synsedimentary faults (e.g. Gibson, 1989; Allen, 1992; McPhie and Allen, 1992; Setterfield *et al.*, 1995; Allen *et al.*, 1996; Gibson *et al.*, 1999; Stix *et al.*, 2003; Gibson, 2005).

Major VMS districts of all ages show characteristic geologic constraints on ore genesis, magmatic associations, and tectonic setting (Allen *et al.*, 2002; Franklin *et al.*, 2005; Galley *et al.*, 2007). The Albemarle rifted-arc basin is consistent with these characteristics:

- it is a localized extensional regime imposed on an older volcanic arc
- crustal extension and thinning is accompanied by the diapiric rise of asthenospheric mantle
- it is characterized by bimodal magmatism with mantle-derived mafic magmas forming tholeiitic basalt and basaltic andesite and felsic crustal melts forming calc-alkaline or tholeiitic dacite-rhyolite magmas
- known VMS deposits occur in a specific time-stratigraphic interval associated with late-stage proximal felsic volcanic centers at the end of a major syn-rift volcanic episode that is followed by an abrupt change in the composition and intensity of volcanism and sedimentation
- VMS deposits cluster in local environments, including calderas, at scales from 1-2 or 5-10 and up to 50 kilometers across

- the mineralogy of the VMS deposits is strongly related to the chemistry, temperature, pH, and sulfur activity of the fluids and the composition of the footwall sequence, with variable direct input from magmatic fluids.

VMS deposits are commonly classified into five categories based on host-rock assemblages (**Barrie and Hannington, 1999; Franklin *et al.*, 2005; Piercey, 2010**):

- 1) **Mafic**: Mafic-dominated host assemblages, typically ophiolite (Cyprus, Oman, Newfoundland Appalachians).
- 2) **Bimodal-mafic**: Mafic-dominated sequences with up to 25% felsic rocks, which often directly host the deposits (Noranda, Flin Flon-Snow Lake, Kidd Creek camps).
- 3) **Mafic-siliclastic**: Sequences with subequal proportions of mafic \pm ultramafic and siliclastic rocks \pm minor felsic rocks (Besshi, Outokumpu, Windy Craggy).
- 4) **Felsic-siliclastic**: Fine-grained siliclastic dominated sequences with abundant felsic rocks and less than 10% mafic rocks (Bathurst, Iberian Pyrite Belt, Finlayson Lake).
- 5) **Bimodal-felsic**: Hosted by bimodal sequences where felsic rocks $>$ mafic rocks and minor sedimentary rocks (Kuroko, Buchans, Skellefte).

Assessing the VMS potential of the Albemarle Basin

The potential for these categories of VMS deposits within the Albemarle Group can be assessed relative to the character and composition of the sedimentary and volcanic rocks present. Categories 1-3 are dominated by mafic material in juvenile magmatic environments with minimal input from continental crustal rocks. Felsic rocks are derived primarily from melting of hydrated mafic crust, and mafic rocks are predominantly sourced from asthenospheric mantle. These VMS deposits are enriched in Cu + Zn with only minor Pb.

Category 1 and 2 VMS deposits are not consistent with the character and tectonic setting of the Albemarle Basin and the character of the basin sequence. However, the Mudstone Member of the Cid Formation is potentially consistent with the character of the category 3 lithologic association. This is predicated on the alternative theory of Albemarle Basin felsic magmatism proposed in this analysis; that felsic units of Morrow Mountain rhyodacite in the Tillery and Cid Mudstone Member are dominantly or entirely intrusive in character. If this suggestion is valid, then the lithologies of the Mudstone Member of the Cid Formation are dominantly siliclastic sediment with up to 20-30% basalt to andesitic basalt volcanic units.

Category 4 and 5 VMS environments are associated with evolved magmatic environments dominated by continental rocks or sediments derived from them. Felsic rocks form by melting of continental crust or continent-derived rocks, with mafic rocks sourced

from the lithosphere and asthenosphere. These VMS deposits are typically dominated by Zn + Pb + Cu. The character of the Flat Swamp Member of the Cid Formation is consistent with category 5, as are the associated VMS deposits of the Cid and Gold Hill mining districts.

The potential for VMS deposits in the Tillery Formation appears low, due to the low associated volcanic content and the absence of evidence for deposition in an active rift environment. The presence of VMS mineralization is contra-indicated for the Floyd Church and Yadkin formations. They post-date active rifting and appear to represent passive basin filling by coarsening epiclastic sediments despite continued mafic volcanism.

The limitations of this analysis

The information contained in this analysis is largely taken from publically available material published from the mid-1800s to the present. This is supplemented by information from the files of various mining and exploration companies that have conducted exploration programs and prospect evaluations in the Albemarle sequence. This includes the personal experience and direct knowledge of the author gained at NC State University (1970-1978) and with various mining companies (1979-1999), especially Phelps Dodge Exploration East (1979-1982) and Amselco Exploration/BP Minerals/Rio Tinto/Kennecott (1983-1990), and as an independent consultant (1997-1999). This continued during research on the character and origin of the Kennecott Ridgeway gold deposits in South Carolina through the Centre for Ore Deposits Research and Earth Sciences (CODES) at the University of Tasmania (2005-2008).

Mineral exploration is a highly competitive and often secretive business. Extensive geological, geochemical, and geophysical data sets acquired through often large capital expenditures and the resulting conclusions and insights are seldom made available outside the corporations. Exploration programs end, personnel are dispersed, and the information is too often relegated to eventually forgotten or discarded storage and lost. This is true of the Albemarle Sequence of the Carolina terrane, where an enormous body of information has been accumulated privately but is not available through public sources. Hopefully this study will encourage others to make the results of long-defunct exploration programs available in support of the important work of the North Carolina Geological Survey.

This analysis of the Albemarle Sequence is very much from the perspective of metallogeny and ore deposit geology and models rather than tectonic, structural, stratigraphic, or isotopic geochronology studies. An extensive program of geologic mapping and field verification, litho-geochemical analyses, and especially isotopic geochronological determinations is required to confirm many of the interpretations presented in this analysis, especially the character and timing of felsic igneous units present in the upper Uwharrie, Tillery, and Cid formations. It is hoped that this analysis will help to encourage universities, faculty, and students to undertake MS and PhD research programs to address these questions.

References

- Allen, R., 1992, Reconstruction of the tectonic, volcanic, and sedimentary setting of strongly deformed Zn–Cu massive sulfide deposits at Benambra, Victoria. *Economic Geology*, v. 87, p. 825-854.
- Allen, R., Lundstrom, I., Ripa, M., and Christofferson, H., 1996, Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. *Economic Geology*, v. 91, p. 979-1008.
- Allen, R., Weihed, P., and The Global VMS Research Project Team, 2002, Global comparison of volcanic-associated massive sulphide districts, in, Blundell, D., Neubauer, F., and von Quadt, A., eds., *The timing and location of major deposits in an evolving orogen*. Geological Society of London, Special Publication No. 204, p. 13-37.
- Barrett, T., Maclean, W., and Tennant, S., 2001, Volcanic sequence and alteration at the Parys Mountain volcanic-hosted massive sulfide deposit, Wales, United Kingdom: Applications of immobile element lithogeochemistry. *Economic Geology*, v. 96, p. 1279-1306.
- Barrie, C. and Hannington, M., 1999, Classification of volcanic-associated massive sulfide deposits based on host rock composition, in, Barrie, C. and Hannington, M., eds., *Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Environments*. *Reviews in Economic Geology*, v. 8, p. 2-12.
- Berry, J., Mobley, R., Gillon, K., Yogodzinski, G., and Bates, C., 2015, The Haile Gold Mine, South Carolina, USA, in, Secor, D., Howard, S., and Morrow, R., eds., *Tectonic history of the eastern piedmont in South Carolina: Guidebook for the Annual Meeting of the Carolina Geological Society, October 23-25, 2015*, p. 27-35.
- Boorman, S., Brennan, M., Oliver, J., Hibbard, J., Fodor, R., 2013, 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, in, Hibbard, J. and Pollock, J., eds., *One arc, two arcs, old arc, new arc: The Carolina terrane in central North Carolina*. Carolina Geological Society Guidebook, p. 155-174.
- Dusel-Bacon, C., Wooden, J., and Hopkins, M., 2004, U-Pb zircon and geochemical evidence for bimodal mid-Paleozoic magmatism and syngenetic base-metal mineralization in the Yukon-Tanana Terrane, Alaska. *Geological Society of America Bulletin*, v. 116, p. 989-1015.
- Eager, W., 1997, *Geology and stable isotope geochemistry of the Ridgeway North Pit Au-Ag deposit, Ridgeway, SC: Evidence for a syngenetic origin*. Unpublished MS thesis, University of South Carolina, 154 p.

- Feiss, P., 1982, Ore deposits of the northern parts of the Carolina slate belt, North Carolina, in, Bearce, D., Black, W., Kish, S., and Tull, J., eds., *Tectonic Studies in the Talladega and Carolina Slate Belts, Southern Appalachian Orogen*. Geological Society of America, Special Paper 191, p. 153-164.
- Feiss, P., Vance, R., and Wesolowski, D., 1993, Volcanic rock-hosted gold and base-metal mineralization associated with Neoproterozoic-Early Paleozoic back-arc extension in the Carolina terrane, southern Appalachian Piedmont. *Geology*, v. 21, p. 439-442.
- Foley, N. and Ayuso, R., 2012, *Gold Deposits of the Carolina Slate Belt, Southeastern United States: Age and Origin of the Major Gold Producers*. US Geological Survey, Open-File Report 2012-1179, 48 p.
- Franklin, J., Gibson, H., Galley, A., and Jonasson, I., 2005, Volcanogenic Massive Sulfide Deposits, in, Hedenquist, J., Thompson, J., Goldfarb, R., and Richards, J., eds., *Economic Geology 100th Anniversary Volume*. Littleton, CO, Society of Economic Geologists, p. 523-560.
- Galley, A., Hannington, M., and Jonasson, I., 2007, Volcanogenic massive sulphide deposits, in, Goodfellow, W., ed., *Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods*. Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 141-161.
- Gibson, H., 1989, *The geology and reconstruction of the Mine sequence and the Noranda cauldron of the Noranda complex, northwestern Québec*. Unpublished PhD Thesis, Carleton University, Ottawa, ON, Canada.
- Gibson, H., 2005, Volcanic-hosted ore deposits, in, Marti, J. and Ernst, G., eds., *Volcanoes in the Environment*. Cambridge University Press, New York, NY, USA, p. 332-386.
- Gibson, H., Morton, R., and Hudak, G., 1999, Submarine volcanic processes, deposits, and environments favorable for the location of volcanic-associated massive sulfide deposits, in, Barrie, C. and Hannington, M., eds., *Volcanic-Associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Environments*. *Reviews in Economic Geology*, v. 8, p. 13-51, Socorro, NM, USA.
- Gillon, K., Spence, W., Duckett, R., and Benson, C., 1995, Geology of the Ridgeway gold deposits, Ridgeway, South Carolina, in, Crowe, D., ed., *Selected Mineral Deposits of the Gulf coast and southeastern United States: Part II. - Gold deposits of the Carolina Slate Belt*. Society of Economic Geologists, Guidebook Series, v. 24, p. 53-87.
- Gillon, K., Mitchell, L., Dinkowitz, S., and Barnett, R., 1998, The Ridgeway gold deposits: A window to the evolution of an intra-arc basin in the Neoproterozoic Carolina Terrane, South Carolina, in, Secor, D., Jr., ed., *Special Issue devoted to the 1998 Field Trip of the Carolina Geological Society*. *South Carolina Geology*, v. 40, p. 25-64.
- Hannington, M., Jonasson, I., Herzig, P., and Petersen, S., 1995, Physical and chemical processes of seafloor mineralization at mid-ocean ridges, in, Humphris, S.,

- Zierenberg, R., Mullineaux, L., and Thomson, R., eds., Seafloor Hydrothermal Systems: Physical, Chemical, Biological and Geological Interactions. American Geophysical Union, Monograph, 91, p. 115-157.
- Haywood, N., 1992, Controls on syntectonic replacement mineralization in parasitic antiforms, Haile gold mine, Carolina Slate Belt, USA. *Economic Geology*, v. 87, p. 91-112.
- Hibbard, J., Miller, B., Hames, W., Standard, I., Allen, J., Lavalley, S., and Boland, I., 2012, Kinematics, U-Pb geochronology, and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of the Gold Hill shear zone, North Carolina: The Cherokee orogeny in Carolina, Southern Appalachians. *Geological Society of America, Bulletin*, v. 124, no. 5/6; p. 643-656.
- Hibbard, J., Pollock, J., Bradley, P., 2013, One arc, two arcs, old arc, new arc: An overview of the Carolina Terrane in central North Carolina, in, Hibbard, J. and Pollock, J., eds., One arc, two arcs, old arc, new arc: The Carolina Terrane in central North Carolina. *Carolina Geological Society Guidebook*, p. 35-62.
- Klein, T., Cunningham, C., Logan, M., and Seal, R., 2007, The Russell gold deposit, Carolina Slate Belt, North Carolina. *Economic Geology*, v. 102, p. 239-256.
- Klein, T. and Schmidt, R., 1985, Geology of the Pilot Mountain-Fox Mountain alteration systems, in, Feiss, P., ed., Volcanic-hosted gold and high-alumina rocks of the Carolina Slate Belt. *Society of Economic Geologists, Field Trip 1985 Fall Meeting*, p. 74-107.
- Kiff, I. and Spence, W., 1987, Volcanogenic epithermal-exhalative gold deposits of the Haile-Type in the Carolina Slate Belt. *Geological Society of America, Abstracts with Programs* v. 19, no. 6, p. 394.
- Maddry, J. and Kilbey, T., 1995, Geology of the Haile gold mine, in, Crowe, D., ed., Selected Mineral Deposits of the Gulf coast and southeastern United States: Part II. - Gold deposits of the Carolina slate belt. *Society of Economic Geologists, Guidebook Series*, v. 24, p. 147-172.
- McPhie, J. and Allen, R., 1992, Facies architecture of mineralised submarine volcanic sequences: Cambrian Mount Read Volcanics, western Tasmania. *Economic Geology*, vol. 87, p. 587-596.
- Milton, D., 1984, Revision of the Albemarle Group, North Carolina. *US Geological Survey, Bulletin* 1537-A, p. A69-A72.
- Mobley, R., Yogodzinski, G., Creaser, R., and Berry, J., 2014, Geologic History and Timing of Mineralization at the Haile Gold Mine, South Carolina. *Economic Geology*, v. 109, p. 1863-1881.
- Moye, R. and Stoddard, E., 1987, The Albemarle Basin: a wrench fault pull-apart in the Slate Belt of North Carolina. *Geological Society of America, Southeastern Section Meeting, Abstracts with Programs*, v. 19, n. 2, p. 119-120.

- Moye, R.J., 2013. Advanced argillic epithermal alteration systems (AES) in the Carolina terrane of central North Carolina: possible structural controls and association with Neoproterozoic Uwharrie felsic magmatism, in, Hibbard, J. and Pollock, J., eds., One arc, two arcs, old arc, new arc: The Carolina terrane in central North Carolina. Carolina Geological Society, Field Trip Guidebook, p. 213-238.
- Moye, R. J., 2018a. Ophir District, Randolph and Montgomery Counties, North Carolina: Geologic and metallogenetic analysis. North Carolina Geological Survey, Open-File Report 2018-15, 73p.
- Moye, R. J., 2018b. Sawyer-Keystone Trend of Au-Ag-As deposits in Randolph County, North Carolina: Geologic and metallogenetic analysis. North Carolina Geological Survey, Open-File Report 2018-18, 45p.
- Moye, R., Reid, J., and Lee, D., 2017, Volcanogenic polymetallic massive sulfide deposits (VMS) of the Carolina Terrane in central North Carolina: New perspectives and historical reports and data from the files of Phelps Dodge Exploration East (1975-1982). North Carolina Geological Survey, Special Publication 11, 456p.
- Moye, R., 2023, The Kennecott Ridgeway North Au-Ag-As-Mo deposit, Fairfield County, South Carolina: Late Ediacaran Multi-stage Granite-related Orogenic Alteration and Mineralization in a Thrust Fault Duplex. Preprint at ResearchGate, 79 p.
DOI:10.13140/RG.2.2.18073.49761
https://www.researchgate.net/publication/367097821_The_Kennecott_Ridgeway_North_Au-Ag-As-Mo_deposit_Fairfield_County_South_Carolina_Late_Ediacaran_Multi-stage_Granite-related_Orogenic_Alteration_and_Mineralization_in_a_Thrust_Fault_Duplex
- OceanaGold, 2022, Annual Information Form for the year ended 31 December 2021, 31 March 2022. <https://ogc.irmau.com/site/pdf/35d15fc7-1e4a-44f0-81ce-15896648cf54/OceanaGold-Annual-Information-Form-December-31-2021.pdf>
- Piercey, S., 2010, An overview of petrochemistry in the regional exploration for volcanogenic massive sulphide (VMS) deposits. *Geochemistry: Exploration, Environment, Analysis*, v. 10, p. 1-18.
- Piercey, S., Paradis, S., Murphy, D., and Mortensen, J., 2001, Geochemistry and paleotectonic setting of felsic volcanic rocks in the Finlayson Lake volcanic-hosted massive sulfide (VHMS) district, Yukon, Canada. *Economic Geology*, v. 96, p. 1877-1905.
- Pollock, J. and Hibbard, J., 2010, Geochemistry and tectonic significance of the Stony Mountain gabbro, North Carolina: implications for the early Paleozoic evolution of Carolina. *Gondwana Research*, v. 17, p. 500-515.
- Pollock, J., Hibbard, J., and Sylvester, P., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina, in, Tollo, R., Bartholomew, M., Hibbard, J., and Karabinos,

- P., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*. Geological Society of America, Memoir 206, p. 1-34.
- Rapprecht, R., Stewart, K., LaPoint, D., and Stein, H., 2013, The Deep River gold-copper-molybdenum prospect: Potential subvolcanic porphyry mineralization in the Hyco arc, central North Carolina, in, Hibbard, J. and Pollock, J., eds., *One arc, two arcs, old arc, new arc: The Carolina terrane in central North Carolina*. Carolina Geological Society, Field Trip Guidebook, p. 193-212.
- Scott, S., 1997, Submarine hydrothermal systems and deposits, in, Barnes, H., ed., *Geochemistry of Hydrothermal Ore Deposits*, 3rd Edition. John Wiley and Sons Ltd, New York, p. 797-875.
- Seiders, V., 1981, Geologic map of the Asheboro Quadrangle, North Carolina, and adjacent areas. US Geological Survey, Miscellaneous Investigations Map I-1314, scale 1:62,500.
- Setterfield, T., Hodder, R., Gibson, H., and Watkins, J., 1995, The McDougall-Despina fault set, Noranda, Quebec; evidence for fault-controlled volcanism and hydrothermal fluid flow. *Exploration and Mining Geology*, v. 4, p. 381-393.
- Spence, W., Worthington, J., Jones, E., and Kiff, I., 1980, Origin of gold mineralization at the Haile mine, Lancaster County, South Carolina: *Mining Engineering*, v. 32, p. 70-73.
- Spence, W., Taylor, A., and Kiff, L., 1987, Discovery of the Ridgeway, South Carolina gold deposit. *Geological Society of America, Abstracts with Programs*, v. 19 no. 6, p. 453.
- Stix, J., Kennedy, B., Hannington, M., Gibson, H., Fiske, R., Mueller, W., and Franklin, J., 2003, Caldera-forming processes and the origin of submarine volcanogenic massive sulfide deposits. *Geology*, v. 31, p. 375-378.
- Stromquist, A., Choquette, P., and Sundelius, H., 1971, Geologic map of the Denton quadrangle, central North Carolina 1:62,500. US Geological Survey, Map GQ-872.
- Stromquist, A. and Sundelius, H., 1969, Stratigraphy of the Albemarle Group of the Carolina Slate Belt in central North Carolina. US Geological Survey, Bulletin 1274-B, 22 p.
- Swinden, H., 1991, Paleotectonic settings of volcanogenic massive sulphide deposits in the Dunnage Zone, Newfoundland Appalachians. *Canadian Institute of Mining and Metallurgy Bulletin*, v. 84, p. 59-89.
- Syme, E., Lucas, S., Bailes, A., and Stern, R., 1999, Contrasting arc and MORB-like assemblages in the Paleoproterozoic Flin Flon Belt, Manitoba, and the role of intra-arc extension in localizing volcanic-hosted massive sulphide deposits. *Canadian Journal of Earth Sciences*, v. 36, p. 1767-1788.
- Tomkinson, M., 1988, Gold mineralization in phyllonites at the Haile mine, South Carolina. *Economic Geology*, v. 83, p. 1292-1400.

Worthington, J. and Kiff, I., 1970, A suggested volcanogenic origin for certain gold deposits in the Slate Belt of the Carolina piedmont. *Economic Geology*, v. 65, p. 529-537.

Introduction to: A geologic analysis of the Charlotte terrane from a metallogenic perspective and a proposed first-order stratigraphy

ROBERT J. MOYE

5 Sunvale Avenue, Sandy Bay TAS 7005, Australia

rjjmoye@gmail.com

This is an introduction to a comprehensive synthesis and geologic analysis of the Charlotte terrane from the perspective of precious and base metal sulfide exploration and ore deposit geology ([link to supplemental resources](#)). It is based in significant part on a long and varied experience in minerals exploration of the Carolina and Charlotte terranes but draws heavily on a wide variety of published work, the resources of the geological surveys of North and South Carolina and Georgia, and those of the US Geological Survey. There is an emphasis on the diversity of mineralization styles and ages and the potential of known ore deposits for new 21st century priority commodity evaluations and the potential for new discoveries.

The Charlotte terrane is a peri-Gondwanan primitive oceanic volcanic arc that forms the second largest component of the Carolina superterrane (**Hibbard *et al.*, 2002**). It collided and sutured to the adjacent Carolina terrane ca. 550 Ma, resulting in regional deformation and metamorphism with uplift and erosion that exposed the Charlotte terrane at higher metamorphic grade and deeper crustal levels (**Shervais *et al.*, 2003**). Widely dominated by large, often composite plutonic bodies ranging from dunite to granite in composition and in age from ca. 580 Ma to ca. 300 Ma, the preservation of volcanic and sedimentary sequences is often limited and their stratigraphy poorly constrained.

Additionally, the Charlotte terrane has been tectonically segmented into three domains: the pluton-dominated North domain; the central Silverstreet domain, uplifted and eroded to granulite facies levels (**Shervais *et al.*, 2003**); and the South domain, similar to the North domain but with more widely preserved volcanic and sedimentary sequences. Much of the geologic study of the North domain has focused on plutonic rocks. However, detailed petrologic, petrographic, and paragenetic studies constrained by high-resolution U-Pb zircon age dates for a portion of the North domain (**Dennis and Shervais, 1991; Dennis and Shervais, 1996; Dennis and Wright, 1997**) define two major magmatic-tectonic episodes in the evolution of the Charlotte volcanic arc; an early Primitive Arc association and a younger Rifted-Arc association.

Extensive detailed and reconnaissance mapping of the South domain has defined the character and stratigraphic relationship between volcanic and sedimentary units associated with these two phases of arc evolution and constrains associated styles of precious and base metal sulfide mineralization. Integration of studies from the North and South domains of the Charlotte

terrane facilitates differentiation of Primitive arc and Rifted-arc plutonic and stratigraphic units in the North domain and constrains the character and age of these units in the South domain.

Significantly less studied and more poorly defined than the adjacent Carolina terrane, the Charlotte terrane has also received significantly less attention from metal resource mining and exploration companies in the modern era. However, the terrane hosts numerous occurrences of hydrothermal alteration and both precious and base metal sulfide mineralization. These include VMS deposits, large zoned highly sulfidized epizonal to epithermal alteration systems, intrusion-centered mineralization, and numerous orogenic low-sulfidation quartz vein deposits. VMS-type deposits are exclusively associated with the Primitive Arc sequence but appear to be base metal-poor in comparison to those of the Carolina terrane. Often very large zones of epizonal to epithermal alteration with often widespread Au mineralization appear exclusive to the Rifted-Arc sequence and show differences between the North and South domains, possibly associated with the level of exposure relative to the depth of formation.

Unique to the South Domain is the Stoney Ridge Mine, an apparently unique occurrence of Au-Ag-Cu-Ba mineralization hosted by a possibly epizonal alteration system developed in a ring dike encircling an otherwise unremarkable granodiorite pluton. It post-dates the Primitive Arc sequence but is older than the Rifted-Arc event. Unique to the North Domain, some plutons of the Salisbury suite of Devonian granites show strong fractionation trends and have associated Cu-Mo mineralization that includes the small subeconomic Newell porphyry deposit. Additionally, the Probst Prospect indicates a significant exploration potential for peripheral skarn mineralization enriched in strategic rare earth elements on the margins of these granites.

Low sulfidation orogenic mesozonal quartz veins with Au ± Cu sulfide mineralization are common in the Charlotte terrane and especially numerous in Mecklenburg County in the North domain, centered on the city of Charlotte. Historic gold production from around 100 mines on dozens of vein systems, many within 15 kilometers of the city center of Charlotte, was a major factor in the local economy in the early 19th century and led to the opening of the Charlotte Mint in 1837.

Individual mines produced from 100s to 50,000 ounces of gold. Much of this production was from the upper, oxidized portions of the ore bodies but some higher-grade lodes were worked to depths of up to 115 meters at grades averaging around 0.3 oz/ton Au (**Gair, 1989**). Other clusters of these veins include the Hamby Branch group, which includes a series of tungsten-bearing quartz veins including the Phoenix and Furniss mines. Most of these orogenic quartz vein gold deposits appear to have formed during the late Ordovician Cherokee Orogeny and during localized tectonism in the Devonian.

