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JAMES HIBBARD, PHILIP BRADLEY
AND BRENT OWENS

RAMPING THROUGH THE PIEDMONT

GEOLOGY OF THE HYCO SHEAR ZONE AND
ASSOCIATED HANGING WALL ROCKS IN NORTH
CENTRAL NORTH CAROLINA

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CAROLINA

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ON THE COVERS

Front: Former NCSU MS student Issac Standard on the Country Line gneiss at Stop 1.2 of this trip.

Back: Stop map for the 2017 Carolina Geological Society field trip. Base map for stops incorporates regional LiDAR coverage (from NCDOT and NC Flood Plain Mapping) for central North Carolina with a portion of the NCGS open file 1:100,000 scale map of the geology of the Hyco shear zone (Hibbard et al., 2017) and the geologic map of the Rougemont 7.5' Quadrangle (Bradley et al., 2011).

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FOREWORD

The theme of the 2017 Carolina Geological Society Annual Meeting and Field Trip is the Hyco shear zone and associated rocks in the Appalachian Piedmont of north central North Carolina. The shear zone was first recognized by the North Carolina State University tectonics research group more than twenty-five years ago. Significant portions of the shear zone and surrounding geology were mapped and studied by Jim Hibbard and his students Glenn S. Shell, Kevin Wilkins (deceased), Phil Bradley, Bart Cattanaach, Mutlu Ozdogan, and John Vines. During these studies, we collaborated with isotopists Dr. Scott Samson, Dr. Greg Wortman, and David Coler of Syracuse University. Since these studies, there have been multiple other geological investigations in the area. Bradley et al. (2011) mapped nearby volcanic arc rocks of the Carolina terrane in the Rougemont 7.5' quadrangle for the North Carolina Geological Survey. More recently, rocks of the Virgilina sequence were investigated by MS student Jeff Bowman and Jim Hibbard of North Carolina State University (Bowman, et al. 2013); Bowman undertook geochronologic analysis at the laboratory of Dr. Brent Miller of Texas A&M University. Dr. Brent Owens and his BS student Shelbi Wilson (2009), of the College of William and Mary, undertook a geochemical study of the unusual Carolina terrane rocks at Hager's Mountain, just north of Roxboro, NC. The intent of this trip and guidebook is to attempt to summarize the essence and implications of these studies.

It is timely for the Carolina Geological Society to visit the Roxboro, NC region, as the society has conducted only one previous trip to the area - more than thirty years ago (Harris and Glover, 1985). In addition, upon Jim Hibbard's retirement

from NCSU in 2015, Phil Bradley and the NCGS offered to digitize and store Hibbard's and his students' field data. This trip is timed to overlap with the 2017 release of some of their data, including an open file geological compilation of the area (Hibbard et al. 2017).

ACKNOWLEDGMENTS

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JH thanks Skip Stoddard (NCSU, emeritus) and Al Carpenter (NCGS, retired) for an introduction to the Hyco Lake area in the fall of 1988, and we all appreciate field consultation with Bob Butler, Allen Dennis, Bill Henika, J. Wright Horton, John Marr, and Don Secor. We also thank our collaborators Scott Samson, Greg Wortman, Dave Coler, and Brent Miller for their laboratory expertise and good company on sampling trips. We are grateful to Mike Medina for providing his cartographic skills. We give special recognition to the geological mapping and studies of F.B. Laney, whose perceptive field observations were largely neglected for some 80+ years.

References cited in this foreword are given in the reference section of the overview paper in this guidebook.

RAMPING THROUGH THE PIEDMONT

AN OVERVIEW OF THE GEOLOGY OF THE HYCO SHEAR ZONE, NORTH-CENTRAL NORTH CAROLINA

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INTRODUCTION

The Carolina Geological Society last visited the Roxboro, North Carolina, region more than 30 years ago (Harris and Glover, 1985). That trip focused on the nature of low grade magmatic and sedimentary rocks now assigned to the Carolina terrane. The main topic addressed during the 1985 trip was a Neoproterozoic tectonic event, the Virgilina deformation; the nature of that event still remains speculative (summarized in Hibbard et al., 2013). However, particularly relevant to our present trip, participants of the 1985 trip were undoubtedly made aware that studies of the 1960's-1970's interpreted the contact of these low grade rocks with underlying, higher grade metamorphic rocks immediately to the northwest of Roxboro (now assigned to the Milton terrane) to be gradational and conformable. The higher grade rocks were viewed as an infrastructural basement to the suprastructural low grade rocks and all were considered to represent a structurally intact section through the Neoproterozoic middle and upper crust (e.g. Tobisch and Glover, 1971; Glover et al., 1983; more recently Baird, 1989, 1991).

During the 1990's, our tectonics group at North Carolina State University recognized that the boundary between the lower grade

magmatic rocks in the Roxboro area and higher grade schists and gneisses to the northwest was tectonic, confirming the original interpretation by Laney (1917). However, Laney (1917) viewed the contact as a discrete fault, whereas our group recognized the contact to be a wide ductile thrust zone that we named the Hyco shear zone (Hibbard et al., 1998; Wortman et al., 1998), after Hyco Lake and the Hyco River¹, both of which are underlain, in part, by the shear zone. In addition, we demonstrated that rocks on either side of the shear zone are significantly different with respect to age, isotopic signature, and structure (Samson et al., 1995; Wortman et al., 1996, 1998; Hibbard et al., 1998). These studies revealed that this contact, rather than representing a subtle crustal transition within a coherent section of Neoproterozoic crust, is one of the most significant structures in the southern Appalachian Piedmont.

In the Roxboro area, the trend of the shear zone bends dramatically from WSW in North Carolina to NNE in Virginia. This sharp bend is interpreted as representing the junction between a WSW-trending lateral ramp and a

¹Laney (1917) reported that the term 'Hyco' derives from the purported native American word for a turkey buzzard, 'hicootomy'.

SIDEBAR 1

What are ribbon continents?

Ribbon continents are microcontinents that in map view are elongate and relatively narrow in width. They can have complex histories and form in multiple different ways – i) as migrating arcs above retreating subduction zones, ii) from repeated rifting of Atlantic-type margins, or iii) by transtensional faulting along a continental margin. One of the best modern examples of a nascent ribbon continent is the Baja Peninsula, where transtensional faulting is rending apart the peninsula from southwestern North America.

Sengor, C.A., 2004, Ribbon continents: a marginal affair of central importance. Geological Society of America Abstracts with Programs, v. 36, no. 5, p. 534.

NNE-trending frontal ramp within an overall thrust regime (Hibbard et al., 1998). Thus, our 2017 field trip will focus on the nature of a first-order thrust in the Appalachian hinterland, where it ramps through the North Carolina Piedmont.

In this paper, we provide an overview of the Hyco shear zone and associated rocks that is distilled from cited theses, reports, and published papers; it is intended to serve as background information for the 2017 field trip. We start with the regional lithotectonic setting of the field area, continue with summaries of lithotectonic elements and structures associated with the shear zone, and conclude by attempting to place the shear zone in the context of the late Paleozoic Alleghanian orogeny.

REGIONAL LITHOTECTONIC SETTING

The Hyco shear zone is a segment of the central Piedmont shear zone, the fundamental polygenetic tectonic contact between two orogen-scale realms in the southern Appalachians – the Peri-Gondwanan realm and the Axial, or Iapetan, realm (Fig. 1)(Hibbard et al., 2007). The central Piedmont shear zone places hanging wall peri-Gondwanan realm rocks over footwall Iapetan realm rocks. The Hyco shear zone portion has been traced from the area just southwest of Yanceyville, North

Carolina, to just north of South Boston, Virginia (Fig. 2).

The hanging wall peri-Gondwanan realm is a collection of Neoproterozoic to early Paleozoic magmatic arcs and ribbon continents (Sidebar 1) now assigned to Carolina. They formed along the periphery of Gondwana, subsequently drifted from it, and now define the onshore eastern flank of the Appalachians (for paleogeographic background, see Sidebar 2). Carolinian rocks on the southeast side of the Hyco shear zone are assigned to the mainly magmatic, generally low metamorphic grade, Carolina terrane.

The Iapetan realm is composed of oceanic rocks and continental scraps that resided in the Paleozoic Iapetus Ocean, between Laurentian and peri-Gondwanan elements. In our field trip area, the Iapetan realm is represented by the Milton magmatic arc, to the northwest of the Hyco shear zone. A second major Paleozoic oceanic tract, the Rheic Ocean, lay between the peri-Gondwanan terranes and Gondwana (Sidebar 2).

In the southern Appalachians the peri-Gondwanan realm element of Carolina was initially sutured to Laurentia during the Late Ordovician-Silurian closure of Iapetus marked by the Cherokee orogeny (Hibbard et al., 2012; Hughes et al., 2013, 2014a, 2014b, 2014c). Following the Cherokee event, the

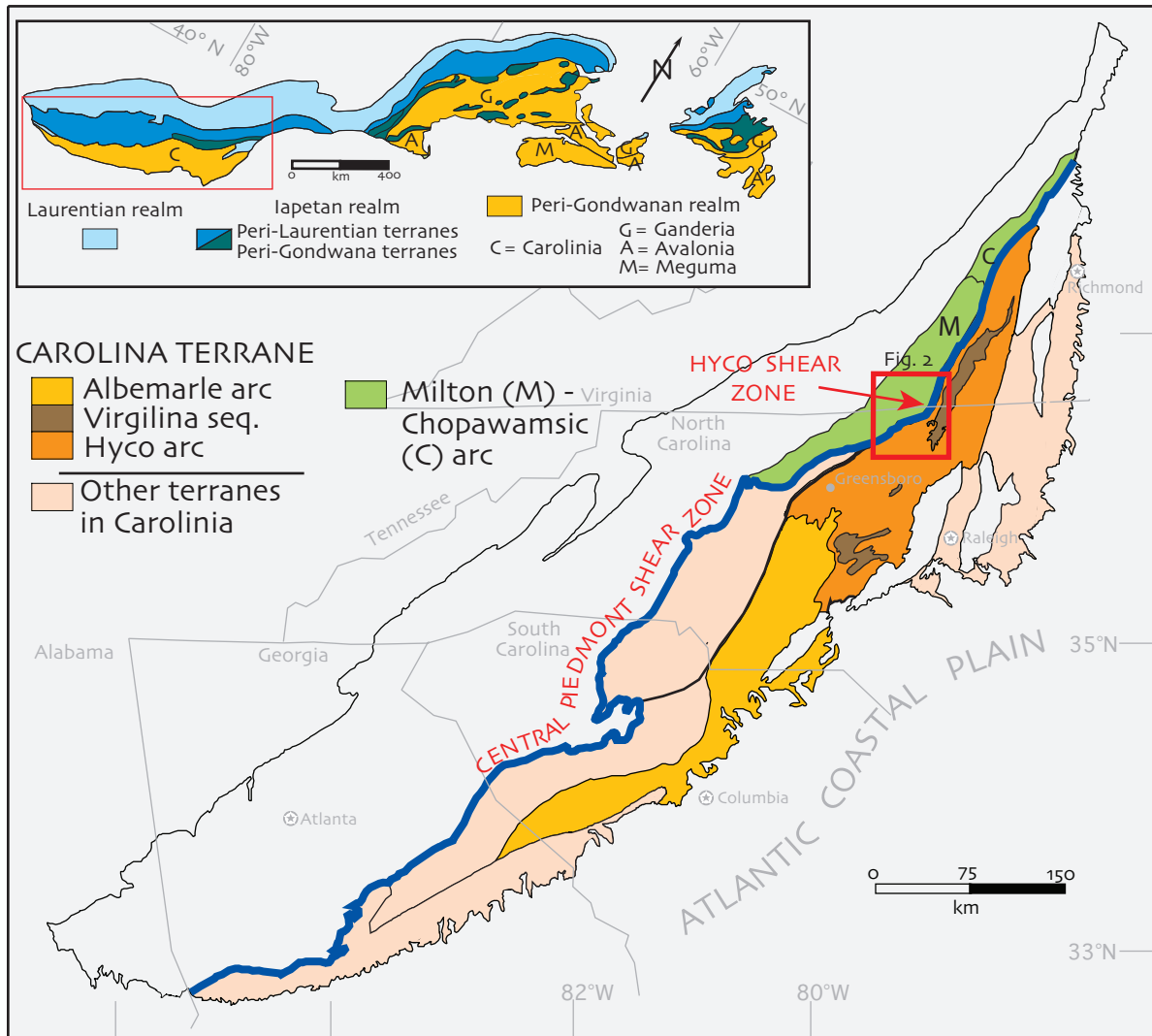


Figure 1. Distribution of the major lithotectonic elements of the southern Appalachian peri Gondwanan and Iapetan realms relevant to the 2017 field trip; red box indicates approximate area of the field trip. Inset: orogen-scale elements of the Appalachian orogen. From Hibbard et al., 2002, 2006, 2007).

Rheic Ocean persisted between the modified Laurentian margin and Gondwana. Subsequently, during the late Paleozoic, Alleghanian, closure of the Rheic Ocean, Gondwanan elements (Africa) collided with Laurentia and shortened Carolina over the Milton arc; the central Piedmont shear zone appears to represent the main Alleghanian thrust system in the Piedmont of North Carolina and Virginia (e.g. Hibbard et al., 1998). The late Paleozoic Alleghanian event was also marked by extensive syntectonic granitoid plutonism that in our field trip area appears to have been

ponded within and structurally below the Hyco shear zone.

GEOLOGY OF THE HYCO SHEAR ZONE

The Hyco shear zone is a ductile thrust that emplaces hanging wall rocks of the Carolina terrane onto footwall rocks of the Milton magmatic arc (Fig. 2). It affects an approximately 8 km thickness of Carolina terrane rocks. Footwall Milton rocks are strongly sheared as far west as we have mapped

SIDEBAR 2

Paleogeographic Considerations

CONTINENTAL MASSES: The Appalachian orogen contains lithotectonic elements that were associated with the Paleozoic continental masses of **Laurentia** and **Gondwana**. Laurentia and Gondwana were two of multiple continents formed by the Neoproterozoic breakup of the supercontinent of Rodinia.

Laurentia refers essentially to Paleozoic North America, which included Greenland, as well as portions of Ireland, Scotland, and Spitsbergen that rifted away from North America in the Mesozoic. The term 'Laurentian' was first used in reference to the metamorphic rocks underlying the Laurentian Mountains, Québec (Logan, 1854). Similar rocks constitute the bulk of the Canadian shield and the term 'Laurentia' evolved into a synonym for the shield (e.g. Willis, 1907). Eduard Suess (1904) appears to have been one of the first to apply it in a paleogeographic context, similar to modern usage.

Gondwana refers to the Paleozoic continental amalgamation of Antarctica, South America, Africa, Australia, India, and the Arabian Peninsula that formed between 600-530 Ma during the breakup of Rodinia. Magmatic arcs and ribbon continents that formed near or along the periphery of Gondwana in the late Neoproterozoic-early Paleozoic are termed '**peri-Gondwanan**'. Some of these peri-Gondwanan elements must have formed in an older ocean than Iapetus because they either pre-date or are coeval with the birth of Iapetus. The continent of Gondwana was named, again, by Suess (1904) for the distinct Gondwanan fossil flora from the Gondwana region of north central India.

OCEANIC TRACTS: Oceanic realms between these continental masses have had a confusing history of terminology mainly because they were distinguished on the basis of opposing side continents without the recognition that more than one continent can define the margin of an ocean basin.

At present, we recognize **Iapetus** to be the early Paleozoic ocean that was generated along the eastern Laurentian margin by the breakup of Rodinia. Within Iapetus, some magmatic arcs and microcontinent fragments were distributed either proximal to Laurentia or near the peri-Gondwanan terranes, as deduced mainly from fossil faunal provinciality, paleomagnetic data, isotopic data, and lithotectonic history. Those near Laurentia are termed '**peri-Laurentian**', whereas those near the peri-Gondwanan side of Iapetus are commonly referred to as '**peri-Gondwanan**' elements (*technically, they are peri-peri-Gondwanan*), although they are clearly younger than the bulk of the Neoproterozoic peri-Gondwanan elements that formed adjacent to Gondwana. The Paleozoic ocean that separated Gondwana from peri-Gondwanan is recognized in modern paleogeography as the **Rheic Ocean**. The names of these Paleozoic oceans were derived from Greek mythology, Iapetus being Atlas's father, whereas Rhea was Atlas's aunt.

Logan, W.E., 1854, Report of Progress, 1853-1854. Geological Survey of Canada, Montreal, Quebec, 103 p. of America. Text to accompany U.S. Geological Survey Map I-2329, 17 p.

Suess, E., 1904, *The Face of the Earth*; translated from *Das Antlitz der Erde*. Oxford, V volumes.

Willis, B., 1907, A theory of continental structure applied to North America. Geological Society of America Bulletin, v. 18, p. 389-412.

(Danville, Virginia area). We have arbitrarily placed the western boundary of the shear zone along the trace of where Milton tectonites lose concordancy with the Milton-Carolina terrane boundary (Fig. 2). Carboniferous plutonic

rocks form independent bodies as well as 'hybrid' complexes hosted by both footwall and hanging wall rock units that are within the shear zone. Following a description of the major rock units associated with the Hyco

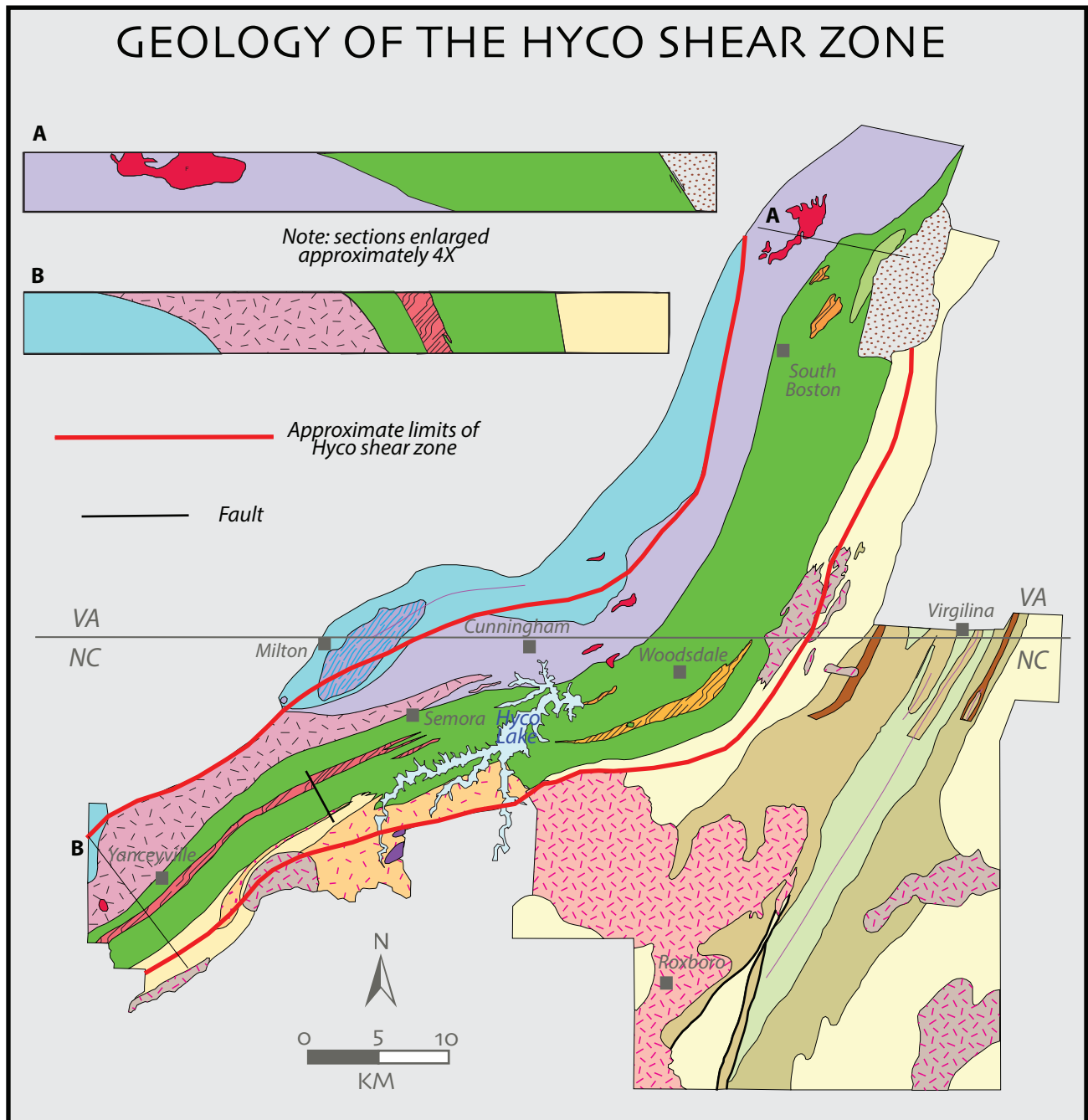


Figure 2. Geological map of the Hyco shear zone and the general Roxboro field trip area.

shear zone, we will describe its structure and timing.

