STRUCTURAL ANALYSIS OF METASEDIMENTARY AND METAVOLCANIC UNITS IN UWHARRIE NATIONAL FOREST: DETERMINATION OF A POSSIBLE FOLD STRUCTURE

by

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ABSTRACT

ANDREW ALAN SPATZ. Structural Analysis of Metasedimentary and Metavolcanic Units in Uwharrie National Forest: Determination of a Possible Fold Structure. (Under the direction of DR. ANDY R. BOBYARCHICK)

Cambrian metasedimentary and metavolcanic rocks in the Albemarle Group in south-central North Carolina are part of the peri-Gondwanan Carolina terrane. These rocks are part of the Neoproterozoic to Cambrian Albemarle arc. The tectonothermal imprint left by mid-Paleozoic orogeny is represented by greenschist facies metamorphism and generally northwest-dipping slaty cleavage that is approximately axial planar to regional folds. These folds verge toward the southeast. We have investigated very detailed cleavage-bedding relationships in the Tillery and Cid formations of the Albemarle Group in Uwharrie National Forest, North Carolina. These relationships were used to determine a characteristic fold geometry that explains local, sometimes sharp variations in bedding attitudes, and to apply these results to a postulated but previously undetected doubly-plunging antiform outlined by two horseshoe-shaped metavolcanic units previously mapped as either one unit in the upper part of the Tillery Formation or as two different units in the upper Tillery and lower Cid formations. We propose that this outcrop pattern is the effect of the closures of a doubly-plunging anticline. Our spatial statistics suggest that the geometrical exemplar for primary folds is steeply inclined to overturned, verges southeast, and plunges moderately northeast-southwest. Pervasive cleavage, while anastomosing, is axial planar to these folds. Previous mapping of the lower contact(s) between metavolcanic and metasedimentary rocks often show that this contact follows topographic contours, suggesting low dip angles. We have remapped this contact and found that in many locations the contact can be placed farther upslope in ephemeral stream valleys, thus changing map projections to better represent dips controlled by folding. Where the contact coincides with fold hinges, however, it is possible for the contact to be locally horizontal. Our conclusion is that the map geometry may reflect folding of a single volcanic unit (though more geochemical analysis is needed), that together with stratigraphically lower argillite composes the main doubly plunging, northeast-southwest anticline.

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1 INTRODUCTION

1.1 General Statement

The Albemarle Group in south-central North Carolina is composed of Neoproterozoic to Cambrian metasedimentary and volcanic rocks of the Carolina Terrane (Secor et al., 1983). All rocks in the Albemarle sequence were deposited proximal to the Amazonian craton and tectonically active western margin of Gondwana (Hibbard et al., 2001; Pollock et al., 2010). Because of precious metal content in volcanogenic massive sulfide deposits and veins, the structural geology of this group has been fairly well studied in areas rich in economic minerals (LaPointe and Moye, 2013). The focus of this study is structural analysis of a fold or fold group in the Albemarle Group south of the Cid ore district (Fig. 1) in the Uwharrie National Forest in North Carolina. This area includes volcanic and sedimentary parts of the Tillery and Cid formations, that are in the lower part of the Albemarle Group (Fig. 2). The investigation specifically analyzes cleavage and bedding geometric relationships across the study area and how those relationships suggest the existence of a large, doubly-plunging anticline.

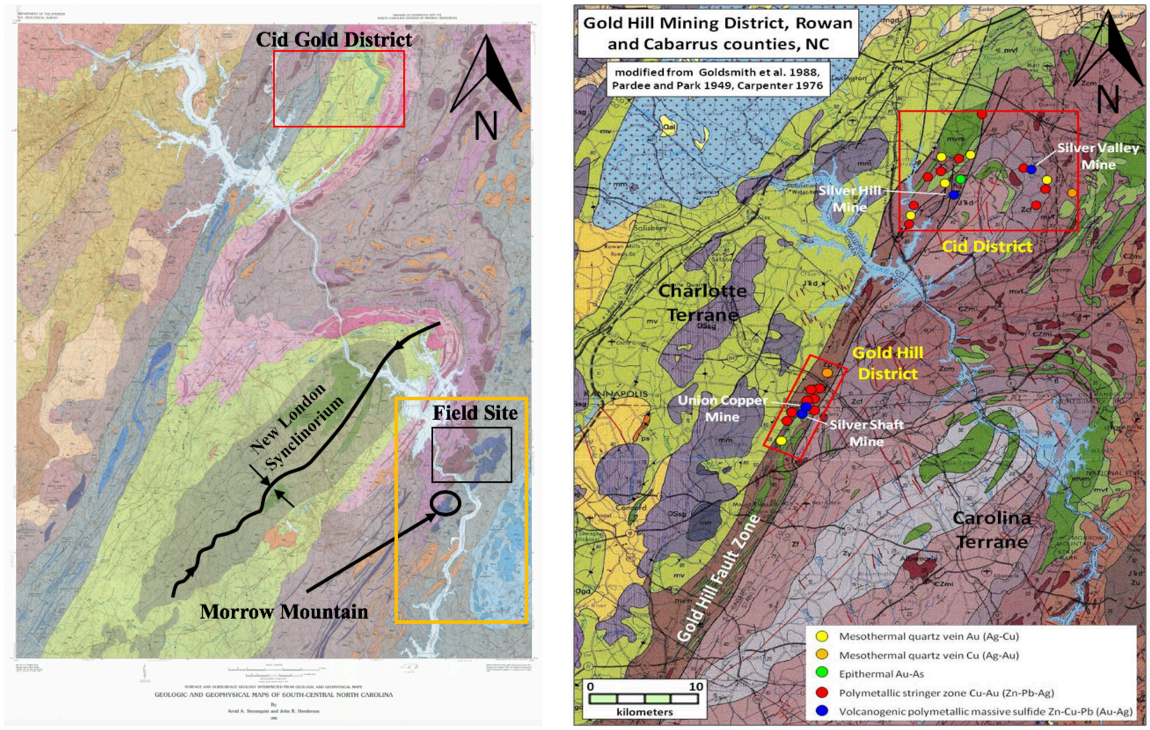

Figure 1 – Left: Geologic map of south-central North Carolina from Stromquist and Henderson (1985), with the Cid Gold District highlighted in red, area previously mapped by Conley and Bain (1965) in orange, and field site of this study in black.
Right: Mines in the Cid and Gold Hill districts (LaPoint and Moye, 2013).

Albemarle Group	Age constraints
Yadkin Graywacke	528 ma
Floyd Church Formation	540 +/- 7 ma
Cid Formation -Flat Swamp Member -Unnamed Mudstone Member	539 +/- 5 ma
Tillery Formation	552 ma

Figure 2 – Stratigraphy of the Albemarle Group (Stromquist and Sundelius, 1969). Ages from Milton (1984).

1.2 Introduction to Study Area and Problem Statement

The study area (Fig. 3) is in the central part of the Carolina terrane in North Carolina and lies within Uwharrie National Forest (Fig. 4). The area includes sedimentary and volcanic rocks of the Tillery and Cid formations. The national forest covers roughly 20,700 hectares in Davidson, Montgomery, and Randolph counties in North Carolina (Conlon, 2014), and is fragmented by privately owned rural lands (Suttles, 2017).

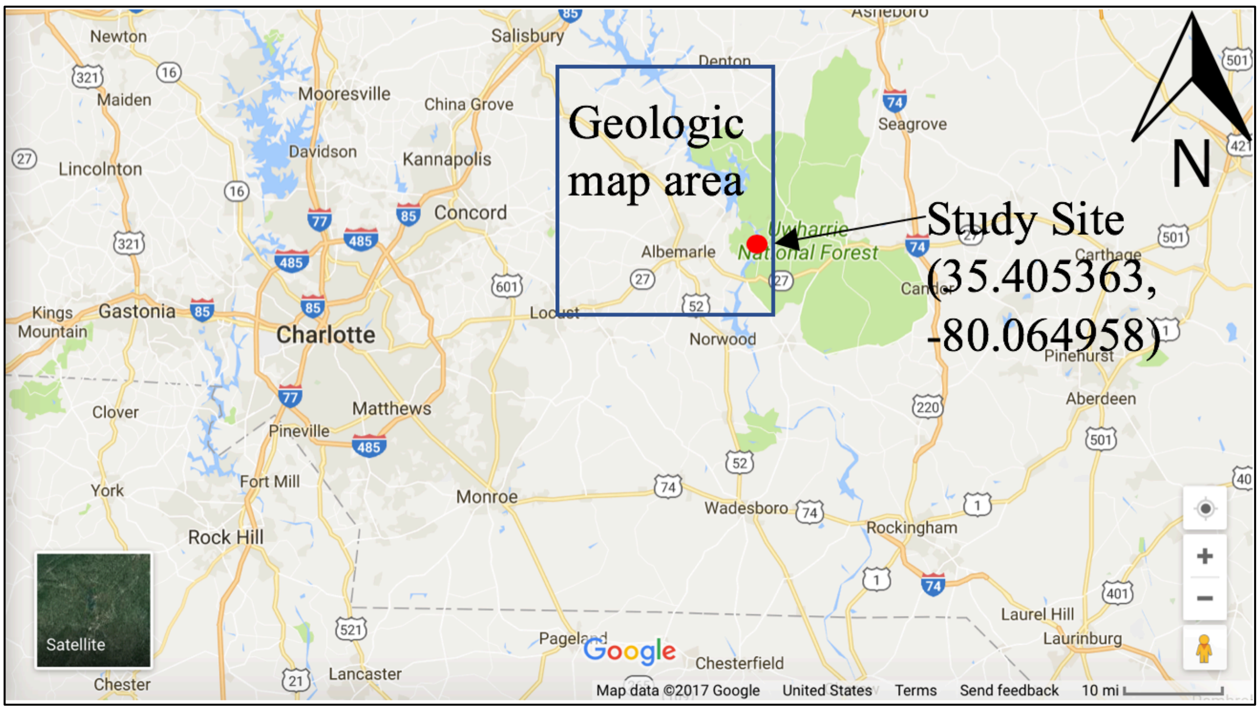

Figure 3 - Location of the geologic maps done by Conley and Bain (1965), later revised by Stromquist and Henderson (1985), and study site with respect to south central North Carolina. Base map from Google Earth (Google, 2019).

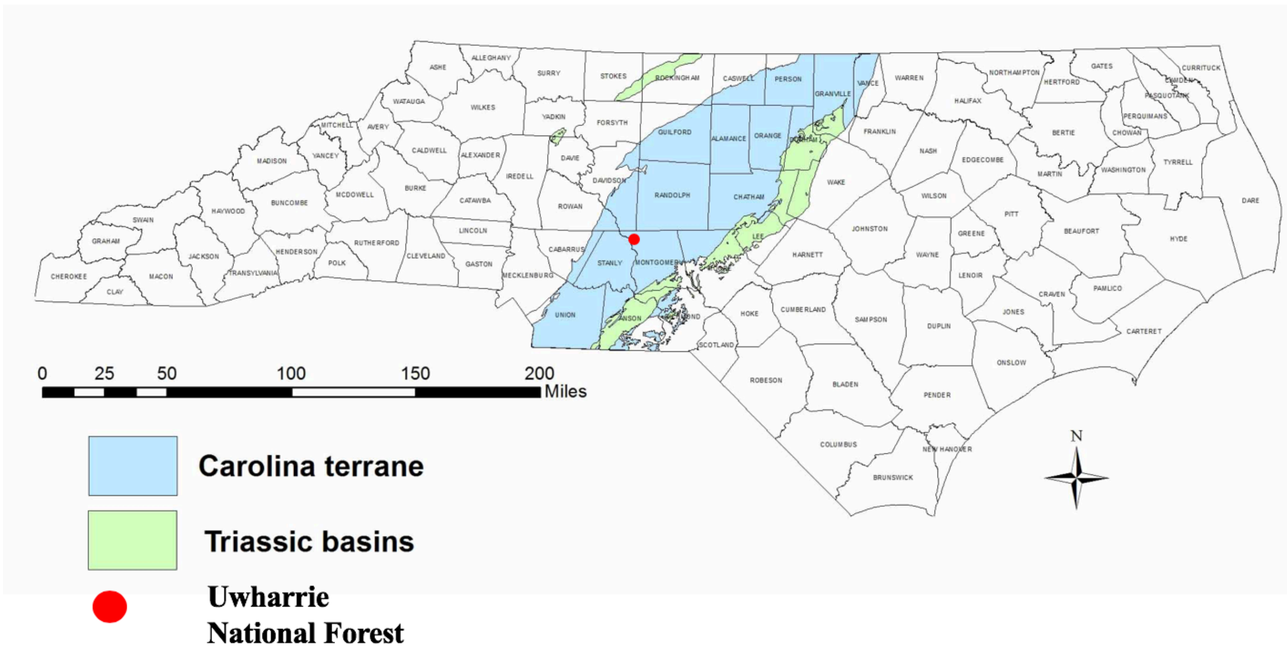

Figure 4 – The Carolina Terrane in North Carolina, with the location of Uwharrie National Forest denoted in red. From the North Carolina Department of Environmental Quality (https://deq.nc.gov/about/divisions/energy-mineral-land-resources/north-carolina-geological-survey/geologic-hazards/expansive-soils-shrink-swell-clays).

In Figure 5, two horseshoe-shaped volcanic units are largely enclosed by metasedimentary rocks in the Tillery Formation. The metasedimentary rocks are mainly argillite and mudstone with rare intercalated tuffaceous fine sandstone. All of these rocks have been metamorphosed to greenschist facies (LaPoint and Moye, 2013).