Despite locally intense urbanization, the Charlotte terrane in North Carolina offers significant potential for under-explored metallic mineral resources. This is especially true of the Devonian age Salisbury intrusive suite, where the highest potential appears to be along the periphery of the plutons. Clusters of orogenic quartz vein deposits with Au + Cu ± W

mineralization where multiple parallel or intersecting veins are present may also represent possible bulk-mining targets. This is especially true of the Hamby Branch group of deposits, where many veins were only exploited to shallow depths in the oxidized zone. As tungsten is identified as a strategic metal in the modern economy, perhaps it would be appropriate to review the potential for this resource in the Hamby Branch veins and those to the northeast and southwest.

Additionally, a better understanding of the various styles and extent of hydrothermal alteration and metallic element mineralization throughout the Charlotte terrane facilitates and constrains environmental assessments of soil and water quality issues relative to land use. Gold and base metal sulfide mineralization, even at low concentrations, and associated hydrothermal alteration are reservoirs of potentially toxic trace elements that are subject to mobilization, dispersal, and both inorganic and organic concentration at the surface and in the shallow subsurface.

Acknowledgements

The author is profoundly grateful to the North Carolina Geological Survey and the Carolina Geological Society for their encouragement and support in making this study available to a wider audience interested in the geology and mineral resources of the Carolina and Charlotte terranes of the Southeastern Piedmont. I am also greatly indebted to Dr. James Hibbard of NC State University for his encouragement, advice, and indefatigable review and editing skills.

The project benefitted materially from consultations with Dr. Gil Allard of the University of Georgia at Athens and from the work of his many MS students. These essential contributions extend into the mid-1990s and include his work with Dr. James Whitney at the University of Georgia (**Allard and Whitney, 1994**).

Background to this analysis

While working for Amselco Exploration Inc. (BP Minerals/Rio Tinto/Kennecott) based in Camden SC, the author conducted an extensive review of historic gold and base metal sulfide mines and prospects in the Carolina and Charlotte terranes in NE Georgia and SW South Carolina in 1984-1988 to identify large metalliferous hydrothermal systems with the potential to host economic ore deposits. This involved extensive reconnaissance and locally detailed geologic mapping. Around 25-30 different occurrences were located, examined, sampled, and initially

assessed. Numerous other mining and exploration companies were active in the same area throughout the 1980s and 1990s.

Deposits identified as potentially favorable in the Charlotte terrane include Stoney Ridge, Parson's Mountain, Big Mountain, the TM prospect (obtained from AMAX in 1985), and mineralized areas along the Fishing Creek shear zone. As project geologist for these properties, the author was responsible for detailed geologic mapping and planning and overseeing geochemical and geophysical surveys, surface trenching, and core-drilling operations. Although none of the deposits proved to host economically significant mineralization, the results of the project provided a broad understanding of the geology of the Charlotte terrane and the character and genesis of various forms of mineralization.

More focused work by the author in the Charlotte terrane in North Carolina for Phelps Dodge Exploration East (1979-1982) included exploration of the tungsten potential of the Hamby Branch area vein deposits and the REE potential of the Probst skarn deposit. Work for Amselco Exploration Inc. (BP Minerals/Rio Tinto) in 1983-1991 included reconnaissance of the character and possible gold mineralization of metamorphosed hydrothermal alteration zones of possible epizonal or epithermal origin in Mecklenburg County.

The geology of the North Domain of the Charlotte terrane is provided by the integrated studies of **Goldsmith *et al.* (1989)** for the Charlotte 1° x 2° Quadrangle. Essential resources in understanding the character and evolution of the Charlotte terrane in the North domain include the pioneering work of **Robert Butler (1984; 1991)** and his student **Tom Brazzell (1984)** in the type area on the NC-SC border area and detailed multidisciplinary studies of the Mean Crossroads and Wildcat Branch zoned intrusive complexes in northern South Carolina (**Dennis and Shervais, 1991; Dennis and Shervais, 1996; Dennis and Wright, 1997**). The tectonic framework is constrained by the work of **Hibbard *et al.* (2002)**, **Shervais *et al.* (2003)**, and **Hibbard *et al.* (2012)**. Among the numerous useful resources of the South Carolina Geological Survey, the published work of **Griffin (1978, 1979)** and **Weisenfluh and Snoke (1978)** were especially important in understanding Rifted Arc magmatic differentiation trends and the association with gold mineralization.

This analysis developed with the intent to document and make available results of the author's work on the geology and ore deposits of the Charlotte terrane in Georgia mid- to late-1980s, especially the unique Stoney Ridge mineralized ring dike and the TM and Tyrone VMS deposits. Additionally, there was the recognition of two distinct and separate stratigraphic sequences and ore deposit associations that were not fully developed in the existing literature.

With the publication of key studies in the 1990s through 2010s, it became possible to better constrain the original work and expand the observations and interpretations into the Charlotte terrane in North Carolina. The result is the present integrated analysis of the geology and metallogeny of the North and South domains of the Charlotte terrane. It is intended to

promote a better understanding of the character and evolution of this complex volcanic arc and the character, origin, and exploration potential for metallic mineral resources.

Additionally, there is the hope that this work will encourage further academic interest in the Charlotte terrane to address the many unanswered questions; especially needed are detailed geologic mapping, petrographic and petrologic studies, and new geochronological data to better indentify and differentiate plutonic and stratigraphic members of the Primitive Arc and Rifted Arc sequences. It is also hoped that this publication will encourage other private industry geologist, especially those who have studies and data from long defunct projects, to make those studies available to the public through the North Carolina Geological Survey to promote knowledge of mineral resources and facilitate future exploration for strategic materials in the state.

The limitations of this analysis

This analysis is based in significant part on the direct personal experience and knowledge of the author gained at NC State University (1970-1978) and with various mining companies, especially Phelps Dodge Exploration East (1979-1982) and Amselco Exploration/BP Minerals/Rio Tinto/Kennecott (1983-1990), and as an independent consultant (1997-1999). This continued during research on the character and origin of the Kennecott Ridgeway gold deposits in South Carolina through the Centre for Ore Deposits Research and Earth Sciences (CODES) at the University of Tasmania (2005-2008). This is supplemented by publically available information published from the mid-1800s to the present, information from the files of various mining and exploration companies that have conducted exploration programs and prospect evaluations in the Charlotte terrane, and discussions with geologist in the public and private sectors.

Mineral exploration is always a highly competitive and often secretive business. Extensive geological, geochemical, and geophysical data sets acquired through often large capital expenditures and the resulting conclusions and insights are seldom made available outside the corporations. Exploration programs end, personnel are dispersed, and the information is too often relegated to eventually forgotten or discarded storage and lost. This is true of the Charlotte terrane, where an enormous body of information has been accumulated privately but is not available through public sources.

This analysis is focused on understanding the metallogenic character and evolution of the Charlotte terrane and the diverse array of ore deposits from an ore deposit geology and resource exploration perspective. It is largely based on personal knowledge and experience but constrained by published tectonic, structural, stratigraphic, and isotopic geochronology studies. There is equal emphasis on a proposed first-order stratigraphic model for the Charlotte terrane.

However, many of the conclusions offered require extensive geologic mapping and field verification, petrographic and petrologic constraints, and isotopic geochronological data for a wide range of intrusions and stratigraphic units.

References

- Allard, G. and Whitney, J., 1994, Geology of the Inner Piedmont, Carolina terrane, and Modoc Zone in Northeast Georgia. Georgia Geologic Survey, Project Report 20, 36 p. + map.
- Butler, J., 1984, Geologic history of the Charlotte belt at the Old Pineville Quarry, northeastern York County, South Carolina. *South Carolina Geology*, v. 27, p. 13-24.
- Butler, J., 1989, Review and classification of ultramafic bodies in the Piedmont of the Carolinas, in, Mittwede, S. and Stoddard, E., eds., *Ultramafic Rocks of the Appalachian Piedmont*. Geological Society of America, Special Paper, v. 231, p. 19-31.
- Brazell, T., 1984, The geology and economic potential of the west half of the Lake Wylie 7.5' Quadrangle, South Carolina. Unpublished MS thesis, University of Georgia, Athens, Georgia, 88 p.
- Dennis, A. and Shervais, J., 1991, Arc rifting of the Carolina terrane in northwestern South Carolina. *Geology*, v. 19, p. 226–229.
- Dennis, A. and Shervais, J., 1996, The Carolina terrane in northwestern South Carolina: insights into the development of an evolving island arc, in, Nance, D. and Thompson, M., eds., *Avalonia and Related Peri-Gondwanan Terranes of the Circum-North Atlantic*. Geological Society of America, Special Paper, v. 304, p. 237–256.
- Dennis, A. and Wright, J., 1997, The Carolina terrane in northwestern South Carolina, USA: Late Precambrian-Cambrian deformation and metamorphism in a peri-Gondwana oceanic arc. *Tectonics*, v. 16, p. 460–473.
- Gair, J., 1989, Gold-Quartz and Gold-Pyrite-Quartz Veins, in, Gair, J., ed., *Mineral Resources of the Charlotte 1° x 2° Quadrangle, North Carolina and South Carolina*. US Geological Survey, Professional Paper 1462, p. 61-64.
- Goldsmith, R., Milton, D., and Horton, J., 1989, Geologic map of the Charlotte 1° x 2° Quadrangle. US Geological Survey, Miscellaneous Investigations Series, Map I-1251-E.
- Griffin, V., 1978, Geology of the Calhoun Creek, Calhoun Falls, and portions of the Chennault and Verdery Quadrangles, South Carolina. South Carolina Geological Survey, Map Series, MS-23, 47 p.

- Griffin, V., 1979, Geology of the Abbeville East, Abbeville West, Latimer, and Lowndesville Quadrangles, South Carolina. South Carolina Geological Survey, Map Series, MS-24, 58 p.
- Hibbard, J., Stoddard, S., Secor, D., Jr., and Dennis, A., 2002, The Carolina Zone: overview of Neoproterozoic to early Paleozoic peri-Gondwanan terranes along the eastern flank of the southern Appalachians. *Earth-Science Reviews*, v. 57, p. 299-339.
- Hibbard, J., Miller, B., Hames, W., Standard, I., Allen, J., Lavallee, S., and Boland, I., 2012, Kinematics, U-Pb geochronology, and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of the Gold Hill shear zone, North Carolina: The Cherokee orogeny in Carolina, Southern Appalachians. *Geological Society of America, Bulletin*, v. 124, n. 5/6; p. 643-656.
- Shervais, J., Dennis, A., McGee, J., and Secor, D., 2003, Deep in the heart of Dixie: Pre-Alleghanian eclogite and HP granulite metamorphism in the Carolina terrane, South Carolina, USA. *Journal of Metamorphic Geology*, v. 21, n. 1, p. 65-80.
- Weisenfluh, G. and Snoke, A., 1978, An epizonal trondhjemite quartz keratophyre complex near Calhoun Falls, South Carolina. South Carolina Geological Survey, *Geologic Notes*, v. 22, n. 2, p. 48-73.

Is a Large Complex Impact Crater Hiding in Plain Sight in Central North Carolina?*

MCDANIEL, R. D., ronalddeanmcdaniel@gmail.com; STODDARD, E. F., stoddard@ncsu.edu LUMPKIN, B. L., lumpkinbarry@gmail.com, POWERS, J. A., jpowers@carolinagoldresources.com., Capps, R. C., crisscapps@gmail.com

[Link to Supplemental Paper 2](#)

Abstract

A tantalizing series of clues suggests the possible existence of a regional-scale complex meteorite impact crater in central North Carolina near Raleigh. Although not definitive of an impact origin, the following observations merit further study. The first piece of evidence is a striking semicircular feature visible on the statewide LiDAR imagery. Much of the semicircle is defined by the western edge of the Triassic Durham sub-basin. The semicircle extends beyond the northern termination of the basin and then follows the Tar River ESE for 26 km. The proposed crater is roughly centered within the ca. 300-Ma Rolesville granitic batholith. A combination of LiDAR patterns, regional magnetic and gravity data, and existing geologic mapping supports the recognition that this may constitute a complex crater having a diameter of at least 200 km and including a central uplift and peak ring. Stream drainage patterns and detailed LiDAR lineaments suggest the presence of multiple concentric fault rings within the inferred structure. Under the microscope, grains of quartz and feldspar in rocks from the proposed central uplift area locally display features tentatively interpreted, but so far unconfirmed, to be planar fractures (PFs), isotropic twin lamellae in plagioclase, and possible diaplectic glass. The latter is especially evident in quartz breccia dikes within an area inferred to represent part of the eroded crater floor. A late Permian age date of 255 ± 2 Ma has been obtained for brittle-ductile deformation within an area of the Jonesboro fault zone containing one such dike (Hames *et al.*, 2001). A limited search for shatter cones was conducted in three quarries within the proposed central uplift of the proposed crater structure. No shatter cones were observed, although curved, striated surfaces as well as large conical structures were observed in one of the quarries near Cary, NC. Evidence of hydrothermal activity, common in complex craters, is found within the proposed central uplift and peak ring areas. However, these areas could be related to preexisting alteration systems. Impact structures sometimes contain enrichment of platinum group elements. Gold recovered from a prospect within the Rolesville batholith in the proposed central uplift contains up to 1.2 % palladium, a platinum group element. Previous studies (Gaughan and Stoddard, 2003; Carpenter and Reid, 2015) have argued that areas near the center of the proposed impact structure have been uplifted 10-15 km, consistent with the possibility of an impact-induced central uplift (e.g., Wieland *et al.*, 2005). Preservation of unannealed high strain features in the quartz breccia dikes suggests the timing of the proposed impact would post-date the late Permian metamorphism in the area, ca. 260 Ma (Hatcher, 2008). Furthermore, Carnian-stage and younger Triassic sedimentary rocks fill a

portion of the proposed central crater. Therefore, the proposed Raleigh impact could have occurred between the late Permian and the middle to late Triassic. Could it be linked to a major extinction event and perhaps even the breakup of Pangea?

Citations

- Carpenter, R.H., and Reid, J.C., 2015,** [Permian, Triassic, and Jurassic History of the Raleigh – Durham Area, North Carolina:](#) , Southeastern Section Meeting, Geological Society of America, Poster Session, Chattanooga, TN.
- Gaughan, A., and Stoddard, E.F., 2003,** Contact Aureole of the Rolesville Batholith, Eastern North Carolina Piedmont: Petrology and Implications: *Southeastern Geology*, v. 42, no. 1, p. 19–46.
- Hames, W. E., Clark, T. W., Blake, D. E., Hibbard, J. P., and Stoddard, E. F., 2001,** Late Permian $^{40}\text{Ar}/^{39}\text{Ar}$ age of brittle-ductile deformation within the Jonesboro fault zone adjacent to the Mesozoic Deep River basin, North Carolina: *Geological Society of America Abstracts with Programs*, v. 33. p. A-19.
- Hatcher, R.D., 2008,** ["Tracking lower-to-mid-to-upper crustal deformation processes through time and space through three Paleozoic orogenies in the Southern Appalachians using dated metamorphic assemblages and faults"](#), *Geological Society of America Abstracts with Programs*, Vol. 40, No. 6, p. 513.
- Wieland, F., Gibson, R. L., & Reimold, W. U., 2005,** Structural analysis of the collar of the Vredefort Dome, South Africa—Significance for impact-related deformation and central uplift formation. *Meteoritics & Planetary Science*, 40(9–10), 1537–1554.

Appeal for Researchers

In 2014, two of the authors of this paper (RDM and JAP) stood before a wall-sized composite state-wide image of the legacy North Carolina LiDAR and were transfixed by a distinctive circular feature in the Raleigh, NC area (**Figure 1**). Scientific curiosity has driven us to search for the answer to what caused the feature. The abstract above is from a paper that presents our thoughts and research. We are looking for curious-minded people to join the search and carry it forward. While some of our findings so far are inconclusive, they are compelling. The project is at the point where we now want to engage others who are interested in impact phenomena and who have access to the analytical tools required for their possible confirmation. If you are intrigued and would like to join the investigation, please contact one of us. The complete paper with more details is available for digital download from Supplemental Papers for 2023 on the CGS website.

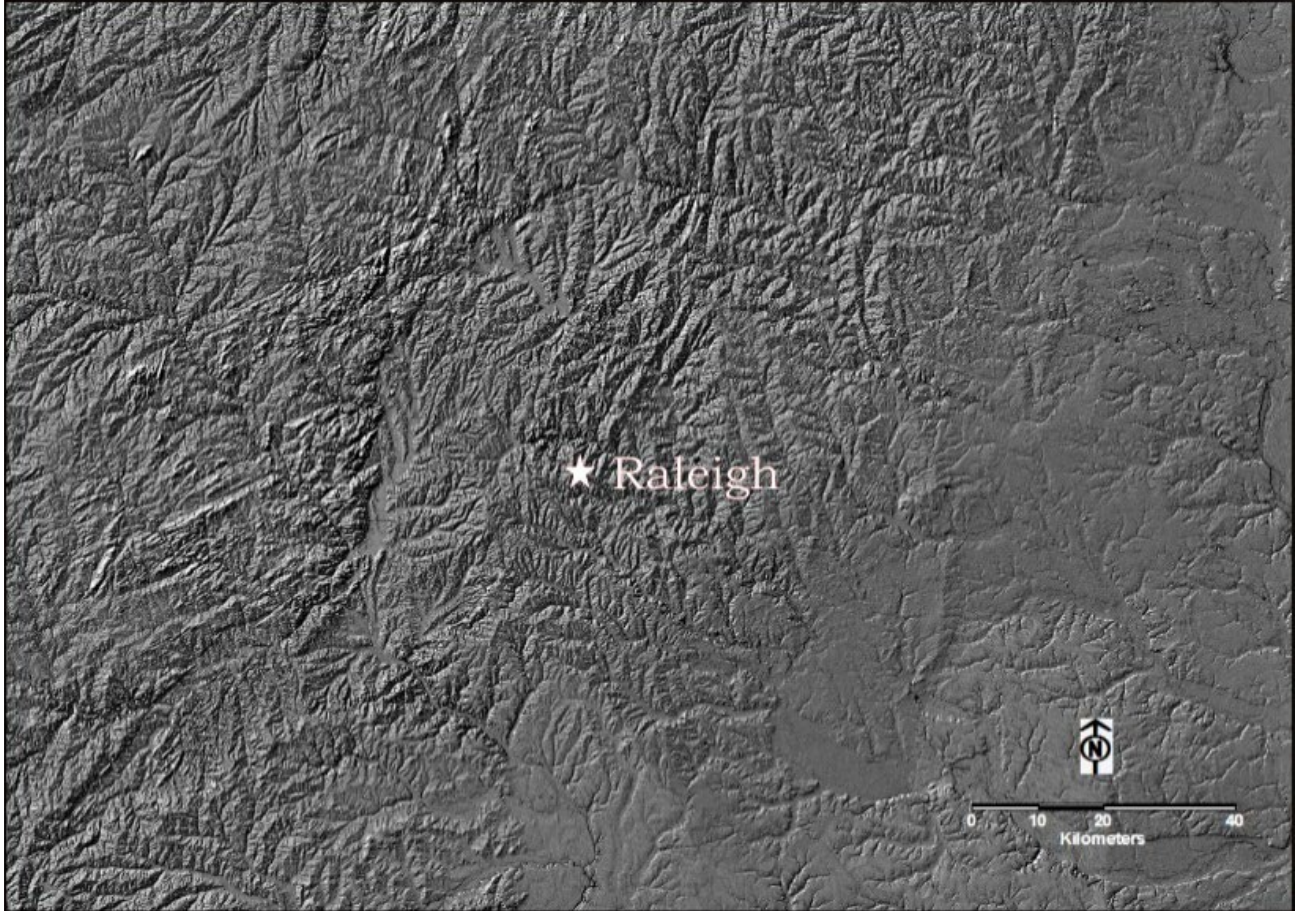


Figure 1: Legacy Light Detecting and Ranging (LiDAR) Hillshade image for central North Carolina. Circular feature is near center of image above. (North Carolina legacy LiDAR is available at: <https://sdd.nc.gov/>)

Inquiry Based Field Trip – Investigations of Two Contrasting Sites at Jordan Lake, North Carolina

Robert M. Greenberg - Science instructor at Hawbridge School, Saxapahaw, NC

rgreenberg@hawbridgeschool.org

The introduction to this paper includes text from Gronback et al. (2001) and is presented with permission from the author.

Figures provided by NC Geological Survey.

INTRODUCTION

Science inquiry is an effective approach to teaching and learning whereby students are made responsible for their own learning and are encouraged to discuss findings and develop ideas with others. Its outcomes are often full of pleasant surprises including the eventual grasp of more abstract concepts. During science inquiry, the learner is encouraged to ask questions - not necessarily come up with the correct answer. The cultivation of good questioning skills, a product of deeper thinking and productive discussion and debate are attributes that can be applied in many areas of life.

In 2001, several science teacher colleagues (Lynne Gronback, Ruben Giral and Mary Watson) and I contributed to the Geological Society of America Southeastern Section meeting field trip with “Inquiry based field trip to outstanding geological sites in the Triangle” (Gronback et al. 2001). In our collective teaching careers, we’ve each embraced the inquiry approach, designing, leading and evaluating labs and field trips.

In order to allay confusion, the text below describing inquiry is a slightly modified version of Gronback et al. (2001). Hence, in this writing, Wake County (2001) is replaced with the current field trip location, Chatham County.

This will guide the reader in using inquiry-based learning in the field and will facilitate the learning of basic geologic concepts as highlighted in the North Carolina science standards. Many years of research and classroom teaching support the use of inquiry-based teaching and learning in the classroom and in the field.

The benefits include:

- Student curiosity and enthusiasm for science is enhanced,
- Student clearly see evidence of the connections between the earth, physical and life sciences,
- Student interest is sustained and attention is cultivated when given the opportunities to observe details in the field,
- Student learning is “personalized” when they are involved in understanding the area where they live and,
- Students are far more enthusiastic about science and learning, in general, when the traditional lecture is supplemented with inquiry-based investigations.

It is most helpful in teaching to examine the broader picture before honing in on the specifics. An understanding of the big picture helps ground additional observational information. Helping students connect the finer details to the big picture is truly a foundation of learning. Big things are more easily grasped; the fine details tell the bigger story.

On a teacher-led geology field trip, the process of inquiry should be modeled for the participants by providing them with a series of inquiry focus questions designed to develop a base knowledge about the geology of several key sites in Chatham County. Students will be given instructions leading to the acquisition of skills needed to collect meaningful data at outcroppings of rocks.

Skills learned will facilitate significant data collecting as it relates to the inquiry focus questions. As the trip progresses, the students will find themselves becoming increasingly independent as they become proficient at using the skills practiced throughout the day. As the students make observations, collect data, and construct explanations, their knowledge of the area’s geology will evolve.

Hopefully, students will become better aware of how their knowledge evolves as a result of the way the questions and skills learned are related. Over the course of the day, we want participants to see how the inquiry focus questions are the core of the learning model. Inquiry learning is analogous to a spiral staircase. The learner climbs the staircase (i.e., the content being investigated) as he or she acquires new skills and information. As the content develops, the learner will have more sophisticated questions and begin to use skills that involve measuring and analysis. The learner is progressing up the staircase with more knowledge and skills. The further up the staircase (the deeper into the content area) a student climbs, the more likely they are to begin to look for relationships, causality, and patterns. (Nancy West, written communication, 1998)

Inquiry learning is a constant process that yields multiple results. The inquiry learning model facilitates two simultaneous learning events. 1) It increases a learner's base content about a content area, and 2) it provides the learner with a more diverse set of skills. The use of these skills will foster a learner's continued intellectual growth.

The overarching question for the day is: "How are each of these sites related, and how does each site contribute to the understanding of the geologic history of Chatham County?"

In order to address these ideas, it will be necessary for the participants to learn and practice the following skills:

- Make basic observations at an outcrop
- Identify minerals
- Recognize structural geologic features
- Relate soils to parent material, and
- Use maps to construct the temporal relationships between the stops

The two chosen sites, one of which is visited during the 2023 Carolina Geological Society field trip (Bradley 2023, this volume), have very different geology and are fairly close to each other. The two outcrops are: 1) igneous (volcanic) rocks of Late Precambrian Era and 2) sedimentary rocks of the Triassic period with an intrusion of a diabase dike (an igneous rock).

WHAT IS INQUIRY?

Inquiry is the most natural way of learning because it values human curiosity. Traditional lecture and verification type labs do not promote the skills or the type of knowledge gained in the inquiry process because these traditional methods are passive in nature. Inquiry learning requires that the learner designs a model or an investigation, uses equipment to collect data, organize and analyze data, and finally present results - in essence, to behave like a real scientist. The skills of inquiry grow along with the body of knowledge being investigated.

In the beginning of the inquiry process, students are usually presented with or generate an overarching question that ties what they know to some phenomena that cannot be explained at the time. As learners master skills and content, their questions become increasingly specific until the learner has generated a question that takes them down a different path of content investigation.

Kinds of inquiry

Guided inquiry and Socratic inquiry are variations of inquiry-based instruction. In guided inquiry, very often students are provided with questions designed by teachers. This is often used when introducing new skills in a group setting. A teacher can coach students in the learning and practicing of new skills and facilitate discussions that are centered on findings collected by the whole class. The data collected helps to support a specific topic being developed.

The Socratic seminar method is a great fit in a classroom where you may have multiple investigations going on about a particular topic. The seminar approach is very useful when the goal is to get students to discuss their findings as they relate to a particular problem or conceptual idea. This technique involves thinking about and evaluation of data and its meaning.