GEOLOGY OF THE HANGING WALL

In the hanging wall of the Hyco shear zone, the structurally higher rocks of the Carolina terrane are distinct from structurally lower

Carolina rocks that lie immediately above the footwall Milton rocks. The structurally higher Carolina terrane rocks display relatively simple structure, are at greenschist facies, and commonly display primary features and stratigraphy; in contrast, the structurally lower rocks have a complex structural history

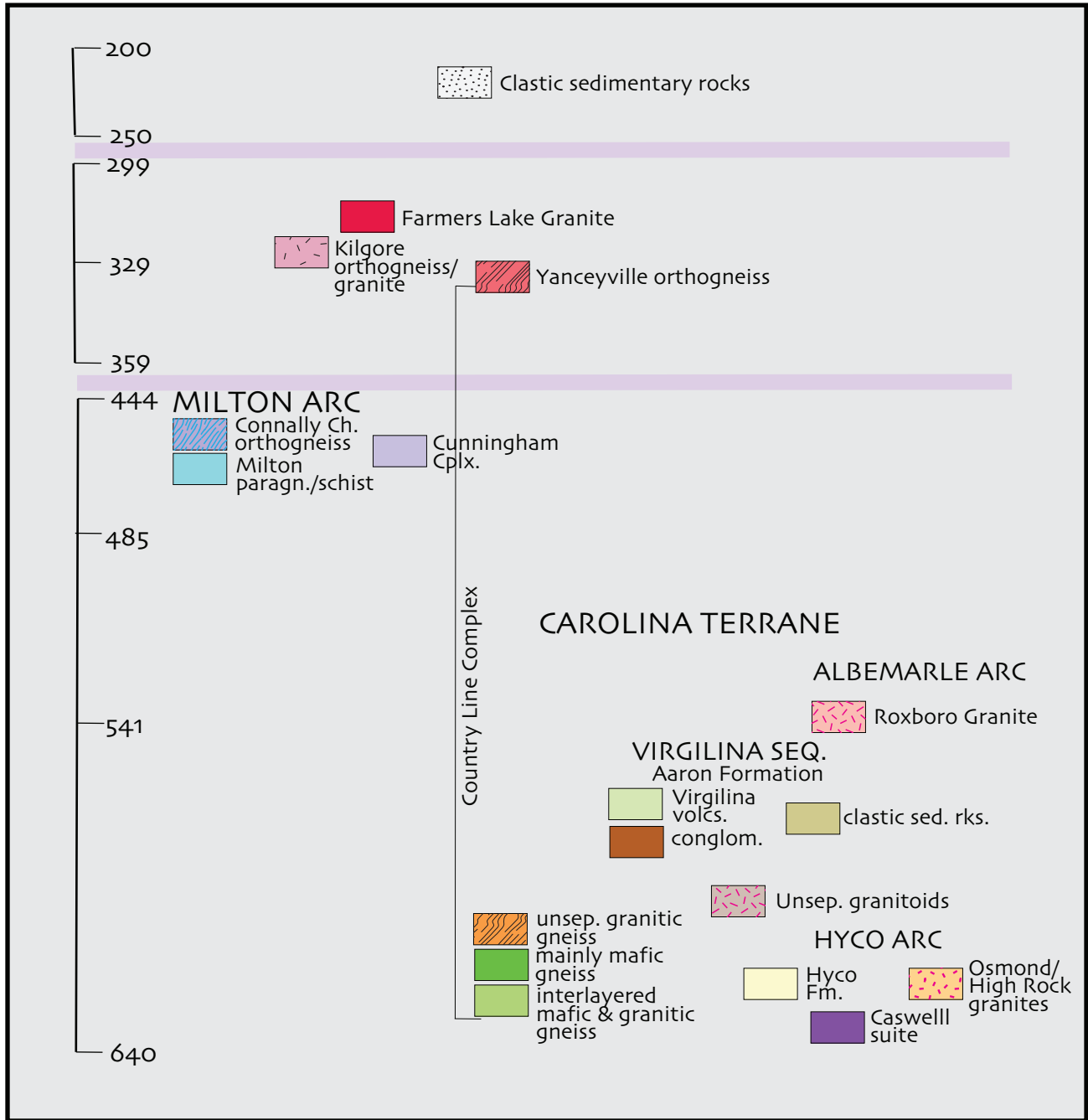


Figure 2 (continued). Explanation of rock units for the geological map. Violet bars represent breaks in time scale.

related to the shear zone, rarely display primary features, lack stratigraphic order, are at mainly amphibolite facies, and are intimately intermixed with Carboniferous plutons.

The structurally higher rocks are divided into three major lithotectonic elements, including

two magmatic arc systems that are separated in time by a 'magmatic influenced' sequence of unknown tectonic setting (Figs. 2, 3). The older magmatic arc, the Hyco arc, is disconformably overlain by the Virgilina sequence of unknown tectonic origin, which is separated from the overlying, younger, Albemarle arc by an unconformity. Struc-

turally lower hanging wall rocks are assigned to the Country Line Complex (Hibbard et al., 1998).

THE HYCO ARC (Figs. 2, 3) is the older magmatic arc preserved in the Carolina terrane. It is composed mainly of the Hyco Formation (Laney, 1917, modified by Kreisa, 1980; Harris and Glover, 1988), which records dominantly felsic to intermediate magmatism during a *ca.* 20 m.y. span starting at *ca.* 633 Ma (Wortman et al., 2000; Bradley and Miller, 2011). The formation has a minimum thickness of 4900 m (Glover and Sinha, 1973). The volcanics of the Hyco arc are dominantly sub-aqueous pyroclastics interpreted to have been deposited in shallow water with local subaerial volcanic centers (Glover and Sinha, 1973; Harris and Glover, 1988; Bradley et al., 2006; Bradley, 2013). Towards the top of the formation, volcanic derived clastic rocks contain a controversial Ediacaran trace fossil that has been attributed to the metazoan *Vermiforma antiqua* (Cloud et al., 1976). The trace fossil locale is Stop 2A.2 of the 2017 trip and the controversy is discussed under the stop description. Although the Hyco Formation has been metamorphosed under greenschist facies conditions, an unusual quartz-kyanite rock has been reported in the unit (Owens and Wilson, 2009); the setting and nature of this occurrence is the subject of our Stop 2B.

Geochemically, magmatic rocks in the formation are tholeiitic to calc-alkalic and interpreted to have formed in a suprasubduction zone magmatic arc (e.g. Black, 1980; Bland and Blackburn, 1980; Rogers, 1982; Feiss, 1983). Characteristically, ϵ_{Nd} isotopic values of Hyco magmatic rocks are highly positive with model ages that are close to the crystallization ages of the rocks (Kozuch, 1994; Samson et al., 1995). Hyco magmatic rocks also lack evidence for inherited zircons (Samson et al., 1995; Ingle et al., 2003). Collectively these observations strongly

suggest that the Hyco arc is composed of largely mantle-derived crust and likely represents a mature arc build upon an oceanic substrate (Samson et al., 1995; Mueller et al., 1996; Fullagar et al., 1997; Ingle et al., 2003).

In the Roxboro area (Figs. 2, 3), the Hyco Formation is the main unit in the hanging wall of the Hyco shear zone. It is associated with two major plutonic bodies in the immediate hanging wall of the shear zone, including the **Osmond Granite** and the **High Rock Church Granite** (Shell, 1996). The Osmond granite has yielded a U-Pb zircon age of 612 \pm 5.2/-1.7 Ma (Wortman et al., 1998). The High Rock Church pluton is undated; however, because it is petrographically identical to the Osmond granite (Vines et al., 1998) the two are considered to be mutually correlative.

THE VIRGILINA SEQUENCE (Figs. 2, 3) stratigraphically intervenes between the older Hyco arc and the younger Albemarle arc in central North Carolina. It is composed of the Aaron Formation, a mildly metamorphosed unit of dominantly volcanic-influenced clastic sedimentary rock that ranges up to 4500 m thick (Harris, 1984); it contains a mappable volcanic member, the Virgilina volcanics, sandwiched within the clastic rocks. The most distinctive and conspicuous rock type in the unit is conglomerate that contains pebbles and cobbles of vein quartz, quartz arenite, and a variety of other clasts mostly derived from the underlying Hyco Formation. Sedimentological studies indicate that the Aaron Formation was deposited in a submarine fan to abyssal plain setting (Harris, 1984).

In the Roxboro area, the Aaron Formation is disconformable above the Hyco Formation (Bowman, 2010; Bowman et al., 2013). Considering that Aaron Formation metasedimentary rocks contain detrital zircons as young as *ca.* 588-578 Ma (Samson et al., 2001; Pollock et al., 2010) and that the youngest dated Hyco magmatism is *ca.* 612 Ma

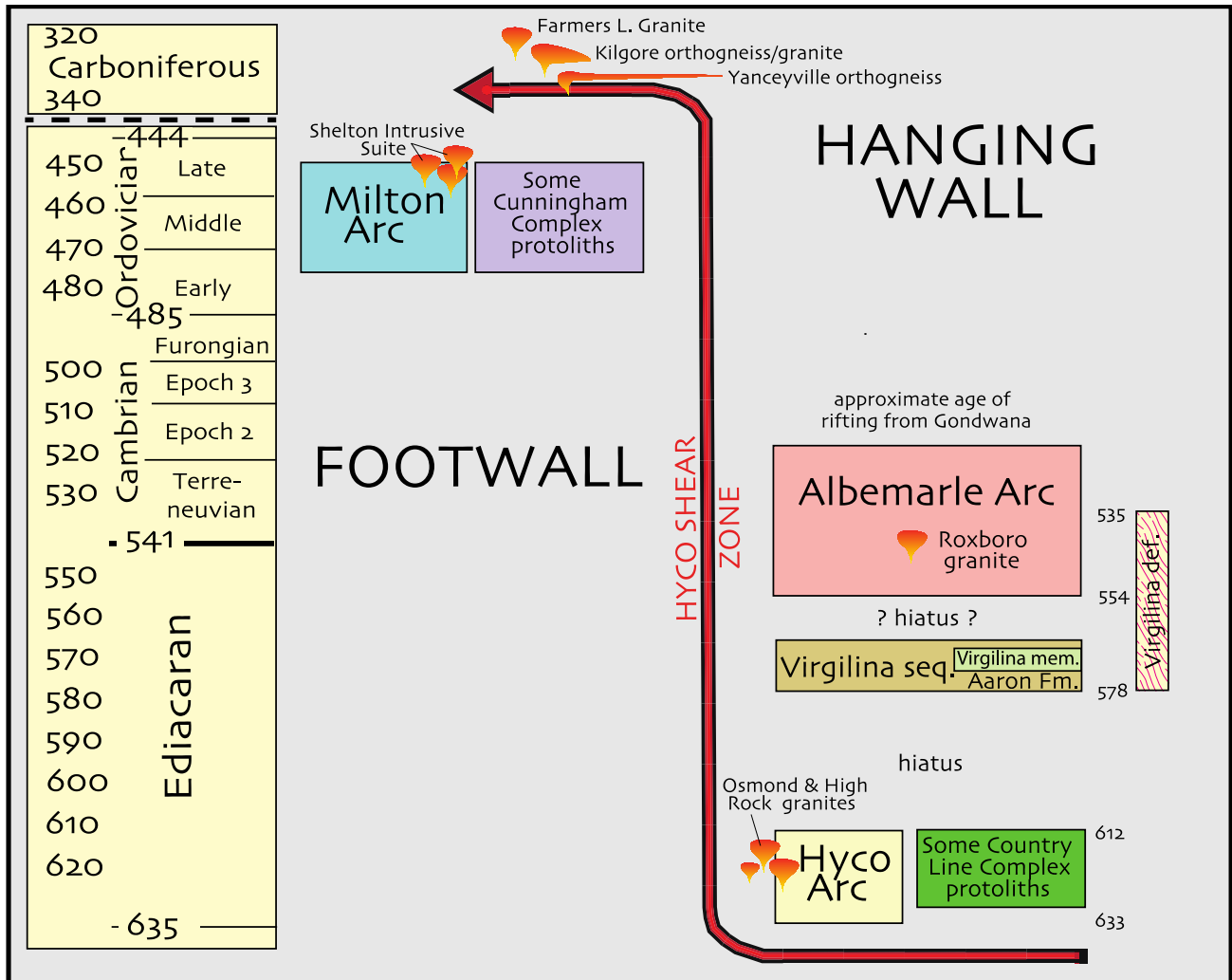


Figure 3. First-order lithotectonic elements and events related to the Hyco shear zone in the Roxboro, NC area.

(Wortman et al., 2000), this disconformity appears to record a time gap of *ca.* 24 m.y. The Virgilina sequence was initially interpreted as an intra-arc basin (Harris and Glover, 1988) within the Hyco magmatic arc. In light of the *ca.* 24 m.y. hiatus between the Hyco arc and Aaron Formation, this interpretation is not viable and the tectonic setting of the Virgilina sequence remains ambiguous.

We will not visit any outcrops of the Virgilina sequence during the scheduled 2017 field trip. However, we provide two supplemental stops, one in conglomerate, the other in the Virgilina volcanics, for those interested in viewing them at some other time.

THE ALBEMARLE ARC (Figs. 2, 3) is the younger magmatic arc preserved in the Carolina terrane. It is characterized by a thick felsic volcanic base, the Uwharrie Formation, conformably overlain by Neoproterozoic to Early Cambrian clastic sedimentary rocks with interspersed lenses, dikes, and stocks of felsic to mafic magmatic rocks of the Albemarle Group. The minimum collective thickness of the Albemarle arc in central North Carolina is approximately 12,700 m (Stromquist and Sundelius, 1969; Butler and Secor, 1991). Geochemically, magmatic rocks of the Albemarle arc have been characterized as tholeiitic to calc-alkaline and are interpreted to represent suprasubduction zone magmatism (e.g. Black, 1980; Bland and Blackburn, 1980;

Rogers, 1982; Feiss, 1983; Ingram, 1999). Nd isotopic studies on rocks of the arc document ϵ_{Nd} isotopic values in the range of -4 to +4 with middle Mesoproterozoic to early Neoproterozoic model ages (Mueller et al., 1996; Fullagar et al., 1997). In addition, inherited zircons in some of the extrusive rocks yield Mesoproterozoic ages (Mueller et al., 1996). Based on these data, it appears that the Albemarle arc has a basement with some form of ca. 1 Ga continental material (Mueller et al., 1996).

The youngest magmatic phase preserved in the Albemarle arc, the Stony Mountain gabbro (Ingram, 1999), is believed to record the opening of the Rheic Ocean between Gondwana and Carolina (Pollock and Hibbard, 2010). A U-Pb zircon TIMS age on the gabbro suggests that rifting started as early as ca. 545 Ma (DeDecker et al., 2013).

In the Roxboro area (Figs. 2, 3), the Albemarle arc is represented by a single, ca. 545 Ma granitoid, the Roxboro pluton. This pluton has played an important role in our recognition of a Neoproterozoic tectonic event in the Carolina terrane, as discussed in a section below and in the stop description for Stop S.3 (this guide) (Glover and Sinha, 1973; Hibbard and Samson, 1995). We will visit the pluton on the trip and as well, we have provided a supplemental stop that highlights its role in the recognition of the Virgilina deformation.

THE COUNTRY LINE COMPLEX is the structurally lowest unit in the Carolina terrane in the Roxboro area and lies completely in the Hyco shear zone. It is composed mainly of amphibolite facies mafic gneisses with interlayered granitoids and subordinate biotite gneiss, and minor metapyroxenite, semipelitic schist, and felsic schist. The unit has been continuously mapped from Yanceyville, North Carolina, to South Boston, Virginia (Fig. 2). It is a structural assemblage that shows neither internal stratigraphy nor primary structures.

The mafic gneisses range from amphibolites to biotite-amphibolite gneisses that are commonly interlayered on a cm to m scale, although in places they are massive, with a gabbro-like texture.

The layered mafic gneisses are typically intruded by, and interlayered with granitoids and associated pegmatites; the pegmatites are usually structurally disaggregated, forming nebulous layers that, in places, have transitional contacts with the mafic gneisses. One mappable granitoid in the complex, the **Yanceyville granite orthogneiss** (Sidebar 3) is a deformed biotite granite that is overprinted by the same structures as the host mafic gneisses, contains xenoliths of the mafic gneisses, and locally crosscuts layering in the mafic gneisses. Other granitic sheets in the complex are lithically similar to Hyco arc and Albemarle arc plutons that lie structurally above the shear zone.

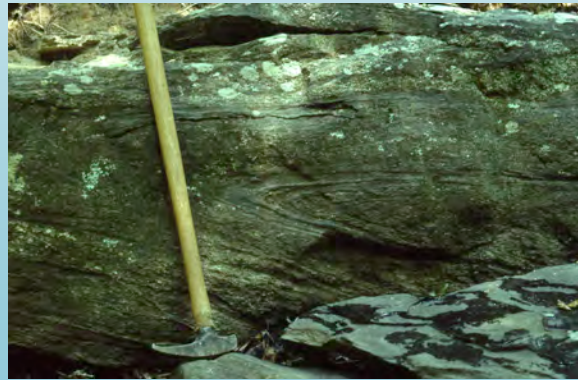
The age of the Country Line Complex is constrained by U-Pb dates on mafic gneisses at South Boston and on the Yanceyville granite orthogneiss. Zircon from a hornblende gneiss has yielded an age of 613.9 ± 9.3 Ma (Wortman et al., 1998). This date leads to potential correlation with other rocks in the hangingwall outside of the shear zone. The mafic gneisses may represent strongly deformed and metamorphosed equivalents of a ca. 615 Ma mafic-ultramafic assemblage, informally termed the Caswell suite (Butler, 1989) in the nearby Hyco arc. The mafic gneisses could also have originated as part of the Hyco Formation, for along the southeast border of the complex, the Hyco Formation contains mafic fragmental volcanic rocks. A third possible interpretation is that the complex contains both Caswell suite equivalents and portions of the lower Hyco Formation. In addition to the Neoproterozoic age for the mafic gneisses, the Yanceyville orthogneiss has a U-Pb zircon crystallization age of 335 ± 2 Ma (Wortman et al., 1998). The pegmatites

SIDEBAR 3

Ortho- and Para- gneiss?

Orthogneiss: A gneiss with mineralogy and texture indicating derivation from a phaneritic igneous rock protolith. Typically orthogneiss bodies have a massive, homogeneous character.

Paragneiss: A gneiss with mineralogy and texture indicating derivation from a sedimentary rock protolith. Composition tends to be more variable at outcrop scale than that of an orthogneiss.



On the left, Yanceyville orthogneiss at Blanch prison quarry (Leasburg 7.5' quadrangle); darker layers likely represent either deformed xenoliths or partially assimilated layers. On the right, isoclinally folded Milton biotite paragneiss on an unnamed creek in southern Virginia (Alton 7.5' quadrangle).

that are commonly interlayered with the mafic gneisses in the complex increase in volume in the vicinity of the Yanceyville orthogneiss, suggesting that they are related to the that body. If so, a significant portion of the complex is Mississippian.

In summary, the Country Line Complex is a structural assemblage of intimately interlayered mafic gneisses, schists, and granitoids; dated mafic components are Neoproterozoic whereas some granitoid parts are late Paleozoic. The complex appears to contain equivalents of the Hyco arc, the Albemarle arc, as well as Carboniferous plutons.

TECTONIC EVENTS IN THE CAROLINA TERRANE: there are four general periods of tectonothermal activity in the Carolina terrane of North Carolina, including i) late Neoproterozoic to earliest Cambrian Virgilina events, ii) Late Ordovician-Silurian Cherokee events, iii) Late Devonian-Early Mississippian events, and iv) Mississippian-Pennsylvanian,

Alleghanian, activity (Hibbard et al., 2013). In addition, the structural geometry of the terrane has been modified by Mesozoic rifting responsible for the Atlantic Ocean. In the Roxboro, NC, area, the most obvious structures are related to the Virgilina and Alleghanian events.

The Neoproterozoic Virgilina event was first proposed by Glover and Sinha (1973). They recognized that faults truncating the Virgilina synclinorium in the Neoproterozoic Virgilina sequence are intruded by the ca. 545 Ma Roxboro granite (Fig. 2). They concluded that folding of the Virgilina sequence was Neoproterozoic. Subsequently, further evidence supporting a Neoproterozoic event was provided by multiple observations that indicated foliations in Hyco arc rocks were generated prior to intrusion of the Roxboro granite (Hibbard and Samson, 1995; Stop S.3, this guide). In addition, a late Neoproterozoic event has been documented in Carolinian rocks in South Carolina (Dennis and Wright, 1997; Barker et

al., 1998). The Virgilina event ranges from ca. 578 – 535 Ma in the Carolinas, but its nature is not clear. It has been noted that the timing of the event temporally overlaps with a Nd isotopic change recorded in Carolina terrane magmatic rocks from older juvenile crust to more evolved material and thus, may be related to an accretionary event involving the interaction of the juvenile Hyco arc with a more isotopically evolved crustal element (Hibbard and Samson, 1995).

The Alleghanian event in the hanging wall Carolina terrane is penetrative only in the Country Line Complex. This event is discussed in a section on the structure of the Hyco shear zone, below. Cogently, no features lying structurally above the Country Line Complex in the Carolina terrane can be unequivocally assigned to the Alleghanian event.

GEOLOGY OF THE FOOTWALL

The footwall of the Hyco shear zone in the Roxboro area is composed of two major lithotectonic units, including the structurally lower Milton arc, and the structurally higher Cunningham Complex. Primary structures in both of these units have been obliterated by multiple phases of ductile deformed and amphibolite facies metamorphism. Consequently, stratigraphy of the terrane in this area is unknown. The footwall rocks are also host to two distinct Carboniferous granitoids.