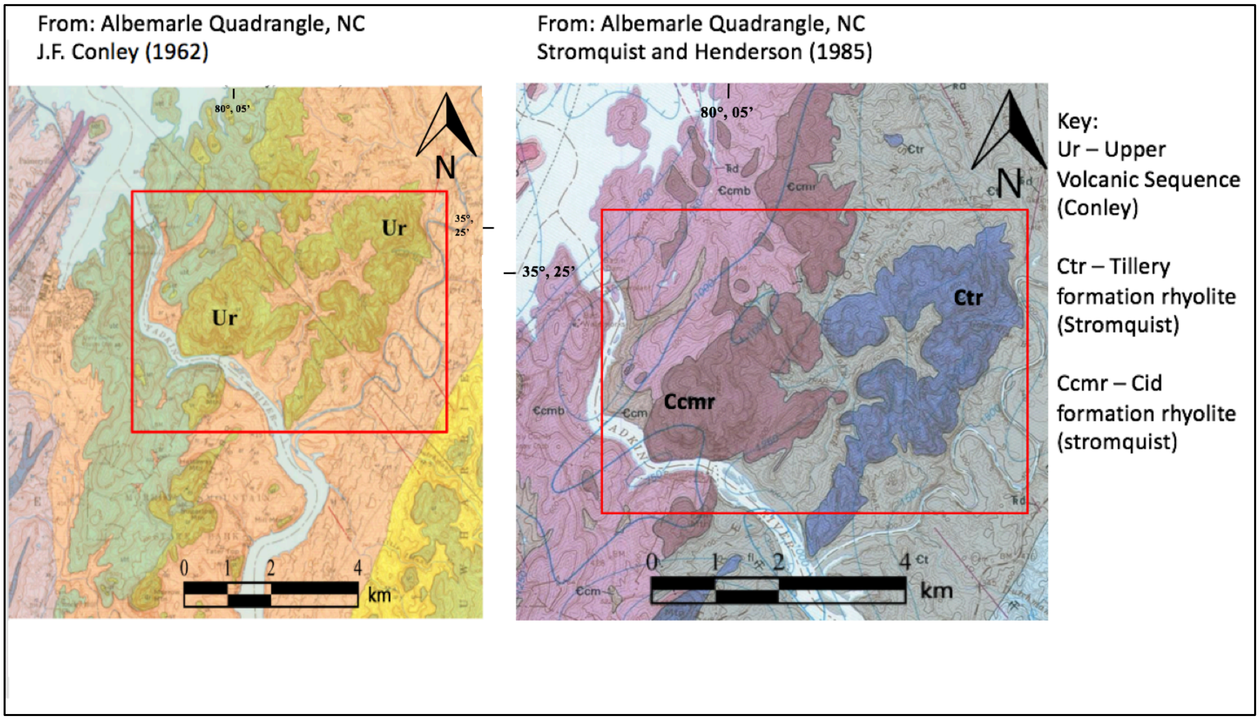

Figure 5 - Left: Map done from 1962-1965 by Conley and Bain (1965). Two horseshoe shaped rock units ("Ur" and in green) are classified as one unit.
Right: Map section from compilation in 1985 by Stromquist and Henderson, separated into two units, one in the Tillery Formation and one in the Cid formation.

Conley and Bain (1965) mapped the two spatially separate volcanic units as one stratigraphic unit within the Upper Volcanic Sequence (Fig. 6, "Ur"). Conley mapped several attitudes in the adjacent sedimentary rocks that he interpreted to be steeply dipping bedding. When this area was remapped by Stromquist and Henderson (1985) (Fig. 7), they showed the volcanic units as two separate formations. (The 1985 map was in part a compilation and reinterpretation of previously published maps.) Stromquist and Henderson placed the more southwestern rhyolite in the Cid Formation and left the northeastern rhyolite body in the Tillery Formation. The volcanic part of the Cid Formation is generally recognized as having more pyroclastic and mafic components than many other rhyolite units in the Uwharrie Mountains (Stromquist and Sundelius, 1969). Also, Stromquist and Henderson (1985) separated the Cid Formation here into rhyolitic and andesitic/basaltic volcanic components and a mudstone in the lower part of the formation. In the present area, the Cid mudstone is very thin or absent.

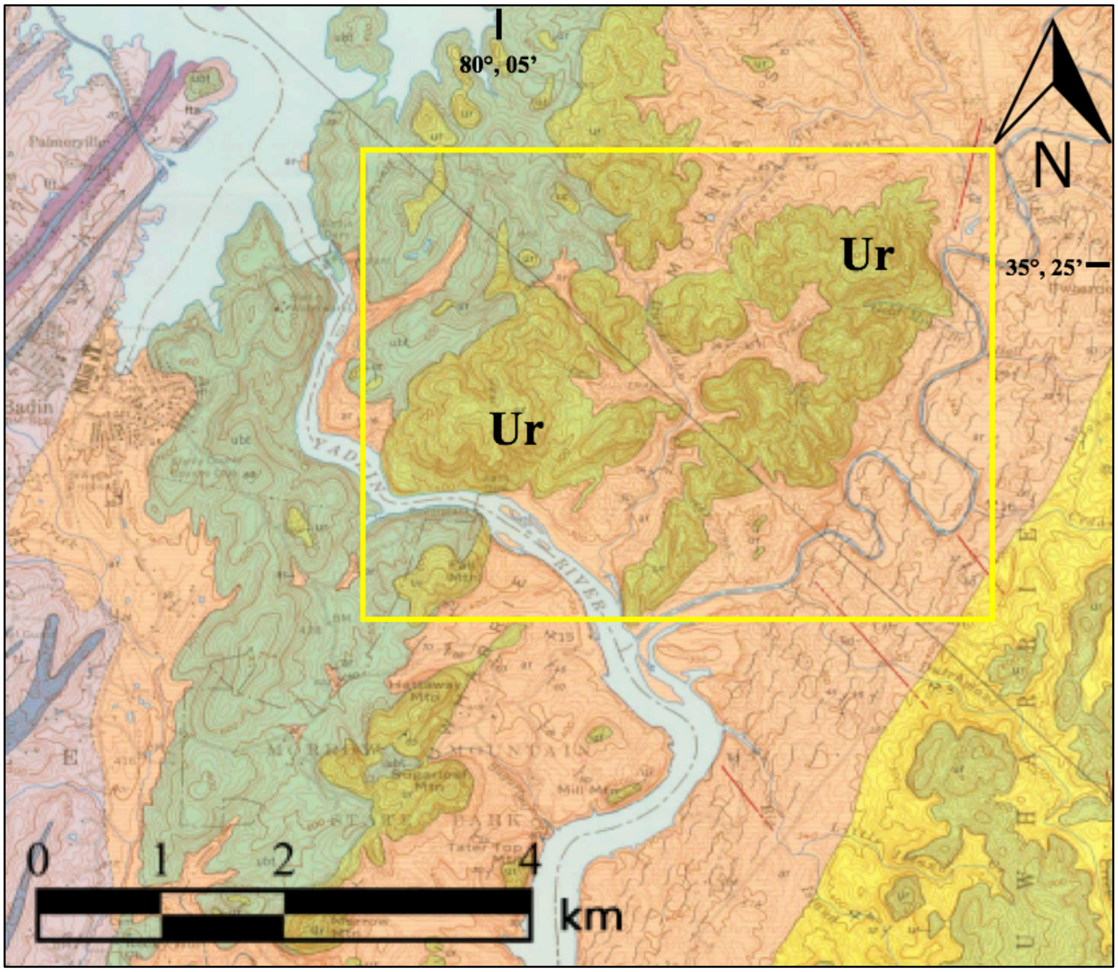

Figure 6 - Conley geologic map, depicting the rhyolites (in green) as a single unit ("Ur") (Conley and Bain, 1965).

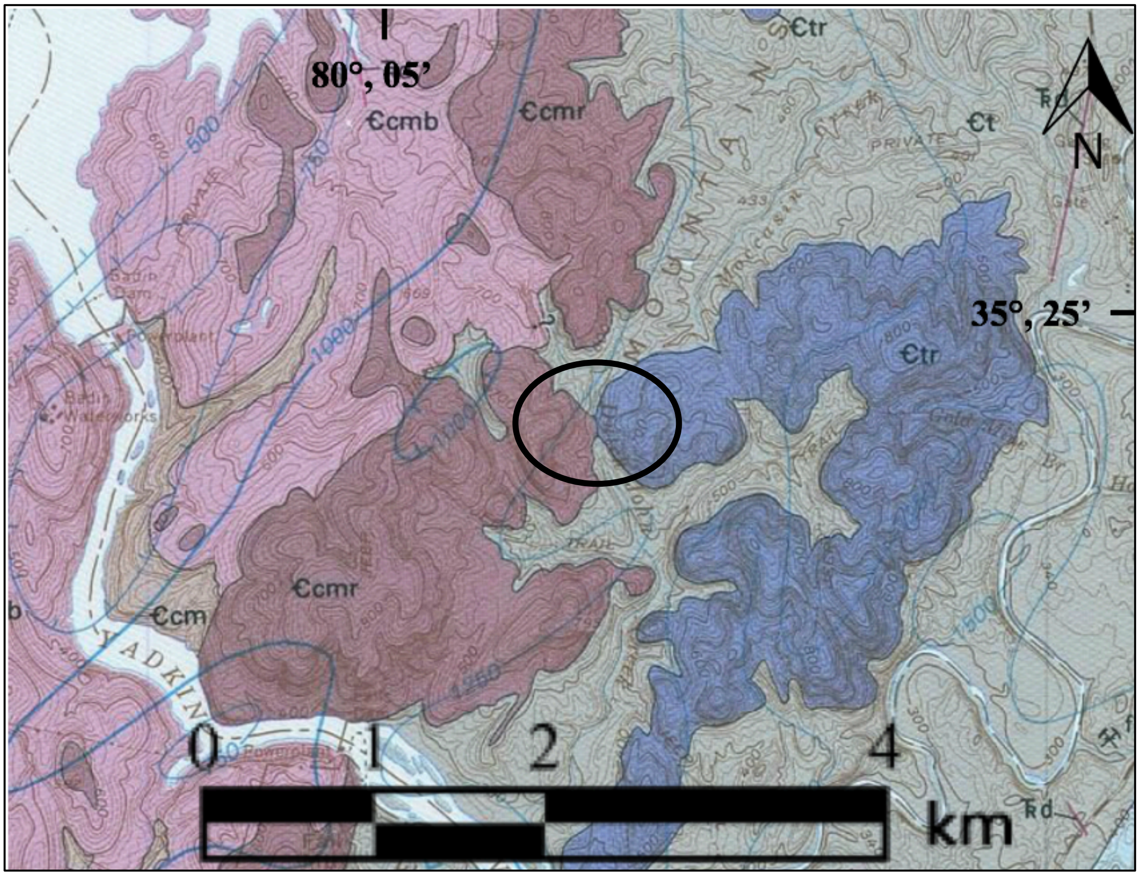

Figure 7 - Stromquist and Henderson (1985) geologic map. Tillery rhyolite (Ctr) shown on the right with Cid rhyolite (Ccmr) on the left. Where the two volcanic units touch (circle), both formations consist of aphanitic rhyolite.

The placement of these two volcanic sequences into a proper structural model is the fundamental objective of this investigation. The map pattern of the volcanic bodies suggests a doubly-plunging fold (Figs. 8, 9) cored by metasedimentary rocks with steeply northwest-dipping axial planar cleavage and trending northeast-southwest. A consequence of this pattern is that the volcanic rocks are partly correlative between the upper Tillery Formation and lower Cid Formation. The double fold is a parasitic fold on the eastern limb of the New London synclinorium (whose major structure is itself a doubly-plunging syncline) (Fig. 1, left map) but of a much smaller size than the large regional folds. Furthermore, macroscopic folds in the study area reflect persistence of the regional fold structure down to a fine scale. Through very detailed mapping we can describe the relationships between fold geometries and cleavage formation, extrapolate those observations to folding mechanisms, and explain how these structures are related to the Cherokee orogeny (Hibbard et al., 2013) and accretion of peri-Gondwanan fragments to the Paleozoic margin of Laurentia.