What Goes into Crafting a Good Question?

In order to grow as an inquiry learner, students need to know how to ask questions that are scientific in nature. Many appropriate questions will start with the words “How” and “What.” “How” and “What” questions are typically process oriented questions. For example, “How did this group of minerals happen to occur in these rocks?” This question could be followed by: “What conditions had to exist in order for these minerals to occur?” These questions require students to collect data and make observations in order to construct an explanation. Examples of skills that may help in the construction of an explanation may include reading and interpreting geologic and topographic maps and field techniques for identifying minerals. “How” and “What” questions are better suited for investigations than “Why” questions. Some questions that start with the word “Why” can be difficult to answer in a scientific way. For example, “Why does geology matter?” is a question that is more likely to elicit opinions and beliefs rather than reasoning and logic. Inquiry learning is developmentally appropriate because the questions generated by the students are the products of their own experience and level of understanding.

In general, questions are best when they are tied to features in the environment and are wide-ranging enough to allow for the potential of multiple investigations. Good inquiry focus questions facilitate the need for observation and/or measurement, which in turn sets the stage for analysis. Good questions further require that time be available for constructing explanations.

How is Inquiry Threaded Through this Field Experience?

This field trip and guide will model several aspects of inquiry both in format and in practice. The questions for each stop give the learner aspects of the content to think about. However, these questions are in no way to serve as an agenda. Any questions that the participants should have will be given attention in this investigation. The facilitators should not instruct the group, rather, use the guided inquiry format to “coach” the participants to a certain level of skill proficiency. The two aforementioned stops can be places to implement the guided inquiry format. The two stops can be places where skills are introduced and practiced, then later the applications of those skills can be supported as the learner further understands the geology of Chatham County in the area of Jordan Lake.

So that learners will be motivated to generate their own questions, it’s important that they feel supported in the beginning and that their confidence increases throughout the day. At the end of the investigation period, the leader should facilitate a discussion that allows for the assimilation of everyone’s data and thoughts about what they each think they understand. At this point, students should be encouraged to discuss their findings and the skills they used to gain information. Throughout the field trip, learners will be asked to reflect on what they already know about basic geology. Using what is known as a springboard, learners will then explore and explain what is unknown at each site. For example, one learner may have extensive knowledge about minerals, but is unable to differentiate a fault from a fracture. In this instance, the facilitator should continue to engage in discussions with this learner to coach them into a situation where the need to label or name particular features associated with a fault or a fracture become necessary. At this point, the facilitator will know that the learner has internalized the basic differences between the two features.

To sum up, inquiry learning creates situations where the need to identify what is being observed becomes necessary. The vocabulary of geology becomes meaningful as the learner’s ability to recognize features, patterns and trends improves.

How do I Cultivate an Inquiry Learning Environment in my Classroom?

The power of the inquiry learning technique is that the learner takes a more active role and the teacher a more facilitative one. This dynamic creates an opportunity for the student to discuss their understanding of what is happening. As the teacher facilitates these discussions, they are in a position to uncover concepts that have been inappropriately or incorrectly learned. Begin by simply engaging in meaningful discussions with your students. Ask them what they already know about a topic, ask them what they would like to know, and ask them how they would go

about finding out what they would like to know. With these discussions you can discover your students' interests and prior knowledge. The following suggestions will help you get started in cultivating inquiry learning in your classroom:

- 1) Try doing your labs first. Process the information gathered in a discussion or presentation format.
- 2) Take science outdoors. The natural world is a place where inquiry can and will occur without much set-up, if given the opportunity. Take the time to let students wonder and reflect.
- 3) Inquiry in the earth and environmental sciences is what is or has happened in a three-dimensional space. To facilitate your students' ability to visualize changes that occur within and/or around a space, make and use maps to illustrate what is known about an area. For example, investigating your river basin will require that students understand that events that happen upstream can have measurable and mappable impacts on your local area.
- 4) Utilize resources such as science articles and science in the news. Podcasts are also a great resource for information and launching discussions.

Consider the impact of storytelling and injection of humor by the teacher as a possible and effective way to engage students prior to launching an inquiry with a seed question. Consider an inquiry that precedes the main inquiry - the crafting of the investigation questions, themselves, by the learners.

DESCRIPTIONS OF TWO OUTSTANDING GEOLOGICAL SITES AT JORDAN LAKE WITH GUIDED QUESTIONS

Each of the two outcrops described below can be easily accessed from parking areas and short trail walks. Another method of doing these two sites is via kayak from the Farrington Point Boat Access of Jordan Lake.

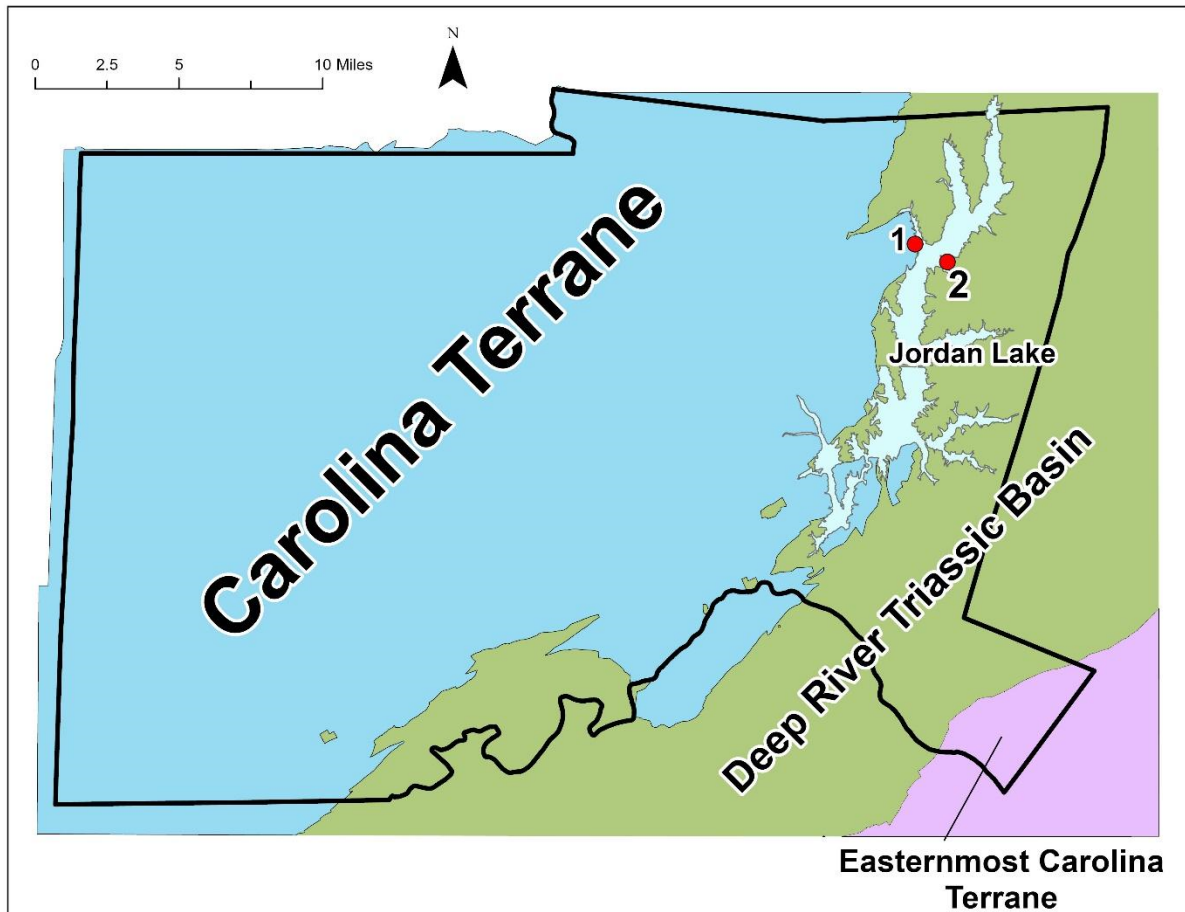


Figure 1: Field trip stops presented in the paper with the major geologic elements present in Chatham County and surrounding areas: Carolina terrane, Deep River Triassic basin, and Easternmost Carolina terrane.

The themes of the two chosen sites could not be more different geologically - plate convergence at one (Stop 1) and plate divergence at the other (Stop 2). Together they offer a nice field trip as the two sites are a short drive from each other (Figure 1). Another option is to investigate both sites by kayak. It is entirely doable and adds a layer of adventure to the field trip.

STOP 1: BIG WOODS QUARRY

This stop is located in a partially flooded abandoned quarry at the NC Wildlife Resources Commission – Rock Quarry Public Fishing Area (Figures 2, 3 and 4).

Latitude and Longitude of stop area = 35.7984, -79.0258



Figure 2: Location of stop 1 on the Farrington 7.5' Quadrangle

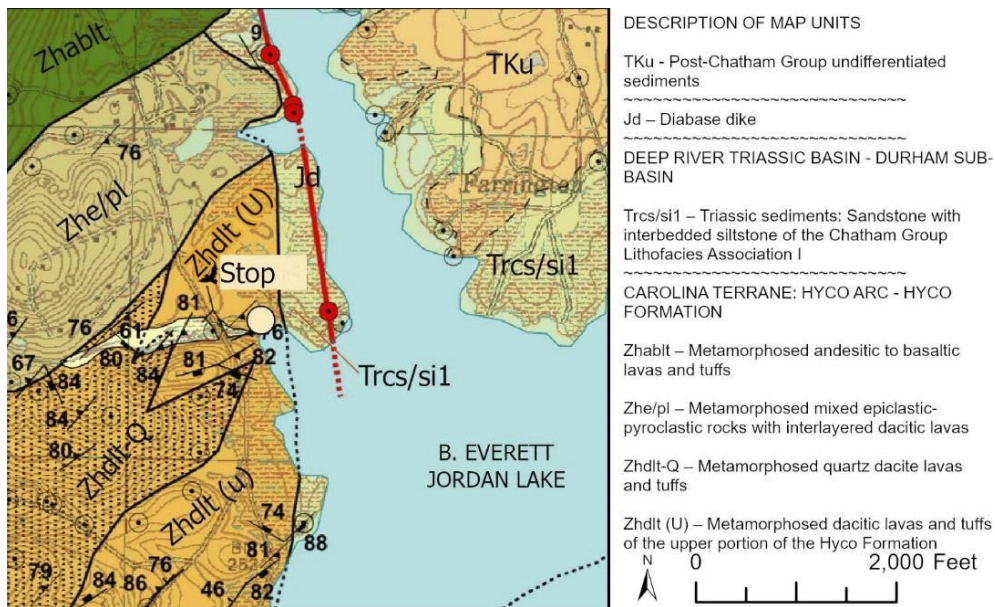


Figure 3: Location of Stop 1 on the Geologic Map of the Farrington Quadrangle (Bradley et al, 2007 and compiled Chatham County Geology)

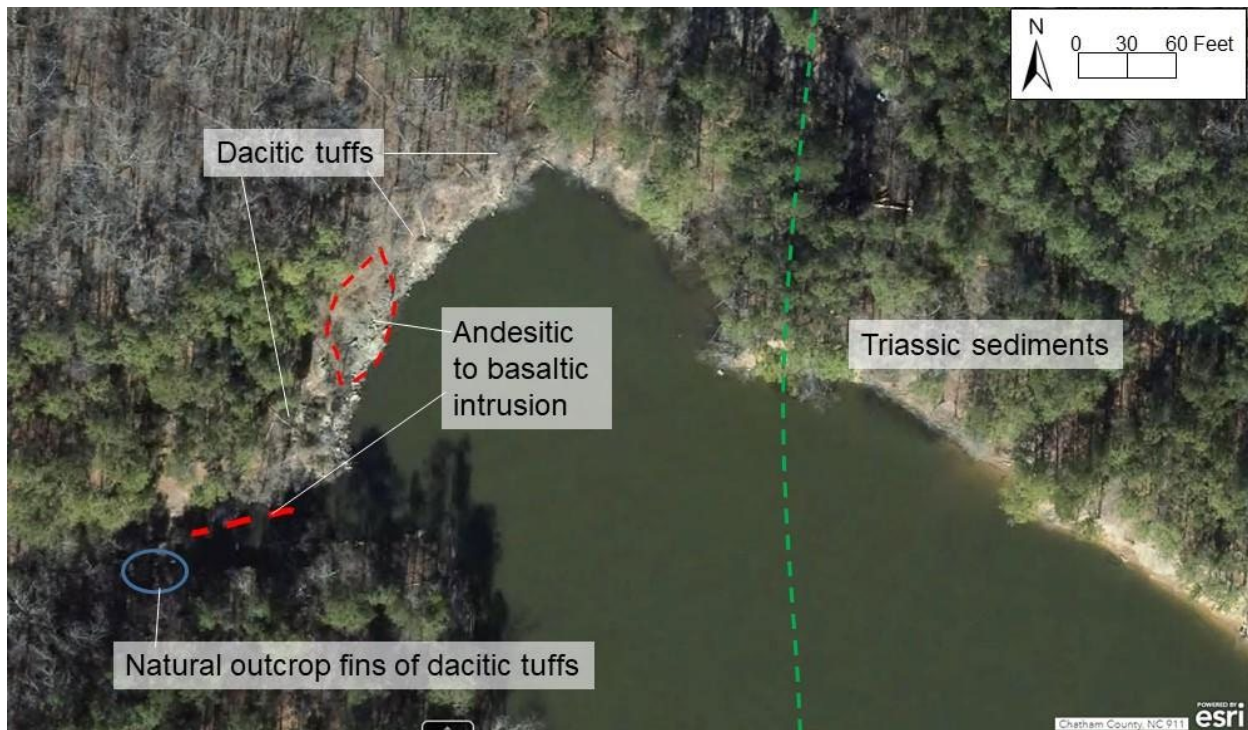


Figure 4: Sketch of approximate locations of rock types at Rock Quarry Public Fishing Area. Aerial photograph base (2017) from Chatham County GIS.

A variety of metamorphosed igneous rocks can be investigated at this stop with origins both below the Earth's surface (intrusive) and at the surface (extrusive). Intrusive igneous rocks come from magma and cool slowly below the surface thus creating larger crystals that can be seen without magnification. Extrusive igneous rocks, also called volcanic, come from material ejected to the surface (Figure 5). Crystallization is much quicker leading to smaller crystals or no crystals at all (glassy texture). Another important item to consider is the magma source. Is it high in silica and oxygen and lower in iron, calcium, or magnesium - or the opposite? The former lends itself to magma that is viscous (think: molasses) where high pressure builds up leading to powerful eruptions.

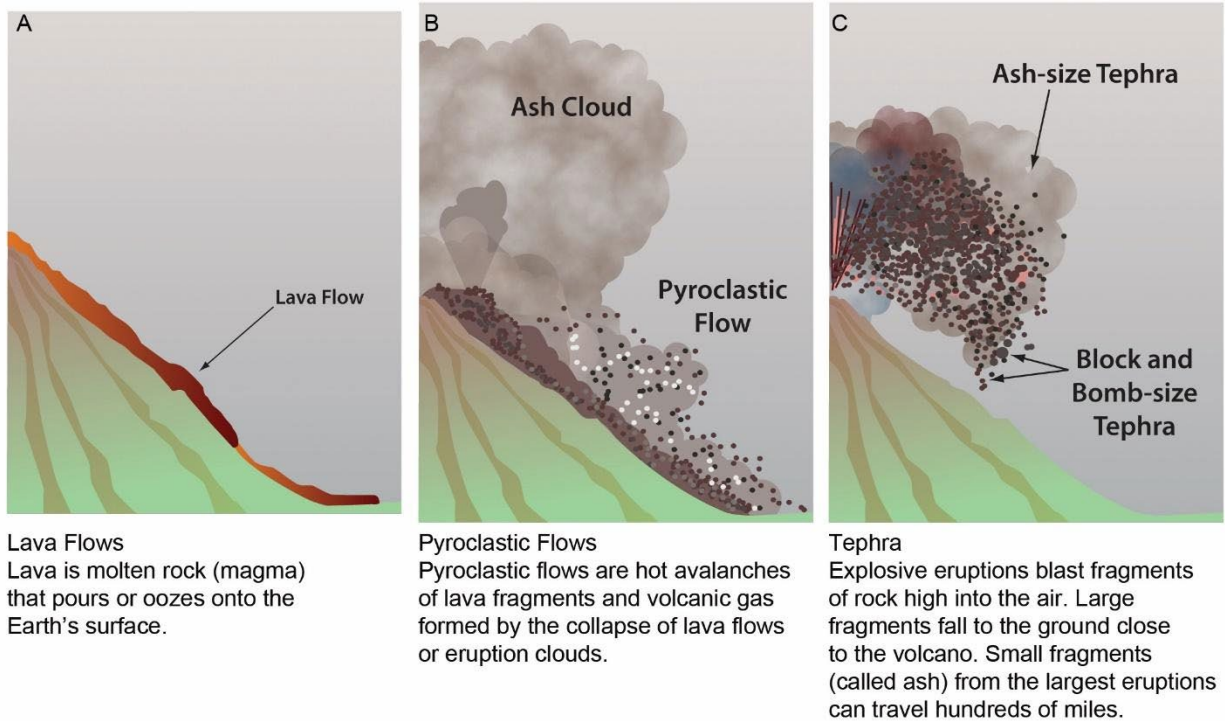


Figure 5: Generalized basic volcanic deposits associated with modern volcanoes and with the ancient volcanoes of the Carolina terrane. (Base figures modified from the USGS.)

The outcrops at the abandoned Big Woods Quarry consist of weakly metamorphosed volcanic rocks within the Hyco Formation of the Carolina terrane (Figure 1). The rock types include dacitic lavas and tuffs as well as andesitic to basaltic lavas (Figure 4). The rocks were once part of a volcanic island arc (Figure 6), which is estimated to have existed 630-530 million years ago based on radiometric dating (Bradley, 2023, this volume). Present day volcanic island arcs include the islands of Sumatra, Java, the Philippines, and the Aleutian Islands of Alaska.

To the east near the lake shore, a Jurassic-aged (200 million years old) diabase dike that intruded into sedimentary rock of the Triassic Period (252-201 million years ago) can be observed.

Essentially you have a history of island arc chains colliding with other island arc chains and then colliding with ancient North America. Three separate plate collision/mountain-building episodes occurred during the Paleozoic Era (Taconic, Acadian and Appalachian orogenies). The final collision (Appalachian orogeny) contributed to the formation of the supercontinent Pangea as the African plate collided with the North American plate. (Stewart and Roberson, 2007).

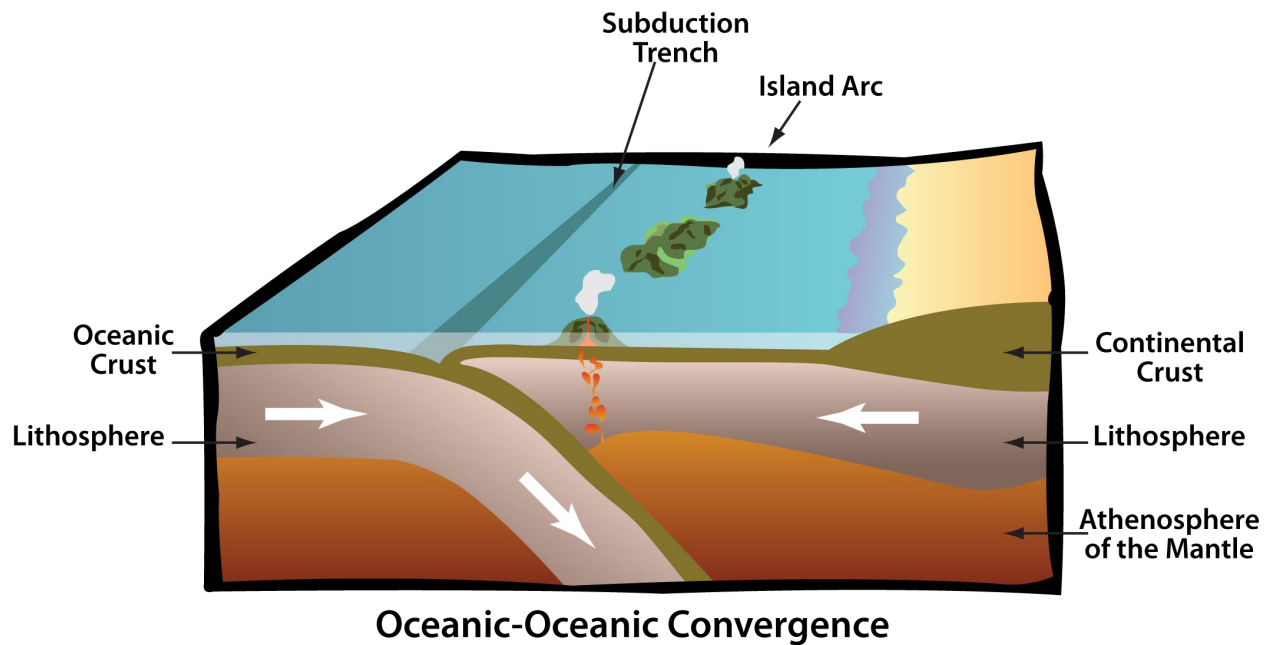


Figure 6: Diagram of an oceanic-oceanic plate convergence zone showing subduction trench and volcanic island arc (NCGS).

Age dating of these rocks is attributed to zircon crystals, an accessory mineral in igneous rocks. Zircon, unlike quartz, feldspar or mica, is not common and it locks in the ratio of naturally occurring U and Pb. The U-Pb geochronology provides a very long-time clock. Zircon essentially locks in the “birthdate” of parent rock. The “birthdate” of the zircon at this location are not known but zircons from similar outcrops in the Hyco Formation of the Carolina terrane range from approximately 630 to 615 million years old. (Phil Bradley, communication during site investigation, 2022).

The rocks at this site include metamorphosed felsic (dacite) and intermediate to mafic (andesite to basalt) rock. Dacitic rocks originate from felsic magma, which is a term for higher amounts of silicon and oxygen (Figure 7). Andesitic and basaltic rocks are lavas that have a lower silicon content, but higher amounts of magnesium and iron. Silica-rich magma is much more resistant to flow, in other words, it is viscous. This type of magma produces explosive volcanic eruptions, including pyroclastic flows, explosive and fast moving volcanic eruptions consisting of hot gas, rock fragments and ash. It was this type of cloud that erupted from Mt. Vesuvius and covered Pompeii with ash. A flow like this would incinerate anything in its path. Flows like these result from the collapse of lava domes and/or dense eruption clouds (Figures 7 and 9). In pyroclastic flows, the ash grains are very hot and when settled, stick to each other. The temperature of a pyroclastic flow is hot and would have exceeded 900 degrees F.. The dacitic tuffs at this stop are from the result of a pyroclastic flow. Close observation (with a hand lens) shows flattened fragments of compressed pumice called fiamme (Italian term for candle flame) (Figure 8). The overall shape of the outcrop of rock is “fin-shaped” like a shark fin as opposed to a blocky nature. The original ash deposits were flat-lying. Folding and related low-grade metamorphism

turned these rock layers from horizontal to nearly vertical. (Phil Bradley, communication during site investigation, 2022).



Figure 7: 7a – Left photograph: sample of dacitic lava from the Haw River in the vicinity of HWY 64 bridge crossing (NCGS). 7b - Right photograph – modern day example of a dacitic lava dome in the crater of Mt. St. Helens in Washington State (USGS). Arrow indicates person for scale.

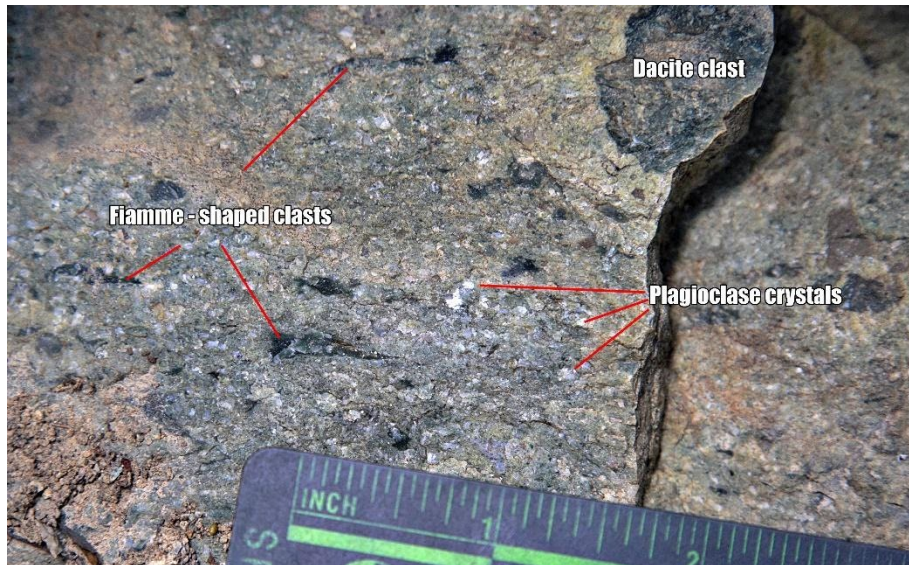


Figure 8: Annotated photograph of outcrop surface at the Big Woods quarry site. Fiamme-shaped clasts, dacite clast and plagioclase crystals indicated (Photograph by NCGS).



Figure 9: Modern day pyroclastic flow eruption at Mt. St. Helens on August 7, 1980 (USGS).