THE MILTON ARC: is the lowest lithotectonic element in the footwall of the Hyco shear zone (Fig. 2). It is the southern, higher grade, portion of a contiguous belt of metamorphosed and deformed magmatic arc and related sedimentary rocks that extends along strike through Virginia (e.g. Hibbard et al., 2016). The lower grade northerly portion is termed the Chopawamsic arc. The entire magmatic tract ranges in age from Early to Late Ordovician (ca. 474-450 Ma)(Coler et al., 2000; Horton et al., 2010; Hughes et al., 2013;

2014a,b,c). Considering the sparse available geochemical and geochronological data, the magmatic tract could well represent more than a single magmatic arc (Hibbard et al., 2016).

The Milton arc is composed of amphibolite, felsic metavolcanic rock, biotite gneiss, granitoid gneiss, and mica schist with subordinate quartzite, calc-silicate gneiss, and marble (Tobisch and Glover, 1971; Tobisch, 1972; Henika, 1977, 2002; Baird, 1991; Bradley, 1996; Baird and Glover, 1997; Ozdogan, 1997; Nelson and Nelson, 1997; Cattanaach, 1998; Hibbard et al., 2001, Henika et al., 2006). In general, metavolcanic units are most common in the western portion of the arc and decrease towards the east, concomitant with an increase in biotite gneiss and mica schist (e.g. Henika, 2002). Traditionally and up until the mid-1990's, many geologists considered Milton rocks to represent a conformable basement to rocks now designated as part of the Carolina terrane (e.g. Tobisch and Glover, 1971; Tobisch, 1972; Glover, 1989; Baird, 1991; Baird and Glover, 1997; Gates, 1997); however, this interpretation has subsequently been invalidated by structural, isotopic, and geochronologic studies that show the Milton arc to be geochemically distinct from, and younger than, the Carolina terrane (Wortman et al., 1996, 1998; Hibbard et al., 1998; Coler et al., 2000).

On the basis of geochemistry, high resolution zircon crystallization ages, xenocrystic zircon ages, and evolved Nd isotopic signatures the Milton-Chopawamsic arc has been interpreted to represent an Ordovician suprasubduction magmatic arc that developed on Mesoproterozoic continental crust (Pavlidis, 1981; Coler et al., 2000; Hughes et al., 2014a,b,c; Hibbard et al., 2016). In terms of paleogeographic setting, the stratigraphic character, limited Pb isotope data, and detrital zircon populations of Chopawamsic arc rocks are all consistent with an Iapetan realm setting

proximal to its Gondwanan side (Hughes et al., 2014b,c; Hibbard et al., 2007, 2016).

In the area to the northwest of Roxboro, NC, the Milton arc rocks are dominated by a distinctive **biotite schist and paragneiss** and the **Connally Church orthogneiss** (Fig. 2, 3; Sidebar 3). The schist and paragneiss are typically medium-grained gray to gray-brown, contain biotite±garnet±sillimanite and commonly enclose porphyroclasts of feldspar and/or feldspar-quartz ±biotite pegmatite that range from 1mm-60mm in diameter (e.g. Shell, 1996) Locally the biotite schist and paragneiss are interlayered with quartz-muscovite-garnet±sillimanite schist, thinly layered quartzite, calc silicate gneiss, intermediate amphibolite gneiss, amphibolite, and marble.

These Milton rocks are intruded by a light gray, medium-grained garnetiferous, granite orthogneiss, the **Connally Church orthogneiss**, in the core of the Milton antiform (Fig. 2). The Connally Church orthogneiss is petrographically and structurally similar to a lithically homogeneous collection of orthogneiss bodies in the Milton arc termed the Shelton Intrusive Suite (Henika, 2002; Henika et al., 2006). A nearby member of the suite in southern Virginia has yielded a U-Pb zircon crystallization age of 450±1.8 Ma (Coler et al., 2000); we suggest that the Connally Church body is similar in age.

During the 2017 field trip, we will have one stop in the Milton paragneiss unit and a stop in the Connally Church orthogneiss.

THE CUNNINGHAM COMPLEX: is a heterogeneous mixture of biotite gneiss, biotite schist, and granitic gneiss that extends from the north side of Hyco Lake to the South Boston, Virginia area (Fig. 2). The main rock types in the complex range from massive equigranular granitic gneiss to layers and

lenses of biotite±garnet±sillimanite schist; the most common rock type is biotite gneiss that represents a hybrid between these two endmembers, although distinct irregular outcrop areas of either endmember can be found. Layering is generally subtle in the complex, defined on cm-m scale by porphyroclast concentration and biotite content. The granitic gneiss is compositionally similar to, and appears to grade into the less deformed Carboniferous granitoids. In many places, meter-scale pods of amphibolite, dioritic gneiss, and calc-silicate gneiss are enveloped in a matrix of biotite gneiss.

On the basis of these observations, we interpret the Cunningham Complex to be a highly deformed broad zone of migmatite (sensu lato). The biotite schist and calc-silicate gneisses represent a Milton arc paleosome, the amphibolite and diorite pods may represent either a Country Line Complex paleosome or Milton arc rocks, and the granitic gneiss forms a deformed neosome that intrudes the country rocks and unifies the complex. The complex is considered to be a hybrid unit with Ordovician, Carboniferous, and possibly Neoproterozoic components (amphibolite/diorite).

CARBONIFEROUS GRANITOIDS IN THE HYCO SHEAR ZONE: The Hyco shear zone is host to three texturally and structurally distinct granitoids; they intrude the footwall rock units and the hanging wall Country Line Complex; they are not found in the hangingwall above the complex. The Yanceyville granite orthogneiss, part of, and confined to, the Country Line Complex, has been described above with the complex. The two granitoids intruding the footwall units and the Country Line Complex are the **Kilgore** and **Farmers Lake granites** (Figs. 2, 3). Both granitoids are generally less deformed than the country rock and both are commonly associated with granite pegmatite dikes and layers. The coarse-grained **Kilgore granite** crops out in the area west and northwest of Hyco Lake (Fig. 2). It is a K-

feldspar-plagioclase-quartz-biotite granite that is locally megacrystic and it is heterogeneously deformed. Deformation ranges from a single weak to moderate foliation to the northwest, to an intense gneissic foliation in the southeast, along the contact between the pluton and the Country Line Complex. In most places along this contact, the Kilgore granite is concordantly interlayered with gneiss of the Country Line Complex, although locally, it crosscuts layering in the complex (Shell, 1996). A 327 ± 1.5 Ma U-Pb zircon age from the Kilgore granite gneiss is considered to represent the crystallization age of the pluton (Wortman et al., 1998).

The **Farmers Lake granite** is a weakly to moderately foliated, homogeneous fine- to medium-grained biotite granite. It occurs as sporadic stocks and dikes, most of which are too small to be resolved on 1:24,000 scale maps. The Farmers Lake granite intrudes the Kilgore granite gneiss, the Cunningham Complex, and the Country Line Complex. A U-Pb zircon age of 319.6 ± 0.7 Ma on the granite is interpreted to reflect the crystallization age of the pluton (Wortman et al., 1998).

We will view the reference section for the Kilgore granite gneiss on Kilgore Creek during our field trip. We will not be seeing the Farmers Lake granite.

TECTONIC EVENTS IN THE FOOTWALL: In the area mapped during our studies, we only observed penetrative structures related to and identical to those of the Hyco shear zone in rocks in the footwall. If any earlier penetrative structures existed, they have been obliterated by the deformation and metamorphism related to the Hyco shear zone.

STRUCTURE AND TIMING OF THE HYCO SHEAR ZONE

The structure of the Hyco shear zone is complex and it has been described in detail by

Hibbard et al. (1998); in this section, we provide a summary of their salient points concerning the geometry, kinematics, and the relative and absolute timing of structures in the shear zone.

The most obvious feature of the Hyco shear zone in map view is its arcuate trace, from east-northeast in the vicinity of Hyco Lake to north-northeast in Virginia. This bend in the shear zone defines two structural segments, termed the Hyco Lake and Virginia segments, respectively (Fig. 4). Around this bend, structures within the shear zone vary with respect to geometry and kinematics; however, some aspects of their geometry and kinematics also vary with structural level across strike of the zone – main zone structures are developed in the footwall Milton arc and in the structurally lowest part of the Country Line Complex, whereas upper zone structures are developed in the structurally upper portion of the Country Line Complex and in the Carolina terrane rocks (Fig. 4).

GEOMETRY: The **main zone** structural sequence is constant from the Hyco Lake to the

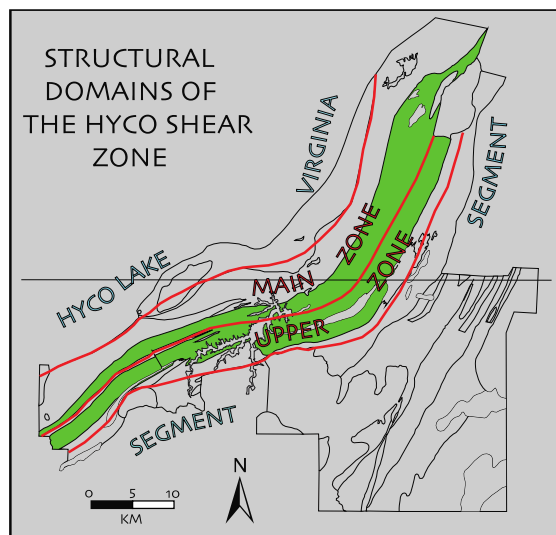


Figure 4. Structural domains of the Hyco shear zone. Country Line Complex is highlighted in green in order to show that the domain boundary between the main zone and the upper zone is within the hanging wall and not at the Carolina-Milton interface.

Virginia segments of the shear zone. It involves gneissic layering (S_G) and main phase foliation (S_M) with associated folds (F_M) and mineral lineations (L_M), all of which are overprinted by a late phase foliation (S_L) and associated folds (F_L) and lineations (L_L).

In most places, S_G is parallel to sub-parallel with S_M . S_M includes a suite of foliations that define S-C and shear band geometries, with the C foliation generally parallel to the gneissic layering. There is abundant evidence for shear along S_G/S_M including transposition of F_M in places intense enough to produce rootless folds, grain size-reduction of pegmatitic layers, asymmetric winged porphyroclasts, asymmetric foliations, and asymmetric boudinage of layers.

The geometry of this sequence of structures varies from segment to segment of the shear zone. In the Hyco Lake segment, S_G and S_M are subhorizontal in the Milton arc, but steepen to the southeast and have moderate to steep dips in the Country Line Complex (Fig. 2 cross section). Structures in this segment all trend east-northeast. The geometric relationships between the foliations and folds across the Hyco Lake segment are schematically depicted in Figure 5. In the Virginia segment,

S_G and S_M are subhorizontal in the Milton arc, but steepen to only moderate dips in the Country Line Complex (Fig. 2, cross sections). In this segment, S_G and S_M trend north-northeast and fold axes show a wide range of orientations within the plane of S_M . The orientation of lineations remains constant at east-northeast from one segment to the other.

The Carolina terrane rocks in the **upper zone** display similar structures to those in the main zone, but generally lacks well developed late phase structures. In addition, the upper zone straddles the structural transition between the main zone gneisses and Carolina terrane rocks with recognizable primary structures; layering in the upper zone ranges from gneissic, similar to that in the main zone, to primary bedding (S_O). Another concern in the upper zone is that the Carolina terrane rocks have been involved in at least one deformational event that predates the Hyco shear zone (see 'Tectonic events in the Carolina terrane', above). The relict Carolina terrane structures include upright folds, a regional foliation (S_E), and possibly a stretching lineation. In this zone, it is particularly challenging to determine whether a given structure is related

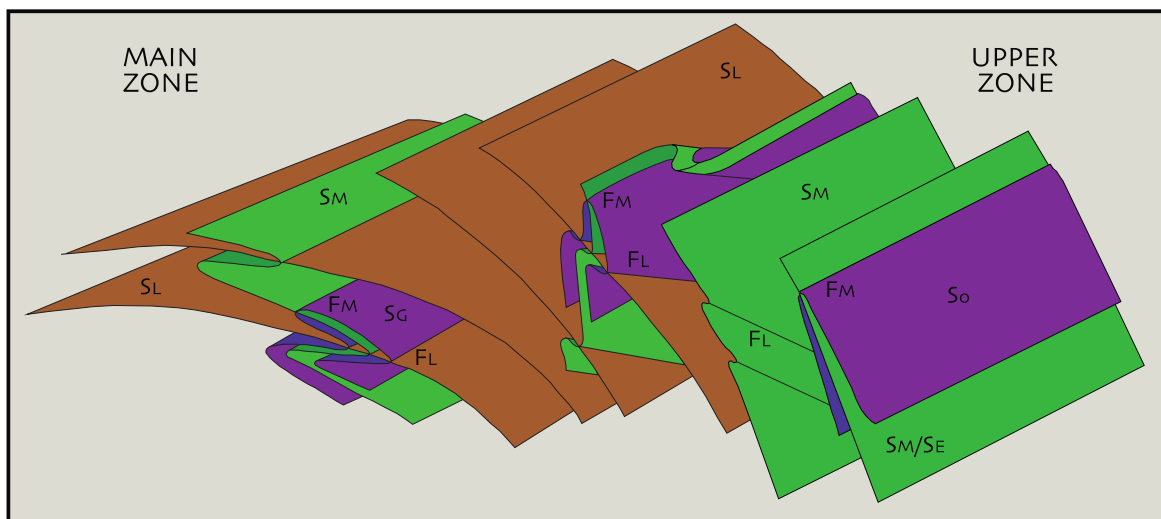


Figure 5. Schematic depiction of structural relations between foliations and folds along the Hyco Lake segment of the Hyco shear zone. Foliation and fold designations given in text; view towards the northeast.

to the shear zone or an older Carolina terrane event. In terms of the orientation of minor structures, the difference between main zone and the upper zone is that lineations in the upper zone mainly plunge to the southwest.

KINEMATICS: The two main zone segments display different, yet structurally compatible, kinematic pictures for the Hyco shear zone. All shear sense indicators in the Virginia main zone consistently indicate an east-over-west polarity of shearing for ductile deformation in the Hyco shear zone (Bradley, 1996). In contrast, structures in the moderate to steep dipping portion of the Hyco Lake segment consistently indicate dextral shear along the shear zone. The only interpretation that is structurally compatible with the kinematics outlined above is that the Virginia segment represents a frontal ramp, whereas the Hyco Lake segment is a lateral ramp, within an overall ductile thrust regime (Fig. 6). Shear sense indicators are less common in the upper zone. In conjunction with foliation and lineation orientations, shear sense indicators in the upper zone suggest motion ranging from dextral to normal, with oblique dextral-normal sense most common. It appears that the upper zone moved independently of the main zone. This motion could reflect either

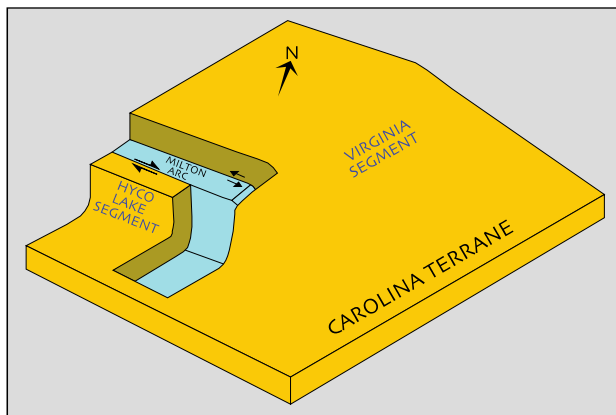


Figure 6. Schematic depiction of frontal and lateral thrust ramps corresponding to the Virginia and the Hyco Lake segments of the Hyco shear zone.

i) local kinematics associated with the ramp couple, ii) regional oblique extension in the hanging wall of the shortening system, iii) partitioning of Alleghanian dextral transpression in a triclinic shear zone (e.g. Lin et al., 1998), or iv) any combination of i – iii.

There is no direct evidence for the magnitude of thrust displacement on the Hyco shear zone. However, fabric analysis in the sigma-porphycroclast shaped High Rock granite body allows for a minimum estimate of displacement. Vines et al. (1998) noted an early foliation in the pluton in addition to two overprinting foliations that are clearly related to motion on the lateral ramp of the shear zone. A lineation on the early foliation, when rotated to a horizontal attitude around the trend of the early foliation, was found to be parallel (*ca.* 260° azimuth) to thrust flat lineations in the main zone. Considering that microstructures related to the early foliation and the shear zone foliations indicate that they all formed at approximately 450°-500° C, it is likely they all formed during the same event. Consequently, Vines et al. (1998) interpreted the early foliation to have formed along a thrust flat of the active Hyco shear zone. The nearest thrust flat to the High Rock body is at the junction of the Hyco Lake and Virginia segments of the shear zone, 35 km to the east of the pluton (Fig. 7). Thus, they deduced a minimum of 35 km of displacement along the Hyco shear zone. In light of the interpretation that the Hyco shear zone is a northerly segment of the central Piedmont shear zone, which extends for the length of the southern Appalachians, we suspect that there was substantially more than 35 km displacement along this structure.

RELATIVE TIMING OF STRUCTURES: In the main zone, S_L , F_L , and L_L overprint the main phase structures. These late structures are generally less intensely developed than those of the main phase. Locally, both S_L and F_L are transposed along S_M and S_G , indicating that the main phase structures were active after the

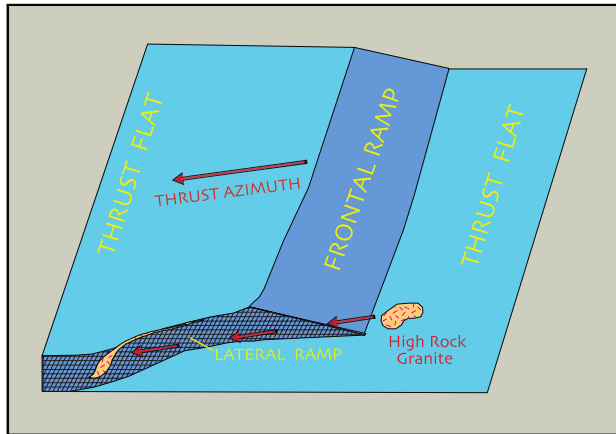


Figure 7. Schematic depiction of the footwall block of the Hyco shear zone showing how minimum displacement for the shear zone is estimated; broken red arrows depict the path of the hanging wall High Rock Granite, from its relatively undeformed state on a thrust flat either at or before *ca.* 335 Ma, to its present position as a sigmoidal 'clast' along the lateral ramp of the shear zone. Distance from the ramp corner to the present position of the High Rock Granite is *ca.* 35 km. Adapted from Vines et al. (1998).

generation of the late structures. This observation suggests that the two phases of deformation overlapped in time. This deduction is further supported by the following observations: i) the consistent parallelism of main and late phase minor structures such as fold axes and lineations, ii) both phases of structures display the same sense of shear, iii) both phases overprint Mississippian granitoids, thus they both are most likely phases of the Alleghanian orogeny, iv) S_M and S_L are locally overprinted by mesoscopic shear bands that have the same sense of shear as both phases, and v) both phases were generated during peak amphibole facies metamorphism. In light of these observations, we conclude that the main and late phase structures represent endmember structures generated during progressive shear in the Hyco shear zone. The main phase structures reflect the finite accumulated strain in the zone, whereas the late phase structures are more closely linked to the instantaneous strain in the zone at the time of their formation.

ABSOLUTE TIMING OF STRUCTURES: The absolute timing of shear zone activity in the main zone is tightly constrained by field relationships and precise U-Pb zircon and titanite ages on associated plutons (Wortman et al., 1998). In particular, the relationship between Alleghanian intrusions and overprinting structures has been critical in determining the absolute timing of Hyco shear zone activity. Field observations indicate that the Yanceyville orthogneiss is pre- to early-syntectonic, the Kilgore granite gneiss is syn- to late syntectonic, and the Farmers Lake granite is late syntectonic. This relative sequencing of intrusions based on field observations was borne out by U-Pb geochronology of zircons from the intrusions. The pre- to early syntectonic Yanceyville orthogneiss has yielded an age of *ca.* 335 Ma, the syn- to late syntectonic Kilgore granite is dated at *ca.* 327 Ma, and the late syntectonic Farmers Lake granite has yielded a *ca.* 320 Ma age.

Ar^{40}/Ar^{39} thermochronological data are available for the footwall in the middle of the Milton arc and for the hanging wall Country Line Complex. The footwall Milton rocks have yielded hornblende ages of *ca.* 323 Ma and *ca.* 313 Ma (Kunk et al., 1995) and hornblende in the Country Line Complex records an age of 322.9 ± 7.8 Ma (Wortman et al., 1998). These ages, interpreted to indicate that the time of cooling through $\sim 500^\circ C$, are consistent the termination of activity along the Hyco shear at *ca.* 320 Ma.

From these ages and relationships it is clear that shortening along the Hyco shear zone was active from at least the Middle Mississippian, *ca.* 335 Ma to the earliest Pennsylvanian, *ca.* 320 Ma. The timing of initiation of slip is unconstrained but must be 335 Ma or older, based on the age of the pre- to early syn-tectonic Yanceyville orthogneiss.

Dextral-normal motion of the hanging wall is not directly constrained; however, the structurally lowest portions of the hanging wall zone are at the same metamorphic grade as the main zone, and shear foliations in both zones are parallel. Based on these observations, we suspect that the oblique motion of the hangingwall was approximately synchronous with motion of the main zone.