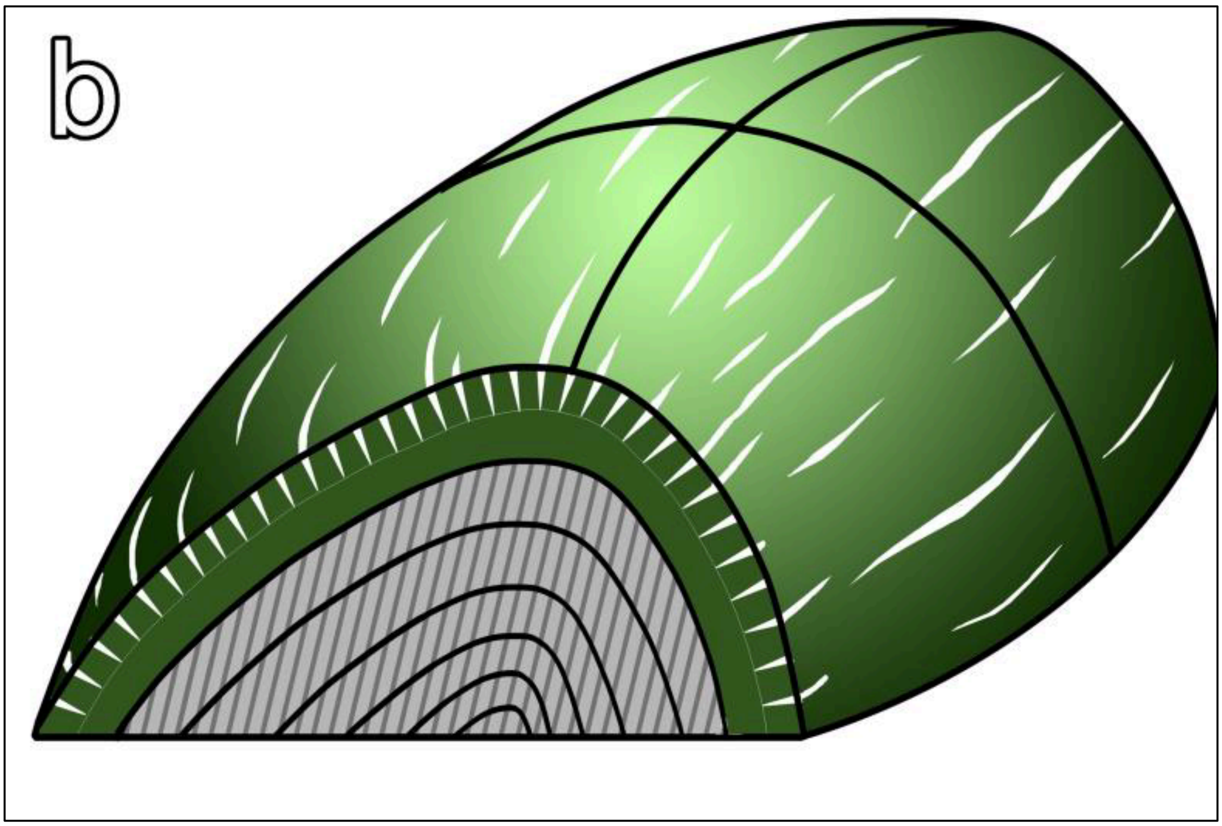

Figure 8 – Cross-sectional view of a doubly plunging anticline of two rock units and associated axial planar cleavage drafted for a thesis report at the nearby Reed Gold Mine (Challener, 2016).

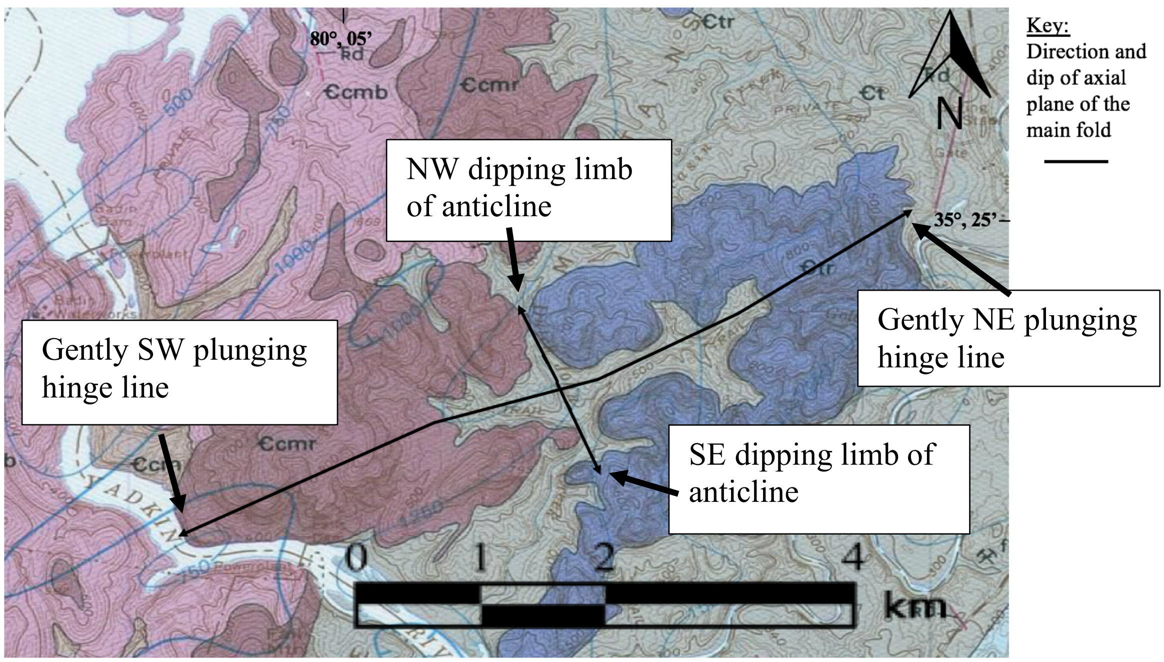

Figure 9 – Plunging hinge line and dip directions of the proposed main doubly plunging anticline in the field area. Stromquist and Henderson (1985) map shown.

2 REGIONAL GEOLOGY

2.1 Carolina Terrane and Albemarle Arc

The Carolina terrane is of Neoproterozoic to Cambrian age and includes parts of the Piedmont in Virginia, central North Carolina, and South Carolina. This terrane represents one of the largest peri-Gondwanan crustal tracts in the Appalachian orogen (Hibbard et al., 2013). It is one of several exotic Neoproterozoic island arc systems that are preserved along the eastern edge of North America and the western edge of Europe. The terrane was accreted onto Laurentia during the Late Ordovician-Silurian Cherokee orogeny. The Carolina terrane contains two volcanic arc systems, the Hyco and Albemarle arcs, which are separated in places by a third unit with an unknown tectonic setting, termed the Virgilina Sequence. This unit is composed of clastic sedimentary rocks and subordinate volcanics (Hibbard et al., 2013).

The youngest arc in the Carolina terrane, the Albemarle arc, is a sequence of metasedimentary and metavolcanic rocks referred to as the Albemarle Group. The arc is composed of Neoproterozoic to Cambrian clastic sedimentary rocks with scattered dikes and felsic to mafic magmatic rocks. The Albemarle Group formations in decreasing age are the Tillery, Cid, Floyd Church, and Yadkin formations, which conformably overlie each other (Fig. 2) (Hibbard et al., 2013). The magmatic rocks of the arc are tholeiitic to calc-alkaline and were formed in a suprasubduction zone magmatic arc (Black, 1980), which were underlain by at least some 1 Ga crustal material (Mueller et al., 1996). Penetrative deformation of these units occurred during the Cherokee orogeny (Hibbard et al., 2012). The orogeny was created by interactions between peri-Gondwanan terranes and Laurentia, marking the closure of the Iapetus ocean. The tectonothermal imprint left by the orogeny is a mineralogic composition of the quartz-albite-muscovite-biotite-chlorite subfacies of Abukuma-type lower greenschist facies metamorphism (Butler and Ragland, 1969), and generally northwest-dipping slaty cleavage. Metamorphic chlorite, actinolite, and epidote have also been observed in the intermediate to mafic rocks of the area (Stromquist and Henderson, 1985). The slaty cleavage is axial planar (McWilliams et al., 2007) to regional-scale inclined folds that are locally inclined to overturned to the southeast (Fig. 10) (Conley et al., 1962). Minor southeast verging thrust faults are also locally associated with these structures. In addition to contraction, southeast sinistral strike-slip motion is recorded in regional folds near the Gold Hill Shear Zone in central North Carolina and west of the present study area (Hibbard et al., 2012). This transpression formed asymmetric and/or doubly plunging folds that are observed throughout the Shear Zone (Hibbard et al., 2013).

In described silt and clay rich rocks (argillites) of the terrane, the cleavage is represented by a marked decrease in quartz percentage and increase in phyllosilicates due to the pressure dissolution mechanism of cleavage formation within cleavage planes (Bell, 1978; Southwick, 1987). Hibbard et al. (2013) also describe Late Devonian and Mississippian mica cooling ages that are localized to the vicinity of the Gold Hill Shear Zone (Allen, 2005), that is west of the study area. Late folds possibly related to these events also occur in the Carolina terrane, mainly in proximity to the Gold Hill shear zone (Hibbard et al., 2013).

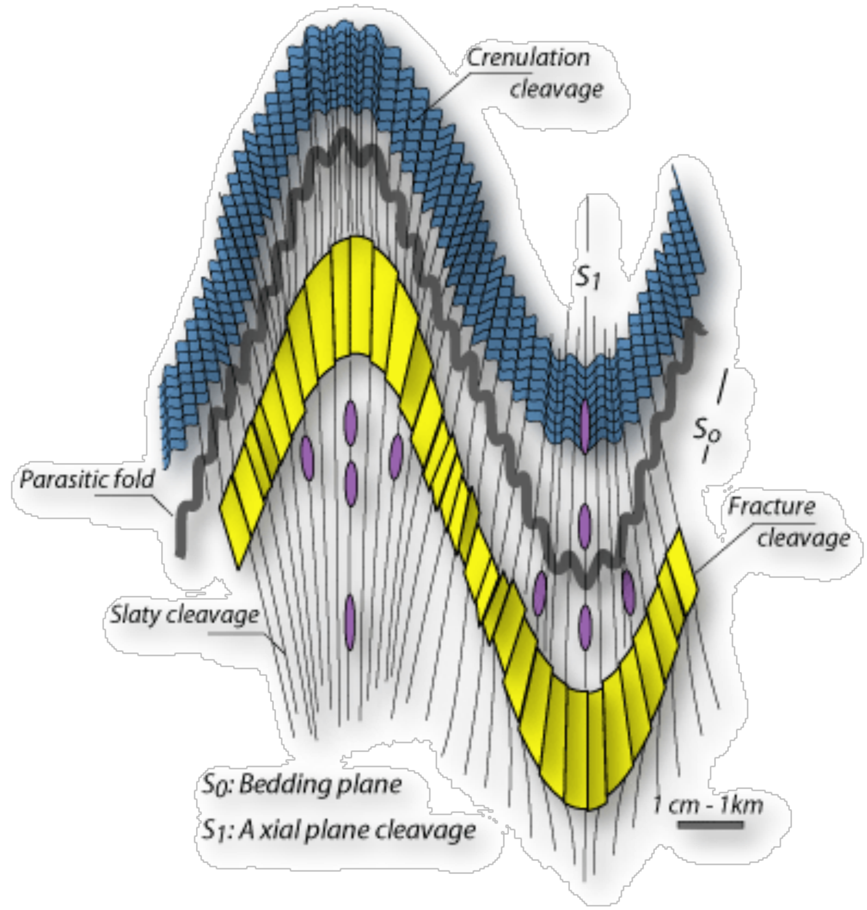

Figure 10 – Cleavage formation in folds. Axial planar cleavage (S1) forms parallel to the axial plane of the fold. Fracture cleavage forms as shear fractures parallel to the axial plane in harder layers. Crenulation cleavage forms due to the alignment of limbs in the parasitic folds (from Rey, 2005). This figure shows cleavage refraction as a response to rheological layer boundaries.

2.1.1 Stratigraphy of the Albemarle Group

The oldest formation of the Albemarle Group, the Tillery Formation, is dominated by siltstone and argillite with subordinate conglomerate and sandstone. Highly silicified argillites are interbedded with tuffs identical to the underlying Uwharrie formation (Boorman et al., 2013). The argillite exhibits laminations of 1-3mm in thickness and grade upwards from silt to clay within individual cycles, which correspond with an increase in metamorphic sericite and chlorite and decrease in quartz and feldspar

(Stromquist and Sundelius, 1969). In places, ribbon laminated argillite has beds up to several centimeters in thickness (Stromquist and Henderson, 1985).

Volcanic debris was the main source material for the sediments of the Tillery Formation based on analyses by Councill (1954) and Stromquist and Sundelius (1969). It is also possible that source materials for the sedimentary rocks were derived from weathering of medial to proximal volcanic edifices. Within the study area, the Tillery volcanic rocks are mainly dark grey aphanitic to porphyritic rhyolite or tuff. Feldspar laths or fragments of up to 3mm in diameter are present in the aphanitic groundmass, along with secondary quartz as amygdules. Scattered grains of pyrite and magnetite are present in some samples as well. Flow bands are visible on weathered surfaces as linear ridges that are a few millimeters wide and high (Stromquist and Sundelius, 1969).

Regionally, the Cid Formation contains an unnamed mudstone member at its base and the upper Flat Swamp member. The mudstone contact is gradational with the underlying argillite of the Tillery Formation. The mudstone is thinly laminated with thick beds of blocky tuff that weather to white, with a mineralogy of quartz, feldspar, and varying sericite and chlorite (Brennan, 2009). The unit includes some interfingering felsic rhyodacites and mafic andesitic basalts. A lull in volcanic activity in the Cid Formation is represented mainly by laminated shale. This lull precedes the explosive volcanic rocks of the Flat Swamp member. The Flat Swamp member also includes felsic and mafic volcanic rocks as well as thin layers of mudstone, but is mainly composed of a felsic crystal lithic-tuff breccia. Bedded fine-grained rocks occur in the member as well, but are felsic volcaniclastic rocks as opposed to the siltstones and argillites in the units below (Stromquist and Sundelius, 1969).

As described later, in the study area Cid Formation mudstone is very thin or absent. The base zones of volcanics both in the Tillery and Cid formations have massive, poorly layered mudstone only a few meters thick that rapidly grade downward into very finely laminated mud and argillite, then also rapidly downward into ribbon laminated argillite and rocks more characteristic of the Tillery Formation sedimentary sequence.

Above the Cid Formation, the Floyd Church Formation consists of bedded argillite, siltstone, and greywacke. Layers of tuff and mudstone can also be found (Pollock et al., 2010). This unit, along with the overlying Yadkin formation, were at one time considered members of the Millingport Formation. However, Milton (1984) supported the idea of a conformable boundary suggested by Stromquist and Sundelius (1969), and thus gave each member formational status.