Along with the dacitic tuffs in the quarry are andesitic to basaltic intrusions (Figure 4). The intrusions originated as molten magma. The rock is grayish-green to green with a very fine textured groundmass (aphanitic). Inclusions (phenocrysts) consist of lighter-colored plagioclase feldspar. Basaltic magma is much less viscous therefore it flows more easily. It tends to produce a darker rock with green minerals such as chlorite and epidote (from metamorphism). The rocks here have a volcanic origin but have been weakly metamorphosed. Cracks can be observed in these outcrops where no appreciable movement is observed. These are sets of expansion joints, which formed as overburden is removed and the rock has the opportunity to expand.

A hyaloclastic texture can be observed in the andesitic to basaltic intrusion (Figure 10). As the magma erupts into or flows into cold sea water or wet volcanic layers, it quickly chills. The rapid chilling of the lava breaks it into pieces ranging from centimeters to millimeters in size, while some of the lava gets crushed into tiny clay-sized glassy shards. Sometimes the fragments will appear to “fit” together like jigsaw puzzle pieces.



Figure 10: Photograph of outcrop surface at the Big Woods quarry site showing jig-saw puzzle fit of clasts of hyaloclastic texture (Photograph by NCGS).

INVESTIGATION QUESTIONS FOR STUDENTS

Collect four rocks that are different from each other. Compare and contrast. Closely investigate each rock using water to wet the surface and wash off the dirt.

- How do the colors compare to each other?
- How do the textures compare to each other?
- Does each rock seem pretty solid or have they weakened due to exposure to water and air temperature?
- If you used a rock hammer to get a fresh surface (unweathered) how does it compare to a weathered surface of the same rock?
- Find an example of a fiamme (the word flame in Italian). Speculate why fiamme exist in one particular rock at this site but not others.
- How can you tell the difference between rocks formed as volcanic ash vs rocks formed from lava?
- What are the conditions that create various texture types in rock?
- Find evidence that the rock was deformed
- What evidence is there for which came first, the welded tuffs or the andesitic to basaltic intrusions?

- Challenge the learners to find a sample of Triassic-aged sedimentary rock at this site. Provide samples of clastic sedimentary rock to examine. Contrast these rocks with the previously investigated volcanic rock. Why is this completely different rock here next to rock that is so much older and very different in appearance?

STOP 2: MARTHAS CHAPEL FISHING AREA

Note: Rock outcrops can only be viewed during low water levels. Check Jordan Lake pool levels on the Corps of Engineers website before visiting. During low lake levels (pool level of approximately 210 to 216 ft) a small beach is present and allows easy walking to view the outcrops. At high lake levels (pool level of 217 ft and above) the beach is flooded and most of the outcrops are not accessible.

Latitude and Longitude of stop area = 35.7918, -79.0000

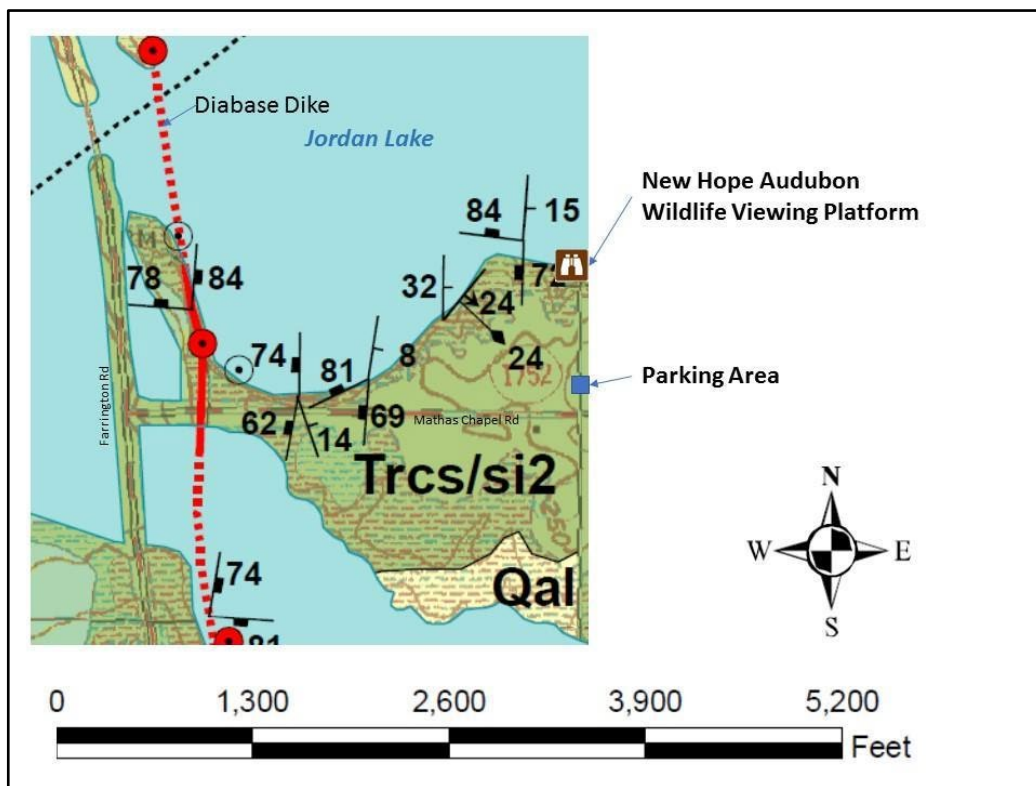


Figure 11: Portion of geologic map of the Farrington Quadrangle (Bradley et al., 2007) in the Wildlife Observation Platform area. Trcs/si2 is an abbreviation for Triassic sediments and Qal is an abbreviation for Quaternary alluvium. Line segments with numbers are strike and dip symbols indicating orientation of rock layering and joints.

The Deep River Triassic basin (Figure 1), one of many in the eastern United States, formed as Pangea rifted apart early in the Mesozoic Era. Although all of these basins, which include Gettysburg, Newark and the Bay of Fundy, were formed due to the rifting of Pangea, they were

never connected to each other. The Deep River Triassic basin is a region of low topographic relief compared to the much more resistant metamorphosed granites and volcanic rocks of the Carolina terrane, which lie adjacent to the west. The basin stretches from Oxford south-southwest to the Sanford area. It contains much of Jordan Lake as well as the towns of Durham, Morrisville and Apex. Research Triangle Park also sits within the Triassic basin.

During the Triassic period, this region was a rift valley, similar to present east Africa. (Stewart and Roberson, 2007). When the basin was forming 220 million years ago, the difference in elevation between the harder rocks related to the volcanic island arc and the rift valley in which Jordan Lake lies was likely much more pronounced (possibly up to ten thousand feet in the Raleigh area). Presently, the difference in elevation is around 250 feet.

The outcrops at Marthas Chapel fishing area is one of the best preserved Triassic sedimentary outcrops in the North Carolina Piedmont region. (Figure 12). Through wave action, this outcrop is continually shaped and new surfaces are constantly exposed. The bed thicknesses range from less than a meter to as thick as over six meters. There is a stark contrast between the lighter-colored sandstones (yellow, white, pinkish gray) and the darker-hued finer grained siltstones and mudstones (dark red, purplish red, gray). Cross bedding can be found in the sandstones, an indicator of moving water such as a stream. Rip-up clasts of clay or mud can be observed within the sandstone, especially above scoured surfaces. (Clark, Gore and Watson, 2001).



Figure 12: Example of outcrop showing layers of the Triassic-aged sedimentary rocks of siltstone and sandstone from the shores of Jordan Lake near the New Hope Audubon Wildlife viewing platform off of Marthas Chapel Road in Chatham County (NCGS).

The resistant layers at this site are coarse-grained or “conglomeratic” arkosic sandstones. The sand-sized particles and inclusions of larger fragments of weathered rock accumulated in the widening rift valley, eventually getting buried and lithified into the rock found at this site. These conglomeratic layers likely represent a point bar in a river. Upon close inspection, one can observe coarse-grained pebbly sandstones over a scoured surface. Storm events that result in fast-moving water, erode and deposit sediment along stream channels. These conglomeratic layers represent evidence of an ancient storm event that rapidly moved and deposited coarse-grained sediment. (Clark, Gore and Watson, 2001).

The sediments forming the arkosic sandstone are speculated to have come from the eroded Rolesville Batholith, a resistant granite body from the Pennsylvanian period, that is exposed east of Raleigh. Ancient stream systems deposited the sands-sized sediment from the eroded Rolesville batholith into the topographically lower basin. The Rolesville batholith is a known radon hot-spot. The arkosic sandstones in the Triassic basin also have elevated radon (Phil Bradley, communication during site investigation, 2022).

The less resistant layers in the outcrops are dark red-, purplish- and maroon-colored siltstones and mudstones. The greenish-gray mottling observed in some of the mudstones indicates the disturbance of sedimentary deposits by living organisms – called bioturbation (Figure 13). The grayish mottled areas are interpreted to be from the roots of plants and the burrowing of organisms when the area was a vegetated floodplain (Clark, Gore and Watson, 2001).

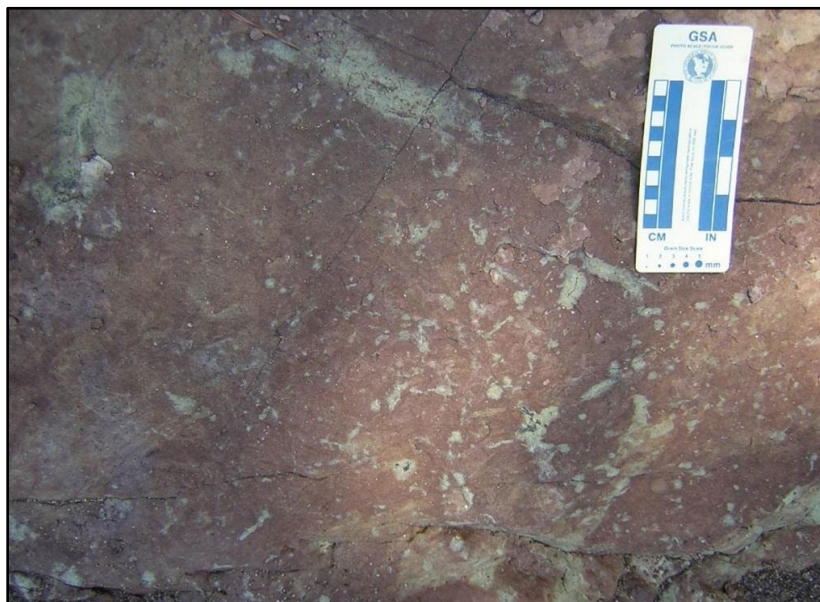


Figure 13: Outcrop of mudstone at Wildlife Observation Platform area exhibiting greenish-gray mottling. The mottled areas are interpreted to be from the roots of plants and the burrowing of organisms when the sediment was being deposited approximately 220 million years ago.

INVESTIGATION QUESTIONS FOR STUDENTS

Collect four rocks that are different from each other. Compare and contrast. Closely investigate each rock using water to wet the surface and wash off the dirt.

- How do the colors compare to each other?
- How do the textures compare to each other?
- Does each rock seem pretty solid or have they weakened due to exposure to water and air temperature?
- What do water currents and lack thereof have to do with grain or sediment size?
- Find an example of the sediment size decreasing upward (going from coarse to fine). What does this tell you about the depositional environment?
- Find evidence of cross-bedding. How can you tell the direction of stream flow?
- Find examples of bioturbation. Explain how the process works using the sample
- This outcrop lies in a rift valley or basin. What was the main source of rock-forming sediment?

REFERENCES

Bradley, P.J., Gay, N.K., Bechtel, R. and Clark, T.W., 2007, Geologic map of the Farrington 7.5-minute quadrangle. NCGS Open-file Report 2007-03, scale 1:24,000

Bradley, P.J., 2017, Field trip guide: geological hike along the Haw River, Chatham County, NC, Spring field trip of the Carolina Chapter of the Association of Environmental and Engineering Geologists, April 22, 2017. <https://www.deq.nc.gov/energy-mineral-and-land-resources/geological-survey/stateparks-geo/haw-river-hwy-64-geology-guide-final-4-17-2017/download>

Bradley, P.J., 2023, Carolina Geological Society 2023 field guide to stops, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.

Clark, T.W., Gore, P.J.W., and Watson, M.E., 2001, Depositional and structural framework of the Deep River Triassic basin, North Carolina, *in* Field Trip Guide, Southeastern Section - Geological Society of America, 2001, p. 27-50.

Gronback, L.T, Watson, M.E., Greenberg, R.M, and Giral, R.A., 2001, Inquiry based field trip to outstanding geological sites in the Triangle: *in* Hoffman, C.W. ed., Field Trip Guidebook 50th Annual Meeting, Southeastern Section Geological Society of America, April 2001, pp. 135-148.

Stewart, K.G. and Roberson, M-R., 2007, Exploring the geology of the Carolinas – A field guide to favorite places from Chimney Rock to Charleston, The University of North Carolina Press, 320 pp.

Carolina Geological Society 2023 Field Guide to Stops

Philip J. Bradley

North Carolina Geological Survey, pbradley@deq.nc.gov

With contributions from David A. Grimley and Emily K. Michael and Heather D. Hanna

The goal of this 2023 Carolina Geological Society (CGS) annual field trip is to present the findings of detailed geologic mapping within Chatham and adjacent counties by the North Carolina Geological Survey. Detailed mapping in the area has been partially supported by STATEMAP - a component of the US Geological Survey (USGS) National Cooperative Geologic Mapping Program. Descriptions of 10 stops are provided (Figure 1). Not all of the stops will be visited during the 2023 trip and are provided for future reference.

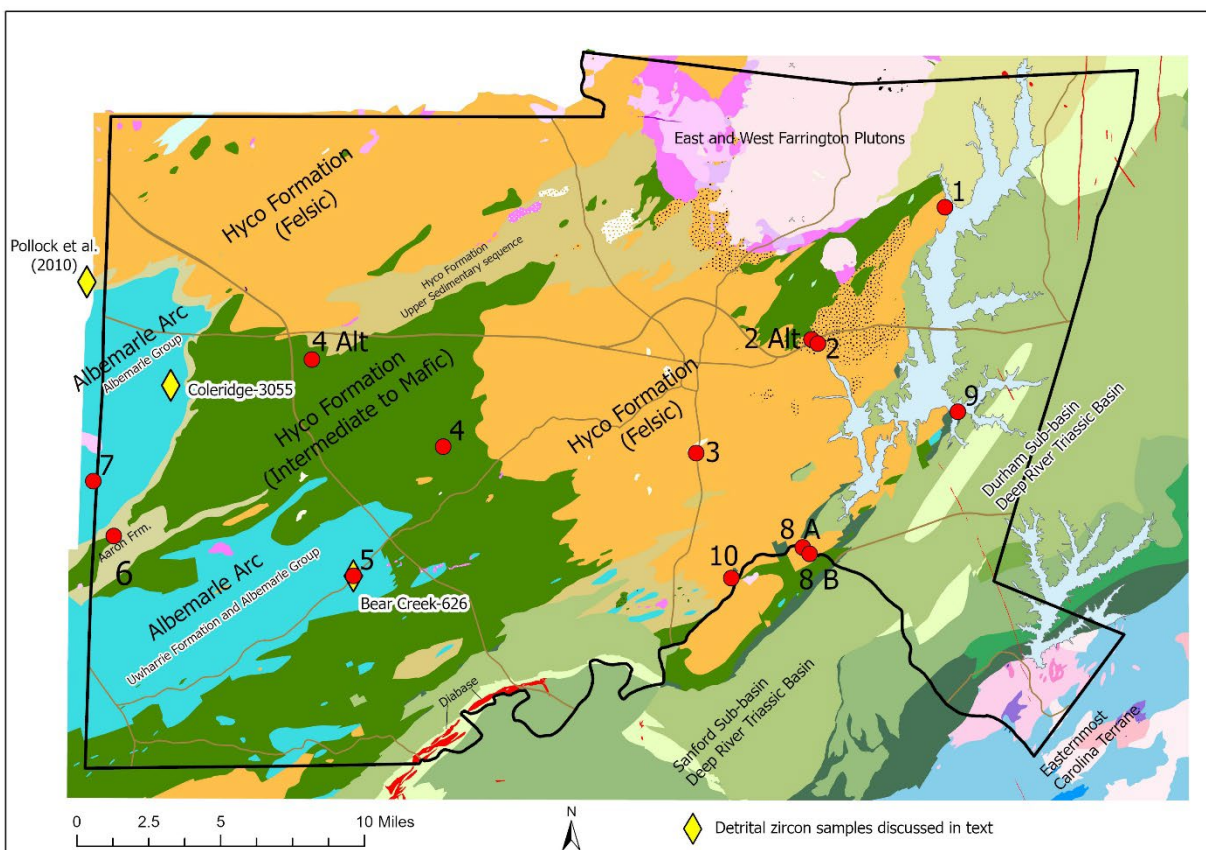


Figure 1: Simplified geologic map of Chatham County, NC and surrounding areas with field trip stop locations.

**STOP 1: DACITIC TUFFS AND ANDESITIC TO BASALTIC ROCKS OF THE HYCO FORMATION, HYCO ARC (35.7984°N, -79.0258°W) ROCK QUARRY PUBLIC FISHING AREA, NORTH CAROLINA WILDLIFE RESOURCES COMMISSION, B. EVERETT JORDAN LAKE, CHATHAM COUNTY, NC.
STOP LEADER: PHIL BRADLEY**

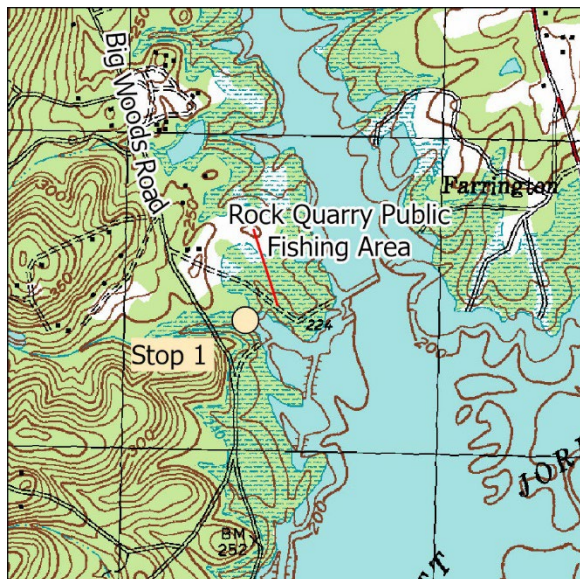


Figure 2: Location of stop 1 on the Farrington 7.5' Quadrangle

Purpose:

To examine examples of weakly metamorphosed volcanic rocks in an abandoned quarry within the Hyco Formation of the Carolina terrane. This stop is located in a partially flooded abandoned quarry at the NC Wildlife Resources Commission – Rock Quarry Public Fishing Area (Figures 2 and 3).

Rock Types:

The majority of the area is interpreted to be underlain by the Carolina terrane unit - *dacitic lavas and tuffs of the upper portion of the Hyco Formation (Zhdlt (U))* (Bradley et al., 2007) (Figure 3). The contact with the Durham sub-basin of the Deep River Triassic basin is located immediately east of the abandoned quarry (Figure 4).

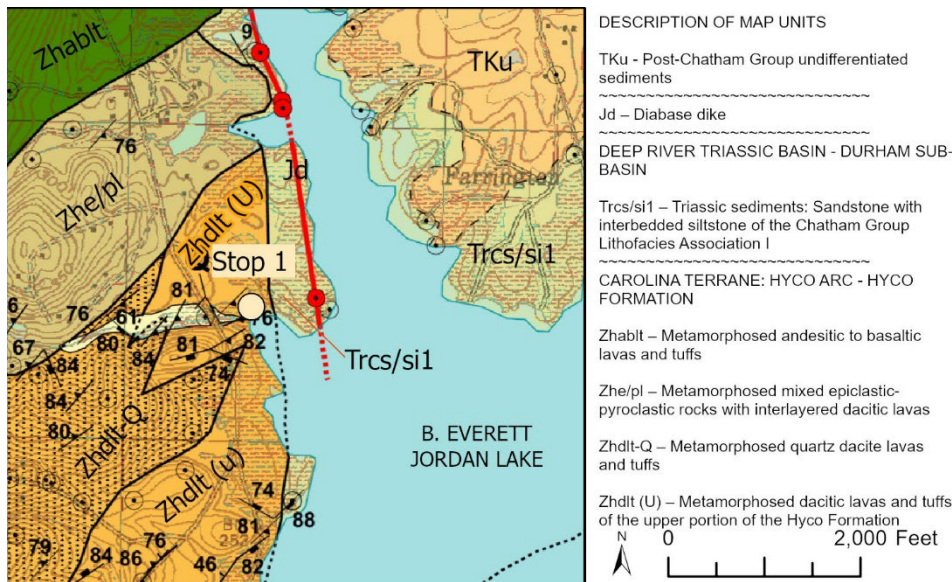


Figure 3: Location of Stop 1 on the Geologic Map of the Farrington Quadrangle (Bradley et al, 2007 and compiled Chatham County Geology)

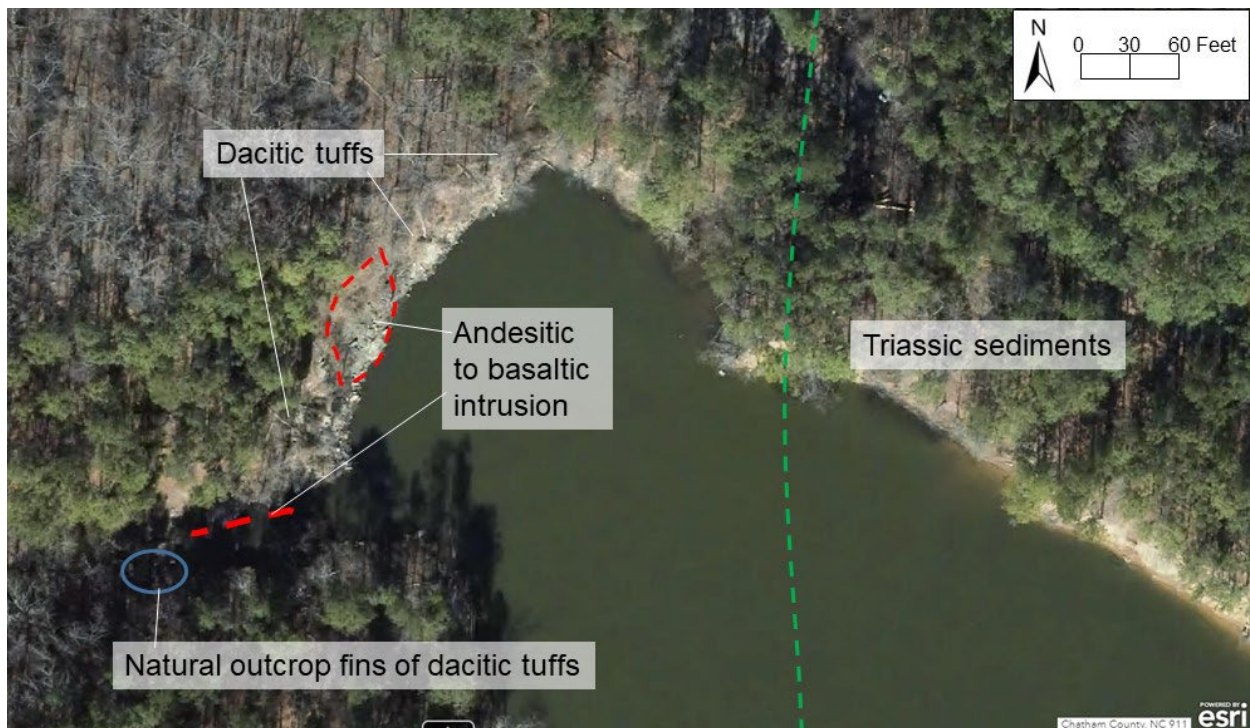


Figure 4: Sketch of approximate locations of rock types at Rock Quarry Public Fishing Area. Aerial photograph base (2017) from Chatham County GIS.

The main rock type in the quarry is metamorphosed dacitic tuff. An intrusion of metamorphosed andesitic to basaltic composition rock is present near the center of the worked areas of the abandoned quarry. Natural exposures of dacitic tuffs are present on the south bank of a small tributary near the south side of the quarry.

In worked areas of the abandoned quarry, the dacitic tuffs have a light-colored weathering rind, are gray to greenish-gray on the fresh surface and contain varying amounts of plagioclase crystal shards and lithic clasts. Lithic clasts are typically angular clasts of aphanitic dacite and/or plagioclase porphyritic dacite. Locally, elongated and wispy, black-colored clasts are interpreted as compacted pumice (a typical volcanic texture present in tuffs called *fiamme*).

The andesitic to basaltic rocks are green, range in texture from aphanitic to containing plagioclase phenocrysts, abundant lithic clasts of felsic rock and infilled vugs(?). Small vesicles are present locally in the aphanitic groundmass. Distinct clast boundaries are visible surrounding the felsic clasts. Amorphous clast-like areas, ranging from a few mm to several cm, exhibit indistinct boundaries and may be mineralized vugs with quartz and epidote infill. Reaction halos are present encircling some clasts. The felsic clasts may be plucked from local wall rock. The andesitic to basaltic intrusion may be related to the map scale body of andesitic to basaltic lavas and tuffs of unit Zhablt present to the northwest of the stop (Figure 3).

Walking toward the south, through the abandoned quarry, natural outcrops are visible in the creek. Natural outcrops on the south bank of the creek include tall fins of metamorphosed dacitic tuffs. A low outcrop, in the center of the creek, of an andesitic to basaltic dike is present. The fin-shaped outcrops of tuff exhibit typical Hyco Formation morphology of nearly vertical fins.