THE HYCO SHEAR ZONE IN THE CONTEXT OF THE SOUTHERN APPALACHIAN ALLEGHANIAN OROGENY

The Alleghanian orogeny in the southern Appalachians was a long-lived and complex tectonothermal event that involved plutonism, heterogeneous ductile and brittle deformation, heterogeneous metamorphism over a span of approximately 80 m.y., from *ca.* 340-260 Ma. It is also somewhat unusual – in studying ancient orogens geologists generally utilize the distribution of rock types and local to regional kinematics in order to deduce the plate dynamic tectonic scenario of an event; for the Alleghanian event, the reverse holds. Reconstruction of the pre-Atlantic configuration of the continents informs us that the Alleghanian, records the collision of Laurentia and the African portion of Gondwana. However, we do not have a satisfactory explanation for the heterogeneous kinematics and distribution of plutonism and metamorphism found in the southern Appalachians. Even such a fundamental concept as the polarity of subduction during the Laurentia-Gondwana collision remains controversial as geophysical interpretation appears to conflict with geological observations. The main reason for this lack of understanding is the dearth of abundant high quality geochronological data coupled with the need for a conscientious synthesis of the voluminous existing geological

data relevant to the event. In light of our current understanding of the Alleghanian orogeny, determining the significance of the Hyco shear zone in the context of the event is challenging.

The Hyco shear zone is considered a northerly extension of the central Piedmont shear zone. The latter was originally considered to be a suture (Sidebar 4), as it separates peri-Gondwanan rocks from Iapetan realm rocks in the southern Appalachians (e.g. Hatcher, 1989). However subsequent research and reasoning demonstrates that it is not a suture. In particular, it has been shown that Carolina had docked with Laurentia by the Silurian (Hibbard, 2000; Hibbard et al., 2002, 2012) and that the footwall Milton arc does not record an earlier penetrative deformation than the Alleghanian imprint. The Hyco shear zone is consequently viewed as an Alleghanian shortening structure that ‘decapitates’ the Late Ordovician peri-Gondwanan-Iapetan realm suture by placing an internal portion of Carolina on an internal portion of the Milton arc (Hibbard et al., 1998)(Fig. 8). These observations and deductions are consistent with, and supported by, reprocessed seismic reflection data (Cook and Vesudevan, 2006; Hibbard et al., 2010) (Fig. 9). This example of a major lithotectonic boundary not representing a suture is an important consideration in assessing the significance of other major southern Appalachian boundaries (e.g. Hopper et al., 2017).

Although not a suture, the Hyco shear zone represents the best kinematically and temporally constrained major structure in the Alleghanian hinterland of the southern Appalachians. As such, it serves as a benchmark to compare and link to other manifestations of the Alleghanian event elsewhere in the hinterland and in the Alleghanian foreland.

SIDEBAR 4

'Suture self'



The question of whether or not the Hyco shear zone and the central Piedmont shear zone represent a suture zone requires definition of the term 'suture'. The following definition, synthesized from Dewey (1977), Howell (1989), and Moores & Twiss (1995) can be applied to these shear zones:

A suture marks the site of a subducted ocean basin; it is commonly delineated on the basis of ophiolitic remnants, high pressure metamorphism, melanges, etc. and rarely is it a simple single, easily recognizable line on a map. Howell (1989) has noted that the distribution of many tectonostratigraphic terranes is due to post-accretion dispersion or shortening; consequently many terrane boundaries are not suture zones.

In light of this definition and Howell's comment, do the Hyco and central Piedmont shear zones qualify as a suture? 'Suture self'.

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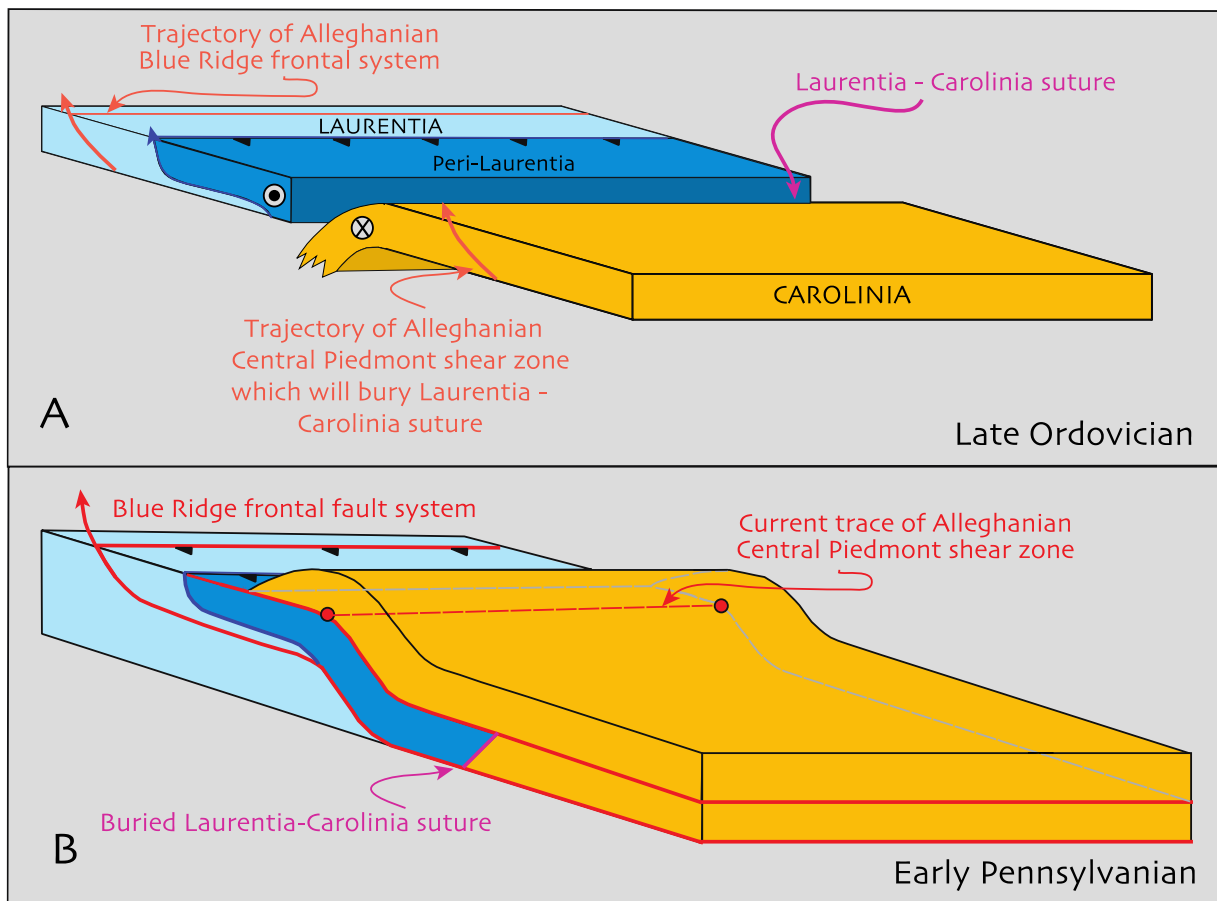


Figure 8. Schematic block diagram depicting Hyco shear zone in relation to the Laurentia-Carolinia suture. A: Late Ordovician docking of Carolina to Laurentia. B: Alleghanian 'decapitation' and burial of the Laurentian-Carolinia suture beneath the central Piedmont thrust sheet. From Hibbard et al. (1998; 2012).

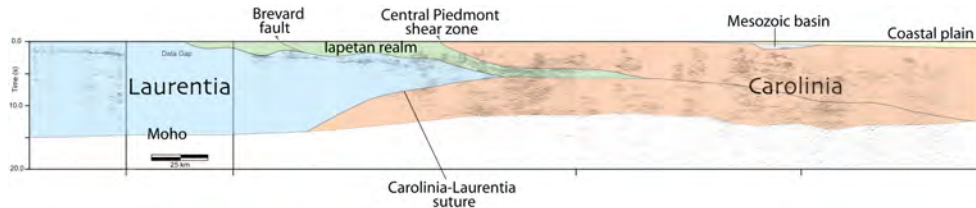


Figure 9. An interpretation of the reprocessed and enhanced southern Appalachian COCORP seismic-reflection line that is consistent with the regional structural geometry of Carolina and the central Piedmont shear zone (also see Fig. 8); seismic data from Cook and Vasudevan (2006). From Hibbard et al. (2010).

In particular, activity on the Hyco shear zone can be temporally linked to events in the Alleghanian foreland clastic wedges (Fig. 10). Deposition of these wedges started in the late Visean (*ca.* 335-330 Ma) following a Meramecian unconformity (*ca.* 340-335 Ma). These events in the foreland temporally overlap with early stages of activity along the Hyco shear zone in the hinterland (Fig. 10). Thrusting along the shear zone would have provided a lithospheric load in the hinterland, and could well be responsible for the development of a foreland basin depository for the Mississippian portions of the clastic wedges (e.g. Ettensohn, 1994). The termination of thrusting along the Hyco shear zone immediately predates a major unconformity in the northern portion of the clastic wedge complex, the earliest Pennsylvanian Morrowan unconformity. Perhaps this unconformity reflects episodic westward migration of the hinterland load from the Piedmont (termination of Hyco shear zone activity) into the Blue Ridge. Alternatively, the Morrowan unconformity could reflect a change in hinterland kinematics. It has long been recognized that dextral strike slip faulting is a hallmark of the Alleghanian event in the southern Appalachian hinterland (Hatcher et al., 1977; Bobyarchick, 1981). In general, the timing of dextral motion on faults of the system is poorly constrained. However, along the western margin of the Milton arc in southern Virginia, dextral motion along the Brookneal shear zone has been constrained to the time period of 324 – 300 Ma (Gates et al., 1986);

that is, dextral motion at the west side of the Milton arc started either in the waning stages or after active shortening along the Hyco shear zone. Could the Morrowan unconformity in the foreland clastic wedge reflect this change in Alleghanian hinterland kinematics from dominantly shortening to dominantly dextral strike slip? Clearly, a considerably greater data base than that available at present is required to formulate an answer to this teasing question.

TAKE HOME BULLETS

- the Hyco shear zone emplaces medium and low grade Neoproterozoic rocks of the Carolina terrane onto medium to high grade rocks of the Ordovician Milton arc.
- in the Roxboro, NC area, the surface trace of the shear zone is sharply arcuate, interpreted to reflect the junction of a frontal thrust ramp in Virginia with a lateral thrust ramp in North Carolina.
- Alleghanian granitoids ponded in the footwall Milton arc and within the structurally lower Carolina rocks, but did not penetrate into the low grade Carolina terrane rocks.
- relative ages of Alleghanian granitoids associated with the shear zone were assigned in the field on the basis of their relations to shear zone structures; these relative ages are confirmed by absolute U-Pb zircon ages.

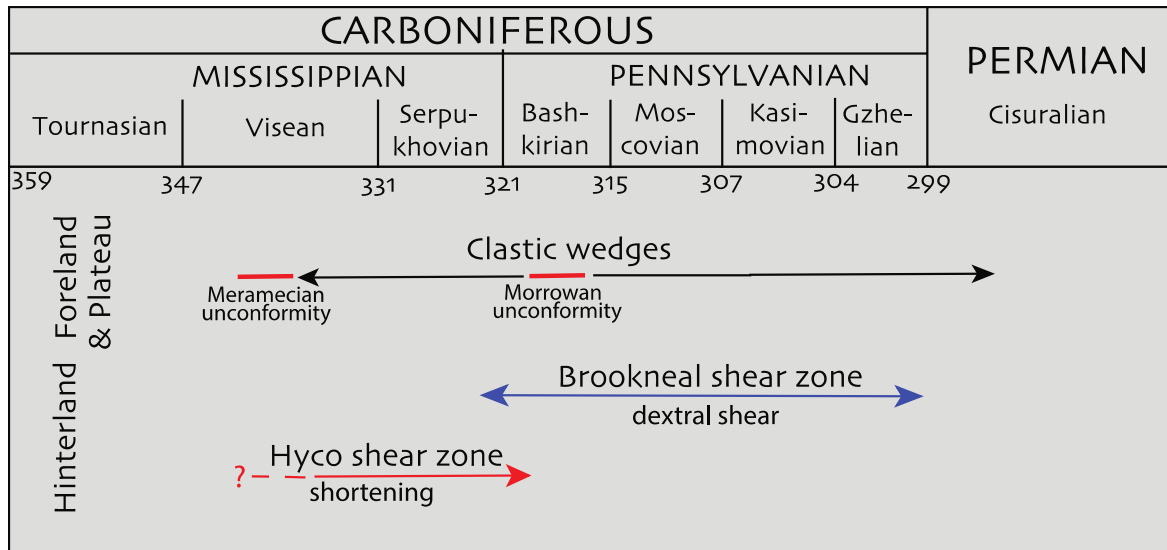


Figure 10. Alleghanian events in the northern portion of the southern Appalachian foreland basin and in the hinterland at the latitude of the Milton magmatic arc.

Intrusion was active throughout the history of the active shear zone, between *ca.* 335-320 Ma.

- kinematic data indicate that thrusting was in an approximately 260° direction and shortening is conservatively estimated to be 35 km, and is likely much greater.
- kinematically and temporally, the Hyco shear zone is arguably the best constrained, major Alleghanian structure in the southern Appalachian hinterland.
- the Hyco shear zone is the boundary between the peri-Gondwanan and Iapetan

realms; however it does not mark the site of a former ocean and thus, is not a suture.

- activity along the Hyco shear zone appears to be temporally related to the development of unconformities in the Alleghanian foreland clastic wedges.

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2017 FIELD GUIDE TO STOPS

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INTRODUCTION

This one and a half day field trip highlights field mapping and specialized studies that have been undertaken in the Hyco Lake region of north-central North Carolina during the last decade of the 20th century and thereafter. This guide incorporates material from earlier field guides, theses, publications, and field reviews of former NCSU geology students, including Glenn S. Shell, Kevin J. Wilkins, Philip Bradley, Jeff Bowman, and John Vines. In addition, it draws from 21st century studies in the vicinity of the shear zone by Phil Bradley and Brent Owens and his student Shelbi Wilson. The stop map for this trip is on the back cover of this guidebook.

Typical of southern Appalachian Piedmont field trips, our stops will generally be at relatively small, unassuming outcrops that might be difficult for all members of a group such as ours to view at one time. In the area of this trip, granitoids tend to provide the best fresh exposures in easily accessible locales, hence more than half of Saturday stops are at granitoid outcrops. These seemingly mundane granitoids, however, provide important field and lab data that are essential for understanding the history of the Hyco shear zone.

Saturday stops will cumulatively represent a traverse across the the Hyco Lake (lateral ramp) segment of the Hyco shear zone, although our path will be circuitous with respect to the shear zone (back cover this guide). We will view outcrops in the Yanceyville, Leasburg, Milton, Olive Hill, and Roxboro 7.5' quadrangles. These stops will focus on the main rock units, kinematics, timing and regional significance of the shear zone. With a group of our size, we must make a trade off of outcrops that reveal evidence critical to our interpretations for stops with

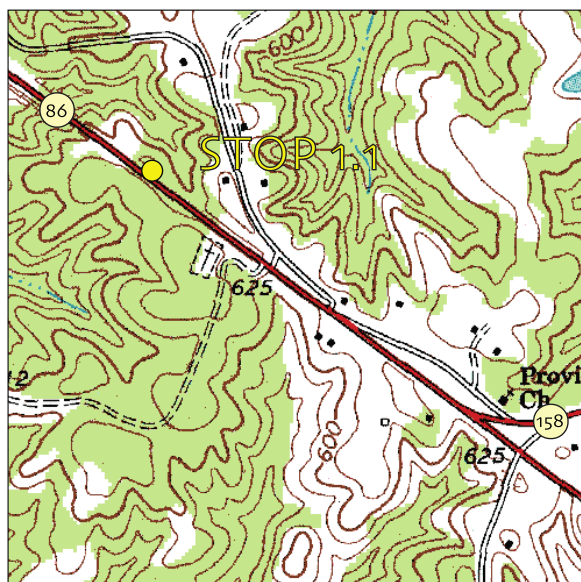
relatively easy access. This trade off is particularly germane to our kinematic interpretations of the shear zone; good shear sense indicators, though plentiful throughout the mapped region, are not well represented at outcrops that can easily accommodate our group. The leader for Saturday stops will be Jim Hibbard. On Sunday, we will investigate different aspects of the Neoproterozoic Hyco arc in the hangingwall of the Hyco shear zone. Our understanding of these rocks has recently been enhanced by multiple studies, including those by Bradley et al. (2011) and Owens and Wilson (2009). Participants will have the option of either visiting volcanic, stratigraphic, and Ediacaran faunal aspects of the Hyco arc with leader Phil Bradley (Rougemont 7.5' quadrangle) or viewing unusual kyanite-bearing rocks at Hager's Mountain under the leadership of Brent Owens (Roxboro 7.5' quadrangle).

As with most field guides, there are more stops described below than we can comfortably visit in the allotted day and a half. The extra stops are included to both lend flexibility to the choice of stops in case of unforeseen circumstances (weather, time, etc.) and document important stops that we will not be able to visit on this particular trip. The supplementary stops are described following the intended stops for Saturday and Sunday. Also note that because of the prevalence of GPS software in modern field geology, we include the latitude and longitude for each stop and a thumbnail topographic map inset, rather than a detailed road log. The total mileage for day one stops is approximately 80 miles (129 km) and that for day two part A is approximately 45 miles (72 km) and for day two part B, approximately 13 miles (21 km).

SATURDAY, NOVEMBER 4, 2017

STOP 1.1: HYCO ARC IN HANGING WALL, OF THE HYCO SHEAR ZONE - HIGH ROCK GRANITE: EAST SIDE OF RT. 86 JUST NORTHWEST OF THE CROSSROADS OF PLEASANT GROVE, NC (36.3923°N, 79.2792°W). STOP LEADER: JIM HIBBARD

• **PLEASE BE CAREFUL!** *This stop is on a busy, highway with fast moving vehicles; please stay on the east side of the road where the buses drop you off and stay in the grass and off of the shoulder of the road.*•



from the Yanceyville 7.5' quadrangle

We start the day along the lateral ramp segment of the Hyco shear zone (see Hibbard et al., this guidebook) in the High Rock granite (Vines et al., 1998). It is located relatively high in the hanging wall, near the southern margin of the shear zone. The purpose of this humble stop is to view the main body of the High Rock granite and discuss its importance in determining some kinematic aspects of the Hyco shear zone.

The High Rock granite is a stock that in map view strikingly resembles a dextral



FIGURE 1: Medium-grained, foliated High Rock biotite granite at Stop 1.1.

sigma porphyroclast, with an elongate wing extending from its northeast corner (back cover)(Shell, 1996; Vines et al., 1998)(see Supplemental Stop S.2, this guidebook). It is named for the small community of High Rock, at the northeastern end of the wing. The granite straddles the strain gradient along the south-southeastern margin of the Hyco shear zone. The stock intrudes Neoproterozoic mafic and felsic volcanic rocks equivalent to those of the Hyco Formation, and locally known as the Pleasant Grove formation (Shell, 1996). The southwestern portion of the granite consists of K-feldspar (orthoclase and microcline), plagioclase, biotite, and quartz, with lesser amounts of muscovite, chlorite, epidote, garnet, titanite, and zircon; muscovite increases in abundance northeastward, across the strain gradient into the Hyco shear zone.

Deformation in the stock ranges from non- to weakly foliated granite in the southwest to intensely mylonitic granite in the wing to the northeast. Vines et al. (1998) reported that microstructures in the granite are consistent with low to moderate (400°-500°C) temperature, solid state, deformation.

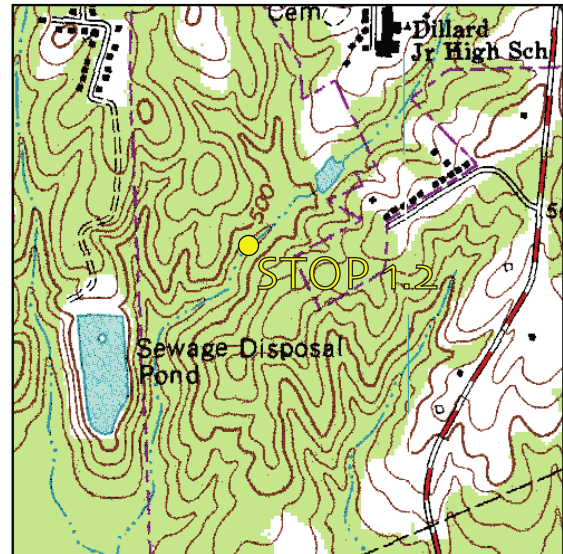
The High Rock granite is petrographically very similar to the larger, *ca.* 612 Ma, Osmond granite to the east. The two granites are also overprinted by the same solid state foliation and both contain the same microstructures (Vines et al., 1998). On the basis of these observations, the High Rock granite is considered to be correlative with the Osmond granite and part of the Neoproterozoic (Ediacaran) Hyco magmatic arc.

At this stop, three small outcrops of medium-grained, foliated, biotite granite surround an exposure of chlorite phyllite. The foliation in the granite at this stop has been interpreted to be the early foliation in the body that is overprinted by two shear zone foliations to the northeast. The chlorite phyllite bears close resemblance to rocks of the Pleasant Grove formation, not far to the southeast of this stop; the foliation in the phyllite is concordant with that in the granite. We interpret the chlorite phyllite to be a xenolith of the Pleasant Grove formation in the High Rock granite.

The High Rock body allows for interpretation of two different kinematic aspects of the Hyco shear zone. First, the map view shape of the High Rock body is clearly consistent with dextral shear along the Hyco Lake segment of the Hyco shear zone, as deduced from outcrop scale shear sense indicators in the region. In addition, structural analysis of the stock has also constrained the minimum displacement on the shear zone to *ca.* 35 km (Vines et al., 1998)(see explanation in Hibbard et al., this guidebook).