The youngest member in the Albemarle Group, the Yadkin formation, is composed of dark greenish-grey volcanic sandstone and siltstone. The rocks are composed of mostly quartz and plagioclase in a matrix of sericitic muscovite, chlorite, quartz, and plagioclase. Interbedded andesitic basalt flows and crystal lithic tuff breccias also occur throughout the formation (Stromquist and Sundelius, 1969).

2.1.2 Previous Work

Despite the general structure of the Albemarle Group being known from mapping (Conley and Bain, 1965; Stromquist and Henderson, 1985), some problems in local structure and association have yet to be resolved. One of these less studied areas is shown outlined and labelled in the southeast section of the left map in Figure 1. This area is underlain by rhyolites and a metaargillitic unit (Conley, 1962; Stromquist and Sundelius, 1969). (We will use the term “rhyolite” as it has been traditionally applied, but geochemically some of these rocks may not be true rhyolite. “Felsite” may be a better general term to use for these rocks.)

Conley and Bain first mapped the Albemarle Group near Morrow Mountain, NC (circled in Fig. 1) from 1962-1965. They considered rhyolites at Morrow Mountain and within the present study area as a single unit, termed the Upper Volcanic sequence (Fig. 6, “ur”), that produces steep-sloped hills in the region. The rhyolite they described was a grey to dark-grey rock with flow bands and phenocrysts of feldspar and quartz. They did note that in some areas the rhyolite contained more pyroclastic textures and appeared different in thin section, but still categorized it all as a single unit. When noting the structural relationship between the rhyolite and the enclosing metasedimentary rocks near Morrow Mountain, Conley (1962) described an angular unconformity between the two units. He came to this conclusion by observing relatively flat bedding in the rhyolite and steeply dipping bedding in the sedimentary unit (Conley, 1962, p.14).

A second map done in this area by Stromquist and Sundelius (1969) (and later included in the compilation by Stromquist and Henderson in 1985) noted some important differences from the earlier mapping of Conley. Here they separated the two horseshoe-shaped volcanic bodies into distinct units (Fig. 7). The northeastern unit they included as part of the Tillery formation of the Albemarle Group, describing the rock as “aphanitic crystal lithic tuff”. The southwestern volcanic sequence was included in the lower Cid formation, distinguished from the Tillery volcanics by having more phenocrysts (vitrophyre) imbedded in its groundmass, and associated bodies of andesitic basalt. The authors also noted that the unconformity near Morrow Mountain proposed by Conley (1962) did not exist. Their reasons for rejecting previous work were that the units seemed to be interbedded with one another and had both undergone the same amount of metamorphism (Stromquist and Sundelius, 1969), although this would not rule out a pre-metamorphic unconformity.

Pollock et al. (2010), partly based on detrital zircon ages from older rocks in the Carolina terrane (the Virgilina sequence and Albemarle Group), viewed felsite occurrences in the Tillery Formation and underlying older Uwharrie Formation to be the products of a more or less continuously evolving active continental margin with a ~ 1 Ga component. They considered these felsites as a group to be time transgressive across the age range of the Tillery Formation but declined to connect volcanics in the lower part of the Cid Formation to the felsite sequence. Hibbard et al. (2013) suggested that parts of the Uwharrie Formation may actually be younger than the youngest part of the Tillery Formation and thus roughly equivalent in age to the Cid Formation. Boorman et al. (2013) correlated felsic volcanic rocks in the Uwharrie Formation, Cid Formation, and Tillery Formation (Morrow Mountain member) among two geochemical groups suggesting that these stratigraphically distinct units evolved in similar magmatic environments.

2.2 Metamorphism

Metamorphism occurred during the middle Paleozoic Cherokee orogeny (Hibbard et al., 2013). Stromquist and Sundelius (1969) reported the metamorphic minerals quartz, albite, microcline, biotite, chlorite, sericite, clinozoisite, and epidote in the felsic volcanics of the Albemarle Group. Mafic volcanics of the group include andesitic basalts and contain albite, tremolite-actinolite, quartz, epidote, chlorite, sphene, and calcite

(Stromquist and Sundelius, 1969). This mineralogy is characteristic of mafic rocks at greenschist facies metamorphism (Fyfe et al., 1958).

In argillaceous rocks, that make up the majority of the sedimentary rocks in the study area, axial planar slaty cleavage was formed through pressure solution. This process causes rocks to respond to stresses by dissolution when in the presence of their solution fluid in zones of largest normal stress, like cleavage. Deposition of soluble minerals occurs in areas of least stress, like in veins (Gratier et al., 2013). In the case of these rocks, this caused the cleavage to be defined by white micas and insoluble minerals (Kurek, 2010). Kurek (2010) also stated that pressure solution is generally recognized by quartz pressure shadows on pyrite and sericite grains in these rocks. Cleavage tends to change from slaty to phyllitic towards contacts between volcanic and sedimentary units because of increased hydrothermal alteration through pressure solution mechanisms during metamorphism (Challener, 2016). This is discussed by Klein et al. (2007) and others as being a common occurrence in zones of silicification in the Carolina Terrane. Due to the hydrothermal remobilization during metamorphism, quartz veins, gold, and silver can be enriched by as much as a 15-20 times background values in northeast trending, asymmetric anticlinal folds in these zones in the terrane (Klein et al., 2007; Hibbard et al., 2012).

2.3 Folds and folding in the Carolina Terrane and Uwharrie Mountains

The abundance of gold resources in the Carolina terrane and the importance of understanding the structural geology of those deposits resulted in several site-specific investigations focused more on mineralogy than structural geology. The few areas that have been studied are mostly limited to the gold districts outlined in Figure 1, including the Russell gold deposit in the Uwharrie Mountains (Klein et al., 2007). It is essential to study the structural geology of the areas outside of these districts in order to fully understand the resources, hazards, and full geologic history of the Carolina terrane.

The following case studies describe more detailed structural studies in the Carolina terrane. They were done in association with geological research on gold mines.

2.3.1 Reed Gold Mine

An area in which the study of the deformation features of rocks plays a critical role is with economic minerals. A study done by Stephen Challener (2016) on the Reed Gold Mine in central North Carolina set out to better understand the geology of the area. The mine followed a metagabbro unit in the Albemarle Group's folded Tillery argillite and is located in the Gold Hill shear zone (Allen, 2005) of the Carolina terrane, host to a multitude of mines. Despite the highly productive nature of these mines, the geology of the area is not well understood. The study done by Challener aimed to create a more accurate model for the geology of the Reed gold mine. Some of his methods included mapping bedrock to compare to previous work, geochemical analysis of the metagabbro to compare to gabbro of the nearby Stony Mountain Suite, and structural mapping on limited outcrops of the argillite fold and quartz veins of the Reed Gold Mine (along with other methods). He concluded that the fold at Reed Gold Mine is a doubly-plunging anticline with axes to the NE and SW. This allowed for the formation of veins in fractures and the entrapment of precious metals in the center of the fold.

Challener also analyzed the whole rock elemental composition of the metagabbro with a lithium metaborate/tetraborate fusion ICP, while trace elements were analyzed with an ICP-MS. He then used multiple elemental comparisons like an alkali vs. silica chart to compare the known Stony Mountain suite with the metagabbro of Reed Gold Mine. His findings indicate that the metagabbro of the Reed Gold Mine is indeed part of the Stony Mountain Suite, despite being previously listed as a separate unit (Challener, 2016).

The methods described above present an accurate and efficient approach for determining the structure and rock relationships of an area. More specifically, his structural analysis which determined that a doubly plunging NE-SW anticline was at the center of Reed Gold Mine and geochemical analysis provide guidance to uncovering the structural geology and relationships between volcanics in our field area, which we also postulate to be a NE-SW doubly plunging anticline. The use of multiple stereonets by structural domain across the site to determine the nature of folding and relationship between bedding and cleavage provides a method to structurally analyze folding in our area as well. Moreover, while we do not have access to access to an ICP-MS to determine volcanic relationships like in the above study, XRD (X-ray powder diffraction) analysis and reference to Challener's work will allow us to estimate the relationship between the two volcanic units in the study area.

2.3.2 Russell Mine

The Russell Mine is a historic, mainly open pit gold mine that is to the northeast along strike of the present study area (Klein et al., 2007). The dominant structure there is a doubly plunging anticline that trends northeast. The gold rich, base metal-poor ores in this mine are in epithermal, silicified zones in massive sulfide deposits in the metasedimentary rocks of the Tillery Formation. Bimodal rhyolite-basalt volcanism was present during formation in the Cambrian. Geochemical and sulfur isotope data suggest the rhyolitic magmas were the source of heat and some of the metals that formed this deposit. The gold rich sulfide deposits were remobilized by hydrothermal fluids during the Taconic Orogeny in the middle Ordovician according to these authors. This occurred during syntectonic regional deformation of the rocks into northeast-trending, asymmetric, anticlinal folds that formed the multiple, parallel ore leads (Klein et al., 2007).

Gold ores are not known to occur within the study area, although a similar silicified zone is noted in the field area near the argillite-rhyolite contact in the Tillery Formation and there are mine prospects typically in massive quartz veins likely explored for gold. This is roughly in a comparable stratigraphic position to ore bodies in the Russell Mine. We suspect that the fold generation described by Klein et al. (2007) are equivalent to the folds in rhyolite units in the study area. Traverses in the study area suggest qualitatively that there is an increase in silicification and intensity of deformation in the argillite approaching its contact with rhyolite. There are also numerous quartz veins in the argillite, some of them appearing to have formed in dilated cleavage zones.

Klein's work and descriptions allow us to better recognize and describe structural features and rock types found in our field area. Categorization of volcanics and a silicified zone in the area will be partially based on his descriptions, as our study site resides roughly in equal stratigraphic position to the ones studied at Russell Mine. The doubly plunging anticline at the center of the Russell Mine has an axis that trends N 45° E, and limbs dipping 50° NW and 80° SE, respectively. This geometry is similar to what we expect to find in Uwharrie National Forest based on the double horseshoe formation of volcanics on the map by Stromquist and Henderson (1985) and provides information on the nature of folding in the central North Carolina portion of the Carolina Terrane.

2.4 Rhyolite Geochemistry

The Albemarle Group (Fig. 2) contains a complex volcanic sequence with major mafic and intermediate components along with the felsic components and an increasing proportion of epiclastic sediments in the upper units (Feiss, 1982). Most of the volcanic rocks are volcaniclastic, with tuffs representing about 83 percent and are interstratified with finely graded siltstones and mudstones along with an absence of pumice. A study done by Hauck (1977) at a known volcanic center near Callus Mountain, North Carolina in the Carolina Slate Belt (now the lower grade part of the Carolina terrane) showed that volcanics with this composition are generally submarine. Seiders (1978) emphasized the bimodal character of the volcanics in the Albemarle area based on the differences in SiO_2 content in the rocks, with the majority being felsic (Fig. 11).

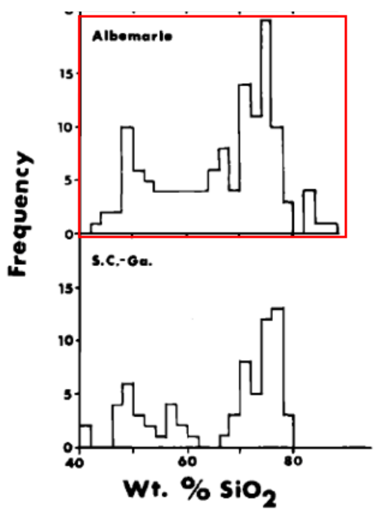

Figure 11 - Weight percent of volcanic rocks SiO_2 in the Albemarle Group (outlined in red), showing a bimodal distribution in the volcanics, with the majority being felsic (Seiders, 1978).

2.4.1 Major and Minor Element Geochemistry

The volcanics in the Albemarle Group are calc-alkaline, and tectonic discrimination diagrams categorize them as having formed in a volcanic arc (Black, 1980). Based on the major element geochemistry of the volcanics, Dennis and Shervais (1991) and others interpret them to have formed in a suprasubduction zone magmatic arc setting. Boorman et al. (2013) analyzed felsic rocks of the Morrow Mountain member of the Tillery Formation using immobile trace element ratios (Zr/Ti, Nb/Y, etc.) in order to uncover how they relate to similar felsic volcanics in the Uwharrie and Cid formations. Based on differences in Zr/Hf abundance ratios controlled by zircon crystallization, the authors concluded that there are at least two groups of rhyolitic magmas throughout the Uwharrie formation and Albemarle group (Fig. 12). Differentiation as a cause for the two separate magmatic groups was ruled out, as the two Zr/Hf groups have similar SiO_2 concentrations. They also stated that the two groups are not stratigraphically controlled. Namely, both groups can be found throughout the Uwharrie formation and Albemarle Group, and are most likely magmatically linked.

The study by Boorman et al. (2013) further supports the theory of a conformable contact throughout the Albemarle Group, with one magmatic episode producing the two magma types found in the group. Based on the findings by Boorman et al. (2013), in which two magma types formed from one magmatic environment in the formation of the Albemarle Group, it’s possible that the aphanitic rhyolites of the lower Cid and Tillery formations in our area are equivalent and formed during the same magmatic episode.