The natural outcrops consist of crystal- and clast-rich tuffs that are interpreted to show evidence of welding. Plagioclase crystal shards are abundant. Lithic clasts are angular, dark gray to black colored fragments of dacitic lavas ranging from mm to several cm in size. Some clasts appear to display a relict pumice-like texture. The rock exhibits a distinct planar fabric defined by aligned clasts and thin *fiamme*-like lenticular-shaped clasts that are interpreted as flattened pumice. Weathered-out lithic fragments and *fiamme*-shaped clasts (1-10 mm long) give the rock surface perpendicular to the cleavage a pock-marked appearance and define the primary welding/compaction foliation.

The welding/compaction foliation trends approximately 204/84NW (right-hand rule). A metamorphic cleavage is also present with a strike and dip generally parallel to welding/compaction foliation. This steep (sub-vertical) metamorphic cleavage is typical of Hyco Formation lithologies. The andesitic to basaltic dike in the bed of the adjacent creek displays a similar oriented metamorphic cleavage.

In hand samples of the dacitic tuffs, crystals are dominantly plagioclase crystal fragments. With the unaided eye or with hand lens, the groundmass is cryptocrystalline and display conchoidal-shaped fractures whose flake-like terminations may be weakly translucent. We interpret this texture to be a relict vitric texture that was originally volcanic glass – now devitrified and recrystallized by metamorphism. Thin sections of rocks with cryptocrystalline groundmass show a completely recrystallized groundmass consisting of a mosaic of primarily quartz and feldspar. Relict vitric texture is common in felsic tuffs, lavas and tuffaceous sedimentary rocks in the Hyco Formation.

Elsewhere in the unit, metamorphosed dacites ranging from aphanitic to porphyritic texture and interlayered welded and non-welded tuffs are common. Locally, interlayers of immature conglomerate and conglomeratic sandstone with dacite clasts are present. The dacites are interpreted to have been coherent extrusives or very shallow intrusions associated with dome formation. The tuffs are interpreted as episodic pyroclastic flow deposits and air-fall tuffs generated during formation of dacite domes. Conglomerates and sandstones are interpreted as reworked tuffs and eroded pyroclastic debris. The dacitic lavas and tuffs unit occurs as map-scale pods surrounded by clastic rocks of the *Mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas (Zhe/pl)* unit (Figure 3).

Wortman et al. (2000) reported that single zircons from a similar rock type in the Rougemont Quadrangle yielded an upper intercept age of $615.7 \pm 3.7 / -1.9$ Ma. This date and others (Wortman et al., 2000; Bowman, 2010; and Bradley and Miller, 2011), coupled with lithologic relationships from detailed mapping in Orange and Durham Counties led to the tentative interpretation that the Hyco Formation may be divided into lower (ca. 630 Ma) and upper (ca. 615 Ma) portions. Subsequent U-Pb zircon LA-ICPMS ages indicate that magmatism in the lower member of the Hyco Formation may be as old as ca. 650 Ma (Barefoot, 2015 and Bradley et al., 2016).

Triassic Sedimentary Rocks and Diabase

If the water level is low in Jordan Lake, you may be able to see weathered outcrops of Triassic sediments and boulders of diabase along the lakeshore (Figure 3).

STOP 2: ANDESITIC AND DACITIC LAVAS OF THE HYCO FORMATION, HYCO ARC (35.7297°N, -79.1038°W) EAST SIDE HAW RIVER AT HWY 64, CHATHAM COUNTY, NC.

STOP LEADER: PHIL BRADLEY



Figure 5: Location of stop on the Merry Oaks 7.5' quadrangle



DESCRIPTION OF MAP UNITS

Jd – Diabase dike

CAROLINA TERRANE: HYCO ARC - HYCO FORMATION

Zhablt – Metamorphosed andesitic to basaltic lavas and tuffs

Zhe/pl – Metamorphosed mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas

Zhadlt (U) – Metamorphosed andesitic to dacitic lavas and tuffs of the upper portion of the Hyco Formation

0 1,000 2,000 Feet

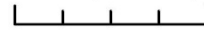


Figure 6: Location of stop on the Geologic Map of the Merry Oaks Quadrangle (Bradley et al, 2021a and compiled Chatham County Geology)

The stop 2 area provides some of the most extensive rock outcrops in this part of the Piedmont (Figures 5 and 6). At low water, the outcrops can be explored with great care. There are many slippery surfaces and potential hazards. During high river flow, these outcrops are often under water and alternative stop 2 should be visited.

These outcrops are primarily metamorphosed andesitic lavas (Figure 7). Some dacitic lavas may also be present. The outcrop surfaces are periodically “polished” by the rapid flow of water during high flow events and provide many excellent fresh surfaces to investigate. Splashing or pouring water on the outcrop surfaces can help make the rock textures more easily visible. Many different textures typical of fine-grained volcanic rocks and lavas flows can be found on the outcrops. Portions of this text were adapted from a layperson’s guide to the Haw River, as such, simplified explanations of the textures are provided (Bradley, 2017).

Textures include:

Aphanitic (fine-grained) texture: Aphanitic texture refers to an igneous rock in which the crystals are so small (so fine-grained) they cannot be seen with the naked eye. Aphanitic texture generally indicates the magma cooled quickly at or near the surface of the Earth. An example of a rock with an aphanitic texture is provided in Figure 8.

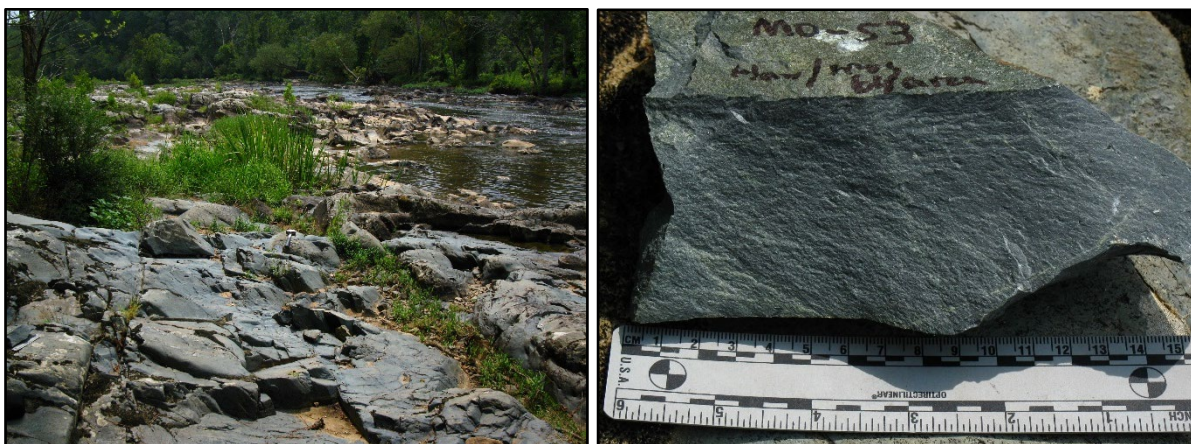


Figure 7: Left photograph, stop 2 area showing extensive outcrops in the Haw River. Figure 8: Right photograph, close-up of freshly broken surface of metamorphosed andesite showing aphanitic texture.

Porphyritic texture: Porphyritic texture refers to a volcanic rock that has distinct crystals visible in an aphanitic groundmass. Porphyritic texture is a typical texture of a volcanic rock formed from cooling magma.

Hyaloclastic texture: Hyaloclastic texture is formed when lava is erupted into water or flows into water and is quickly chilled. The rapid chilling caused the lava to fragment into multiple pieces ranging from a few mm to m in size. Sometimes the fragments will appear to “fit” together like jigsaw puzzle pieces.

Peperite texture: Peperite is a rock type that forms when magma comes into contact with wet sediments. The magma rapidly cools, identical to the hyaloclastic texture formation process, but is mixed with fine-grained sediments. Peperite and hyaloclastic texture can look identical and are hard to tell apart.

Amygdaloidal texture: Amygdaloidal textures refer to a rock with amygdules. Amygdules are mineral filled (often quartz) air pockets in the rock (fossil gas bubbles). Magma often contains

gas that will concentrate in small cavities called vesicles. When minerals infill the vesicles, they are called amygdules. Amygdules get their name from the Greek word for almond. Sometimes amygdules look like little almonds.

Fracture trace study of Haw River outcrops south of HWY 64 bridge.

The outcrops in the Haw River on the south side of the US HWY 64 bridge offer one of the best exposed areas of continuous outcrop in Chatham County. The primary rock type is metamorphosed andesite with lesser amounts of basalt of the Hyco Formation of the Carolina terrane.

The outcrops display pronounced jointing and fracturing. A simple fracture trace study was performed by georeferencing high-resolution aerial photographs of the area and tracing the fractures in ESRI ArcMap (Figure 9). Following the digitization of the fractures, the Data Management Toolbox-Features Toolset-Add Geometry Attributes-Line-Bearing tool was utilized to calculate the bearing of the fracture.

A rose diagram was constructed from the bearing data of the fracture traces (Figure 10A). The rose plot shows a dominant “rose petal” oriented to the south and south-southeast (corresponding to fracture sets trending north-northwest and south-southeast). A less dominant “rose petal” is oriented to the east (corresponding to fracture sets trending east-west). The east-west fracture set is generally parallel to local primary layering and metamorphic foliation.

The north-northwest/south-southeast fractures are the dominant fractures observed in the aerial photograph and in outcrop; they can be traced for hundreds of feet in the photographs. East-west fractures are generally parallel to layering and foliation/cleavage. The east-west fracture set appear to be cut by the north-northwest/south-southeast set of through-going fractures and are likely older.

A rose plot of joints from the Merry Oaks Quadrangle collected during detailed geologic mapping is provided as Figure 10B. Joint orientations are consistent with orientations of the north-northwest/south-southeast fractures and the east-west fractures in the Haw River. A rose plot of joints within the Carolina terrane identified in Chatham County through detailed geologic mapping is provided as Figure 10C. Orientations are also consistent with orientations of the north-northwest/south-southeast fractures in the Haw River. Other orientations are also present.

Assumptions on fracture systems in other lineaments in Chatham County.

In Chatham and nearby counties, abundant lineaments are present on the hillshade elevation map constructed from LiDAR elevation data. Many of the lineaments have been identified as brittle faults and/or contain diabase dikes. The Haw River is interpreted to occupy one of these lineaments. If fracture density as observed on the outcrops of the Haw River south of the Hwy 64 bridge are typical of such lineaments, then the lineaments may be good locations for water supply well installation. Conversely, the lineaments could provide preferential pathways for contaminant migration.

STOP 2 ALTERNATIVE: DACITIC LAVAS OF THE HYCO FORMATION, HYCO ARC (35.7321°N, -79.1084°W) WEST SIDE HAW RIVER AT HWY 64, CHATHAM COUNTY, NC.

In the event there is high water in the Haw River this alternative stop can be visited (Figures 5 and 6).

This stop has a large outcrop of metamorphosed dacite with prominent joint faces parallel to the river. It is suspected that this location may have been used as a small-scale quarry as a stone source for the foundations of former bridges over the Haw. A fresh surface of the rock shows a greenish-gray, fine-grained (aphanitic) groundmass with whitish-colored plagioclase crystals (phenocrysts). Interpreted relict vitric texture can be observed as mm- to sub-mm-sized translucent flakes on the fresh surfaces. If you explore around the outcrop flow banding may be observed.

This stop and others on the west side of the Haw River were described in a field trip guide for the Spring 2017 AEG – Carolinas Chapter field trip (Bradley, 2017) and can be downloaded at: <https://deq.nc.gov/media/9904/download>

STOP 3: BOULDERS FROM 3M ROOFING GRANULE QUARRY, DACITE OUTCROPS AND ALTERED VOLCANICS – HYCO FORMATION, HYCO ARC. BOULDERS OF EAST FARRINGTON PLUTON (35.6749°N, -79.1792°W), ROCK RIDGE PARK, TOWN OF PITTSBORO PARK, CHATHAM COUNTY, NC. STOP LEADER: PHIL BRADLEY

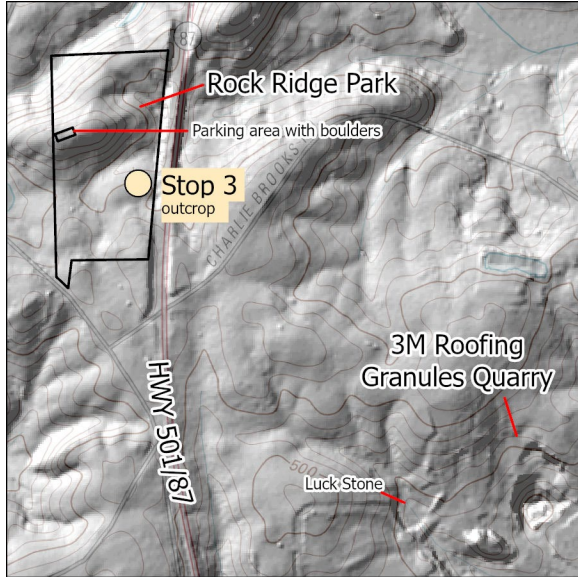
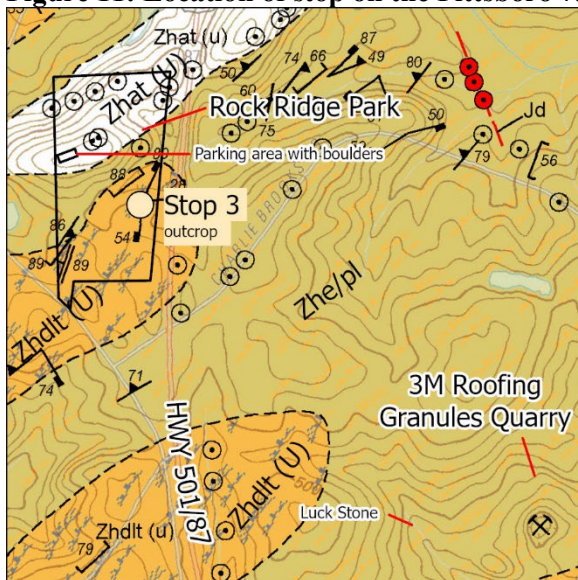


Figure 11: Location of stop on the Pittsboro 7.5' quadrangle and hillshade LiDAR topographic data



DESCRIPTION OF MAP UNITS

Jd – Diabase dike

CAROLINA TERRANE: HYCO ARC - HYCO FORMATION

Zhat (U) – Altered tuffs (upper portion of Hyco Formation)

Zhe/pl – Metamorphosed mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas and local intermediate to mafic lavas

Zhdlt (U) – Metamorphosed dacitic lavas and tuffs of the upper portion of the Hyco Formation

0 1,000 2,000 Feet



Figure 12: Location of stop on the Geologic Map of the Pittsboro Quadrangle (Bradley et al., 2014 and compiled Chatham County Geology)

Purpose:

To examine: boulders of rock types present in the 3M Pittsboro roofing granule quarry, boulders of locally derived altered volcanics on a walking trail in park, boulders of the East Farrington Pluton and an outcrop of dacite.

Rock Types:

This stop is located in the Town of Pittsboro Rock Ridge Park. There are multiple boulders of andesitic to basaltic lava (with intermingled volcano-sedimentary rock types), boulders of volcano-sedimentary rock and boulders of the East Farrington Pluton. Splashing the boulders with water will help bring out the various textures in the boulders.

3M Pittsboro Plant - roofing granules quarry boulders:

The 3M Pittsboro roofing granules quarry and plant is located to the southeast of the park (Figure 11 and 12). The land for the Rock Ridge Park was donated by 3M for use by the Town of Pittsboro for the park. Several boulders of rock donated by the nearby 3M Pittsboro Plant line the gravel parking area and are examples of the raw material used to make the roofing granules at the 3M plant. The boulders show a variety of rock types and textures including aphanitic andesite to basalt with hyaloclastic textures, andesite to basalt mixed with sediments, volcano-sedimentary rocks ranging from bedded sandstone to conglomerate. All rock types have been metamorphosed to greenschist facies and have abundant metamorphic chlorite and epidote.

Boulders of East Farrington Pluton:

Boulders of the East Farrington Pluton (Figure 1) are also present in the gravel parking area. The rock type outcrops in northeastern Chatham County and southeastern Orange County. The closest outcrop is approximately eight miles (13 km) to the north. The main phase of the East Farrington Pluton is metamorphosed, unfoliated, orange pink to pinkish gray to gray, medium- to coarse-grained, equigranular to slightly porphyritic, amphibole granite. Amphiboles are typically acicular hornblende that have chlorite intergrowth from metamorphism.

In southern Orange County and northeastern Chatham County, Hyco Formation units are intruded by the East Farrington pluton and associated West Farrington pluton. Two age dates are available for the East Farrington Pluton: a recent date of 569.0 ± 1.1 Ma from Goliber (2020) and a previous date of ca. 579 Ma of Tadlock and Loewy (2006).

Cobble and boulder debris of hydrothermally altered rock in woods and north side of parking area:

Multiple small rock chips, cobbles and boulders of hydrothermally altered rock, interpreted to be representative of the underlying unit of Zhat (U) (Figure 12) line the paved trail to the north of the gravel parking area. A few small outcrops and abundant rock debris are present on and off the trail system in the northern portion of the park. Abundant altered rock debris is present in road cuts on strike on HWY 501. Rock types include sericite phyllite, sericite + pyrophyllite + chloritoid phyllites. These hydrothermally altered rocks are identical to the general lithologies present in the pyrophyllite-bearing areas of Glendon and Hillsborough.

Outcrop of dacite near disk golf tee 17:

Several outcrop of dacite are present in the vicinity of disk golf tee 17. The outcrops are lichen covered and massive with prominent northeast-southwest and north-south oriented joint sets. Fresh surfaces of the rock are plagioclase porphyritic with an aphanitic groundmass. Thin sections of similar dacites indicate that the groundmass consists of a microcrystalline mosaic of quartz and feldspar. A sample was collected from this outcrop in 2019 for analysis by the UNC-Chapel Hill Isotope Geochemistry Lab. However, the sample was too silicic and several attempts to crush the sample for zircon separation were unsuccessful.

STOP 4: MAFIC CONGLOMERATES – HYCO FORMATION, HYCO ARC. (35.6777°N, -79.3357°W), GLOVERS GROVE CHURCH ROAD, CHATHAM COUNTY, NC.

STOP LEADER: PHIL BRADLEY



Figure 13: Location of stop on the Siler City NE 7.5' quadrangle

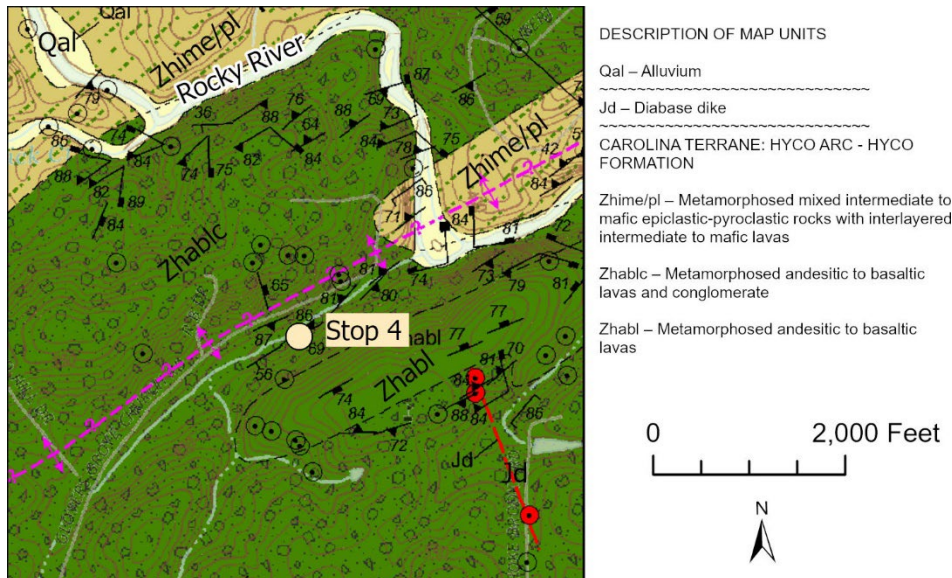


Figure 14: Location of stop on the Geologic Map of the Siler City NE Quadrangle (Hanna et al., 2015 and compiled Chatham County Geology)

Purpose and Background:

To examine outcrop fins of metamorphosed andesitic to basaltic conglomerates that are interpreted to be part of the Hyco Formation.

In their reconnaissance scale mapping Harris and Glover (1988) interpreted these rocks as part of the Virgilina Formation of the Virgilina Sequence. The Virgilina Sequence has been redefined by Hibbard et al. (2013) as being composed of the Aaron Formation with a felsic to mafic volcanic member – the Virgilina member.

In our new mapping, we interpret the unit as part of the Hyco Formation. Detailed mapping indicates that felsic volcanics and epiclastic rocks of the Hyco Formation (Zhe/pl) are intermingled with intermediate to mafic lithologies (Zhime/pl) and are interpreted to be in gradational contact with each other. It is interpreted that the top of the felsic portions of the Hyco Formation appears to intermingle with the bottom of the intermediate to mafic portions of the Hyco Formation (i.e. intermediate to mafic volcanism is contemporaneous with the waning phases of felsic magmatism). Additionally, new mapping indicates that the East Farrington pluton intrudes the intermediate to mafic units (Figure 1). Age dates of the East Farrington pluton overlap (within error) with the youngest detrital zircon date for the Aaron Formation (Pollock et al, 2010). If the East Farrington pluton is coeval with Aaron Formation sedimentation, then the intermediate to mafic volcanic and volcanoclastic units in Chatham County are older than the Aaron Formation and the Virgilina member.

Rock type:

The outcrops at the stop are part of the *Andesitic to basaltic lavas and conglomerate* (Zhabc) unit of Hanna et al. (2015). The unit contains weakly foliated, amygdaloidal, plagioclase porphyritic, amphibole/pyroxene porphyritic and aphanitic; andesitic to basaltic lavas and shallow intrusions. Hyaloclastic texture is common and imparts a fragmental texture on some outcrops and float boulders. Interlayers of conglomeratic rocks consisting of angular clasts of andesite and/or basalt are common and are interpreted as resedimented hyaloclastite. These

rocks are locally interlayered with pyroclastic rocks and meta-sediments identical to the Zhime/pl unit.

At this stop, finned-shaped outcrops of immature conglomerate, having angular clasts of andesite to basalt, are present. These outcrops are interpreted as resedimented hyaloclastites proximal to an intermediate to mafic volcanic center. Outcrop fins strike northeast and are steeply dipping – typical of Hyco Formation outcrops (Figure 15).



Figure 15. Outcrop fins of conglomerate at Stop 4. Steeply dipping finned outcrops are typical of Hyco Formation outcrops (NCGS station SNE-2694).

STOP 4 ALTERNATIVE: INTERMEDIATE TO MAFIC VOLCANOSEDIMENTARY ROCKS OF THE HYCO FORMATION, HYCO ARC (35.7212°N, -79.4171°W) CENTRAL CAROLINA BUSINESS CAMPUS, SILER CITY, CHATHAM COUNTY, NC.

This is an alternate stop for Stop 4.



Figure 16: Location of stop on the Siler City 7.5' quadrangle and aerial photograph composite

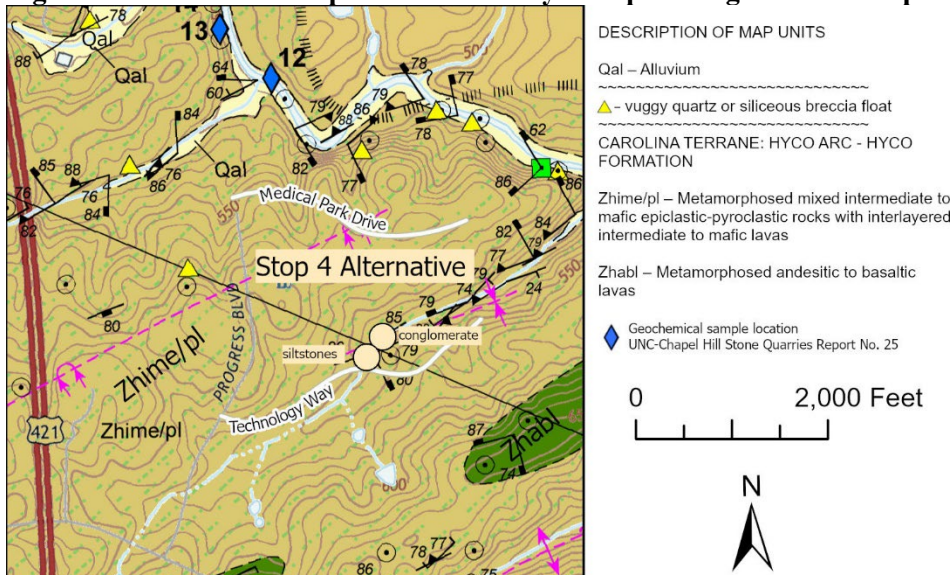


Figure 17: Location of stop on the Geologic Map of the Siler City Quadrangle (Bradley et al., 2017 and compiled Chatham County Geology). Blue diamonds refer to geochemical samples reported in Steponaitis et al. (2006).

Purpose:

To examine outcrop of metamorphosed conglomerates and tuffaceous siltstones assigned to the Hyco Formation.