STOP 1.2: CAROLINA TERRANE ROCKS IN THE HYCO SHEAR ZONE - COUNTRY LINE COMPLEX: UNNAMED BRANCH EAST OF SEWAGE DISPOSAL POND ON THE SOUTH

SIDE OF YANCEYVILLE, NC (36.3947°N, 79.3375°W). STOP LEADER: JIM HIBBARD



from the Yanceyville 7.5' quadrangle

The Country Line Complex forms the base of the Carolina terrane in the hanging wall of the Hyco shear zone. It is composed of heterogeneously deformed, amphibolite facies, mafic gneiss with interlayered granitic pegmatite, subordinate biotite gneiss, and minor metapyroxenite, semipelitic schist, and felsic schist. This stop is at an exceptional exposure of interlayered mafic and granitoid gneisses of the complex (Fig. 2).



FIGURE 2: Very regularly layered mafic and granitoid gneisses at Stop 1.2.



FIGURE 3: Two adjacent exposures of Country Line Complex gneisses on Cane Creek, on the north side of Hyco Lake. On the left, an agmatite of mafic and granitoid gneiss shows no evidence of layering; the photo on the right is taken a few meters downstream, where agmatitic features, though present, are subordinate to a gneissic layering and moderate foliation that is developed. We interpret this change from relatively undeformed agmatite to layered gneiss as representing a strain gradient within the agmatitic rocks. Consequently, we suggest that the strong mafic-felsic interlayering at Stop 1.2 may be a high strain facies of an agmatite.

Overall, the mafic gneisses in this outcrop are fine-grained and display a strong, planar, cm-scale layering that trends approximately N60E and dips moderately to steeply southeast. Late granitoids and pegmatites that intrude across layering lack chill margins, suggesting that the rocks were at regional metamorphic conditions at the time of intrusion. The gneissic layering here has been isoclinally folded around subhorizontal axes; these isoclinal closures are subtle and only locally evident. In addition, gneissic layering is locally overprinted by minor folds with a dextral asymmetry.

The most prominent aspect of this exposure is the pronounced, regular layering.

Based on observations of the complex at many other localities where the rocks are less intensely deformed, we interpret the protolith of this outcrop to be an agmatite¹ with older mafic rocks intruded by a neosome of granite (Fig. 3).

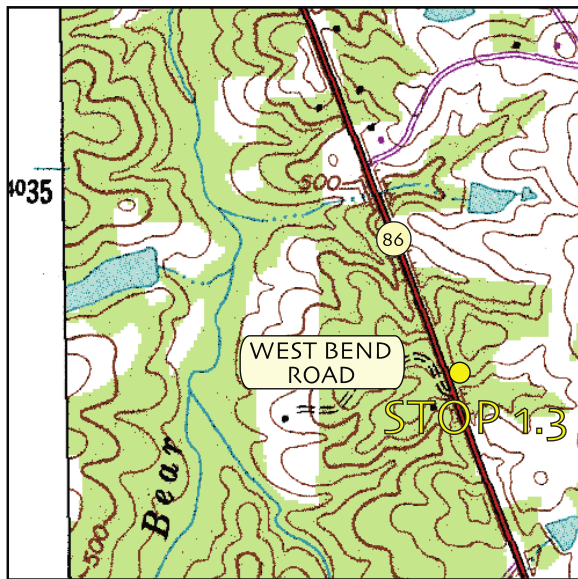
The age of the mafic gneisses in the complex is constrained by a U-Pb zircon age of 614 ± 9 Ma on layered mafic gneisses of the complex in a quarry at South Boston, VA (Wortman et al., 1998). The granitic layers that are concordant with the mafic gneisses

¹ An agmatite is a migmatite containing random blocks of country rock surrounded and veined by intrusive rock.

tend to increase in abundance towards the contact between the gneisses and the Yanceyville metagranite; this relationship suggests that the concordant granitic layers may be related to the *ca.* 335 Ma Yanceyville metagranite. Other, coarser grained and less intensely foliated granitoids in this outcrop are reminiscent of the *ca.* 327 Ma Kilgore metagranite and they may be related to this pluton.

STOP 1.3: MILTON ARC IN THE FOOTWALL OF THE HYCO SHEAR ZONE - BIOTITE SCHIST AND PARAGNEISS: HWY. 86 AT WEST BEND RD., JUST NORTH OF YANCEYVILLE, NC (36.4471°N, 79.3658°W). STOP LEADER: JIM HIBBARD

• **PLEASE BE CAREFUL!** *This stop is on a busy, highway with fast moving vehicles; please stay on the east side of the road where the buses drop you off and stay in the grass and off of the shoulder of the road.*•



from the Yanceyville 7.5' quadrangle

This biotite schist is typical of the Milton terrane in the immediate footwall of the Hyco shear zone. The schist is composed of Kfs + Pl + Qtz + Bi + Grt ± Ms and it

forms the matrix for pods and porphyroclasts of quartz-feldspar pegmatites. Hence our informal field name 'chunky gneiss' for this unit. Compositional layering in this unit is generally defined by both biotite content and the diffuse concentration of porphyroclasts, although locally we find pods, lenses, and layers up to 1 m thick of either amphibolite, or fine-grained granite embedded in the gneiss. The age of the gneiss is unknown; however, it is intruded by the *ca.* 327 Ma Kilgore granite in a quarry on the west side of Hwy. 86, just south of this location. An approximately 1 m thick sill of granite gneiss at the north end of this outcrop may be an apophyse of the Kilgore granite. Rocks similar to those at this outcrop interfinger with Ordovician metavolcanic rocks in nearby Danville, VA; thus, we tentatively assign an Ordovician age to these footwall rocks.

The fabrics and folds in this gneiss typify the structural character of the Milton terrane. The main schistosity is subhorizontal and defined by the preferred orientation of biotite, quartz ribbons, pegmatitic porphyroclasts, and wings extending from some of these porphyroclasts. Locally, wings on the porphyroclasts and asymmetric fabrics define a tops-to-the-west motion along the main foliation. In some places in this outcrop, a WWSW-trending mineral lineation is associated with this foliation. The main foliation is affected by tight to isoclinal recumbent folds that have strongly curved hingelines (Fig. 4). In the eastern Milton terrane, the separation line between minor late folds with a 'Z' down-plunge asymmetry and an 'S' down-plunge asymmetry is oriented subparallel to the regional mineral lineation and the minor fold asymmetries indicate an E over W sense of shearing (Bradley, 1996). Locally, a weak late foliation is developed axial planar to the late folds; usually this

foliation is only evident in the hinge area of the late folds. Note that this roadcut has been made approximately along the hinge line of a late mesoscale warp, as the foliation on either side of the highway dips away from the centerline.



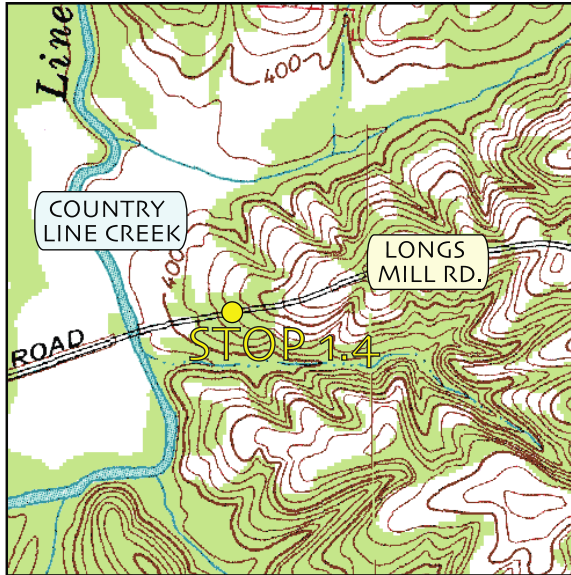
FIGURE 4: Noncylindrical fold in paragneiss at Stop 1.3. Note fold hingeline is parallel to hammer handle just below hammer, but is suborthogonal to exposure at right side of photo.



FIGURE 5: Granitic sill in biotite schist at the north end of the outcrop at Stop 1.3; this body may represent an apophyse of the nearby Kilgore granite.

STOP 1.4: ALLEGHANIAN GRANITOID WITHIN THE HYCO SHEAR ZONE - YANCEYVILLE ORTHOGNEISS IN THE COUNTRY LINE COMPLEX: LONGS MILL RD. (36.4655°N, 79.2112°W). STOP LEADER: JIM HIBBARD

This stop provides a quick look at an easily



from the Leasburg, NC 7.5-minute quadrangle

accessible outcrop of the Alleghanian Yanceyville orthogneiss (Shell, 1996). This orthogneiss is a medium- to coarse-grained granite gneiss that forms an elongate sill up to 0.5 km thick within the Country Line Complex. The main minerals composing the orthogneiss are $Pl(Olg)+Qtz+Kfs+Bt \pm Ms$. At this outcrop, there are a couple of thin layers of blackish green amphibolite that may represent either unassimilated layers or deformed xenoliths of Country Line Complex mafic gneiss (Fig. 6). The main foliation in the orthogneiss here is oblique to the amphibolite layers, suggesting that we may be near the hinge of a mesoscale isoclinal fold.

Yanceyville gneiss displays all of the structure found in the surrounding Country Line gneisses. At the Blanch prison quarry (now inaccessible), just to the south of this stop, Yanceyville orthogneiss cross-cuts tectonic layering in Country Line mafic gneisses (Shell, 1996); in addition, the orthogneiss contains xenoliths of Country Line mafic gneisses that contain a foliation askew to the regional foliation. Thus, we interpret the Yanceyville orthogneiss to be an early syntectonic intrusion into the

Hycoshear zone. The Yanceyville orthogneiss has yielded a high precision U-Pb zircon age of 335 ± 2 Ma. Considering the syntectonic nature of the pluton, this age indicates that the Hycoshear zone was active in the Late Mississippian.

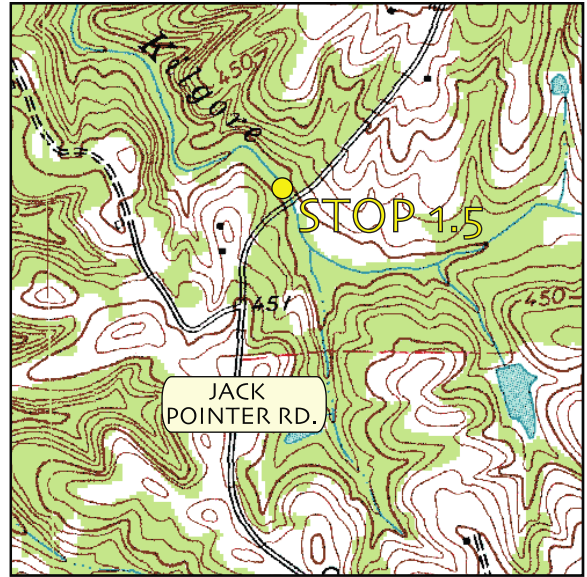
Granitic pegmatites that are commonly concordant to, and deformed with, layering in the Country Line Complex increase in abundance near the main body of Yanceyville orthogneiss. This observation suggests that the pegmatites are genetically related to the Yanceyville orthogneiss. If so, a substantial volume of the complex is Mississippian.



FIGURE 6: Medium-grained Yanceyville orthogneiss with two thin layers of amphibolite at Stop 1.4.

STOP 1.5: ALLEGHANIAN GRANITOIDS - KILGORE GRANITE/ORTHO GNEISS IN THE IMMEDIATE FOOTWALL OF THE HYCO SHEAR ZONE: JACK POINTER RD. AT KILGORE CREEK (PRIVATE PROPERTY OF JIM AND CATHY LONG, (36.4868°N, 79.2025° W). STOP LEADER: JIM HIBBARD

The Kilgore granite/orthogneiss is a heterogeneously deformed, generally coarse-grained, biotite granite and granite gneiss that is locally megacrystic. In most places, the orthogneiss has a distinct clastic texture defined mainly by feldspar grains (Fig. 7).



from the Leasburg, NC 7.5' quadrangle.

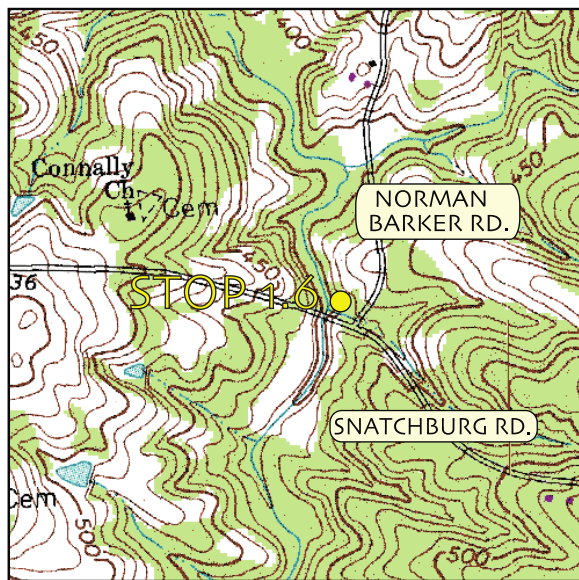
This outcrop is our reference section for the pluton. Here the orthogneiss locally displays typical enclaves of mafic gneiss, biotite schist, and amphibolite; at many localities in the pluton, these enclaves contain a fabric that is randomly oriented with respect to the regional foliation in the granite gneiss. The bulk of the pluton is affected by a single subhorizontal foliation such as seen at this outcrop; however, along its border with Carolina terrane rocks, it is intensely deformed and concordantly interlayered with mafic gneisses of the Country Line Complex, although locally it cross-cuts layering in the complex (Shell, 1996; Hibbard et al., 1998). Based on these field relationships, we have interpreted the pluton to be synkinematic with respect to the shear zone.

The granite proved difficult to date because it contains a complex xenocrystic component. However, utilizing multigrain and single grain analyses, Greg Wortman obtained a nearly concordant U-Pb zircon crystallization age of 327 ± 2 Ma for the granite and also identified one population of inherited zircons with an age of *ca.* 335 Ma, identical to the age of the Yanceyville orthogneiss (Wortman et al., 1998).



FIGURE 7: Kilgore orthogneiss with distinct clastic texture; adjacent to bridge on downstream side at Stop 1.4.

STOP 1.6: MILTON ARC – CONNALLY CHURCH ORTHOGNEISS IN THE FOOT-WALL OF THE HYCO SHEAR ZONE: RICHMOND POND MILL SITE AT THE INTERSECTION OF NORMAN BARKER RD. AND SNATCHBURG RD. PRIVATE PROPERTY OF MR. RAY BARKER. (36.5325°N, 79.1706°W). STOP LEADER: JIM HIBBARD



from the Milton 7.5' quadrangle

This stop is on the private property of Mr. Ray Barker, who resides in the first home along Norman Barker Rd.; individuals wanting to view this outcrop should obtain permission first. The Connally Church or-

thogneiss is a distinct garnetiferous granitic gneiss that lies in the core of the Milton antiform (back cover). It is composed mainly of $Pl+Kfs+Qtz+Bt+Gnt$. The rock displays an $S \neq L$ fabric with a shallowly dipping to subhorizontal foliation. The lineation is generally defined by individual minerals and mineral clusters (Fig. 8). The fabric allows the gneiss to break into large elongate slabs; a trait that was utilized by those who built the dam to the Richmond Mill Pond (Fig. 9).

The Connally Church orthogneiss is undated; however, it bears strong resemblance, both petrographically and structurally, to a group of Ordovician plutons that intrude the Milton terrane and that collectively form the Shelton Intrusive Suite (Henika, 1998). A member of the suite just to the north of this stop in Virginia, the Old Mill granite gneiss, has been dated at 450 ± 1.8 Ma (Coler et al., 2000). We consider the Connally Church gneiss to be correlative with the Old Mill gneiss. The Shelton Suite is interpreted to be related to the subduction of Iapetus and Carolina beneath Laurentia (Hibbard et al., 2016).

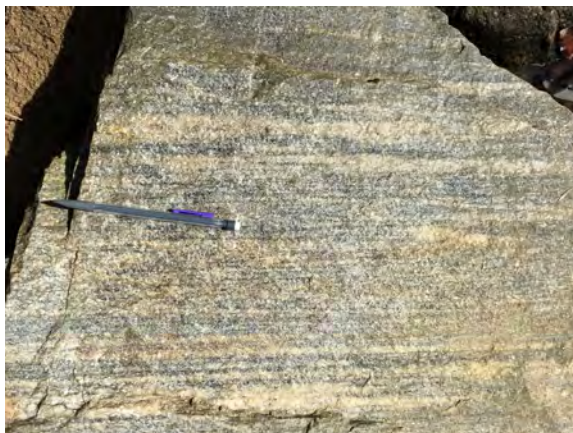
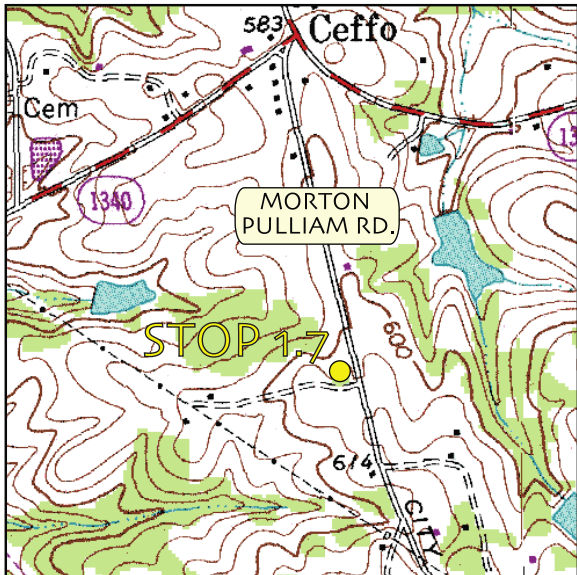


FIGURE 8: Strong mineral lineation evident on foliation plane in the Connally Church orthogneiss at Stop 1.6.



FIGURE 9: The former Richmond Mill Pond dam at Stop 1.6 was constructed with slabs of Connally Church orthogneiss.

STOP 1.7: ALBEMARLE ARC – THE ROXBORO GRANITE IN THE HANGING WALL OF THE HYCO SHEAR ZONE: CLAYTON FARM, MORTON PULLIAM RD. (36.4505°N, 79.0456°W). STOP LEADER: JIM HIBBARD



from the Olive Hill 7.5' quadrangle

The Roxboro Granite (metagranite of Briggs et al., 1978) resides above the upper zone of the hanging wall of the Hyco shear zone (see Hibbard et al., this guidebook). It is the sole representative of the Ediacaran-earliest Cambrian Albemarle magmatic arc in the field trip area. The pluton is



FIGURE 10: Massive Roxboro Granite at Stop 1.7.

is important to understanding the regional geology, for it embodies evidence for the Neoproterozoic Virgilina deformation (see Supplemental Stop S.3). The pluton intrudes the Hyco and Aaron formations and the Osmond Granite. The Roxboro Granite is mildly metamorphosed and composed mainly of Plag + Kfsp + Qtz + Bt (Briggs et al., 1978). Based on petrological studies, Briggs et al. (1978) interpreted the pluton to represent a shallow intrusive body and an eruptive center, although extrusive equivalents have not been identified in the area of the pluton. The Roxboro Granite has yielded a U-Pb zircon age of 546.5 \pm 3/-2.4 Ma, which is interpreted to represent the crystallization age of the pluton (Wortman et al., 2000).

At the northern end of the body, in the vicinity of the Hyco shear zone, the Roxboro Granite is undeformed. However, Briggs et al. (1978) report the development and intensification of a foliation towards the southern end of the body; they noted that this foliation is parallel to that in the surrounding Hyco and Aaron Formations.

The Roxboro Granite, unlike other granitoids in the region, has a distinct geomorphological signature. It is commonly marked by a residual boulder field (Figs. 11, 12). We suspect that this expression results from weathering and formation of core

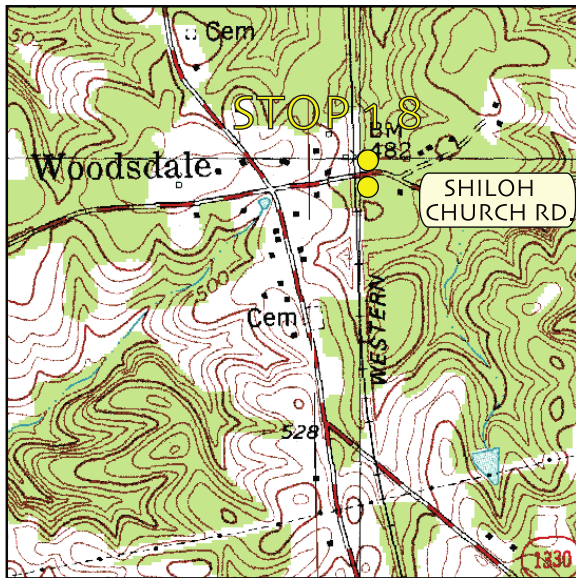


FIGURES 11 (LEFT) Residual boulder field of granite that is the typical geomorphological expression above the Roxboro pluton. FIGURE 12 (RIGHT): Residual Roxboro boulder camouflaged as a strawberry.

boulders being controlled by joints in the Roxboro Granite, whereas in other granitic bodies in the region intense foliations control weathering and inhibit the formation of core boulders.