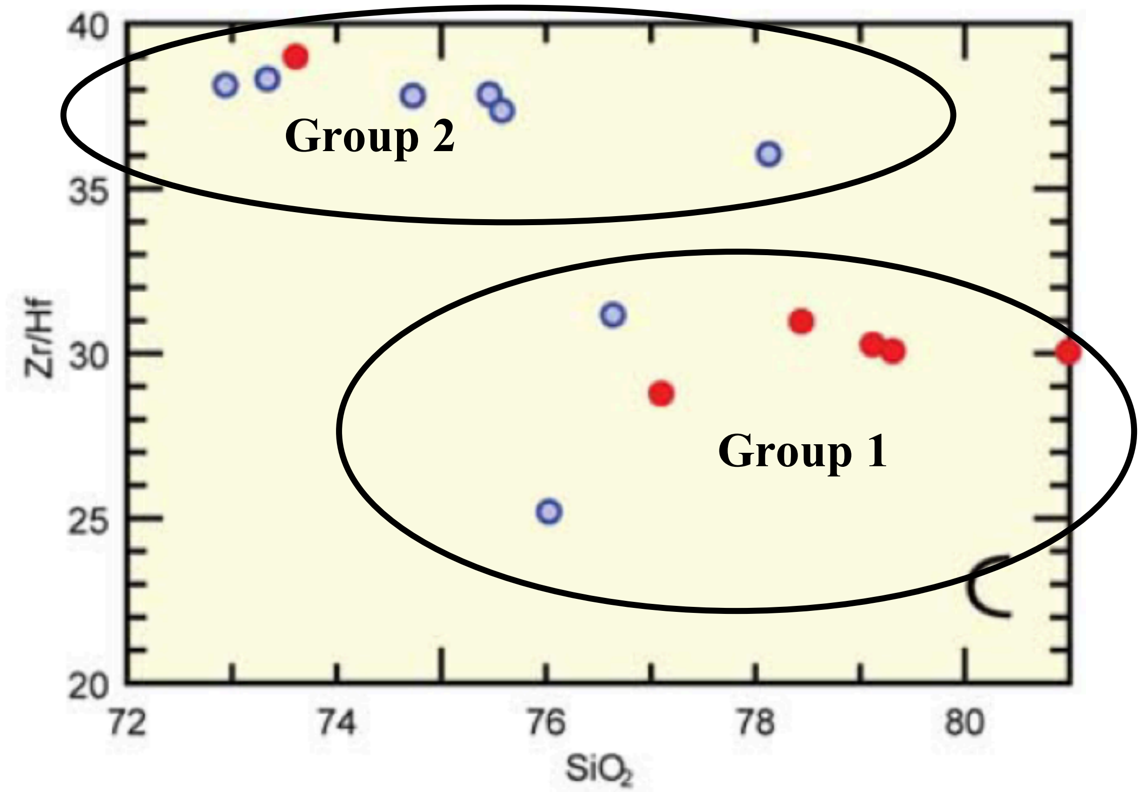

Figure 12 – Graph by Boorman et al. (2013) of analyzed volcanic rocks from the Uwharrie Formation (blue circles) and overlying Albemarle Group (red circles). At least two groups of volcanic rocks exist, with one having a lower Zr/Hf ratio than the other. Each group has rocks from both the Uwharrie Formation and Albemarle Group, meaning the groups are not stratigraphically controlled and most likely formed from the same magmatic source (Boorman et al., 2013).

3 METHODS

3.1 Field Mapping

Field work was conducted in an 800-hectare area in Uwharrie National Forest (Fig. 3). Detailed bedrock mapping occurred during the summer and fall of 2018, with areas of further interest completed in the spring of 2019. This work entailed accurately noting the type of bedrock exposed at a given location, and the contact between the rhyolite and argillite units using the application GaiaGPS (GaiaGPS.com), which allowed us to obtain a more detailed understanding of the nature of the contact between the units. There are abundant tree tip-ups in the forest where root bundles excavated surficial materials as trees fell. As outcrops were sparse in areas, these tree tip ups were used to denote rock type and aid in the determination of contact locations. Visible contacts between the two units are also rare, so most contact points were estimated based on soil type, tree tip ups, and nearby outcrops of either rock type. 1:24,000 USFS 2016 topographic maps (FSTopo, 2016) and higher resolution LiDAR data (NC OneMap, 2013) were used as a base, along with the most recent geologic map of the area by Stromquist and Henderson (1985).

Attitudes of *in situ* outcrops of Tillery Formation metasedimentary rocks were measured for bedding and cleavage, along with any joints and cleavage-bedding intersections. These outcrops were mainly limited to stream bottoms, undercut stream channel margins, road cuts, and as occasional saprolite patches. The argillite creates a characteristic chippy, loamy soil. Rhyolite is more difficult to find in situ as it is prone to intense jointing and fragmentation and mass wasting. The best opportunities for measurable cleavage and layering in rhyolite were on ATV trails and near the crests of some ridges. Observable flow banding as linear ridges in the rhyolites was limited to weathered surfaces (Fig. 13) as the dark gray matrix made discerning layering on a fresh surface difficult. Where possible, rhyolite cleavage and jointing were measured. Intense, almost columnar-type jointing was observed in places (Fig. 14), allowing a bedding surface to be determined and measured if those structures are primary. Rhyolite forms a sandy soil on slopes and ridge tops and a white to tan clay-rich sediment in slope wash and on forest trails.

Cleavage tends to be well developed in metaargillites and mudstone because of the fine grain size of the rock and its susceptibility to pressure solution mechanisms and recrystallization. Cleavage is also prominent in parts of the area underlain by volcanic rocks where weathering produces distinct fin-shaped outcrops. In sedimentary rocks lacking clear bedding, it can be difficult to discern bedding from cleavage. This may partly account for "bleeding" of attitudes in stereonets for cleavage and bedding. Where possible, oriented specimens were collected to be cut into rock slabs and thin sections so that bedding could be more easily observed.

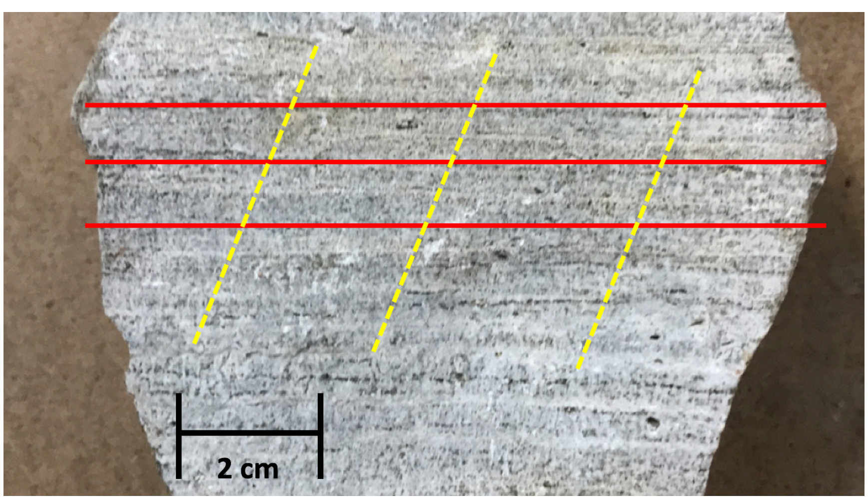

Figure 13 – Visible layering (solid lines) on a weathered surface of Tillery rhyolite, determined based on descriptions of layering in Cid and Tillery formation rhyolites by Stromquist and Sundelius (1969). Cleavage shown with dashed lines.

Figure 14 – Intense jointing (in yellow) in Tillery rhyolite. If the joints are in part residual primary features, flat surfaces normal to them could be layer surfaces. Elsewhere, mesoscopic layering roughly correlates in orientation to this assumption as does bedding in sedimentary rocks beneath this horizon.

3.2 Sample Analysis

3.2.1 Thin Sections and Deformation Analysis

It was anticipated that at greenschist facies deformation of quartz in particular will be visible in thin section. Careful examination of quartz grain boundaries and sub-boundaries were used to help describe deformation conditions. Thin sections of argillite and rhyolite were created through the National Petrographic Service. Due to the fine-grained nature of the rocks, mineral classification was limited to larger porphyroblasts embedded in the matrix. Thin sections were mainly used to identify and describe the deformational features of the rocks. A Leica DM 2700 P polarization microscope was used for the photographing of thin section deformational features of note.

3.2.2 XRD Analysis

Samples of volcanics from both the Cid and Tillery formations (Stromquist and Sundelius, 1969) were bulk powder-analyzed through XRD for mineral composition. The goal of the analysis was to see if there was a distinct mineralogical difference between the Cid and Tillery volcanics in this area, or if they are similar enough to possibly be considered one unit that formed in the same magmatic environment. In the argillites, XRD analysis was used to determine if there was any alteration in the mineral composition closer to the rhyolite contact, due to noted silicified zones in the vicinity (Klein et al., 2007). Based on previous analysis by Challener (2016), pressure solution was most likely the source of fluid in this zone, with the rock fabric transitioning from slaty to phyllitic. Geochemical analysis helped characterize this possibly metamorphic effect. Silicification is also reported in epithermal gold ores in the general area (Klein et al., 2007; Challener, 2016).

3.3 Structural Geologic Maps

Final maps of the area were created with Global Mapper (Blue Marble, 2019) and ArcGIS (ArcGIS, 2019), using the mapping and geochemical data collected. Global Mapper was used to display attitudes of all bedding and cleavage data collected, with the US Forest Service's 2016 topographic map as the base (FSTopo, 2016). ArcGIS was used to modify contacts between the two volcanic units and Tillery Formation sedimentary rocks mapped during this project, as well as denoting the zone of silicification.

Stereonets were created of bedding and cleavage using the modified Schmidt projection in Orient (Vollmer, 2019). Stereonets were created based on discrete zones from across the field site to show possibly systematic variations in bedding and cleavage across the area. These data were then combined into total bedding and total cleavage stereonets of the area. This allowed for the determination of the underlying nature of folding across the site, and the relationship between bedding and cleavage. A maximum point and its associated great circle were then calculated to show the possible main fold hinge assuming mainly cylindrical folding.

Multiple geologic cross sections were drafted parallel and orthogonal to the proposed main fold hinge to visualize the underlying structure.

4 RESULTS

4.1 Geology of the Study Area

4.1.1 Sedimentary Rocks

The Tillery sedimentary sequence is mainly ribbon laminated argillite with alternating layers of silt and clay visible in thin section (Fig. 15). The rocks are medium grey or green, with thin laminations anywhere between 0.3-8mm in thickness (Stromquist & Sundelius, 1969). The argillite tends to break along bedding into large, thin slabs (Fig. 16). Cleavage is well developed in the argillites and is easily visible in thin section along grain boundaries (Fig. 17, yellow lines), though specific minerals in cleavage zones from this study are difficult to determine due to the fine-grained nature of the rocks. The pervasive cleavage causes the argillite to weather into small thin chips (Conley, 1962). Crenulations are visible in some thin sections and hand specimens (Fig. 18). This sequence also contains more massively layered very fine-grained sandstone or siltstone. Some of the latter rocks appear to be tuffaceous. Closer to the contact, tuffaceous volcanics with crystallites can be found interbedded with the argillite as well (Figs. 19, 20).

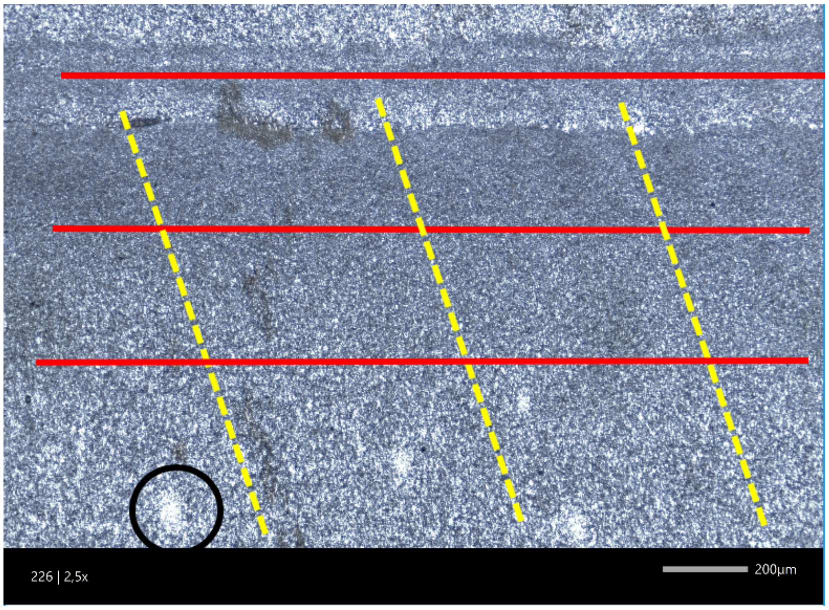

Figure 15 – Thin section of argillite normal to bedding and cleavage at 2.5x with uncrossed polars, graded bedding (solid lines) from silt to clay with axial planar cleavage shown by dashed lines. White patches (circled) are areas of increased quartz and/or feldspar concentration.