Rock type:

The outcrops at the stop are part of the *Mixed intermediate to mafic epiclastic-pyroclastic rocks with interlayered intermediate to mafic lavas* (Zhime/pl) unit of Bradley et al. (2017). The unit contains metamorphosed conglomerate, conglomeratic sandstone, sandstone, siltstone and mudstone, with local interbedded intermediate to mafic lavas identical to Zhablt, Zhabl, and Zhablc units. The unit also contains lesser amounts of fine- to coarse tuff and lapilli tuff; minor dacitic lavas and tuffs. Generally interpreted to have been deposited proximal to active intermediate to mafic composition volcanic centers and/or record the erosion of proximal intermediate to mafic composition volcanic centers after cessation of active volcanism. May be related to Green et al. (1982) unit C - Intermediate to Mafic Volcanics and Graywacke.

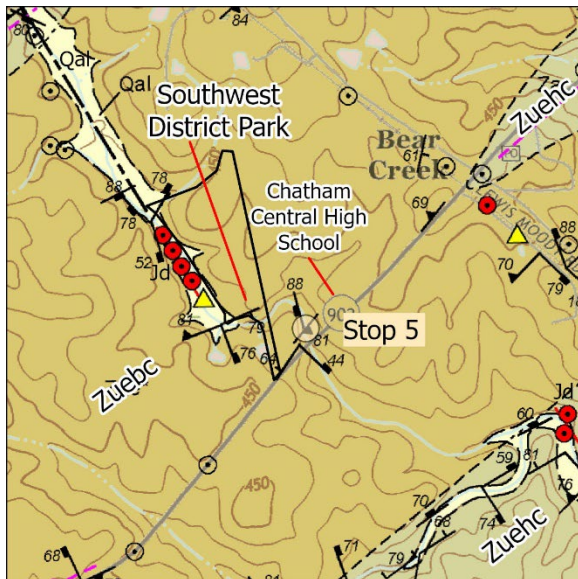
At this stop, along the slope down to the drainage, is a pavement outcrop of immature conglomerate with angular to sub-angular clasts of andesite to basalt. In the creek are outcrops of tuffaceous siltstones and conglomeratic siltstones. The siltstones are dominantly green in color from chlorite and/or epidote and interpreted to have been sourced from intermediate to mafic composition protolith rocks. Light-colored, felsic tuffaceous siltstones are present in lesser amounts.

Detailed geologic mapping in the area, indicates the common presence of coarse-grained sediments similar to those at this location along the edges of the map-scale bodies of Hyc Formation volcanics. These outcrops are interpreted to represent the contemporaneous proximally deposited erosional debris (or re-sedimented hyaloclastite debris) of a nearby volcanic center. The intermediate to mafic composition siltstones and conglomeratic siltstones are interpreted to represent medial to distal deposition from intermediate to mafic volcanic centers. The felsic composition siltstones are interpreted to represent the erosion and distal deposition of erosional detritus from faraway felsic volcanic centers.

STOP 5: METASEDIMENTARY ROCKS OF THE BEAR CREEK AREA, ALBEMARLE ARC – UWHARRIE FORMATION (?) (35.6125°N, -79.3911°W), CHATHAM COUNTY SOUTHWEST DISTRICT PARK AND CHATHAM CENTRAL HIGH SCHOOL, BEAR CREEK, CHATHAM COUNTY, NC. STOP LEADER: PHIL BRADLEY



Figure 18: Location of stop on the Bear Creek 7.5' quadrangle and aerial photograph composite



DESCRIPTION OF MAP UNITS

Qal – Alluvium

Jd – Diabase dike

ALBEMARLE ARC - UWHARRIE FORMATION (?)

Zuehc - Epiclastic rocks of the Harpers Crossroads area: Distinctive metasedimentary package that ranges from fine-grained siltstones to coarse-grained sandstones, pebbly sandstones and conglomerates. Commonly contain rounded to subangular clasts of quartz ranging from sand- to gravel-sized.

Zuebc - Epiclastic rocks of the Bear Creek area: Metasedimentary package that ranges from siltstones, sandstones, conglomeratic sandstone, and conglomeratic siltstones (graywacke). Sand-sized quartz grains are rare or absent.

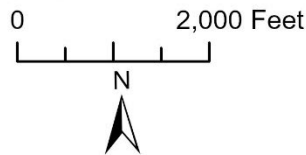


Figure 19: Location of stop on the Geologic Map of the Bear Creek Quadrangle (Bradley et al., 2019 with updated unit names)

Purpose and access to location:

To examine outcrops of metamorphosed sandstones and conglomerates and to discuss recent detrital zircon results.

To access the stop, park at Southwest District Park (Figures 18 and 19). The stop is on the adjacent property of Chatham Central High School. From Southwest District Park walk along the gravel entrance road out to NC HWY 902 and walk toward the northeast along the road. Access the outcrop area from the DOT ROW. Be mindful of potential security concerns that the school may have with visitors on school property. If the school is open and active during your visit, prior approval from the school may be needed.

Rock type:

At this stop, the outcrops contain tuffaceous sandstones, sandstones and conglomeratic sandstones; clasts when present are rounded to subrounded. An intermediate to mafic composition dike is also present. Primary layering is present dipping approximately 65 to 70 degrees toward the northwest. The unit contains siltstones, sandstones, conglomeratic sandstone, and conglomeratic siltstone (graywacke). Siltstones typically display bedding ranging from mm-scale up to 10 cm, bedding layers are traceable for several feet locally, and may exhibit soft sediment deformation. Unit is locally tuffaceous and contains interbedded intermediate to mafic lavas. Conglomerates and conglomeratic sandstones typically contain rounded to angular clasts. Deposition is interpreted as distal from volcanic center. Part of this unit may be correlative to Green et al. (1982) unit B - Felsic Graywacke Unit.

Discussion:**Interpretation of outcrops and unit before detrital zircon data:**

The outcrops at the stop were originally mapped as part of the Hyco Formation in the *Epiclastic rocks of the Southern Chatham County area* (Zhesc) unit of Bradley et al. (2019). In comparison to Hyco Formation units, this unit is texturally more mature and has fewer interlayers of tuff and lavas. It is interpreted to have been deposited distal in place or in time from active volcanism. During original mapping (Bradley et al., 2019), this unit was interpreted to represent portions of the uppermost Hyco Formation before sedimentation of the Aaron Formation.

Based on descriptions of the Aaron Formation (Harris, 1984), Aaron Formation sandstones and conglomerates typically have conspicuous quartz grains or pebbles. During field mapping, sandstones and conglomerates with conspicuous quartz grains were assigned to the Aaron Formation. Sandstones without conspicuous quartz grains were assigned to the Hyco Formation. Hyco Formation lithologies may contain sparse quartz. Outcrops at this stop may contain occasional quartz but are quartz deficient in comparison to typical “Aaron Formation sandstones” like those described in Stops 6 and 7.

Results of detrital zircon analysis:

In April 2022, NCGS Sample Bear Creek-626 was collected from these outcrops for detrital zircon analysis and analyzed by the Arizona LaserChron Center by LA-ICPMS. 316 zircon grains were analyzed, of those grains 212 fell within 90–110% of concordia. Of the 212 near concordia, the 206Pb/238U ages range from 535 ± 3.7 Ma to 2671.1 ± 12.7 Ma. The three youngest detrital zircons are: ca. 535, 535 and 536 Ma. 34 zircons are 554 Ma and younger (16%). 161 zircons

are between 555 Ma and 610 Ma (76%). 13 zircons are between 610 and 650 MA (approx. 6%). 4 zircons are between 685 – 2671 Ma and are 685.7 +/-5.0 Ma, 1255 +/-12.51 Ma, 1420 +/- 10.1 Ma and 2671.1 +/- 12.7 Ma (Figure 20). Detailed plots are provided in Pelt and Bradley (2023, this volume).

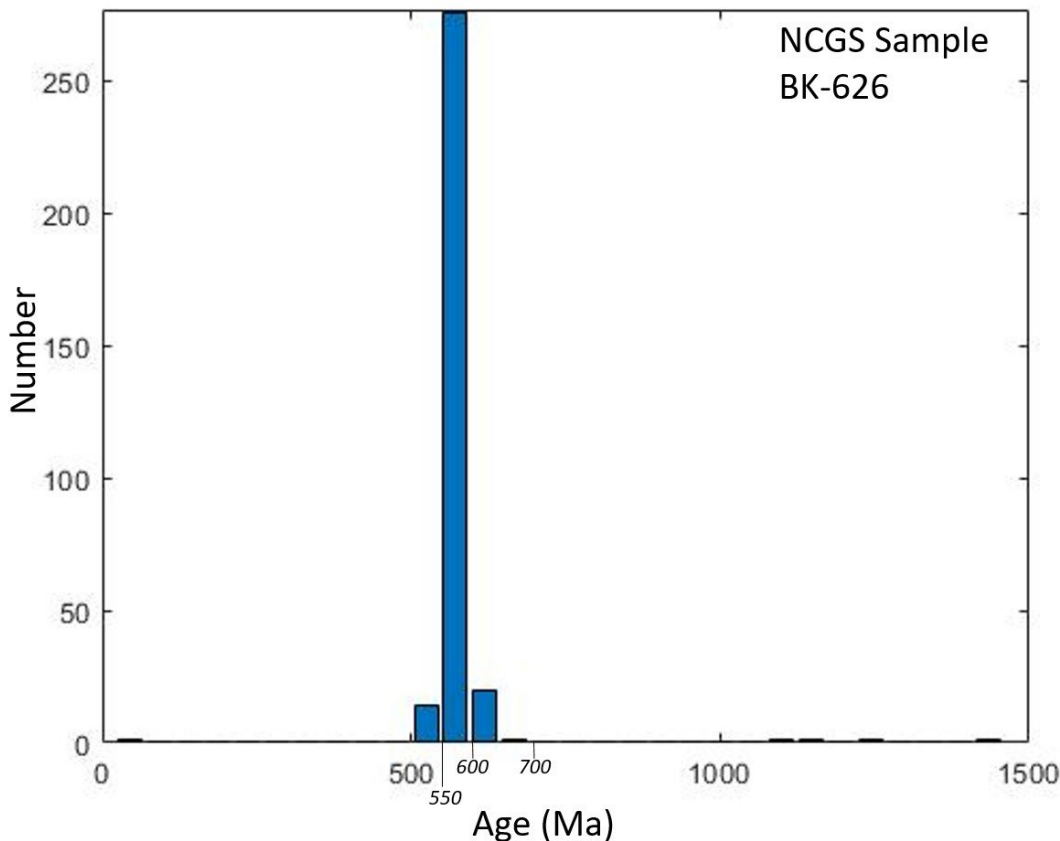


Figure 20: Histogram of detrital zircon results for NCGS BK-626 collected from Chatham Central High School, Bear Creek, Chatham County. Histogram x axis is truncated to show detail in the 500-700 Ma range.

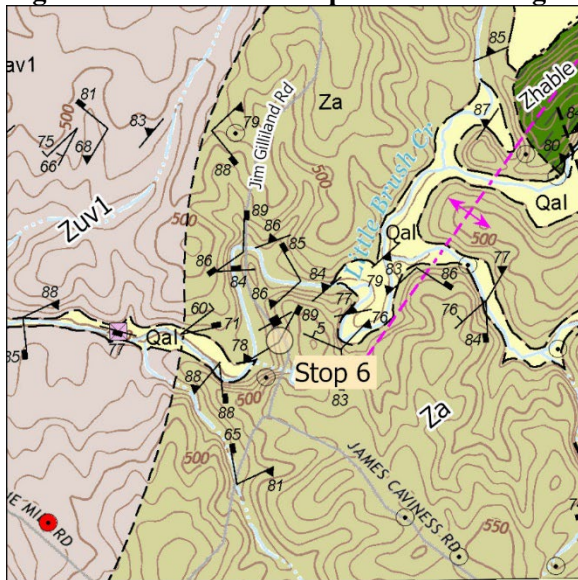
Based on the detrital zircon data, stratigraphic placement of the unit (as being part of the Hyco Formation) needs to be revised. The unit is likely related to distal sedimentation associated with the Albemarle arc. The dates of the youngest detrital zircons are similar to those of NCGS sample Coleridge-3055 collected from the Epiclastic rocks of the Harpers Crossroads area (Zuehc) unit (discussed as part of Stop 7). Unit Zuehc locally includes distinctive quartz-rich sandstones and is texturally similar to the Erect Member of the Uwharrie Formation (Pollock et al., 2010 and Hibbard et al., 2013). The Erect Member of the Uwharrie Formation has a youngest detrital zircon grain with a date of 545 + 7 Ma (Pollock et al., 2010). Hibbard et al. (2013) introduced the idea that portions of the Uwharrie Formation maybe diachronous (occurring at different times) and maybe correlative to the Flat Swamp Member of the Cid Formation. As such, the sample and unit at this stop (NCGS Sample Bear Creek-626) are tentatively reassigned to the Uwharrie Formation and the name changed to Epiclastic rocks of the Bear Creek area (Zuebc) (Figure 19).

STOP 6: CONGLOMERATE – AARON FORMATION (35.6321°N, -79.5393°W), JIM GILLILAND ROAD (SR 1148) AND LITTLE BRUSH CREEK AREA, CHATHAM COUNTY, NC.

STOP LEADER: PHIL BRADLEY



Figure 21: Location of stop on the Coleridge 7.5' quadrangle



DESCRIPTION OF MAP UNITS

Qal – Alluvium

ALBEMARLE ARC - UWHARRIE FORMATION (?)

Zuv1 - Uwharrie Formation volcanics: Metamorphosed mixed felsic to mafic epiclastic-pyroclastic rocks with interlayered felsic to mafic lavas

AARON FORMATION

Za – Aaron Formation: Distinctive metasedimentary package that ranges from fine-grained siltstones to coarse-grained sandstones, pebbly sandstones and conglomerates in contact with Hyco Formation units

CAROLINA TERRANE: HYCO ARC - HYCO FORMATION

Zhable – Metamorphosed andesitic to basaltic lavas with interlayered epiclastic rocks



Figure 22: Location of stop on the Geologic Map of the Coleridge Quadrangle (Bradley et al., 2018 with updated unit names)

Purpose: To examine outcrops of metamorphosed conglomerates

Rock Type:

The outcrops at the stop are mapped as part of the *Aaron Formation (Za)* on the geologic map of the Coleridge Quadrangle (Bradley et al., 2018) (Figure 22). The Aaron Formation is a distinctive metasedimentary package that ranges from fine-grained siltstones to coarse-grained sandstones, pebbly sandstones and conglomerates. Siltstones are similar in appearance to Hyco

Formation lithologies. The sandstones, pebbly sandstones and conglomerates (classified as litharenite, feldspathic litharenite and lithic feldsarenite by Harris (1984)) are distinctive and commonly contain rounded to subrounded clasts of quartz ranging from sand- to gravel-sized. In the sandstones, feldspar is the most prominent mineral type; quartz varies from sparse to abundant in hand sample. Lithic clasts are typically prominent and range from sand- to gravel-size. Harris (1984) performed a detailed sedimentary study of the Aaron Formation to the immediate west of the map area (Figure 23). Harris (1984) interpreted the Aaron Formation to have been deposited by turbidity currents in a retrogradational submarine fan setting with the sediment sourced from the eroding Hyco Arc.

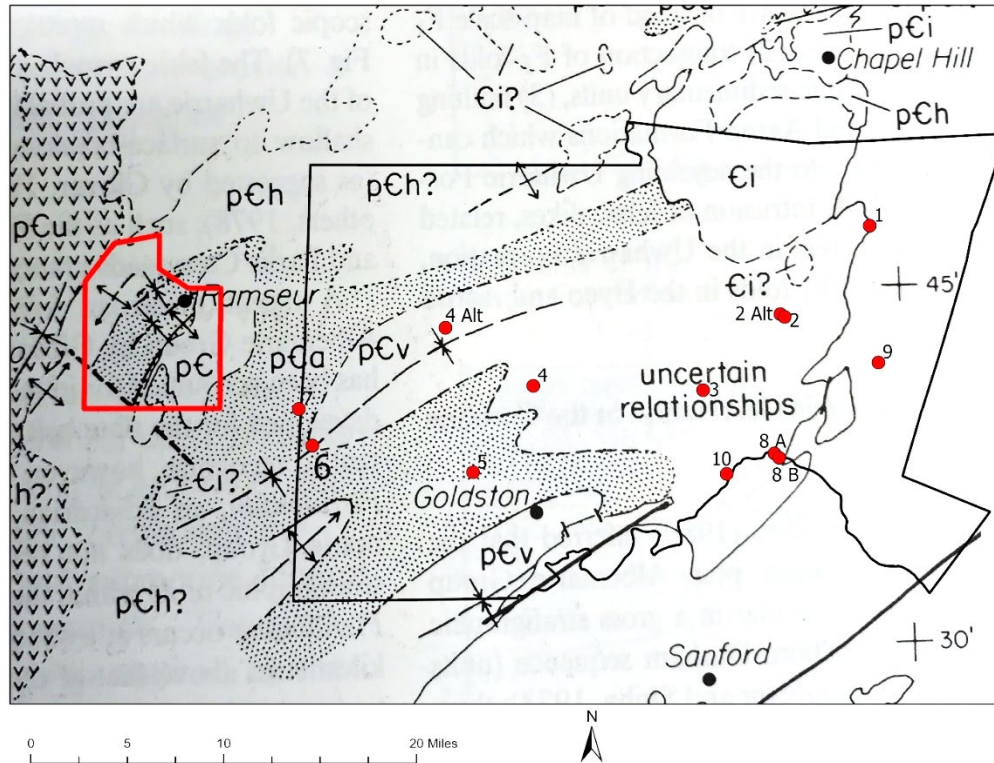


Figure 23: Portion of Figure 10 from Harris and Glover (1988) showing location of Harris (1984) study of the Aaron Formation (red outline). CGS 2023 stops and Chatham County outline included. Unit abbreviations: pCu – Uwharrie Formation, pCh – Hyco Formation, pEv – Virgilina Formation, pE – Parks Crossroads pluton, E – intrusive body.



Figure 24: Conglomerate outcrop at Stop 6.

At this stop the outcrop fins are conglomeratic sandstones and conglomerate (Figure 24). Clasts are rounded to subrounded and composed of volcanic and sedimentary rock fragments and vein quartz. Conspicuous sand-sized quartz grains are present standing out in positive relief on the outcrop. Pressure solution cleavage is likely responsible for the oblate shape of some of the clasts. The outcrop displays a steep foliation that when weathered forms finned-shaped outcrops. Primary layering is present dipping toward the northwest indicating an anticline to the southeast (Figure 22).

Past Work and Discussion:

Harris and Glover (1988) (Figure 23), depicted Chatham County as being underlain by the Virgilina and Aaron Formations with a fold hinge of a major syncline running through the location of Stop 6. NCGS detailed mapping interpreted the intermediate to mafic volcanics Harris and Glover (1988) assigned to the Virgilina Formation as being part of the Hyco Formation and that a major anticline is present near stop 6.

This stop is within the Virgilina Sequence of Harris and Glover (1988). The Virgilina sequence was originally defined as containing the Hyco Formation and the overlying Aaron Formation and Virgilina Formation. Bowman (2010) and Bowman et al. (2013) redefined the Aaron Formation as containing only the Aaron Formation and the volcanic Virgilina member. Part of the evidence for redefining the sequence was from detrital zircon dates reported in Pollock et al. (2010) and Pollock (2007) from a similar outcrop of Aaron Formation conglomerate approximately nine miles (14.5 km) to the north (Figure 1). From that outcrop, a youngest zircon age of 588 ± 11 Ma was reported and likely represents the oldest portion of the Aaron Formation according to Pollock et al. (2010). This age indicates that the Aaron Formation is significantly younger than the youngest rocks in the underlying Hyco Arc (ca. 612 Ma (Wortman, 2000)) and that a disconformity of at least 24 million years is present (Hibbard et al., 2013). The Aaron Formation

is defined as being folded with the Hyco arc during the Virgilina Deformation (Pollock, 2007; Pollock et al., 2010). Subsequent detailed mapping by the NCGS indicates that the outcrop sampled by Pollock et al. (2010) is near the base of the Aaron Formation near Hyco Formation lithologies.

Mapping of the Aaron Formation in Chatham County before detrital zircon data:

The detailed mapping in Chatham County and subsequent publication of the 1:24K open-file maps utilized the description of the Aaron Formation from Harris (1984) to group rocks in the Aaron Formation map unit (Za). Conglomerates, like those present at stop 6, and distinct tuffaceous sandstones with abundant to sparse sand-size quartz grains were all lumped together as part of the Aaron Formation on the individual 1:24K geologic maps that compose Chatham County. New detrital zircon data (Coleridge-3055 and Bear Creek-626 - Figure 1), indicate that the tuffaceous sandstones contain youngest detrital zircons that are ca. 535 MA and are likely related to distal sedimentation associated with the Albemarle arc. Based on the detrital zircon data, large areas previously mapped as Aaron Formation on the individual 1:24K geologic maps of Chatham County have been reassigned to the Uwharrie Formation. As a result of the detrital zircon data, the Aaron Formation map unit was greatly reduced on the compiled geologic map of Chatham County to include rocks that are in direct contact with Hyco Formation units and include conglomerates with rounded quartz pebbles and more intense pressure solution cleavage.

The problem with the “Aaron Formation”

The Aaron Formation, first defined by Glover and Sinha (1973) in the type area near the North Carolina-Virginia line, was later extended into parts of Chatham and Randolph counties by Harris (1984) and Harris and Glover (1988) – Figure 23. The Aaron Formation, as defined by Pollock (2007) and Pollock et al. (2010), contains sediments eroded from the Hyco arc prior to the Virgilina deformation. The new detrital zircon data indicate that large portions of the geologic unit originally grouped with the Aaron Formation contain sediments with detrital zircons sourced from the Albemarle arc and interlayered with detritus eroded off the underlying Hyco arc. These sediments look identical and only the presence or absence of Albemarle arc aged detrital zircons can accurately distinguish “*true Aaron Formation*” as defined by Pollock and parts of the “*Aaron*” associated with distal sedimentation from the Albemarle arc.

Additionally, recent geochronology work by Morrison and Coleman (2023, this volume) on the Parks Crossroads pluton, report a U-Pb zircon age of ca. 552 Ma. Past regional mapping shows the Parks Crossroads pluton truncating units assigned to the Aaron Formation. In light of the new detrital zircon data, parts of the map unit previously assigned to the Aaron Formation are younger than the Parks Crossroads pluton and likely unconformably overlie the pluton.

Both new detrital zircon samples (NCGS sample Coleridge-3055 and NCGS Sample Bear Creek-626 – Figure 1) contain populations of zircons ranging from ca. 545 to 534 Ma. These data suggest that deposition of both units that contain the samples were contemporaneous with the Flat Swamp Member of the Cid Formation of the Albemarle arc. Should these units be assigned to the Cid Formation or to a new Formation? Should the Aaron Formation be re-defined? More work is needed.

**STOP 7: UWHARRIE FORMATION SANDSTONE – ALBEMARLE ARC (35.6597°N, -79.5520°W), LAMBETH MILL ROAD (SR 2641), RANDOLPH COUNTY, NC.
STOP LEADER: PHIL BRADLEY**

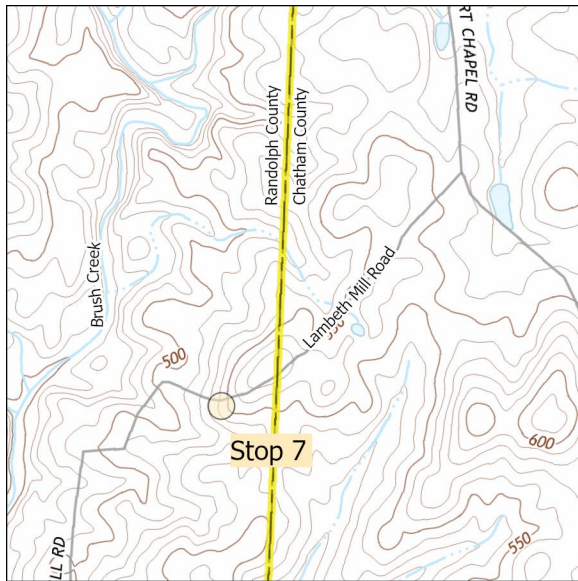
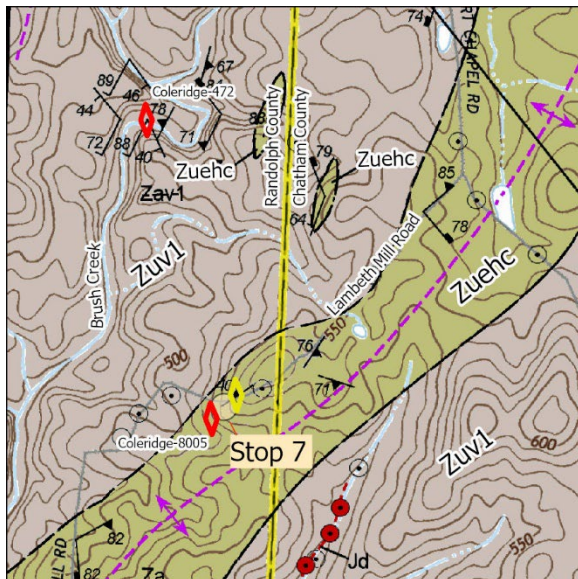


Figure 25: Location of stop on the Coleridge 7.5' quadrangle



DESCRIPTION OF MAP UNITS

Jd – Diabase

ALBEMARLE ARC - UWHARRIE FORMATION (?)

Zuv1 - Uwharrie Formation volcanics:
Metamorphosed mixed felsic to mafic epiclastic-pyroclastic rocks with interlayered felsic to mafic lavas

Zuehc - Epiclastic rocks of the Harpers Crossroads area: Distinctive metasedimentary package that ranges from fine-grained siltstones to coarse-grained sandstones, pebbly sandstones and conglomerates. Commonly contain rounded to subangular clasts of quartz ranging from sand- to gravel-sized.