STOP 1.8: COUNTRY LINE COMPLEX – TECTONIC SLIVERS OF CASWELL MAFIC-ULTRAMAFIC SUITE (HYCO ARC) AT THE SOUTHEASTERN MARGIN OF THE HYCO SHEAR ZONE: NORFOLK AND SOUTHERN RAILROAD TRACKS AT WOODSDALE, NC (36.4895°N, 78.9569° W). STOP LEADER: JIM HIBBARD

Here, at Woodsdale, NC, is the approximate area where the lateral ramp segment of the Hyco shear zone swings north-northeastward into the frontal ramp segment (Virginia segment). The mainly metaplutonic rocks of the Country Line Complex at this stop lie at the SE margin of the Hyco shear zone. The outcrop consists of coarse metagabbro-diorite interleaved with metapyroxenite, mafic schist, and fine-grained felsic rocks. Some of the felsic rocks may represent aplitic apophyses of the Roxboro Granite tectonically entrained into the complex.



from the Roxboro 7.5' quadrangle

Structurally, these rocks display a strong shear-related asymmetric fabric that indicates subhorizontal, dextral-extensional shear, typical of the upper zone of the Hyco shear zone. North of this outcrop, towards the state line, fabrics and kinematic indicators indicate thrust displacement of the Carolina terrane rocks over the Milton arc.



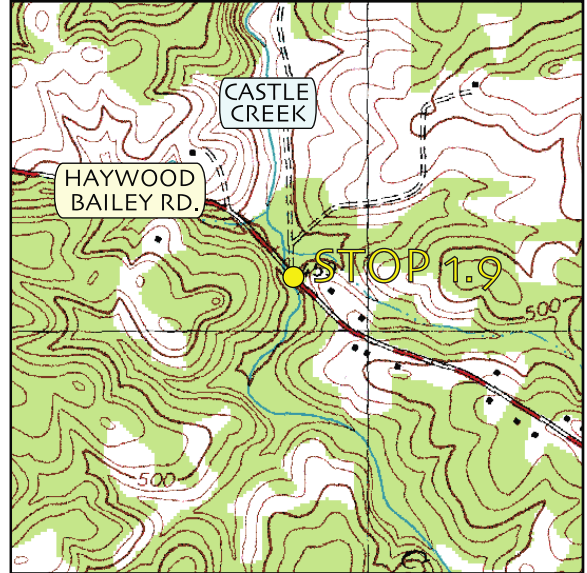
FIGURE 13: Outcrop at Stop 1.8. Shiloh Church Road crossing in background.



FIGURE 14: Coarse-grained pyroxenite at Stop 1.8.

The mafic-ultramafic rocks at this stop lithically resemble rocks of the Caswell mafic-ultramafic suite (Eades, 1988; Butler, 1989), a group of intrusive bodies associated with a large, unmapped area of mainly granitic plutons to the SSW of this stop. The Caswell suite intrudes part of the Hyco Formation (Wilkins et al., 1995) and is intruded by the *ca.* 612 Ma Osmond granite (unpub. notes), suggesting that rocks in this outcrop are also Ediacaran.

STOP 1.9: HYCO ARC - HYCO FORMATION FELSIC LITHIC CRYSTAL TUFF: HAYWOOD BAILEY RD. AT CASTLE CREEK (36°28'22.05"N, 78°56'13.05"W). STOP LEADER: JIM HIBBARD



from the Roxboro, NC 7.5' quadrangle.

Rocks here, less than 2 km from our previous stop, contrast sharply with the mafic-ultramafic rocks at that stop. Here the main rock type is a dacitic lithic-crystal tuff. We have crossed over the contact, likely tectonic, between the Country Line Complex and the Hyco Formation.

In this outcrop, the dacitic tuff contains clasts that superficially resemble fiamme; however, their shape is strongly linear, rather than flattened and their origin remains unclear (Fig. 15). The clast elongation lineation trends approximately 200/55; taken in conjunction with the composite asymmetric fabric present, it suggests a normal component of slip along the main foliation plane (045/72 SE). The significance of this kinematic interpretation is unclear. Low grade Hyco Formation rocks structurally overlie higher grade rocks of the Country Line Complex; although detailed metamorphic studies have not been undertaken, the contact between the two units appears abrupt and geologic intuition and our limited structural data suggest that an oblique normal fault intervenes. Perhaps the fabrics preserved here record such normal motion. Alternatively,

the lineation may be an older Carolina terrane lineation and the two foliations in the outcrop may be of very different ages.

Thinking back to earlier stops during the day, the contrast in structural style across the Hyco shear zone – i.e. between Stop 1.3 in the Milton terrane and this stop - is striking; the steep main foliation here is common to the Carolina terrane rocks in this region, in contrast to the subhorizontal foliation in the Milton terrane to the northwest across the Hyco shear zone.



FIGURE 15: Dacitic lithic crystal tuff at Stop 1.9; pencil lies subparallel to the clast lineation.

SUNDAY, NOVEMBER 5, 2017

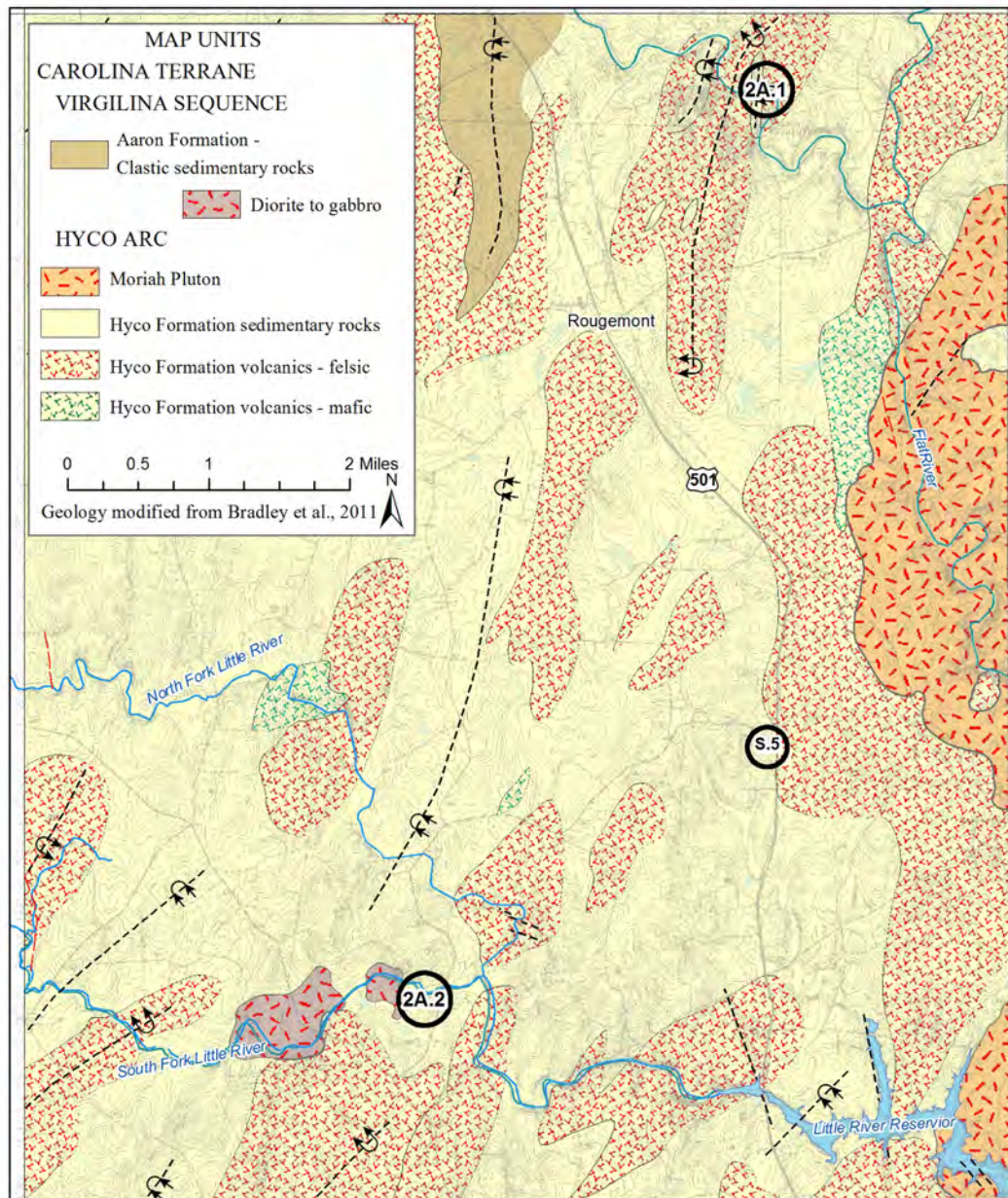
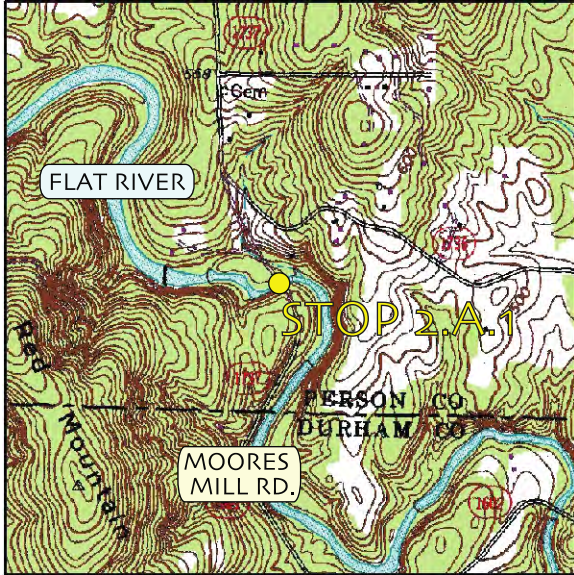


FIGURE 16: Portion of the geologic map of the Rougemont Quadrangle (Bradley et al., 2011) showing locations of field stops 2A.1, 2A.2, and S.5.

STOP 2A.1: HYCO ARC - DACITIC TUFFS AND VOLCANICLASTIC SEDIMENTARY ROCKS OF THE HYCO FORMATION, (36.2421°N, 78.9054°W) MOORES MILL ROAD AND THE FLAT RIVER. STOP LEADER: PHIL BRADLEY

This stop is located directly under the bridge at Moores Mill Road crossing of the Flat River. Private land is on either side of the DOT right-of-way and should be avoided. The stop is located near the northern end of Red Mountain, a prominent topographic feature in northern



from the Rougemont 7.5' quadrangle

Durham and southern Person Counties. The majority of Red Mountain is underlain by the ridge forming rock unit of *dacitic lavas and tuffs of the upper portion of the Hyco Formation (Zhdlt (u))* (Bradley et al., 2011) (Fig. 16).

Directly under the bridge, the main rock types are metamorphosed felsic tuffs that range from aphanitic to clast- and crystal-rich texture. Clasts are angular, dark gray to black fragments of dacitic lavas ranging from millimeter to several centimeters in size (Fig. 17). In hand sample, crystals are dominantly plagioclase crystal fragments. With the unaided eye or with hand lens, the groundmass is cryptocrystalline and display concoidal-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 many rocks with cryptocrystalline groundmass show a completely recrystallized groundmass consisting of a mosaic of primarily quartz and feldspar. Relict vitric texture is common



FIGURE 17: Hyco Formation felsic tuff containing lithic clasts of dacite; directly under the bridge at Stop 2A.1

in felsic tuffs, lavas and tuffaceous sedimentary rocks in the Hyco arc.

A few feet to the east of the bridge are outcrops of sandstones and conglomeratic sandstones. Volcaniclastic - sedimentary rocks are commonly interlayered in the lavas and tuffs units and appear to be in gradational contact with the dominantly volcaniclastic-sedimentary units and are interpreted to contemporaneous with active volcanism.

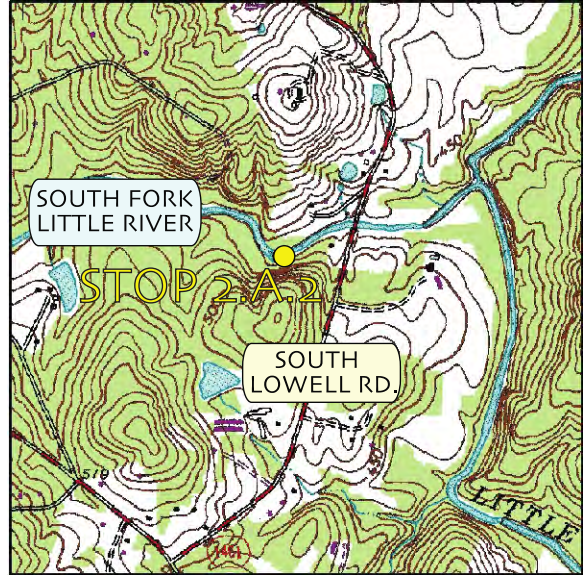
Elsewhere in the unit, metamorphosed dacites ranging from aphanitic to porphyritic texture and interlayered welded and non-welded tuffs are common. Locally, interlayers of immature conglomerate and conglomeratic sandstone with dacite clasts are present. The dacites are interpreted to have been coherent 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 of Bradley et al. (2011) (Fig. 16).

Wortman et al. (2000) reported that single zircons in a sample from beneath the bridge 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) members (informal) with an apparent intervening hiatus of magmatism (Bradley, 2013). 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; Bradley et al., 2016).

STOP 2A.2: HYCO ARC - TUFFACEOUS SILTSTONES OF THE HYCO FORMATION - VERMIFORMA ANTIQUA FOSSIL LOCALITY, (36.1491°N, 78.9491°W) SOUTH LOWELL ROAD AND THE SOUTH FORK OF THE LITTLE RIVER. STOP LEADER: PHIL BRADLEY

This stop is located on land owned by Durham County. Direct access to the outcrop is through land operated by Camp Riverlea for Children. Camp Riverlea should be contacted for access across their property. To access the stop through



from the Rougemont 7.5' quadrangle

Durham County land, enter the woods along the overgrown former road bed and walk toward the river. The path to the outcrop includes areas of downed trees, roots, loose and slippery rocks. Extreme care should be taken.

The stop is on the South Fork of the Little River within the *Mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas* (Zhe/pl) unit of Bradley et al. (2011) (Fig. 16). The unit contains metamorphosed conglomerate, conglomeratic sandstone, sandstone, siltstone and mudstone. Lithologies are locally bedded; locally tuffaceous with a cryptocrystalline-like groundmass. Siltstones are locally phyllitic and locally contain interbedded dacitic lavas and lesser amounts of fine- to coarse tuff and lapilli tuff with a cryptocrystalline-like groundmass. Minor andesitic to basaltic lavas and tuffs are present. Conglomerates and conglomeratic sandstones typically contain subrounded to angular clasts of dacite in a clastic matrix. The unit is interpreted to represent deposition from the erosion of contemporaneous proximal volcanic centers.

The rock types at the stop consists of thinly laminated (millimeter-scale) to thinly bedded (centimeter-scale); tuffaceous siltstones, sandy siltstones, silty sandstones and sandstones (Fig. 18). Soft sediment deformation features consisting of syn-sedimentary faults, folds, slumps and other features are common.

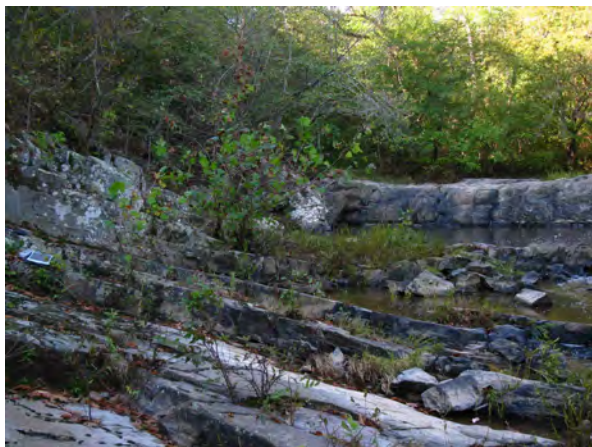


FIGURE 18: Bedded, low grade metasedimentary rocks that host *Vermiforma antiqua* at Stop 2A.2.

Primary bedding is well preserved and dips toward the northwest ranging from 15 – 25 degrees. A steeply dipping northeast striking cleavage is locally developed and is consistent with regional foliation and cleavage trends in the area. The location is interpreted to be located on the northwest limb of an anticline that is cored by the Zhdlt (dacitic lavas and tuffs unit) located to the east (Figure 16.).

In the 1970's, James Wright (then a graduate student from Virginia Tech (Virginia Polytechnic Institute and State University) found some interesting impressions at this location during geologic mapping activities associated with his thesis (Wright, 1974). Wright and Lynn Glover (his academic advisor) showed the impressions to Preston Cloud, an internationally known expert on early life forms. Cloud et al. (1976) later identified the impressions as *Vermiforma antiqua* (Fig.

19). At the time, this fossil was scientifically very significant and was identified as the oldest (ca. 620 Ma) yet known from North America.

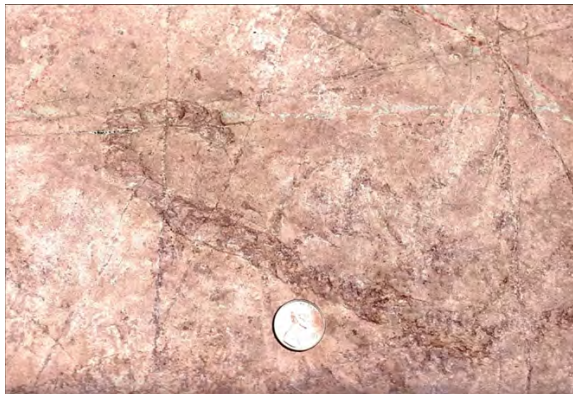


FIGURE 19: *Vermiforma antiqua* on bedding plane at Stop 2A.2; photo courtesy of Dr. Duncan Heron.

With the coordination of Duncan Heron (Duke University), the slab of rock containing the impressions was removed and transported to the U.S. Geological Survey in Reston, VA for display and examination. The original specimens are now part of the Smithsonian National Museum of Natural History Paleobiology collection. A small slab is in the collection of the North Carolina Museum of Natural Sciences and is on display in the Prehistoric North Carolina exhibit hall in Raleigh. Since the publication of Cloud et al. (1976), other Ediacaran fossils have been found in North America and the importance of the *Vermiforma antiqua* specimen found on the Little River has waned.

Cloud et al. (1976) interpreted the impressions as body fossils of possible worm-like organisms. The impressions were later re-interpreted as a trace fossil by several researchers (Fedonkin and Runnegar, 1992; McMenamin, 1998). McMenamin (1998) interprets that the impressions record the in-unison gradual movement of a group of sea pen-like organisms (with mucousy

holdfasts attached to the top of the sedimentary bed) with the prevailing currents. As the currents shifted, so did the group of organisms, thus creating the aligned impressions and similar sinuous forms (Figure 17).

Seilacher et al. (2000) indicates the impressions may be pseudofossils, called a tectograph, and not a true fossil. Seilacher interprets the impressions as being formed in already deposited beds that slid past one

another during folding with particles in the overlying bed etching the concentric marks. Chris Tacker and Patricia Weaver, with the North Carolina Museum of Natural Sciences, indicate that the *Vermiforma antiqua* impressions found at the site are likely true trace fossils (pers. comm., 2017); however, they indicated that they have not conducted their own research on the specimen, one small J-shaped tube, in the collection at the museum.

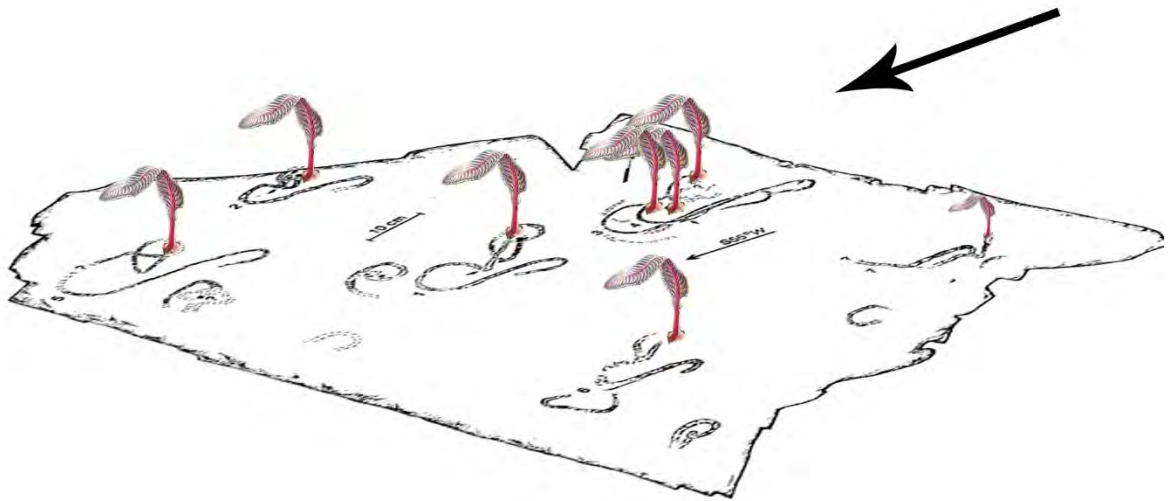


FIGURE 17: Cartoon showing interpreted mode of formation of *Vermiforma antiqua* impressions. Black arrow represents theoretical instantaneous current direction. Composite image created using sketch of *Vermiforma* slab (Cloud et al., 1976) and portion of image by Peter Trusler for the Australia Post.