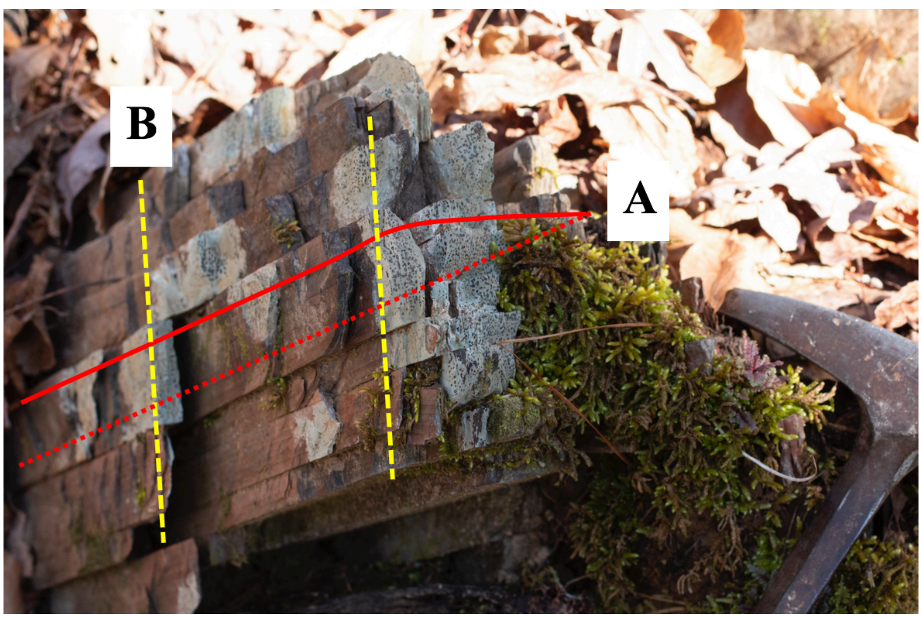

Figure 16 – Tillery argillite broken into slabs along bedding planes (indicated by red solid lines (A)). Dotted lines in A used to depict the bedding plane. Note the steeply dipping axial planar cleavage indicated by yellow dashed lines (B). Intersections of structural planes results in pencil cleavage.

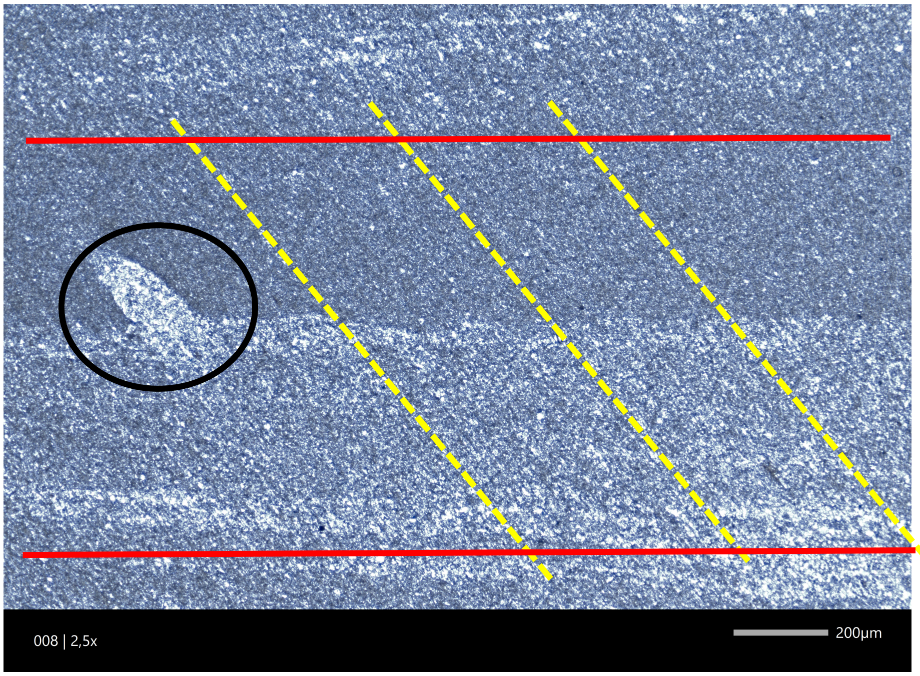

Figure 17 – Thin section with uncrossed polars of Tillery formation argillite normal to bedding and cleavage. Bedding (red solid lines) and cleavage (yellow dashed lines). Circled area is mainly quartz and/or albite.

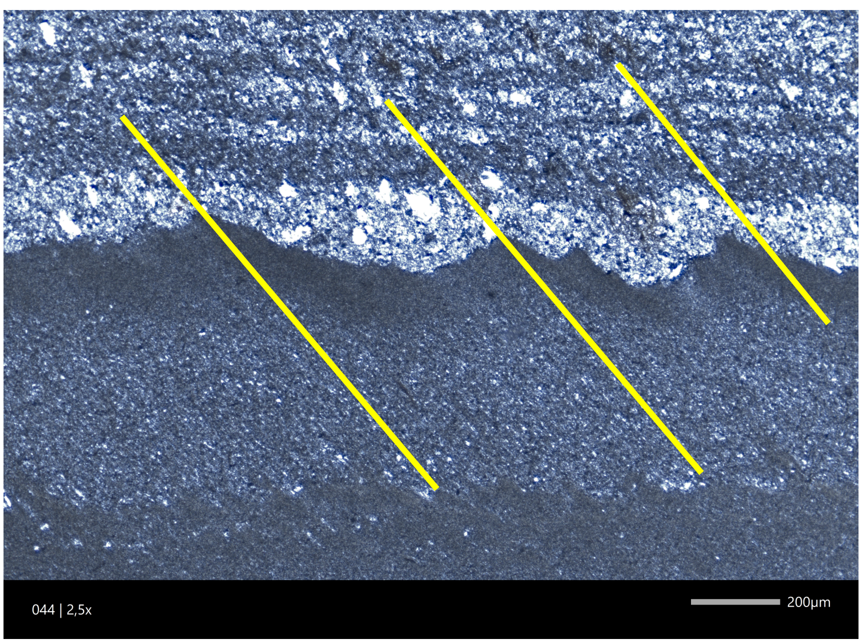

Figure 18 – Crenulations along cleavage (in yellow) with uncrossed polars in Tillery formation argillite. Base of graded layer marked by coarser, quartz-rich zone. Note dimensional alignment of quartz grains in graded layer to cleavage orientation.

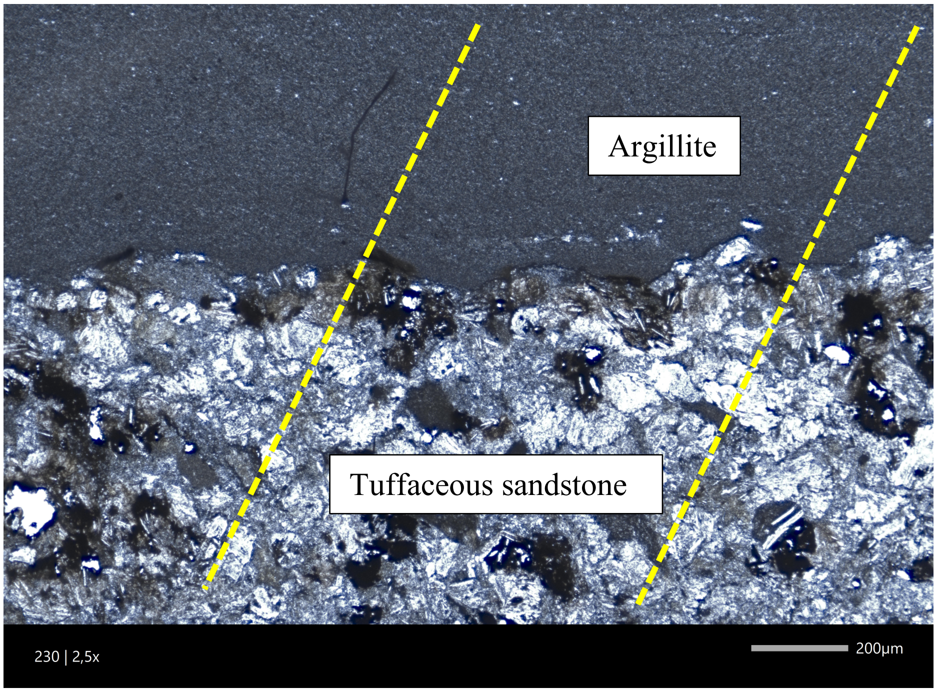

Figure 19 – Laminated Tillery formation argillite interbedded with tuffaceous layer near the argillite rhyolite contact. Tuff composed of quartz, albite, and clinochlore. Cleavage denoted by dashed lines.

Figure 20 – Sample of Tillery Formation argillite interstratified with layers of tuffaceous sandstone. Post-metamorphic faulting along fractures shown as well.

A section of poorly laminated mudstone was mapped by Stromquist and Henderson (1985) at the base of the Cid Formation below most of the volcanic components. We have, however, found a similar mudstone between the Tillery rhyolite and lower sedimentary sequence as well. The mudstone is a very finely laminated, weakly cleaved unit that lies between the argillite and the rhyolite. The mudstone grades downward into finely laminated argillite that makes up the bulk of the Tillery Formation in the area.

Sedimentary rocks in the Tillery Formation have intercalated, thin layers of crystal lithic tuff and the predominantly volcanic mass of Cid Formation in the mapped area similarly has very thin intercalated mudstone layers. These inclusions are too thin or too rarely exposed to be mappable.

4.1.2 Volcanic Rocks

The volcanic rocks in this part of the Albemarle Group include very fine grained, cryptically layered rhyolite, vitrophyre, andesitic basalt, and a range of pyroclastic rocks that are felsic to intermediate in composition. All rocks have been metamorphosed to lower greenschist facies (LaPoint and Moye, 2013). The Tillery Formation rhyolites/rhyodacites are medium grey, aphanitic to porphyritic, with larger feldspar laths embedded in the matrix (Fig. 21). Mineralogically similar aphanitic rhyolite extends into areas of the Cid Formation (western side, pink unit, Fig. 7) in the field area as well.

In thin section, some samples exhibit a planar structure of mineral alignment that wrap around the larger feldspar grains (Fig. 22), possibly due to flow banding. Porphyritic rhyolite showed flattening and strain of phenocrysts or porphyroblasts, which were used to help in determining foliation. In these rocks, that are removed from contacts with the sedimentary sequence, quartz grains tend to have well-defined grain boundaries and sharp rims with little to no dynamic recrystallization (Fig. 21) that is sometimes described in greenschist facies deformed quartz grains (Lloyd and Freeman, 1994). Lithophysae bearing pyroclastic rocks, however show dimensionally aligned strained inclusions, suggesting that these rocks equilibrated well at greenschist facies conditions. Volcanic layers close to major contacts with sedimentary sequences and enclosed within sedimentary rocks, on the other hand, tend to have strongly defined but anastomosing cleavage planes in which microlithons may have dimensionally aligned grains (quartz and feldspar in felsic rocks) reflecting penetrative strain. The cause of strain variations with respect to proximity to contacts between volcanic and sedimentary rocks is likely a result of a softer rheology in the sedimentary sequence under greenschist facies conditions.

Aphanitic rhyolite and fine grained planar layered volcanic rocks in the Tillery Formation crop out as rounded ledges on ridge crests. These rocks are also susceptible to extensive mechanical weathering and as a result most surfaces underlain by them are covered by a carpet of colluvial fragments, rock flows, and debris slides. Few *in situ* outcrops are available. Strongly foliated rhyolite may form erosion fins as landforms influenced by cleavage.

Stratigraphically above the aphanitic volcanics and in the upper part of the Cid Formation is a group of pyroclastic rocks that are mainly (but not limited to) basaltic composition (Fig. 23). These rocks typically are strongly foliated and on ridge crests often compose large fin fields where cleavage has influenced weathering and erosion.

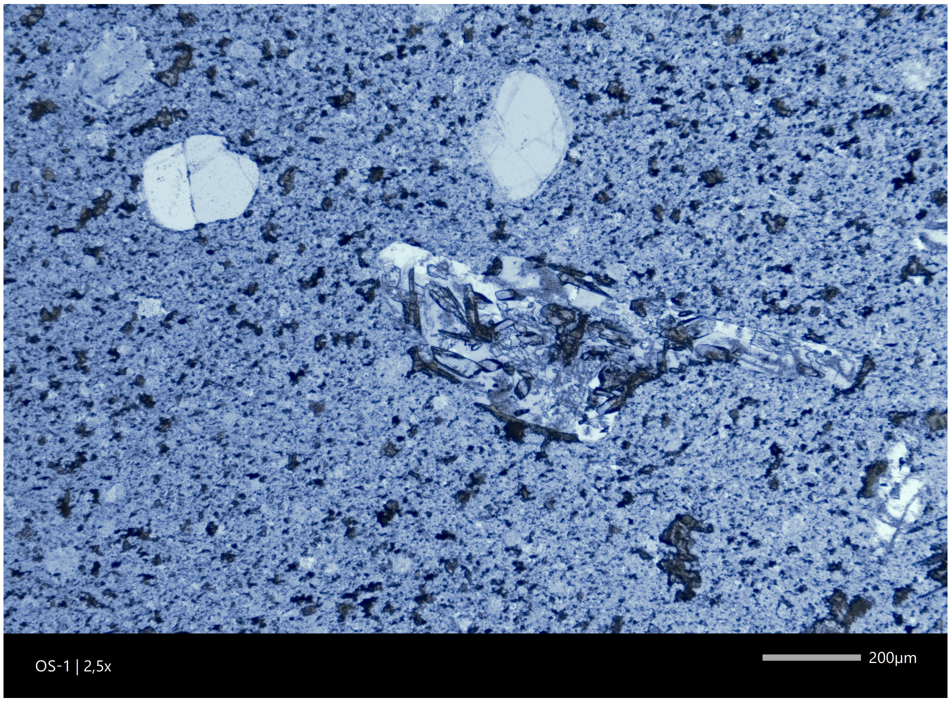

Figure 21 – Thin section at 2.5x and uncrossed polars of a slightly porphyritic volcanic rock with a quartz-albite matrix. Quartz grains exhibit well defined boundaries and sharp rims. Plagioclase in center partially replaced by actinolite. Opaque minerals are either magnetite or pyrite.