◆ Detrital zircon analysis location

◆ TIMS zircon 206Pb/238U date Coleridge-458 (NC-18-02): 551.90 Ma from felsic dike or tuff



Figure 26: Location of stop on the Geologic Map of the Coleridge Quadrangle (Bradley et al., 2018 and compiled Chatham County Geology)

Purpose: To examine outcrops of metamorphosed sandstones with abundant quartz grains.

Rock Type:

The outcrops at the stop consist of distinctive quartz-bearing sandstones that are part of the *Epiclastic rocks of the Harpers Crossroads area unit* (Zuehc) (Bradley et al., 2022). The unit is a metasedimentary package that ranges from fine-grained siltstones to coarse-grained sandstones,

pebbly sandstones and conglomerates. The sandstones, pebbly sandstones and conglomerates commonly contain rounded to subangular clasts of quartz ranging from sand- to gravel-sized. In the sandstones, feldspar is the most prominent mineral type; quartz varies from sparse to abundant in hand sample. Lithic clasts are typically prominent and range from sand- to gravel-size.

Interpretation of outcrops and unit before detrital zircon data:

The outcrops at this stop were originally mapped as part of the Aaron Formation in the (Za) unit of Bradley et al. (2018). This outcrop and others like it were correlated with the Aaron Formation based on the description of the Aaron Formation from Harris (1984) in which Aaron Formation sandstones and conglomerates typically have conspicuous quartz grains or pebbles.

Age data

In 2018, when these outcrops were interpreted as being part of the Aaron Formation, an interlayer of felsic tuff (or felsic dike) was sampled from an outcrop approximately 200 feet to the northeast (Figures 25 and 26) for U-Pb crystallization age by UNC Chapel Hill using LA-ICPMS. The small outcrop was destroyed during the sampling event. At the time of sampling, this location was interpreted as being part of the middle or uppermost part of the Aaron Formation and we were interested in determining the age of this portion of the “Aaron”. Single zircons from the sample (NCGS Station Coleridge-458/ UNC sample NC18-02) yielded a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ (Th-corrected) age of 551.1 ± 0.9 Ma (R. Mills, personal com. 2018). An age of ca. 551 Ma did not match the expected age range of the Aaron Formation (ca. 588-579 Ma). In 2018, the sampled rock was unfortunately interpreted as a younger felsic dike and not indicative of the age of the rock unit.

In early 2022, a sample from the unit was collected adjacent to the Siler City Airport for detrital zircon analysis (NCGS sample COL-3055) – Figure 1. The four youngest detrital zircons are: ca. 534, 538, 538 and 538. The unit has been tentatively re-assigned to the Uwharrie Formation and the name changed to Epiclastic rocks of the Harpers Crossroads area (Zuehc) (Figure 26). Following the results of the new detrital zircon ages, the ca. 551 Ma crystallization age date from nearby this stop, fits well into being linked with the Uwharrie Formation. A sample from this outcrop (NCGS station Coleridge-8005) has been submitted for detrital zircon analysis. Zircon separates have been produced and the sample awaits analysis at the University of South Carolina Columbia Tectonics and Sedimentation Laboratory.

STOP 8: ABANDONED QUARRY AND CATACLASITE IN HYCO FORMATION – MESOZOIC DEFORMATION AREA FROM DOUBLE BREACHED RELAY RAMP(?). (35.6271°N, -79.1131°W), FUTURE DEEP RIVER TRAIL PARK – ADMINISTERED BY JORDAN LAKE STATE RECREATION AREA, CHATHAM COUNTY, NC. STOP LEADER: PHIL BRADLEY (with contributions from Emily K. Michael)

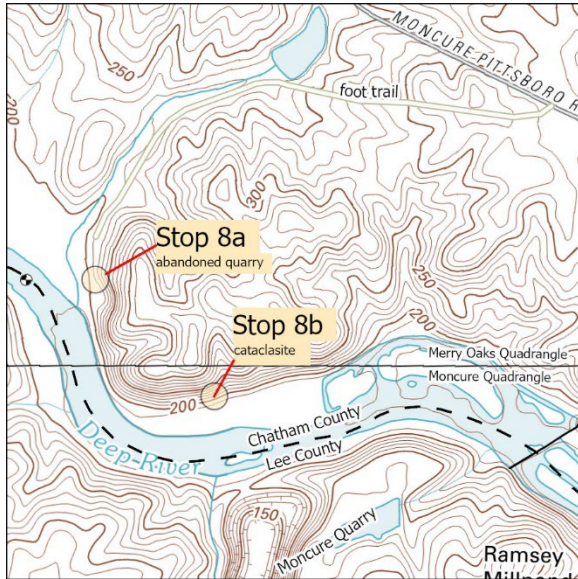


Figure 27: Locations of stop on the Merry Oaks and Moncure 7.5' quadrangles

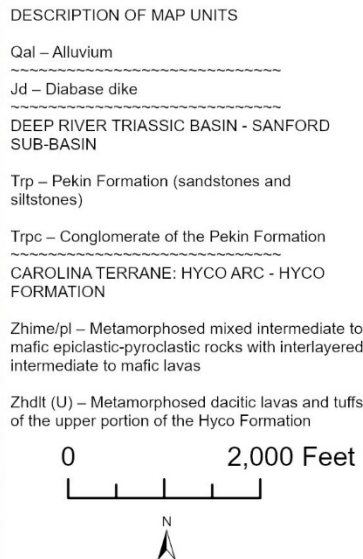
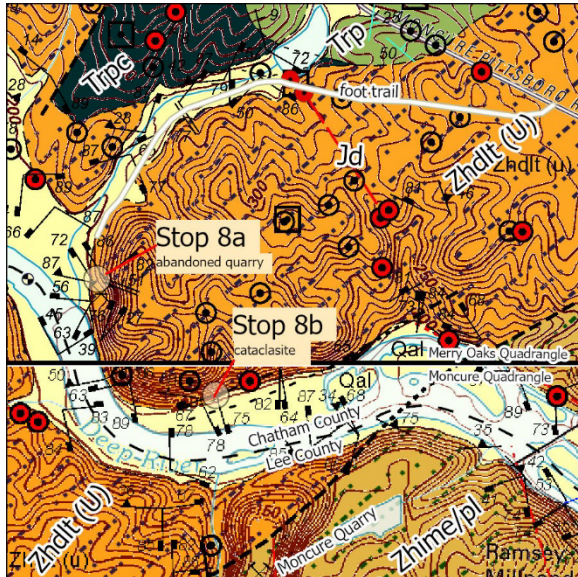


Figure 28: Locations of stop on the Geologic Map of the Merry Oaks and Moncure quadrangles (Bradley et al., 2021a and b and compiled Chatham County Geology)

Background

This stop is located on land owned by the State of NC and is part of the future Deep River Trail Park. The land is administered by the Jordan Lake State Recreation Area. The Deep River Trail

Park, created in 2007, will someday include multiple outdoor recreation opportunities along the entire Deep River.

According to the property records, the land was purchased by the State of NC in 2006 from Hanson Aggregates. An abandoned quarry is present on the land. The walls of the quarry are unstable and are dangerous - Great care must be taken while exploring the area.

Historic aerial photographs show no signs of significant quarry operations in March 1955 (NCDOT), the 1955 soils map of Chatham County shows cleared land and an area labeled “Rock Quarry”, a 1960 photograph (NCDOT) shows cleared land and the probable initiation of visible quarry activities. In 1966 (Chatham County historic photograph), rock conveyors are present. In a 1979 aerial (Chatham County historic photograph), quarrying activities had ended. In 1989, the Nello Teer Company drilled 7 borings and recovered core as part of crushed stone resource evaluation activities. The core is part of the NCGS Legacy Core and Cutting Collection.

Trailhead and stop access:

Park at the Moncure Community Health Center at 7228 Moncure-Pittsboro Road, Moncure, NC. The trailhead is indicated with signage in the southwest corner of the parking lot. Follow the foot trail to its intersection with the Foot Trail indicated on Figure 27. The trail to the abandoned quarry is different from the official trail. Pay close attention to the map and use the latitude and longitude to aid in finding the location.

Rock Types:

Stop 8a is an abandoned quarry in the Carolina terrane unit - *dacitic lavas and tuffs of the upper portion of the Hyco Formation (Zhdlt (U))* (Bradley et al., 2021a) (Figures 27 and 28). The main rock type in the quarry is metamorphosed dacitic tuffs with some phyllitic volcanosedimentary rocks. An intrusion of metamorphosed andesitic to basaltic composition rock is present on the southern portion of the abandoned quarry.

Brittle Overprinting

Local intense brittle overprinting, in the form of brecciation and intense fracturing, can be observed throughout the walls of the abandoned quarry. The strike of the metamorphic foliation in the abandoned quarry and surrounding areas is oriented in a northwest-southeast trend. This is anomalous to the strike of the regional metamorphic foliation trend of northeast to southwest. The trend of the foliation in the quarry is almost 90 degrees “off” from the typical regional foliation (Figures 28 and 29).

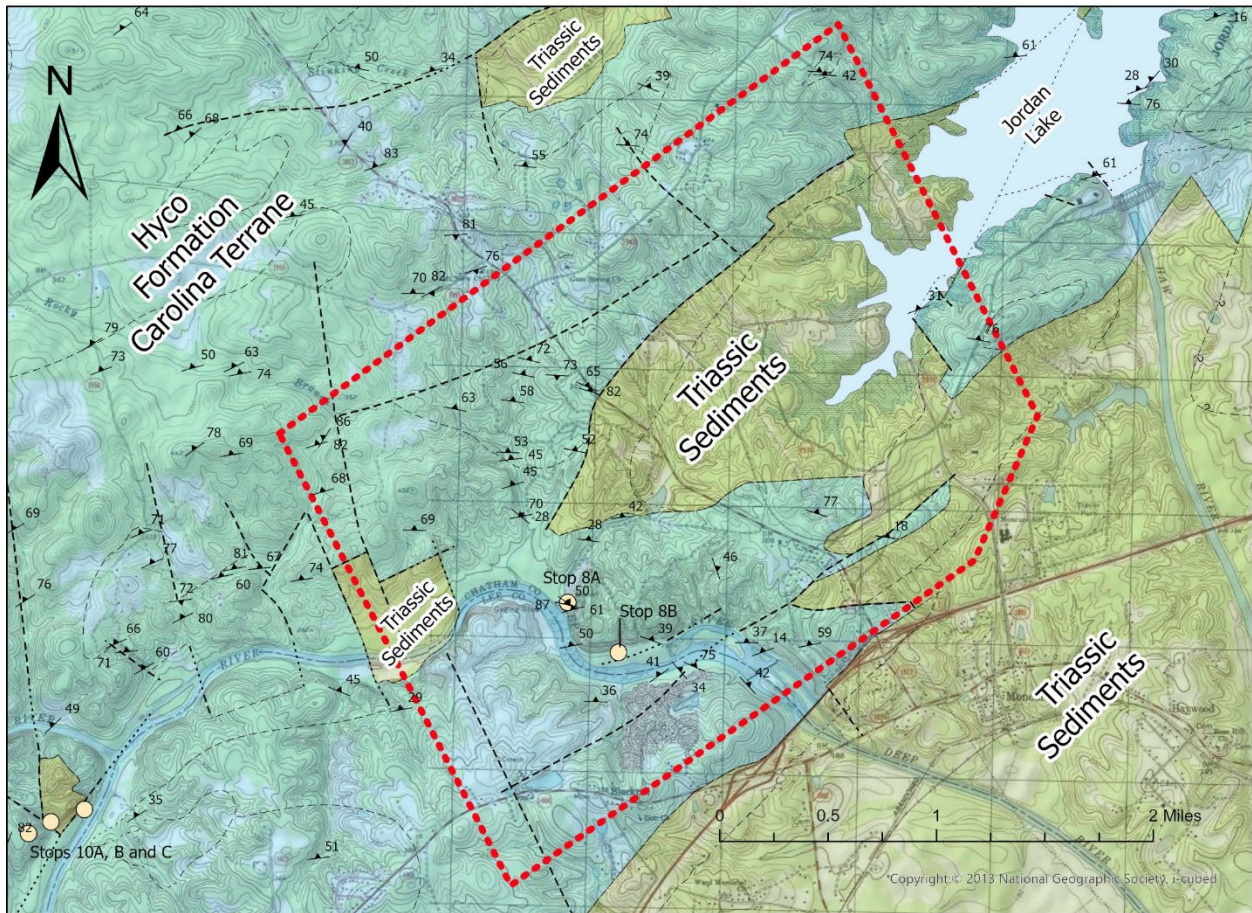


Figure 29: Simplified geologic map of area around Stop 8. Strike of metamorphic foliations within area of dashed red line display anomalous rotation up to 90 degrees from typical foliations outside of area.

Stop 8b is a short walk along the Deep River (Figures 27 and 28). Along the walk are outcrops and float of dacite. A cataclasite (a fault rock that is cohesive) outcrop is present with intense fracturing and openings.

Discussion

The location of Stop 8a and b is on the northeastern edge of the Colon Cross-Structure (Campbell and Kimball, 1923; Reinemund, 1955). This structure is a constriction zone between the Durham and Sanford sub-basins of the Deep River Triassic basin and is characterized by crystalline rocks overprinted by complex brittle faulting.

USGS mapping (Reinemund, 1955) and recent NCGS detailed mapping has identified multiple faults in the area. Metamorphic foliations are present with an apparent rotation of up to 90 degrees clockwise from the regional metamorphic foliation trend. This rotation is speculated to be related to Mesozoic-aged rotation of fault-bounded blocks of Carolina terrane rock possibly related to a double breached relay ramp (Figure 30). For an alternate explanation, see McDaniel et al. (this volume and supplementary digital download).

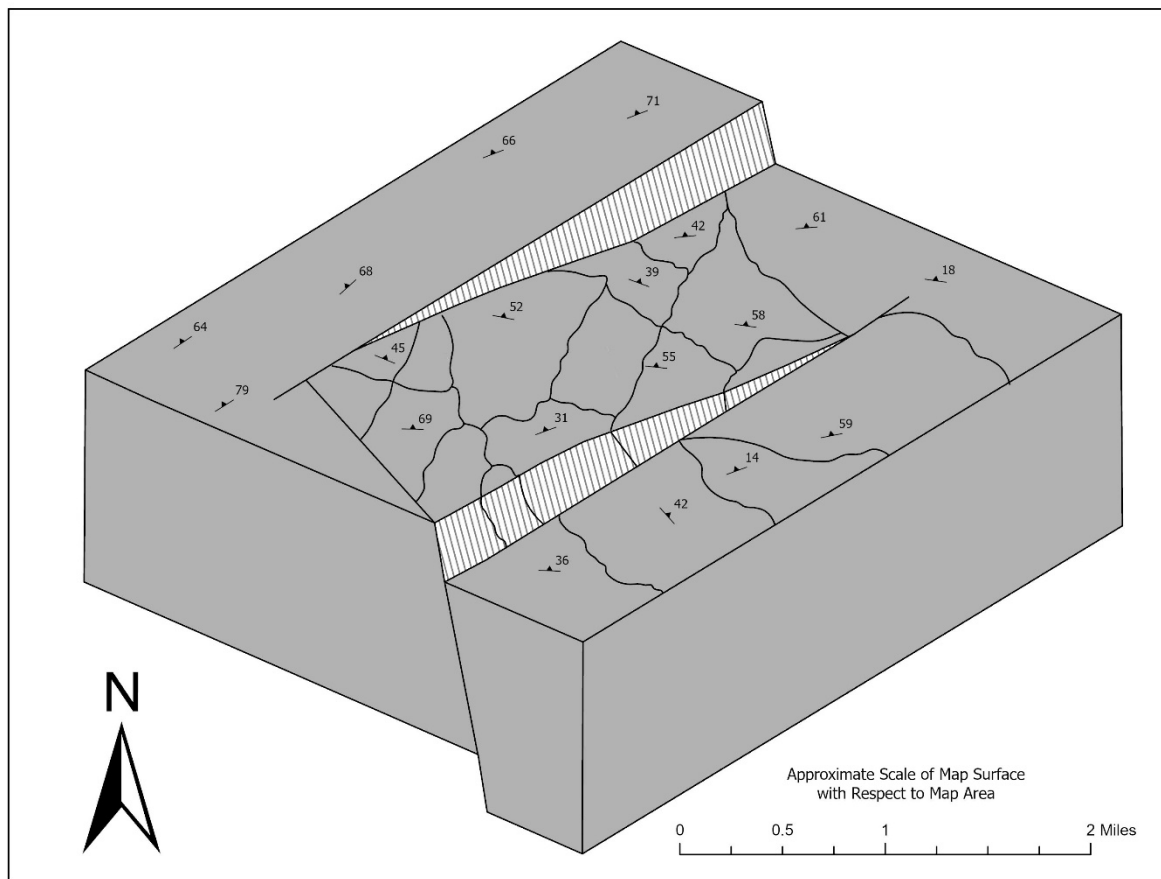


Figure 30: Schematic diagram of a relay ramp structure (before deposition of Triassic sediments) in which ramp is complexly faulted. Individual fault-bounded blocks in ramp may have rotated at varying rates and paths resulting in random-like orientations of metamorphic foliations.

Slope Stability Study

A slope stability study was conducted as part of a senior thesis (Michael, 2020) in the abandoned quarry. The goal of this study was to assess the safety of the quarry before the Deep River Trail Park opened to the public and inform the park administration of any hazardous areas. Using Markland's test, each of the lithologies in the rock quarry was tested for the possibility of planar, wedge, and toppling failure. Markland's test involves evaluating the orientation of measured joints to determine the potential for failure. Each type of failure, planar, wedge, and toppling, has different conditions for failure. Several factors of safety calculations were completed within rock units that were considered 'high-risk' units. Each factor of safety value was less than one, supporting a high probability of failure within the high-risk units. The rest of the lithologies were grouped as moderate or low risk depending on the height of the slope face containing the lithology and the frequency of joint planes or intersections that fall within the critical zone for planar, wedge, and toppling failure. Due to the presence of high-risk units and steep quarry

slopes, the recommendation made to park staff is to post cautionary signs, rope off the quarry to visitors, and consider diverting the trail that leads to the quarry.

STOP 9: TRIASSIC CONGLOMERATES ASSOCIATED WITH THE BONSAI-MORRISVILLE FAULT AND WEST SIDE OF BASIN. (35.6953°N, -79.0175°W), INTERSECTION PEA RIDGE ROAD AND BEAVER CREEK ROAD, JORDAN LAKE STATE RECREATION AREA, CHATHAM COUNTY, NC. STOP LEADER: PHIL BRADLEY

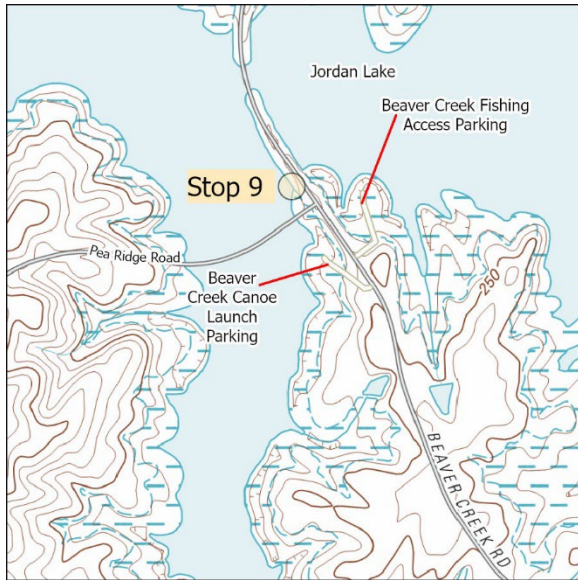
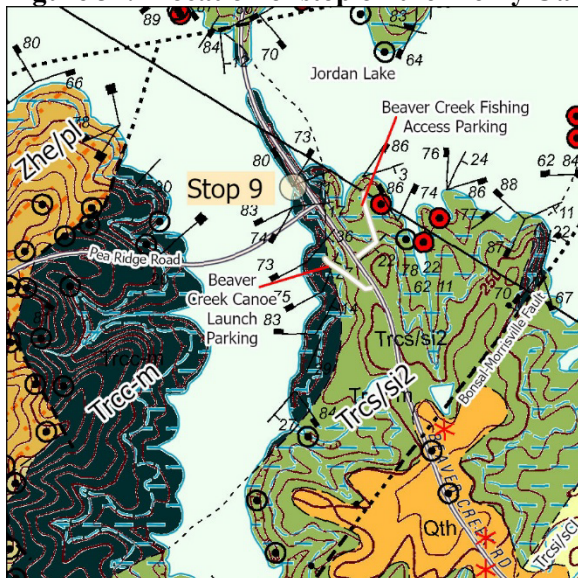


Figure 31: Location of stop on the Merry Oaks 7.5' quadrangle



DESCRIPTION OF MAP UNITS

Qth – Quaternary high terrace deposits

Jd ● – Diabase station

DEEP RIVER TRIASSIC BASIN - DURHAM SUB-BASIN

Trcsi/sCL – Siltstone with interbedded sandstone of the Chatham Group Lithofacies Association II with chert and limestone

Trcs/si2 – Sandstone with interbedded siltstone of the Chatham Group Lithofacies Association II

Trcc-m – Conglomerate of the Chatham Group in the Merry Oaks Quadrangle

CAROLINA TERRANE: HYCO ARC - HYCO FORMATION

Zhe/pl – Metamorphosed mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas

0 2,000 Feet

N

Figure 32: Location of stop on the Geologic Map of the Merry Oaks Quadrangle (Bradley et al., 2021a and compiled Chatham County Geology)

The shoulder on the side of the road near the stop is very narrow and dangerous. Safe parking is available at the nearby NC Wildlife Resources Commission Beaver Creek Fishing Access area or

the Beaver Creek Canoe Launch area (Figure 31). The outcrop is a short walk from both parking locations.

Purpose: To examine outcrops of Triassic conglomerates and to discuss the complicated structure of the Colon Cross-Structure.

Rock Types:

The stop is located in a structurally complex area with Carolina terrane rocks nearby in fault contact with Triassic sedimentary rocks via a series of small relay ramps. Rock types present at the stop include Triassic sandstone and conglomeratic sandstones and conglomerates in the *Conglomerate of the Chatham Group in the Merry Oaks Quadrangle (Trcc-M)* unit of Bradley et al. (2021a). Generally, the unit is reddish-brown to dark brown, irregularly bedded, poorly sorted, cobble to boulder conglomerate. Clasts are chiefly miscellaneous felsic and intermediate metavolcanic rocks and quartz. The unit is typically present adjacent to border faults on the west side of the Durham sub-basin. The rocks are identical to the Pekin Formation conglomerates in the Sanford sub-basin.

Discussion

This area is ripe for future work to better understand the structure of the Colon Cross-Structure and the Bonsal-Morrisville Fault as well as to reconcile the stratigraphic nomenclature between the Durham and Sanford sub-basins of the Deep River basin.

New mapping infers the Bonsal-Morrisville Fault is likely offset by a NE-SW fault (Figure 33). Bain and Brown (1981) reported on a seismic survey along this road prior to filling of the lake and located the fault by seismic reflection in the subsurface. This recent mapping interprets the surface trace to be farther to the east compared to Bain and Brown (1981).

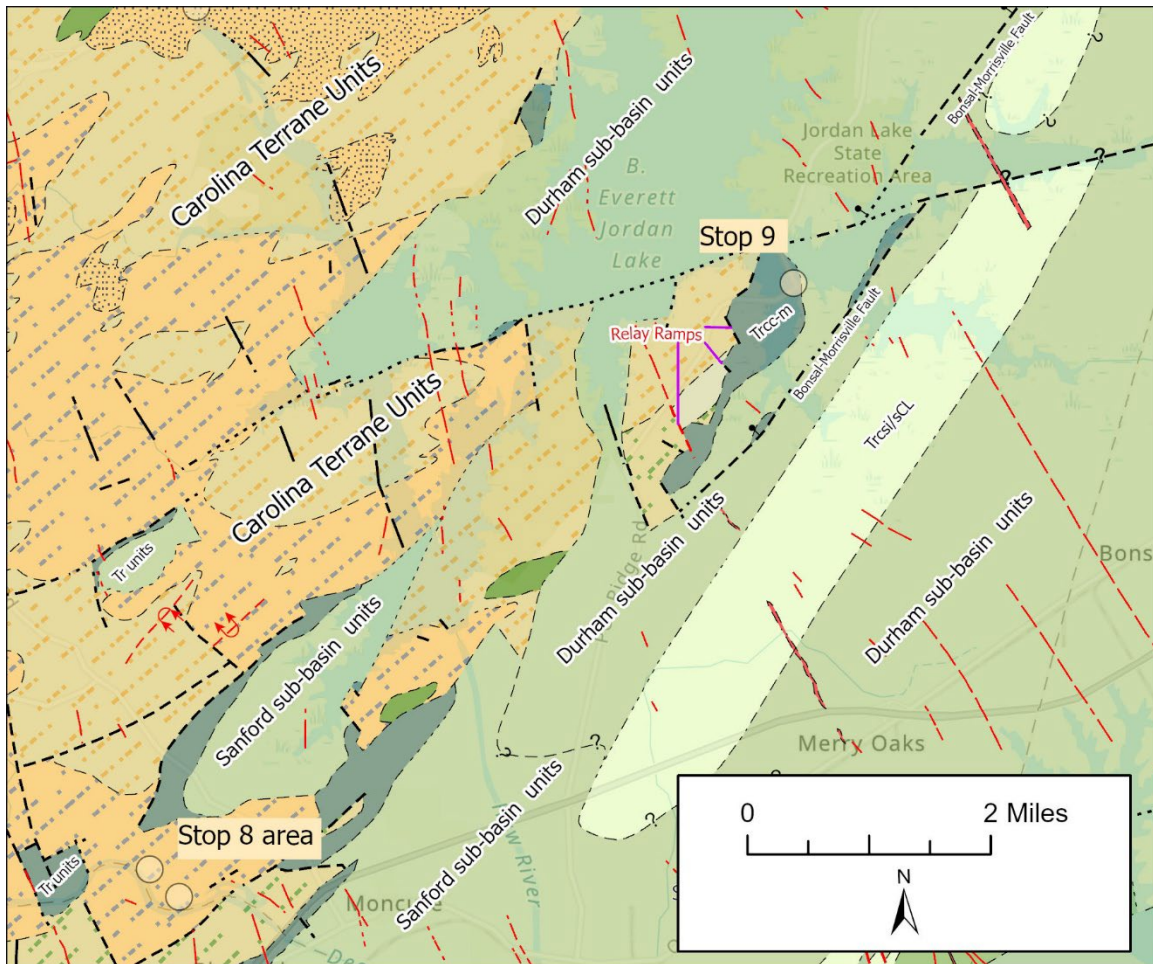


Figure 33: Geologic map with locations of stop 8 and 9

Trcc-m conglomerate clasts appear to be sourced from nearby Carolina terrane rocks to the west. The conglomeratic unit appears to be truncated by the Bonsal-Morrisville Fault implying that movement on the fault is post deposition of the conglomerates – in contrast to Triassic-aged conglomerates on the east side of the basin adjacent to the Jonesboro Fault. Hanging-wall rocks east of the Bonsal-Morrisville Fault are fine grained and are unlikely sources for the conglomerates but could be the source of the finer grained Trcs/si2 unit that appears to overlie the conglomerates.