STOP 2B: HYCO ARC - HAGER'S MOUNTAIN KYANITE OCCURRENCE: HAGER'S MOUNTAIN (36.4651°N, 78.9364°W). **STOP LEADER:** BRENT OWENS

From Rt. 501, take the Woodsdale Rd. north for approximately 1.4 mi (2.3 km) to an unpaved driveway on the west side of the road (Fig. 18). The driveway is just past the north end of a large solar array to

the west side of the road. Park on the east side of Woodsdale Road, opposite the driveway. Follow the driveway up and to the west to a sharp right bend that leads to the last residence on the driveway; at the bend, the trail to Hagers Mountain branches straight ahead from the driveway. From the Woodsdale Road to the top of Hagers Mountain is approximately 1 mi (1.6 km).



FIGURE 18: GoogleEarth image showing the access route to Hagers Mountain from Woodsdale Road. Solar panel array mentioned in text is the gray, roughly rectangular area on the left side of Woodsdale Road. Trail leading to Hagers Mountain is partially hidden by vegetation past the unpaved driveway.

Introduction

The southeastern portion of the Appalachian orogen is notable for an abundance of aluminosilicate-rich deposits, which may contain andalusite, kyanite, or sillimanite depending on metamorphic grade. Espenshade and Potter (1960) described most of these occurrences in detail, including aspects of their field relations and mineralogy. Only a few of the deposits have actually been mined, most notably in open-pit mines in kyanite quartzite at Willis Mt., VA (currently in operation), Baker Mt., VA (closed and reclaimed), Graves Mt., GA (closed), and Henry Knob, SC (closed).

Interpretations regarding the protoliths for these deposits have evolved over the years from relatively simple aluminous sandstones (e.g., Jonas, 1932; Jones and

Eilertson, 1954; Conley and Marr, 1980) to more complex models involving intensely altered volcanic rocks produced by leaching in acidic hydrothermal fluids (Carpenter and Allard, 1982; Schmidt, 1985; Ririe, 1990). Although the latter interpretation seems widely accepted, geochemical data that could be used to both test and elucidate details of such models have not been reported for most of these deposits. In a preliminary investigation at Willis and Baker Mts., VA, Owens and Dickerson (2001) first argued for the hydrothermally altered protolith model, based on mineralogical and chemical criteria. Owens and Pasek (2007) expanded on this work by evaluating the mineralogy and whole-rock compositions of nine separate occurrences of kyanite quartzite throughout the Piedmont Province of Virginia. Owens and

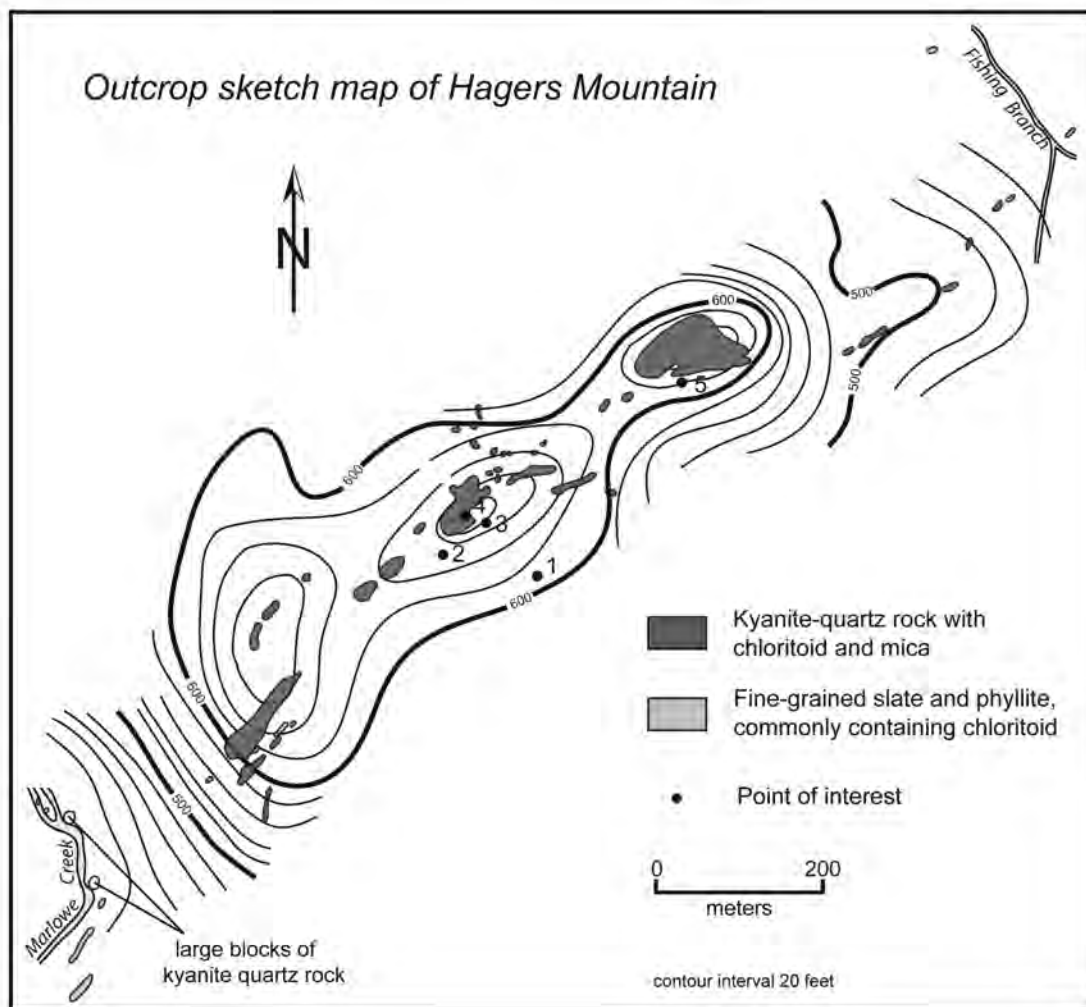


FIGURE 19. Outcrop map of the Hager's Mountain kyanite occurrence, Stop 2A.2, showing points of interest described in the text. Modified from Espenshade and Potter (1960).

Pasek (2007) reported a variety of observations and data to support an interpretation of hydrothermally altered protoliths, which were produced, specifically, in an advanced argillic (high-sulfidation) alteration system. Evidence for this interpretation included: 1) ubiquitous rutile in every sample, consistent with the breakdown of pre-existing Ti-bearing silicates and oxides; 2) major element compositions dominated by SiO_2 and Al_2O_3 , with concentrations of most other oxides (except TiO_2) near or below the limits of detection; 3) unusual ladle-shaped

REE patterns, which can also be found in other examples of hydrothermally altered rocks; and 4) an anomalous depletion of Ga relative to Al in many samples, a feature that apparently can only be achieved by alteration in highly acidic, sulfate-bearing fluids.

The study of Owens and Pasek (2007) was regional in nature, and included data for only a few samples from each of the investigated localities. In contrast, Owens and Wilson (2009) presented a more detailed geochemical investigation of a

similar occurrence at Hagers Mountain, NC (this trip). Although similar to occurrences in Virginia, some rocks at Hagers Mountain contain chloritoid [$\text{FeAl}_2\text{SiO}_5(\text{OH})_2$], a mineralogical contrast to rocks in Virginia that, in part prompted the Owens and Wilson (2009) study.

Overview of field characteristics, mineralogy, and geochemistry

Hagers Mountain forms a rugged ridge about one km long that rises about 50 meters above its surroundings (Fig. 19). Exposure is extensive along the main part of the ridge, with most outcrops consisting of quartz-rich rock. Surrounding rocks are primarily fine-grained, white to gray sericite schists. Typical fresh kyanite quartzite is fine-grained and remarkably white in color, and the white color of the kyanite makes it difficult to recognize in hand sample. This uncommon kyanite color is a feature these rocks share with many occurrences in Virginia, and probably reflects a very low Fe-content (Owens and Dickerson, 2001). Espenshade and Potter (1960) estimated that some rocks contain up to 30% kyanite, but also noted that many rocks contain much less. Chloritoid can locally be recognized in hand sample as small (≤ 0.2 mm across) dark green grains. In the kyanite quartzites, kyanite ranges in texture from typical bladed, elongate grains to highly irregularly-shaped masses of fine-grained kyanite and quartz. In some cases, larger bladed grains are partially to completely surrounded by these aggregates, reflecting some degree of recrystallization as a consequence of deformation. These textures and grain sizes for quartz and kyanite contrast strongly with occurrences in Virginia, which contain blocky kyanite (up to 4 cm long) and much larger (up to 10 mm across) quartz grains. These textural contrasts may be due to the location of Hagers Mountain on the fringes

of the Hyco shear zone. Rutile is a common accessory, occurring in small amounts in most samples.

Owens and Wilson (2009) distinguished three broad rock types at Hagers Mountain, including quartz-sericite schist, chloritoid-sericite quartzite, and kyanite \pm chloritoid quartzite. These types can also be distinguished chemically, and major element compositions of some typical examples are listed in Table 1. Also included for comparison in this table is an analysis of a typical Hyco Formation metarhyolite (Kreisa, 1980). The chloritoid-bearing rocks contain higher Fe than the kyanite quartzites that lack this mineral.

Based on geochemical evidence, Owens and Wilson (2009) interpreted the rocks here to represent hydrothermally altered protoliths, with the extent of alteration increasing from quartz-sericite schist \rightarrow chloritoid-sericite quartzite \rightarrow kyanite-chloritoid quartzite \rightarrow kyanite quartzite. Evaluation of mass losses in the protoliths indicates slight ($\sim 3\%$) to extensive ($\sim 32\%$) leaching of various elements.

Points of interest

This stop requires an initial ~ 1.5 km walk from the main road the last part of which is somewhat steep (but not difficult). Points of interest are shown on the sketch map of Figure 19.

1. (N4037181, E681922) A spot on the trail to observe typical chloritoid-bearing rock. Here are some small pieces broken from a larger float block. Also in this area are numerous blocks of kyanite quartzite in the woods on both sides of the trail. The rock has a peculiar, "bumpy" texture (Fig. 20), the origin of which is not clear. Owens and Wilson (2009) did not investigate this



FIGURE 20. Peculiar 'bumpy' texture that is common in the Hagers Mountain alteration zone at Stop 2B.

texture specifically – we can debate it on the trip!

2. (N4037210, 681868) We have walked over a lot of schistose Hyco Formation saprolite in the trail, but here near the top are abundant exposures of actual bedrock. Sample HM06-10 (Table 1) was collected here by Owens and Wilson (2009). The composition is similar to Hyco Formation rhyolite, but with slightly less alkalis.

3. (N4037262, E681946) Here on the east side of Hagers Mt. is an area with abundant chloritoid-bearing rock (mostly float). Also present here are some low outcrops of Hyco Formation greenstone.

4. (N4037296, E681926) Top of Hagers Mt. (there is a benchmark at the top). The

climb to the top here is short, but not exactly easy – use your best judgement as to whether you can manage it. The view from the top is excellent, and at this time of year should be a full 360°! On fresh surfaces here, kyanite can be observed glistening in the right sunlight.

5. (N4037424, E682146) East side of the northernmost topographic high. This spot is one of the better (although still challenging) places to observe kyanite (Fig. 21). It can be seen in the numerous, fresh broken pieces, but only with patient observation using a hand lens. It can also be seen in a nearby, flat-lying, rectangular-shaped block.



FIGURE 21. Bladed, colorless to whitish gray kyanite crystals at Point of Interest 5.

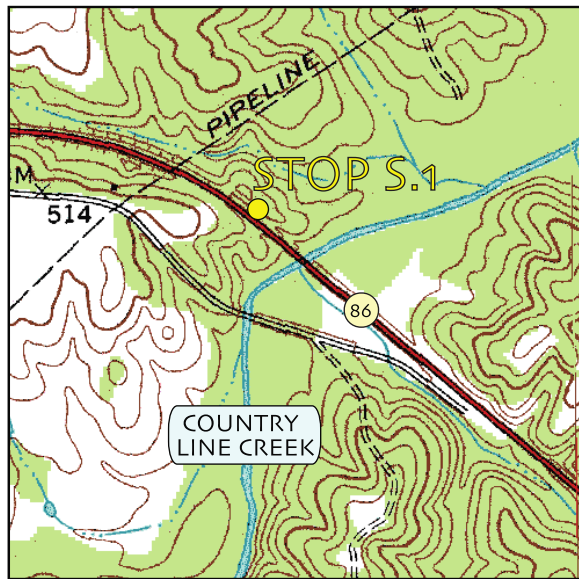
TABLE 1. WHOLE-ROCK MAJOR ELEMENT COMPOSITIONS OF SELECTED HAGERS MT. SAMPLES AND ONE HYCO FORMATION METARHYOLITE (FROM KREISA, 1980).

(b.d. = below detection limit; n.d. = not determined)

Sample	Kreisa, 2	HM06-10	HM06-7B	HM06-3	HM06-6
Rock type	Hyco Formation	qtz-sericite schist	chloritoid- sericite qtzite	ky-chloritoid qtzite	kyanite qtzite
SiO ₂	73.42	77.50	79.06	71.64	79.95
TiO ₂	0.27	0.34	0.47	0.52	0.34
Al ₂ O ₃	13.97	14.50	13.89	24.64	17.76
Fe ₂ O ₃ (T)	2.06	2.34	1.56	2.02	0.06
MnO	0.06	b.d.	0.06	0.01	b.d.
MgO	0.51	b.d.	b.d.	0.01	b.d.
CaO	0.64	0.04	0.15	0.01	b.d.
Na ₂ O	3.10	1.30	1.58	0.21	b.d.
K ₂ O	3.53	2.20	1.02	0.16	b.d.
P ₂ O ₅	n.d.	0.02	0.01	0.63	0.18
LOI	2.46	1.83	1.75	0.63	0.19
Total	100.02	100.30	99.50	100.48	99.20

FIELD GUIDE TO SUPPLEMENTARY STOPS:

STOP S.1: HYCO SHEAR ZONE – GARNETIFEROUS SEMIPELITIC SCHIST OF THE COUNTRY LINE COMPLEX: RT. 86 ON NORTH SIDE OF COUNTRY LINE CREEK (N36°24.304', W079°17.917')



from the Yanceyville 7.5' quadrangle

Semipelite is an uncommon rock type in the Country Line Complex, which is dominated by mafic and granitic, layered gneisses such as those seen at Stop 1.2. We include this stop in order to record the location and description of this rock type in the complex as well as to remind participants about geo-vandalism. In recent years, the outcrop has been greatly diminished by geo-vandalism.

The medium grained semipelite is composed mainly of $\text{Bio}+\text{Ms}+\text{Pl}+\text{Qtz}+\text{Gnt}$, with porphyroblasts of garnet commonly 2mm across, but locally up to 2 cm across. Shell (1996) reported small sillimanite fibers in plagioclase at this stop. In this vein, it is interesting to note that this outcrop is less 2 km north of Pleasant Grove chloritic phyllites (such as those

seen at Stop 1.1). Clearly, displacement along the Hyco shear zone is responsible for this somewhat abrupt metamorphic juxtaposition.

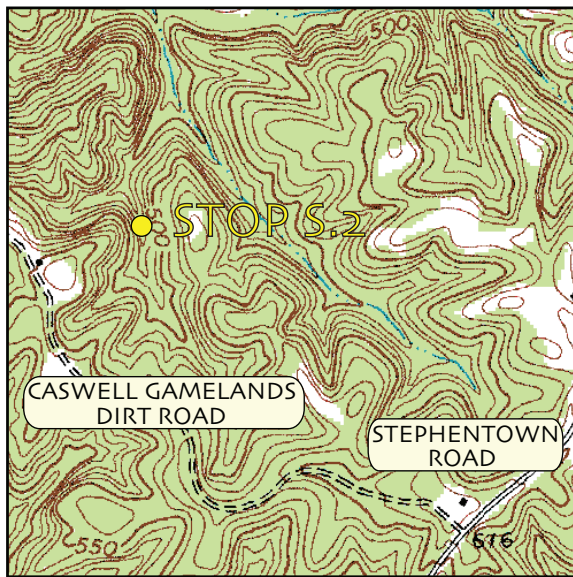
When we first found this outcrop (Fig. 22) in the early 1990's, garnets up to 1 cm across were fairly common and visible on the outcrop. However, since that time, the outcrop has been dramatically reduced in size and pillaged, presumably by garnet collectors. Small garnet porphyroblasts remain, but are not readily obvious. The irresponsible actions of these collectors amounts to vandalism of this outcrop, such that other geologists can no longer view it. Although not a classic outcrop, it was an important one for the area and for geologists to view. The outcrop cannot be replaced; however it can serve as a lesson in outcrop etiquette. Common sense and responsible measures can ensure that an outcrop will be useful to future groups, and are worth repeating here:

- **Always approach an outcrop with the consideration that others will want to see it.**
- **Collect from loose samples or from inconspicuous parts of an outcrop.**
- **Do not make 'mass collections' for teaching laboratories from 'the wild'; there are plenty of commercial outlets for these purposes.**
- **Refrain from pointless hacking and banging at an outcrop. Use your eyes and minimize the use of hammers.**
- **Teach students about 'field responsibility'.**



FIGURE 22. Garnetiferous biotite-muscovite-quartz semipelite of the Country Line Complex at Stop S.1.

STOP S.2 HYCO ARC - HIGH ROCK GRANITE WING IN THE HYCO SHEAR ZONE: ALONG A FEEDER BRANCH TO COUNTRY LINE CREEK, CASWELL GAMELANDS (36.4287°N, 79.2469°W).



from the Leasburg, NC 7.5' quadrangle

From Stephentown Rd., follow a Caswell gamelands dirt road almost a mile northwest to a gate (usually locked) and a small parking area (near small black square on stop map, above). Park in this area, contour the hill to the northeast and drop down to this outcrop an unnamed tributary of Country Line Creek (Fig. 23). The main body of the High Rock pluton is described



FIGURE 23. Exposures of the High Rock granite wing at Stop S.2.

at Stop 1.1 (this guidebook); this stop is in the granite wing, where it is only a couple hundred meters wide. You may need to remove moss and other vegetation to view the best outcrop faces.

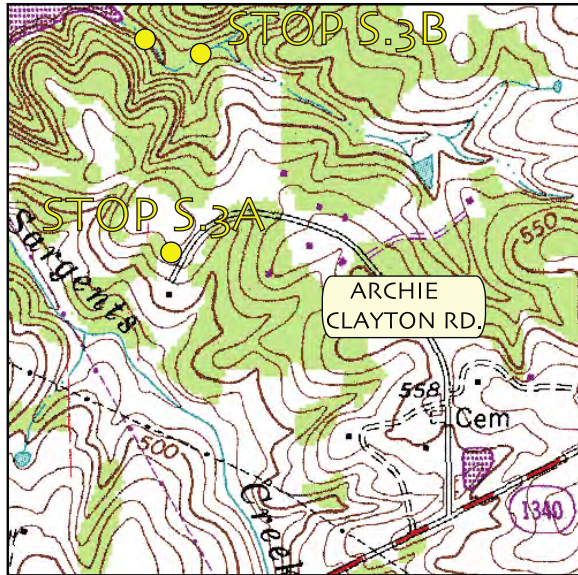
Granite at this outcrop is mylonitic (grain size reduced and strongly foliated) and displays a striking shear-related asymmetric foliation. The shear bands in the outcrop offset an earlier mylonitic fabric and they are sub-parallel to normal slip crenulations in the country rocks to the north in the shear zone (Fig. 24). Typical of the east-west-trending segment of the Hyco shear zone, the shear-related fabrics indicate dextral shear along a shallowly



FIGURE 24. Mylonitic High Rock granite displaying a strong mylonitic foliation overprinted by dextral shear bands at Stop S.2.

west-plunging mineral lineation defined by stretched quartz and feldspar and biotite smears.

STOP S.3: ROXBORO GRANITE -EVIDENCE FOR THE VIRGILINA DEFORMATION: A. ARCHIE CLAYTON RD. (36.4591° N, 79.0575° W) B. SMALL BRANCH OF SARGENTS CREEK (36.4592° N, 79.0531° W).



from the Olive Hill 7.5' quadrangle

These two locales display the relationship between the Roxboro Granite and its Hyco Formation host rocks; both provide evidence for the Neoproterozoic Virgilina deformation.

Stop 3A. Archie Clayton Rd. Since the section of this road with the pavement outcrops of interest was gated, the exposures are being overgrown by vegetation. Multiple, rubbly pavement exposures of the Roxboro Granite enclose enclaves of metagabbro and biotite-rich phyllite. The granite is overprinted by a weak foliation, whereas the enclaves display a stronger foliation that is not concordant with that in the surrounding granite (Fig. 25). These relations indicate that the enclaves were



FIGURE 25. Foliated biotite phyllite enclave (beneath hammer head) in contact with Roxboro Granite (beneath most of hammer handle). Note that a weak foliation in the granite (oriented suborthogonal to hammer handle) is oblique to the strong foliation in the enclave.

deformed prior to incorporation into the *ca.* 547 Ma Roxboro Granite.

Stop 3B. Tributary to Sargents Ck. This section of the tributary (Fig. 26) exposes discontinuous outcrops of Roxboro Granite, quartz diorite (both possibly related to the Roxboro Granite), and strongly foliated Hyco Formation felsic gneiss and metavolcanics. The felsic gneiss (Fig. 27) appears to be an intensely foliated fragmental felsic volcanic rock. The Roxboro exposures range from undeformed to weakly foliated. The contact between the intrusive rocks and the Hyco volcanics and gneiss is unexposed, but strongly foliated felsic metavolcanic rocks outcrop within a meter of undeformed Roxboro Granite (Fig. 28). We interpret the granite as intrusive into foliated felsic volcanic rocks and gneiss. The Roxboro Granite has yielded a U-Pb zircon age of *ca.* 547 Ma, whereas zircon separated from the foliated Hyco felsic gneiss has been dated at *ca.* 620 Ma (Wortman et al., 2000). These observations, interpretations, and age data collectively indicate that the Hyco Formation was penetratively deformed in the Ediacaran, between *ca.* 620 - 547 Ma.