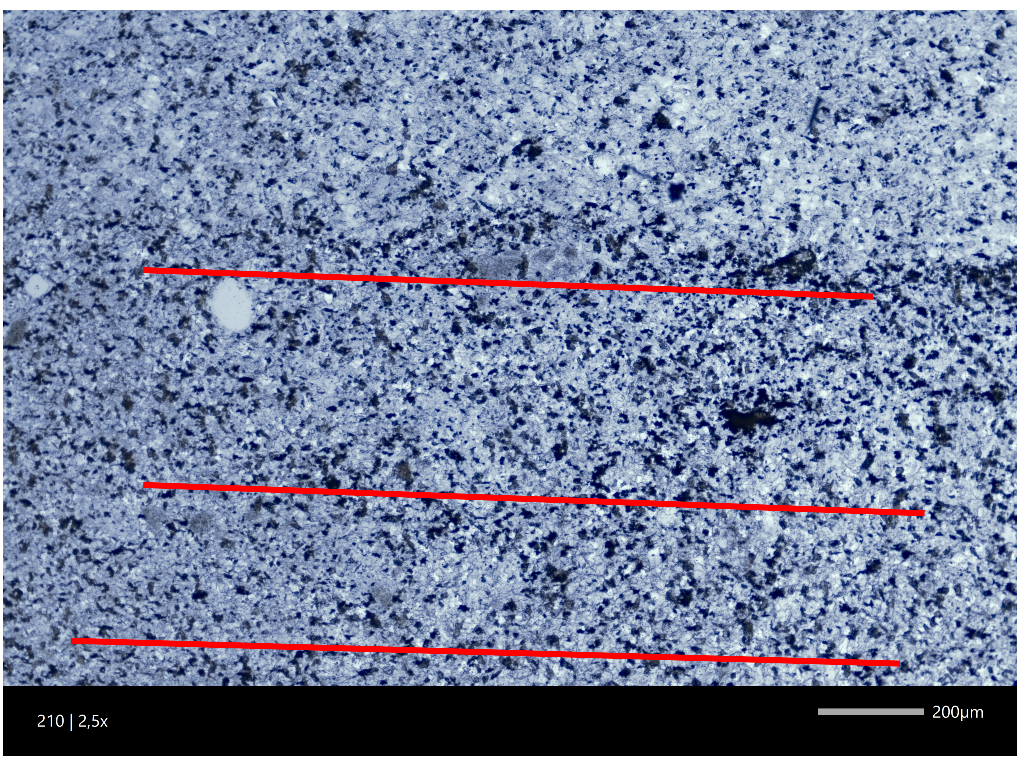

Figure 22 – Possible flow banding in aphanitic rhyolite (in red). Opaque minerals could be hematite, magnetite, or pyrite, but more analysis is needed.

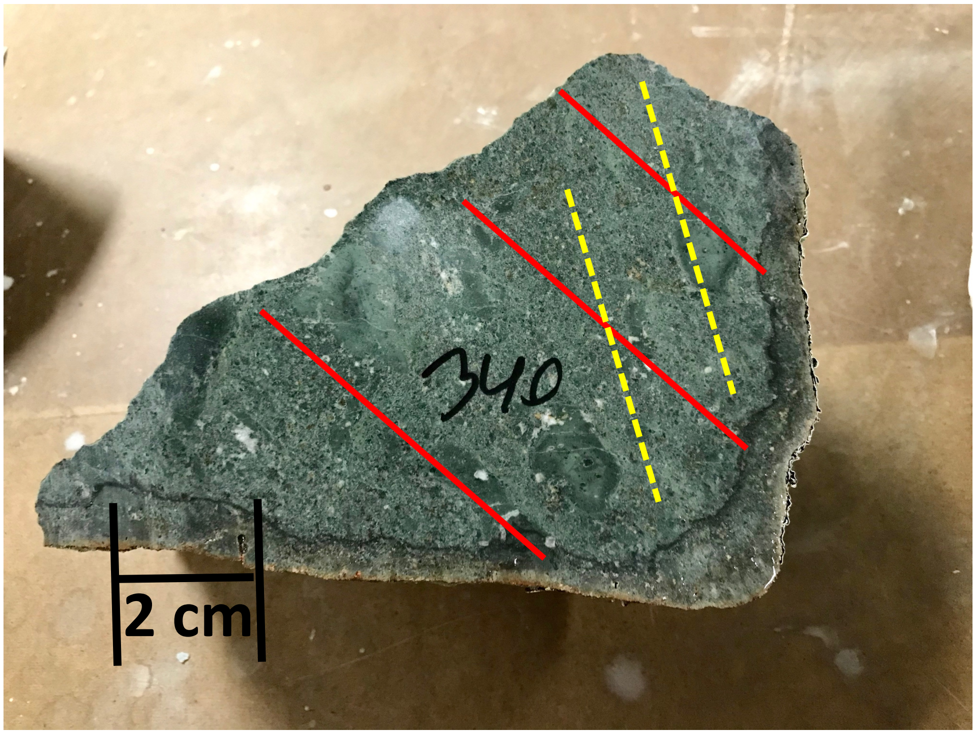

Figure 23 – Metamorphosed lithic-bearing tuff of basaltic composition of the Cid formation. Layering denoted by red solid lines and cleavage by yellow dashed lines.

4.1.3 Silicified Zones

A zone of silicification occurs near the stratigraphic top of the sedimentary sequence in the Tillery Formation and beneath the base of the aphanitic rhyolite unit in the upper part of the formation (Fig. 24, green dots). The silicified zone is noted by an abundance of quartz veins, many of which are pre-metamorphic, a strongly phyllitic appearance in argillaceous rocks, and hydrothermal alteration minerals in the host rock. Finely laminated argillite in the zone is often bleached white upon weathering and enriched in white mica compared to argillite outside the zone. On hillslopes underlain by saprolite of the silicified argillite, the soil is often brilliant hues of orange, red, and yellow (Fig. 25).

The degree of alteration in silicified argillite is to some degree affected by proximity to large quartz veins within the zone. Also, in places the silicified zone contains a very fine-grained, strongly foliated felsic volcanic layer (Fig. 26). Upon weathering, the felsic layer forms hard, resistant masses and ledges that superficially resemble quartzite. These rocks weather to a white or tan, chalky soil that is distinctive compared to weathered rhyolite in the top of the Tillery Formation. These weathering contrasts are likely caused by alterations within the silicified zone.

Less altered but often phyllitic argillite typically occurs between the silicified zone and the base of the main rhyolite unit in the Tillery Formation. A thin layer of massive mudstone occurs near both at the base of the main rhyolite in the Tillery Formation and at the base of volcanic rocks in the Cid Formation. In both positions, the mudstone is only a few meters thick and grades into exceptionally fine layered argillite and mudstone of several meters thickness and then downward into laminated argillite.

Northeast of the study area, several historic gold mines of the Ophir district were located in ore bodies roughly stratigraphically correlative with the silicified zone (Klein et al, 2007; LaPoint and Moye, 2013). The metalliferous ores there are highly silicic zones within bedding thought to be syn-volcanic seafloor alterations (Klein et al., 2007). Some gold prospects in the present study area were located in or near known silicified zones or large quartz veins probably contemporaneous with alteration of the zones.

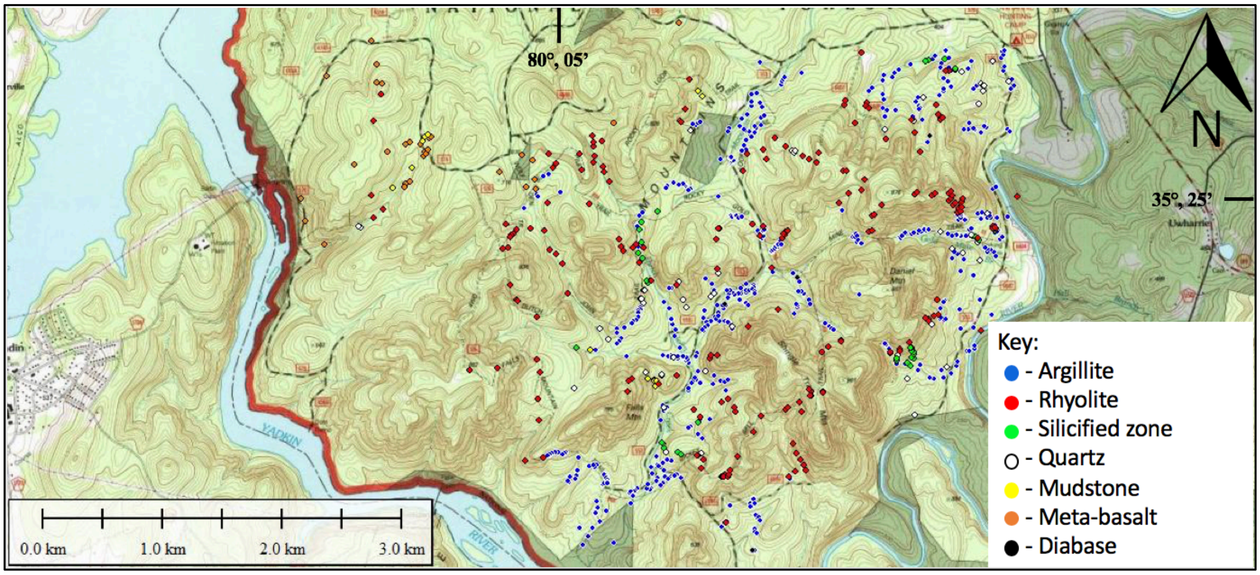

Figure 24 – Rock type waypoints of outcrops and tree tip ups observed throughout the site, Uwharrie National Forest, NC. Base map from USGS Badin 7.5' topographic map.

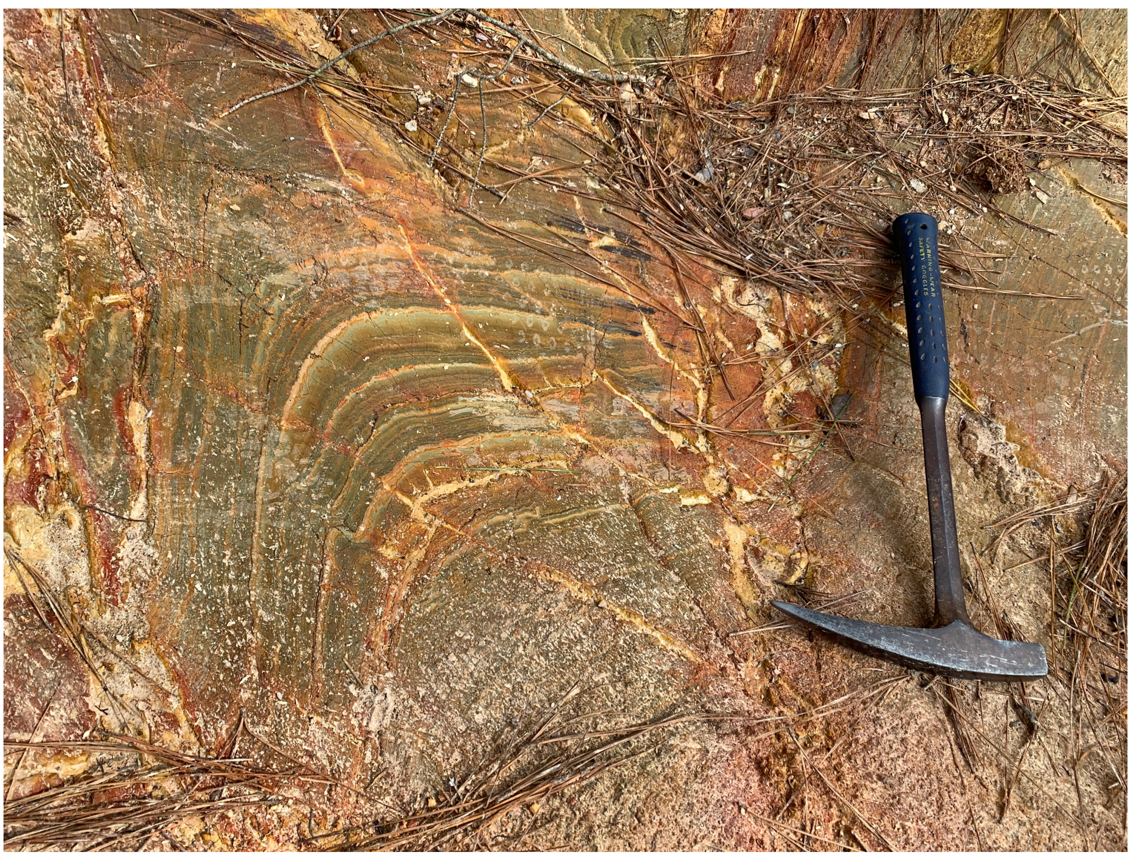

Figure 25 – Orange-red argillitic soil and rhyolite outcrops in the silicified zone of the Tillery Formation. Quartz veins are common in these zones and can sometimes be traced along trend for tens of meters.