STOP 10: GEOLOGIC HIKE OF THE WHITE PINES NATURE PRESERVE – NEWLY DISCOVERED OUTLIER OF TRIASSIC SEDIMENTARY ROCKS WITHIN THE CAROLINA TERRANE. (35.6144°N, --79.1604°W), WHITE PINES NATURE PRESERVE, TRIANGLE LAND CONSERVANCY LAND, ROCKY AND DEEP RIVERS CONFLUENCE, CHATHAM COUNTY, NC.

STOP LEADER: PHIL BRADLEY (with contributions from David A. Grimley, Illinois State Geological Survey)

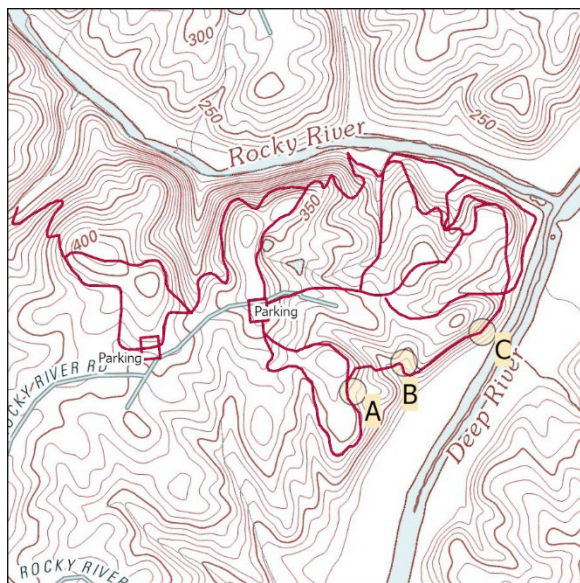


Figure 34: Locations of stop on the Colon 7.5' quadrangle with White Pines Nature Preserve trail system and points of geologic interest.

Background:

The White Pines Nature Preserve is located at the confluence of the Rocky and Deep Rivers in Chatham County. It is a 275-acre nature preserve owned by the Triangle Land Conservancy. The preserve has a rare stand of White Pine trees that are more common at higher elevations and/or latitudes. The White Pine and Mountain Laurel were common in the Pleistocene in the Piedmont, and remain due to the microclimates of the shady north-facing slopes and cooling effect of the confluence of the Rocky and Deep Rivers. North Carolina Geological Survey detailed geologic mapping in 2019 identified a previously unknown small portion of Triassic sedimentary rocks surrounded by Carolina terrane rock units (Bradley et al., 2020) in the preserve.

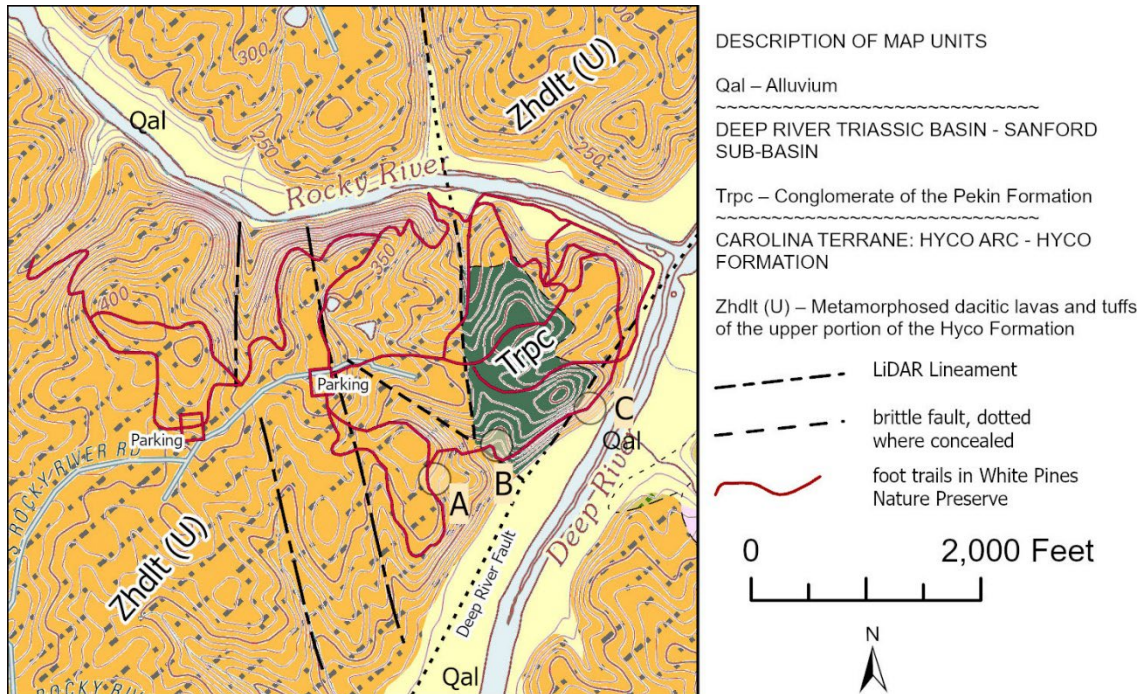


Figure 35: Locations of stop on the Geologic Map of the Colon 7.5' quadrangle with White Pines Nature Preserve trail system and geologic points of interest: A, B and C.

Geologic Hike Description:

This stop is an approximate two-mile (3.2 km) round trip hike along trails in the White Pines Nature Preserve. The hike will present results of detailed geologic mapping by the NC Geological Survey in Chatham County and interpretations of various outcrops and landforms within the Preserve.

The sparse rock debris present in the first part of this hike (from the parking areas to Geologic Point of Interest A – Figures 34 and 35) is an example of typical upland rock debris that is encountered in the Piedmont. Detailed geologic mapping within the Piedmont relies heavily on sparse outcrop and rock debris (assuming the debris is interpreted as being representative of the underlying rock) to help determine the type and extent of geologic units in an area. As you walk from the parking area, take notice of sparse cobbles and boulders and tree throws from downed trees (which often contain rock debris). These cobbles, boulders and other rock debris encountered along areas like these provide useful data in the outcrop-poor Piedmont.

Two main rock types are present in the preserve: 1) metamorphosed volcanic rocks of dacitic lavas and tuffs of the Hyco Formation of the Carolina terrane and 2) Triassic sedimentary rocks of the Sanford sub-basin of the Deep River Triassic basin.

The outcrops of the metamorphosed volcanic rocks are not very impressive, but the float has interesting textures of flow banding and auto brecciation in the dacitic lavas and lithic clasts, plagioclase crystal shards and welding and compaction features in the welded tuffs. The outcrops of Triassic sediments are substantial. The steep slopes from relatively recent stream incision are also noteworthy.

Geologic Points of Interest on the Hike:

Point A

Point A is a small boulder pile and outcrop of white weathered rocks. If on a self-guided walk, the location can be easily overlooked (especially when the trees and shrubs have leaves). The boulder pile is most easily found in the winter when vegetation is at its minimum.

Point A: Boulder pile and small outcrop of metamorphosed dacitic tuffs of the Hyco Formation of the Carolina terrane. The boulders display a pronounced light-colored weathered rind typical of felsic volcanic rocks. Lithic clasts and crystals are visible on weathered surfaces. The main rock type is interpreted as a metamorphosed welded lithic crystal tuff. This location is a good example of the primary volcanic features (lithic clasts, fiamme and crystal shards) still visible in the Hyco Formation rocks. The white weathering rind is indicative of the felsic volcanics chemically weathering to kaolinitic clays with resulting clay-rich soils.

Continuing on the trail toward Geologic Point of Interest B, take note of the several tree throws that have weathered rock chips of white weathered felsic volcanic rock – likely felsic tuffs. When you reach a small foot bridge, pause and notice the jointed small outcrop in the creek. A few boulders are also present in and around the outcrop. This outcrop is a metamorphosed dacitic lava with flow banding. The small creek occupies a prominent LiDAR lineament on the Hillshade LiDAR image. Many of these lineaments are occupied by diabase dikes or are brittle faults.

Continue over the small foot bridge, soon you will enter another small drainage with a foot bridge. This location and the slope to the east is Geologic Point of Interest B.

Point B

Walking toward Point B, a brittle fault is crossed separating the ca. 615 Ma Hyco Formation rocks from the ca. 220 Ma Triassic sedimentary rocks. As you walk east along the trail, look closely at the cobble and boulder debris and small outcrops. Multiple examples of quartz pebble-rich Triassic conglomerate and conglomeratic sandstone are present. Continuing along the trail to the east, several large outcrops of the Triassic sedimentary rocks with sub-horizontal bedding are visible. The Triassic rocks are interpreted to be part of the Pekin Formation of the Sanford sub-basin of the Deep River Basin.

The floodplain of the Deep River occupies the lowland to the immediate east. A major Mesozoic fault (the Deep River fault) is interpreted to occupy the Deep River valley in this location (Figure 35).

Continue along the trail toward Geologic Point of Interest C. Note the steep slopes with an occasional rock ledge of Triassic sedimentary rocks.

Point C

An outcrop of metamorphosed volcanic rock occurs at Geologic Point of Interest C. This rock is interpreted as a metamorphosed tuff and shows intense fracturing. Triassic rocks are above your head in the hanging wall of the fault with the metamorphosed volcanic rocks in the footwall. Continuing along the trail, an additional outcrop and rock debris of the metamorphosed volcanic rocks are present.

Discussion of the steeply incised Rocky and Deep River valleys

The steeply incised banks of the Rocky and Deep River within the preserve are impressive for the Piedmont but not uncommon. The cliffs at Raven Rock State Park are a well-known example of deeply incised riverbank in the Piedmont. Generally, this incision was thought to have occurred gradually over many million years as the Piedmont slowly uplifted differentially at different times over the multiple millions of years. It is generally understood that the majority of the more recent uplift and subsequent erosion occurred during the later stages of the Miocene epoch approximately 10 to 5 million years ago (Pavich, 1989; and Pazzaglia and Brandon, 1996; Poag and Sevon, 1989). So, very generally, the consensus was that the landscape we see today had been forming over the last five million years. In that 5-million-year span, erosion has worn away the land, resulting in hills and topographic highs where more resistant rocks occur.

Recent research along the Potomac River at the Maryland-Virginia border (Reusser et al., 2004), the Mississippi River valley (Wickert et al., 2019) and the mid-Atlantic region (Pico et al., 2019) has indicated that some incision may be relatively recent in timing (less than 100,000 years old). The incision of the Potomac River to form 30- to 60-feet (10- to 20-meter) gorges is thought to have occurred ~35,000 years ago based on cosmogenic dating of fluvially eroded bedrock surfaces on a terrace level that has since been abandoned (Reusser et al., 2004). Along the Mississippi River valley, Wickert et al. (2019) documented 2.5- to 0.8-million-year-old incision of the Mississippi River valley to at least 200 feet (65 meters) at latitude N37° (the latitude of White Pines is approximately N35.6°). The Mississippi River Valley incision is correlated with the deep subsidence under the Laurentide Ice Sheet coupled with induced positive vertical displacement in the immediate periphery of the ice sheet – named the glacial forebulge. According to Pico et al. (2019), the glacial forebulge (or peripheral bulge) on the east coast extended from Pennsylvania and New Jersey (near the ice margin) to the Carolinas, generally decreasing in effect to the south but still significant. Pico et al. (2019) show that, during the last glaciation, the peripheral bulge of the Laurentide Ice Sheet affected the gradient, drainage basins, and pathways of several rivers in the mid-Atlantic. Taken together, these three studies show that differential glacial isostatic adjustments (including the peripheral forebulge), through their effect on river gradients and stream power, can have significant effects on river incision or aggradation over millennial timescales.

The extent of the induced uplift from the Laurentide Ice Sheet in the southeastern US is poorly understood but may have contributed to periods of incision along particular segments of North Carolina Piedmont rivers, such as the Deep River and Rocky River at White Pines Nature Preserve. David Grimley (Illinois State Geological Survey), in collaboration with the NC Geological Survey, mapped terrace deposits originally identified by Reinemund (1955) along the Deep, Haw and Cape Fear Rivers in the Colon, Merry Oaks and Moncure Quadrangles (Bradley et al., 2020, Bradley et al., 2021a and Bradley et al., 2021b). The terrace deposits mark deposition on the ancestral floodplains of the rivers, prior to the incision which formed the terrace landforms. Additionally, preliminary results from a numerical model of the Laurentide Ice Sheet isostatic effects indicates that, theoretically, there could have been up to 8 mm/yr (or 8 m per thousand years) of uplift in the White Pines area during the last glaciation ca. 26,000 years ago (Tamara Pico, personal communication to David Grimley, 2022). Grimley plans to age date material from the higher-level terraces to help determine timing of aggradation and incision and test the forebulge hypothesis (Grimley, personal communication, 2022). Other possible factors that may control river erosion and aggradation include climate (especially precipitation) and vegetation cover in the drainage basin (Leigh, 2008).

References:

Bain, G.L. and Brown, C.E., 1981, Evaluation of the Durham Triassic basin of North Carolina and techniques used to characterize its waste-storage potential: U.S. Geological Survey Open-File Report 80-1295, 133 p.

Barefoot, J., 2015, Chronological and Mineralogical Comparison of Gold Prospect Host Rock with Known Gold Horizon Host Rock - Orange and Chatham Counties, North Carolina, unpublished senior thesis, University of North Carolina at Chapel Hill, 18 pages.

Bowman, J.D., 2010, The Aaron Formation: Evidence for a New Lithotectonic Unit in Carolina, North Central North Carolina, unpublished M.S. thesis, North Carolina State University, Raleigh, North Carolina, 116 p.

Bowman, J.D., Hibbard, J.P. and Miller, B.V. 2013, The Virgilina Sequence Redefined, North Central North Carolina, *in* Hibbard, J.P., and Pollock, J.C., eds., One arc, two arcs, old arc, new arc: the Carolina terrane in central North Carolina, Carolina Geological Society field trip guidebook, p. 127-138.

Bradley, P.J., Gay, N.K., Bechtel, R. and Clark, T.W., 2007, Geologic map of the Farrington 7.5-minute quadrangle, Chatham, Orange and Durham Counties, North Carolina: North Carolina Geological Survey Open-file Report 2007-03, scale 1:24,000, in color.

Bradley, P.J., and Miller, B.V., 2011, New geologic mapping and age constraints in the Hyco Arc of the Carolina terrane in Orange County, North Carolina: Geological Society of America Abstracts with Programs, Vol. 43, No. 2.

Bradley, P.J., 2013, The Carolina terrane on the west flank of the Deep River Triassic basin in the northeastern Piedmont of North Carolina – A status report, *in* Hibbard, J.P., and Pollock, J.C., eds., One arc, two arcs, old arc, new arc: the Carolina terrane in central North Carolina, Carolina Geological Society field trip guidebook, p. 139-151.

Bradley, P.J., Hanna, H.D., and Bechtel, R., 2014, Geologic map of the Pittsboro 7.5-minute quadrangle, Chatham County, NCGS Open-file Report 2014-01, scale 1:24,000

Bradley, P.J., Hanna, H.D., Barefoot, J., Rhodes, D.R. and Blake, D.E., 2016, Geologic mapping in the Carolina terrane in Orange, Durham, and Chatham Counties, North Carolina – A progress report with implications of new age dates: Geological Society of America Abstracts with Programs, Vol. 48, No. 3. <https://gsa.confex.com/gsa/2016SE/webprogram/Paper273609.html>

Bradley, P., 2017, Field trip guide: geological hike along the Haw River, Chatham County, NC, Spring field trip of the Carolina Chapter of the Association of Environmental and Engineering Geologists, April 22, 2017. <https://www.deq.nc.gov/energy-mineral-and-land-resources/geological-survey/stateparks-geo/haw-river-hwy-64-geology-guide-final-4-17-2017/download>

Bradley, P.J., Peach, B.T. and Hanna, H.D., 2017, Geologic map of the Siler City 7.5-Minute Quadrangle, Chatham County, North Carolina: North Carolina Geological Survey Open-file Report 2017-07, scale 1:24,000, in color (Supersedes Open-file Report 2016-08)

Bradley, P.J., Peach, B.T. and Hanna, H.D., 2018, Geologic map of the Chatham County portion of the Coleridge 7.5-minute Quadrangle. NCGS Open-file Report 2018-03, scale 1:24,000, in color.

Bradley, P.J., Rice, A.K. and Peach, B.T., 2019, Geologic map of the Bear Creek 7.5-Minute Quadrangle, Chatham and Moore counties, North Carolina: North Carolina Geological Survey Open-file Report 2019-06, scale 1:24,000, in color. (Supersedes Open-file Report 2018-08)

Bradley, P.J., Rice, A.K., Grimley, D.A. and Blocher, W.B., 2020, Geologic map of the Colon 7.5-Minute Quadrangle, Chatham and Lee counties, North Carolina: North Carolina Geological Survey Open-file Report 2020-04, scale 1:24,000, in color.

Bradley, P.J., Rice, A.K., Grimley, D.A., Hanna, H.D. and Malaska, M.J., 2021a, Geologic map of the of the Merry Oaks 7.5-minute Quadrangle, Chatham and Lee Counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-02, scale 1:24,000, in color (Supersedes Open-file Report 2012-02).

Bradley, P.J., Rice, A.K., and Grimley, D.A., 2021b, Geologic map of the Moncure 7.5-Minute Quadrangle, Lee and Chatham counties, North Carolina: North Carolina Geological Survey Open-file Report 2021-01 scale 1:24,000, in color.

Bradley, P.J. (with contributions in alphabetical order from : Bechtel, R.; Blocher, W .B.; Butler, R.J.; Clark, T.W .; Gay, N.K.; Grimley, D.A.; Hanna, H.D.; Malaska, M .J.; Peach, B.T.; Rice , A.K.; Stoddard , E.F.; and Watson, M.E.), 2022, Compiled Geologic map of Chatham County and surrounding areas, North Carolina: North Carolina Geological Survey Open-file Report 2022-03, scale 1:50,000, in color. <https://deq.nc.gov/energy-mineral-and-land-resources/geological-survey/ofrs-geological-survey/geologic-map-chatham-county-and-surrounding-areas-north-carolina>

Campbell, M.R., and Kimball, K.W., 1923, The Deep River coal field of North Carolina: North Carolina Geological and Economic Survey Bulletin 33, 95 p.

Goliber, S.F.B., 2020, Assessment of the Timing of the Virgilina Deformation with U-Pb Ages of Plutonic and Volcanic Rocks in the Carolina Terrane (unpublished undergraduate thesis), University of North Carolina Chapel Hill, p. 14.

Glover, L., and Sinha, A., 1973, The Virgilina deformation, a late Precambrian to Early Cambrian (?) orogenic event in the central Piedmont of Virginia and North Carolina, American Journal of Science, Cooper v. 273-A, pp. 234-251.

Green, G., Cavaroc, V., Stoddard, E., Abdelzahir, A., 1982, Volcanic and volcanoclastic facies in a part of the slate belt of North Carolina, In: Bearce, D., Black, W., Kish, S., Tull, J. (Eds.), Tectonic studies in the Talladega and Carolina slate belts, Southern Appalachian Orogen. Geological Society of America Special Paper, vol. 191, pp.109– 124.

Hanna, H.D., Bradley, P.J., and Bechtel, R., 2015, Geologic Map of the Siler City NE 7.5 Minute Quadrangle, Chatham County, North Carolina: North Carolina Geological Survey Open-file Report 2015-02, scale 1:24,000, in color

Harris, C.W., 1984, Coarse-grained submarine-fan deposits of magmatic arc affinity in the late Precambrian Aaron Formation, North Carolina, U.S.A., Precambrian Research, 26, pp. 285-306.

Harris, C., and Glover, 1988, The regional extent of the ca. 600 Ma Virgilina deformation: implications of stratigraphic correlation in the Carolina terrane, Geological Society of America Bulletin, v. 100, pp. 200-217.

Hibbard, J.P., Pollock, J.C., and Bradley, P.J., 2013, One arc, two arcs, old arc, new arc: An overview of the Carolina terrane in central North Carolina, Carolina Geological Society field trip guidebook, 265 p.

Leigh, D.S., 2008. Late Quaternary climates and river channels of the Atlantic Coastal Plain, Southeastern USA. *Geomorphology*, 101(1-2), pp.90-108.

Michael, E.K., 2020, Rockfall hazards in an abandoned rock quarry, unpublished report from an independent study, University of North Carolina at Chapel Hill, 87p.

Morrison, D.J., and Coleman, D., 2023, Absolute age determination of the Parks Crossroads granodiorite of the Carolina terrane, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.

Pavich, M., 1989. Regolith residence time and the concept of surface age of the Piedmont “peneplain”. *Geomorphology* 2, p. 181– 196.

Pazzaglia, F.J., and Brandon, M.T., 1996, Macrogeomorphic evolution of the post-Triassic Appalachian mountains determined by deconvolution of the offshore basin sedimentary record: *Basin Research*, v. 8, no. 3, p. 255–278, doi: 10.1046/j.1365-2117.1996.00274.x.

Pelt, K.E. and Bradley, P.J., 2023, Preliminary detrital zircon data from Chatham County, NC, *in* Bradley, P.J., ed., The geology of the Carolina terrane in Chatham County, North Carolina, Carolina Geological Society annual meeting field trip guidebook for 2023.

Pico, T., Mitrovica, J.X., Perron, J.T., Ferrier, K.L. and Braun, J., 2019. Influence of glacial isostatic adjustment on river evolution along the US mid-Atlantic coast. *Earth and Planetary Science Letters*, 522, pp.176-185.

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in post-rift Mesozoic and Cenozoic sedimentary deposits of the U.S. Middle Atlantic continental margin: *Geomorphology*, v. 2, no. 1–3, p. 119–157.

Pollock, J. C., 2007, The Neoproterozoic-Early Paleozoic tectonic evolution of the peri-Gondwanan margin of the Appalachian orogen: an integrated geochronological, geochemical and isotopic study from North Carolina and Newfoundland. Unpublished PhD dissertation, North Carolina State University, 194 p.

Pollock, J.C., Hibbard, J.P., and Sylvester, P.J., 2010, Depositional and tectonic setting of the Neoproterozoic-early Paleozoic rocks of the Virgilina sequence and Albemarle Group, North Carolina: *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 739-772.

Reinemund, J.A., 1955, Geology of the Deep River coal field, North Carolina: U.S. Geol. Survey Prof. Paper 246, 159 p.

Reusser, L.J., Bierman, P.R., Pavich, M.J., Zen, E., Larsen, J., and Finkel, R., 2004, Rapid late Pleistocene incision of Atlantic passive-margin river gorges. *Science*, v. 305, no. 5683, pp. 499-502.

Steponaitis, V.P., Irwin, J.D., McReynolds, T .E., Moore, C., (eds.), 2006, Stone Quarries and Sourcing in the Carolina Slate Belt. Research Report No.25, Research Laboratories of Archaeology, University of North Carolina, Chapel Hill (<http://rla.unc.edu/publications/pdf/resrep25.pdf>): 57.

Tadlock, K.A., and Loewy, S.L., 2006, Isotopic characterization of the Farrington pluton: constraining the Virgilina orogeny, *in* Bradley, P.J., and Clark, T.W., editors, The Geology of the Chapel Hill, Hillsborough and Efland 7.5-minute Quadrangles, Orange and Durham Counties, Carolina Terrane, North Carolina, Carolina Geological Society Field Trip Guidebook for the 2006 annual meeting, pp. 17-21.

Wickert, A.D.; Anderson, R,S; Mitrovica, J.X; Naylor, S; Carson, E.C.; 2019, The Mississippi River records glacial-isostatic deformation of North America, *Science Advances*, 5, eaav2366.

Wortman, G.L., Samson, S.D., and Hibbard, J.P., 2000, Precise U-Pb zircon constraints on the earliest magmatic history of the Carolina terrane: *Journal of Geology*, v. 108, pp. 321-338.