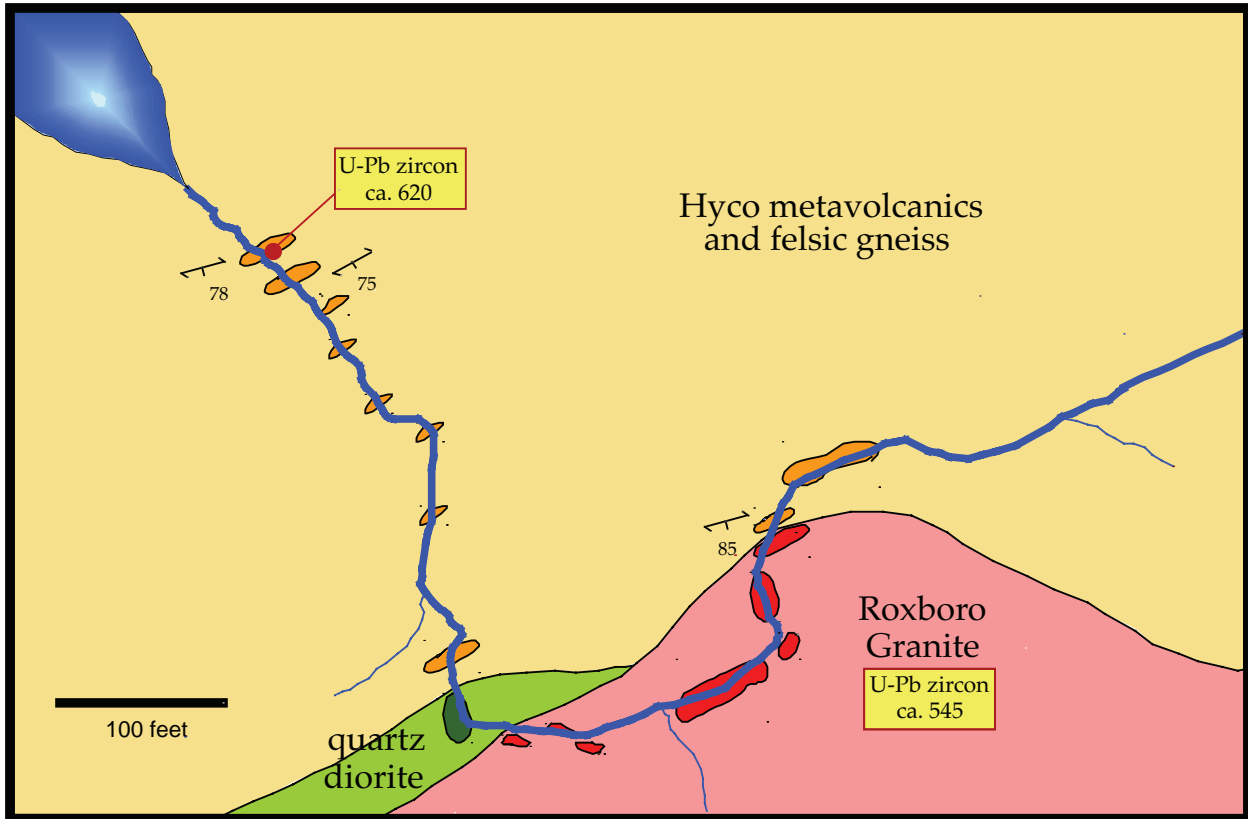


FIGURE 26. Outcrop map of the tributary to Sargents Creek at Stop S.3B. For location see two yellow dots on stop location map for Stop S.3B.



FIGURE 27. Strongly foliated felsic gneiss of the Hyco Formation dated at *ca.* 620 Ma. Ambiguous clast-like forms and feldspar and quartz crystals (not visible in photo) suggest a lithic crystal tuff protolith for this rock. Stop S.3B.



FIGURE 28. Undeformed Roxboro Granite that is approximately 1m from foliated Hyco Formation felsic volcanics. Stop S.3B.

STOP S.4: HYCO SHEAR ZONE - COUNTRY LINE COMPLEX AT INTAKE CANAL AT THE INTERSECTION OF WHETSTONE BRANCH WITH SHORE RD. BRIDGE (36°29'26.93"N, 79°02'50.14" W).

- Please be careful along the edge of the outcrop, as it drops off precipitously into the canal. •



from the Olive Hill 7.5' quadrangle

These exposures show typical mafic and granitoid gneisses of the Country Line Complex. They are located beneath both sides of a bridge that spans the CPL power plant intake canal at Whetstone Branch; the water is used for cooling purposes at the 10th largest coal-burning plant in the USA. The outcrops consist mainly of medium-grained amphibolite and mafic gneiss with concordant layers of grain-size reduced and disaggregated granitic pegmatite (Fig. 29). Locally, the pegmatitic layers are slightly oblique to layering in the mafic gneiss.

Structurally, the layering and the main foliation of the shear zone are folded by late phase folds with a 'Z' downplunge asymmetry. The fold axes trend subparallel to the regional mineral stretching lineation in the shear zone. Hibbard et al.



FIGURE 29. Interlayered mafic and disaggregated pegmatite typical of the Country Line Complex. West side of Whetstone Branch at Stop S.4.

(1998) suggested that this geometry results from a combination of initial folding of layers with a steep attitude along the lateral ramp segment of the Hyco shear zone and subsequent rotation of fold axes by shearing within the zone.

If the small stream that feeds into the canal at this site is relatively dry, visitors can see a brittle-ductile fault with associated pseudotachylyte (Fig. 30). These features appear to be related to a late brittle fault zone that strikes approximately parallel to the canal immediately west of this site. Along that segment of the canal, the rocks record abundant evidence late brittle mobilization, including the retrogression of normally amphibolite facies rocks to a chloritic assemblage, abundant carbonate-filled joints, and abundant brittle fractures with normal slip components. This deformation may be related to Mesozoic extension, as fresh diabase dikes of probable Early Jurassic age are truncated by faults along the canal (Fig. 31). Alternatively, it could be younger, as similar EW trending zones in the Blue Ridge of NC are still seismically active (Stewart and Dennison, 2006).



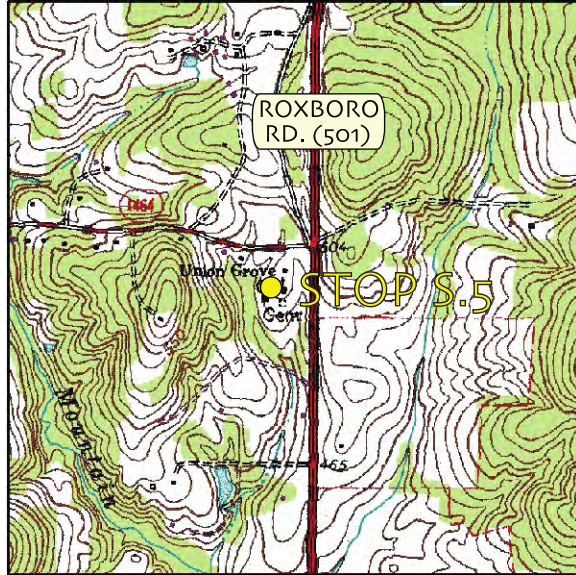
FIGURE 30. Black-burgundy fine-grained pseudotachylyte (couple of inches below quarter) along a small brittle fault at Stop S.4.



FIGURE 31. Greg Wortman points to a steeply dipping Mesozoic dike (dark brown) that is truncated and slightly dragged by a brittle fault just above the waterline. Along intake canal to the west of Stop S.4.

STOP S.5: HYCO ARC - HYCO FORMATION TUFFACEOUS CONGLOMERATIC SANDSTONE AND CONGLOMERATE (36. 1755°N, -78. 9051°W), UNION GROVE CHURCH, ROXBORO RD. (HWY. 501). **STOP LEADER: PHIL BRADLEY**

This stop is located immediately north of the Union Grove Church building. Please be respectful of the Church and limit the use of hammers at the location. There are multiple rounded fins of outcrop and float cobbles to view the texture of the rock.



from the Rougemont 7.5' quadrangle

This stop is near the contact of Hyco Formation sedimentary rocks with Hyco Formation volcanics (Fig. 16). The outcrops at the stop are part of the *Mixed epiclastic-pyroclastic rocks with interlayered dacitic lavas* (Zhe/pl) unit of Bradley et al. (2011). The unit contains metamorphosed conglomerate, conglomeratic sandstone, sandstone, siltstone and mudstone. Conglomerates and conglomeratic sandstones typically contain subrounded to angular clasts of dacite in a clastic matrix. The unit is interpreted to represent deposition from the erosion of contemporaneous proximal volcanic centers. The low ridge immediately to the east across Hwy. 501, is underlain by Hyco Formation volcanics consisting of interlayered dacitic lavas and tuffs (Fig. 16).

The rock types at the stop consists of conglomeratic sandstones and conglomerates consisting dominantly of sub-angular to angular clasts of dacites (Fig. 32). Outcrop fins strike northeast and are steeply dipping – typical of Hyco formation outcrops (Fig. 33).

Detailed geologic mapping in the area, indicates the common presence of coarse-grained sediments similar to this location along the edges of the map-scale bodies of Hyco Formation volcanics. These outcrops are interpreted to represent the contemporaneous proximally deposited erosional debris (or re-sedimented hyaloclastite debris) of a nearby dacite dome (the rocks of the resistant ridge to the east).

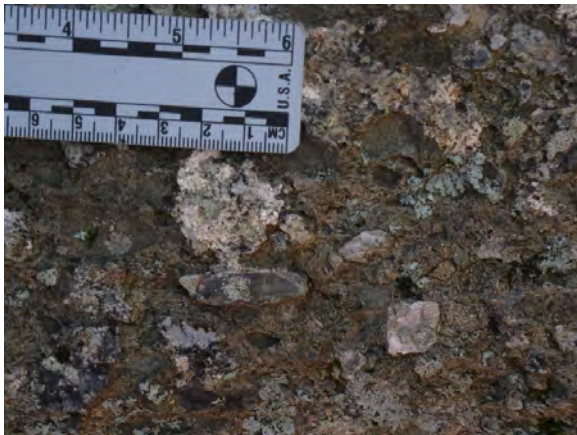
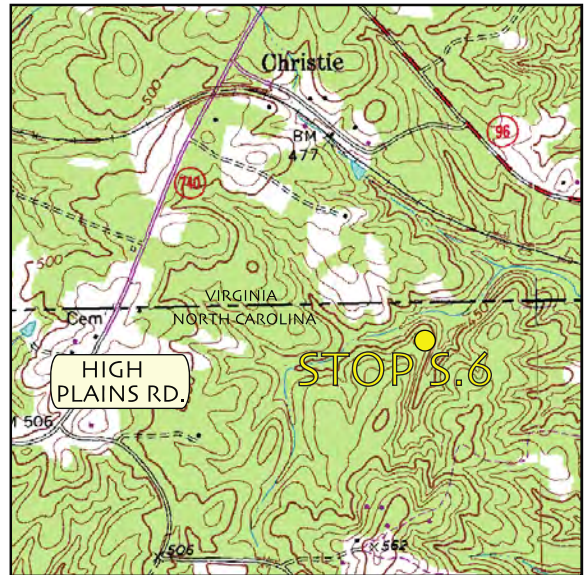


FIGURE 32. Close-up of outcrop surface showing abundant sub-angular to angular clasts of dacite at Stop S.5.



FIGURE 33. Outcrop fins of conglomerate at Stop S.5. Steeply dipping finned outcrops are typical of Hyco Formation outcrops. Red arrow indicates gray-colored 6-inch long scale.

STOP S.6: VIRGININA SEQUENCE – AARON CONGLOMERATE ON EASTWOOD DRIVEWAY, JUST SOUTH OF VIRGINIA-NORTH CAROLINA STATE LINE. (36.5402° N, 78.8353°W). STOP LEADER: JIM HIBBARD



from the Virgilina 7.5' quadrangle

This outcrop is located along the unpaved driveway of Howard Eastwood; his brother Larry lived at the end of this long driveway until his recent passing. The turn for the driveway is just south of the Virginia – North Carolina state line, east off of High Plains Rd.

This stop is a typical exposure of the Aaron conglomerate, part of the Virgilina sequence that disconformably overlies the Hyco Formation. A *ca.* 24 m.y. hiatus separates the Hyco and Aaron formations. Stratigraphically, the conglomerate is just above the base of the Aaron Formation on the west limb of the Virgilina synclinorium (back cover). In this exposure, the rounded to subrounded clasts range in size up to 10 cm long and are mainly composed of vein quartz, quartzite, jasper, magnetite rich rock, and felsic volcanics and volcanoclastics (Fig. 34). Most of the clasts can be

matched to rock types in the underlying Hyco Formation; in particular, the jasper and magnetite rich clasts are reminiscent of an iron formation sequence in the Hyco Formation near Butner, NC.

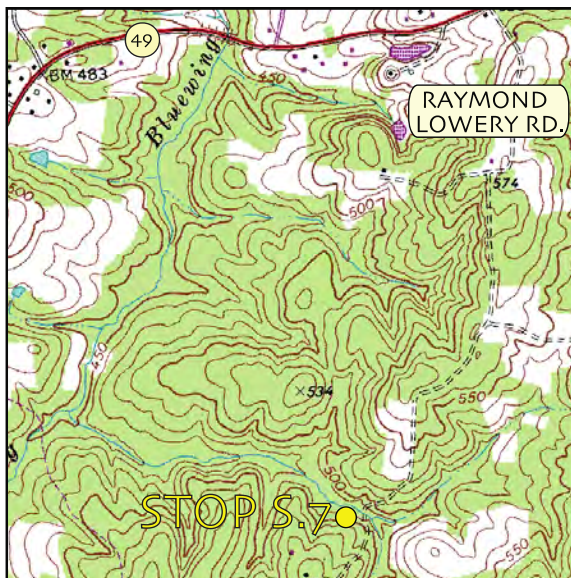
The conglomerate is overprinted by a pressure solution cleavage that renders the clasts as oblate forms; nested clasts, are common as a result of the pressure solution cleavage. Locally, quartz veins that are suborthogonal to the steep cleavage cut across the conglomerate. The orientation of these veins is kinematically compatible with an origin syntectonic with cleavage formation and the veins may represent fluid paths for material dissolved during cleavage formation

The tectonic setting of the Virgilina sequence is unknown and it is a ripe question that could be answered with specialized studies of rocks in the sequence such as this conglomerate and the mafic Virgilina volcanics.



FIGURE 34. Aaron conglomerate at Stop S.6.

STOP S.7: VIRGILINA SEQUENCE - VIRGILINA MEMBER VOLCANIC CONGLOMERATE: TRIBUTARY TO BLUEWING CREEK JUST UPSTREAM FROM WHERE IT CROSSES RAYMOND LOWERY RD. (36.5043°N, 78.8269°W).



from the Virgilina 7.5' quadrangle

This stop displays a typical representative of the Virgilina volcanics on the east limb of the Virgilina synclinorium. The volcanics form a member that is sandwiched within the Aaron Formation clastic sedimentary rocks. This outcrop displays a fragmental rock that has a mafic – intermediate volcanoclastic matrix with matrix-supported epidote-rich volcanoclasts that range up to a meter in length (Fig. 35). We interpret it to be a volcanic conglomerate. This rock forms a marker unit in the local area that can be traced northwards into Virginia.

The outcrop has a distinct L>S fabric that imparts a strong ‘streaky’ aspect to the clasts when viewed on the foliation plane. Unlike lineations associated with the Hyco shear zone, the lineation here is steeply plunging to near vertical. The attitude of the lineation with respect to the Virgilina synclinorium is the classic ‘a’ type lineation of older structural geology texts; we suggest that the lineation here formed as a result of the regional folding, which has been interpreted to be a result of the Virgilina deformation (Glover and Sinha, 1973).



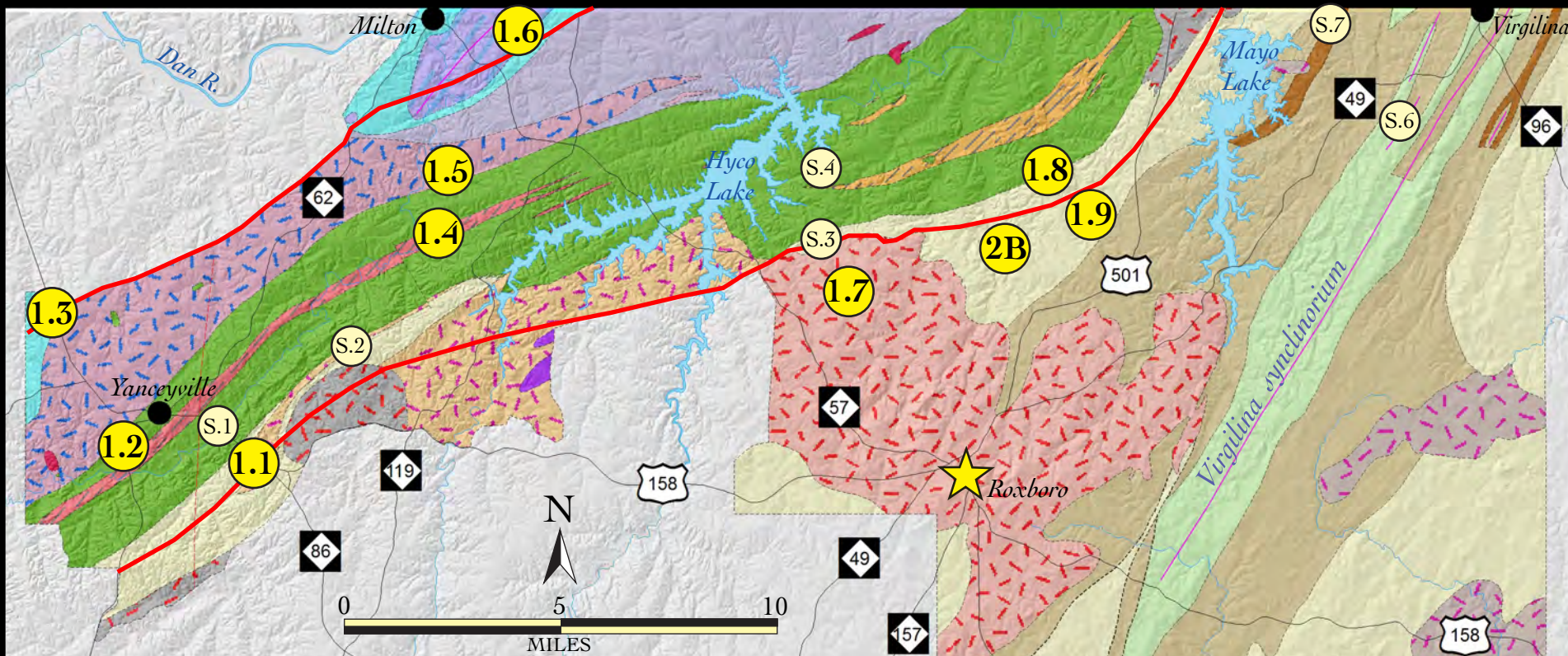
FIGURE 35. The Virgilina volcanic member outcrops as large fins at Stop S.7. This view is looking at the foliation plane; notice the strong, near vertical streaking which is the result of clast elongation that is attributed to the Virgilina deformation (Glover and Sinha, 1973).

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ALLEGHANIAN GRANITOIDS (ca. 335-319 Ma)

- Farmers Lake granite
- Kilgore granite/gneiss
- Yanceyville orthogneiss
- Approximate boundary of the Hyco shear zone

MILTON ARC (ca. 470-450 Ma)

- Connally Church gneiss
- Cunningham Complex
- Milton schist & paragneiss

COUNTRY LINE COMPLEX (ca. 620-325 Ma)

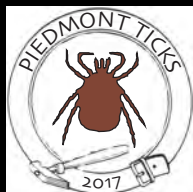
- unseparated granitic gneiss
- mainly mafic gneiss

CAROLINA TERRANE

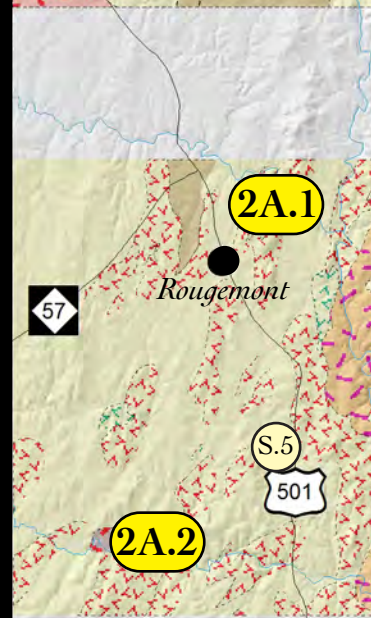
- unseparated granitoids
- ALBEMARLE ARC (ca. 555-525 Ma)**
- Roxboro granite
- VIRGINIA SEQUENCE (ca. 578-555 Ma)**
- AARON FORMATION**
- Virginia volcanics
- Aaron clastic sedimentary rocks
- Aaron cong.

HYCO ARC (ca. 633-612 Ma)

- HYCO FORMATION**
- felsic volcanics
- mafic volcanics
- unseparated volcanic/volcaniclastic rocks
- granitoids
- Caswell suite



- Trip stop
- Supplemental stop



**2017
CAROLINA
GEOLOGICAL
SOCIETY
FIELD
STOP MAP**