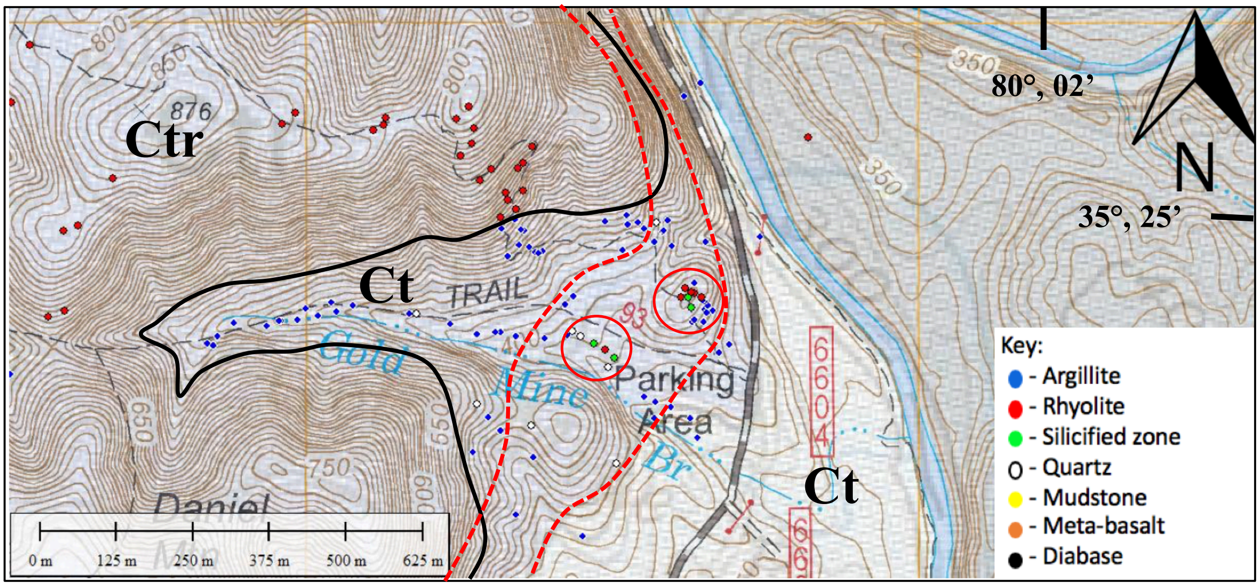

Figure 26 – Strongly foliated volcanic layer (circled) interfingered with argillites in the silicified zone (between dashed lines) of the field area, with the map from Stromquist and Henderson (1985) as the base. This area is stratigraphically lower than the remapped main contact between the argillite and rhyolite (solid black line) in a stream valley on the eastern side of the site.

4.2 Mapped Contacts

For the purposes of this study, lithologic contacts are drawn instead of formational contacts (Figs. 27, 28). In many places, the contacts between sedimentary rocks in the Tillery Formation and volcanic sequences can be located farther upslope than shown on the map by Stromquist and Henderson (1985). (This is caused in part by choosing the where to place the formation contact between the Cid and Tillery formations, but we have also found that the Tillery rhyolite unit is much less extensive than shown on that map). These changes in contact position are most evident in ephemeral stream valleys and on hillslopes dominated by rhyolite colluvium (Fig. 27). As described in the following text, this change in contact locations is partly the result of how Stromquist and Henderson (1985) defined, for example, the base of the Cid Formation. In areas underlain by the silicified zone (dotted lines, Figure 28), that is largely near the upper part of the sedimentary sequence in the Tillery Formation, a small arm of strongly foliated and altered rhyolite interfingers with highly altered argillites and abundant massive quartz veins, usually just stratigraphically below the major contact between the Tillery and Cid formations (Fig. 26). We have chosen to include the silicified zone as a region of some variable thickness (mainly in stream valleys) and area on the map, rather than lump it in with either the argillite or rhyolitic units, due to similar zones being described throughout the Carolina terrane in central North Carolina (Klein et al., 2007; Lapoint and Moye, 2013, Rapprecht et al., 2013; and others). It should be noted however that there is commonly an interval of non-silicified sedimentary rocks stratigraphically between the silicified zone and the contact between distinctive aphanitic rhyolite and argillite in the Tillery Formation.

On the published map (Stromquist and Henderson, 1985), the contact between Tillery sedimentary and volcanic rocks follows topographic contours in many places, suggesting that the contact is nearly horizontal. We think, however, that this contact is near horizontal only near the hinge of the larger anticline or near the hinges of smaller parasitic folds. Furthermore, most slopes on the higher topography underlain by rhyolite are covered by colluvium. There the contacts can sometimes be located farther upslope. Down-slope movement of colluvium through mass wasting tends to bring the surficial and apparent contact between argillite and rhyolite to the toes of those slopes, often at the slope break created by the actual bedrock contact, to run parallel to topographic contours as well. Debris flows and rock slides containing rhyolite detritus further complicate the placement of this contact.

Our XRD data are insufficient to answer the question on whether rhyolitic rocks in the Tillery Formation and rhyolitic units in the Cid Formation are stratigraphically equivalent. Distinctive dark gray or black aphanitic rhyolite are in both sequences and occur at roughly the same elevation and stratigraphic position. The upper parts of the Cid rhyolite do have more coarser pyroclastic materials than Tillery volcanics, but within the study area the Cid Formation occupies elevations higher than the highest points in much of the Tillery Formation; overlying volcanic rocks above the Tillery rhyolites may have been stripped away by erosion. A possible explanation for the variation in pyroclastic components is that the pyroclastic rocks in the Cid Formation represent a near vent volcanic facies of a volcanic center. Similar features are described in the central Carolina portion of the Carolina Terrane, including a lava dome studied by Klein et al. (2007) near the Russell Mine, that is all within the Tillery Formation

Based on mapping results, we agree with the notion (Stromquist and Sundelius, 1969; Milton, 1984; Boorman et al., 2013, Kurek et al., 2013; and others) that the contact between the sedimentary rocks and volcanics is conformable. Whereas some of the volcanics exhibit lower bedding dip angles like Conley (1962) described as being the reason for noting an angular unconformity between the volcanics and steeply dipping argillites, these measurements were most likely taken near the hinge of a fold or of a moderately dipping crenulation cleavage. More steeply dipping bedding in the volcanic rocks are on the limbs of the fold in our area, that correlate with the bedding measurements in the underlying sedimentary rocks.

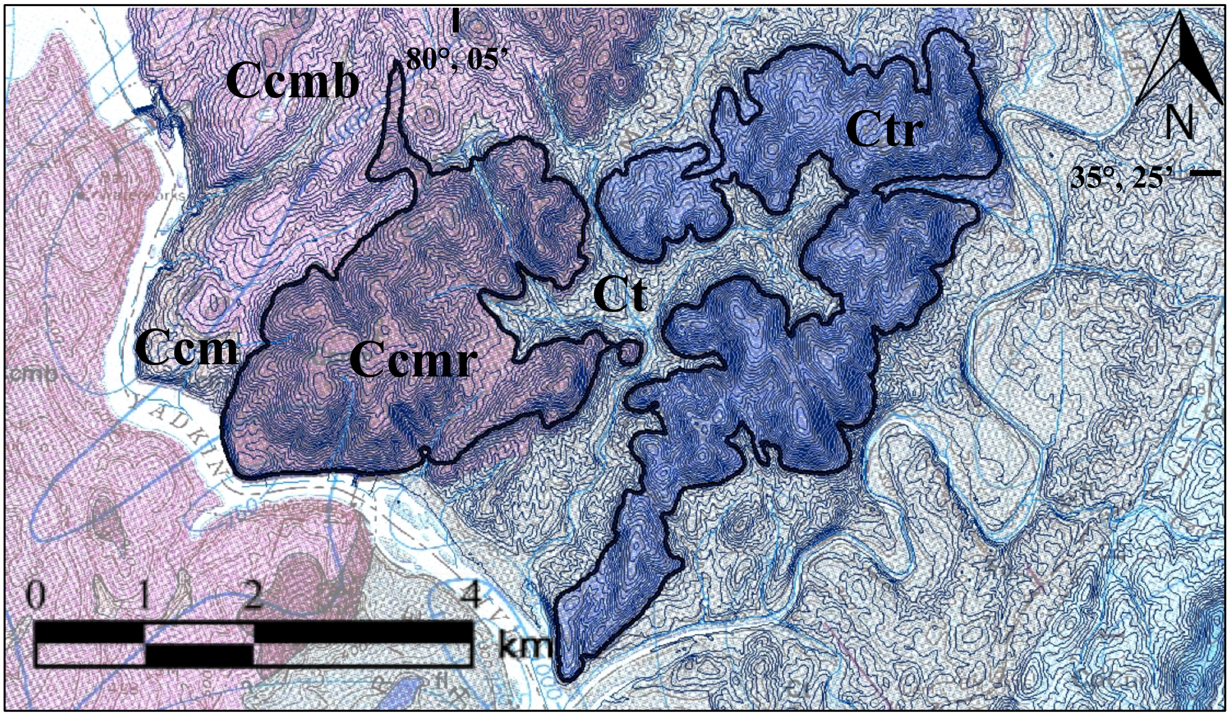

Figure 27 – Stromquist and Henderson (1985) geologic map of the field area overlain by remapped contacts from this study in black. Most new contacts are estimates as visible exposures of the contact are rare.

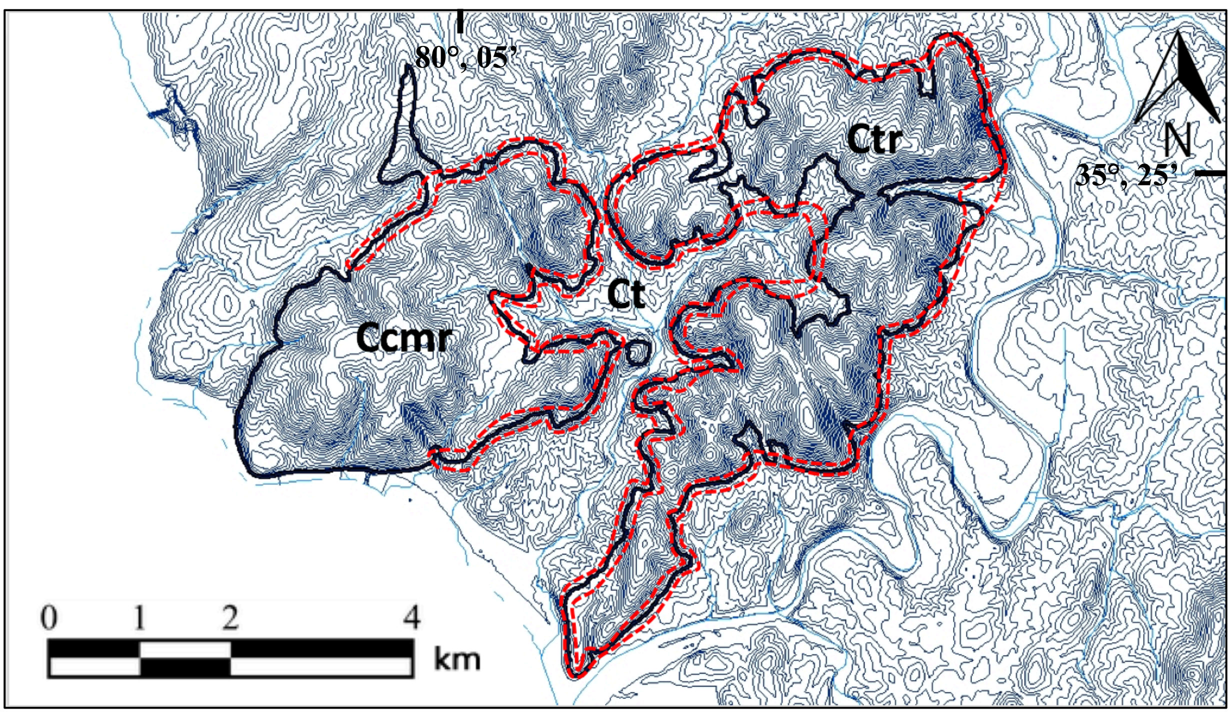

Figure 28 – USFS 2016 topographic map overlain with remapped contact lines and associated rock descriptions (shown below, Figure 28.1). Red dotted lines indicate rough position of the silicified zone. The silicified zone is estimated in places and outcrops as patches.

Description of Map Units

Ctr, Ccmr – Volcanics (Cambrian) – Includes very fine grained, cryptically layered rhyolite with vitrophyre, andesitic basalt, and a range of pyroclastic rocks that are felsic to intermediate in composition.

Ct – Sediments of Stromquist and Henderson's (1985) Ct and Ccm units. Includes poorly laminated, weakly cleaved mudstone, ribbon laminated argillite with alternating layers of silt and clay, and fine grained tuffaceous siltstone and sandstone.

--- – Silicifed rhyolite and argillite – Zone of intense hydrothermal alteration to host rocks. Quartz veins and ore rich hydrothermal alteration minerals are common. Bedding may appear chaotic and laminations within argillite are commonly "bleached" by quartz replacement.

Figure 28.1 – Rock type descriptions.

4.3 X-Ray Analysis of Mineralogy

Based on XRD analysis, the argillaceous rocks in the Tillery Formation contain mainly quartz, muscovite, feldspar, and variable clinochlore (Figs. 29, 30). The feldspar present is mainly albite, though orthoclase, sanidine, and anorthite have been found in rare cases. Sanidine was found in a tuffaceous argillite that exhibited mineralization in joints. Anorthite usually occurs along with clinochlore in some argillites, where the source material is likely Cid basalt. Grain size in these rocks is typically too fine to identify all minerals optically.

Near the contact between Tillery Formation argillite and rhyolite silicification is locally intense. This is marked by an increase in quartz veins (white dots, Fig. 24), and the presence of hydrothermal alteration minerals like friedrichbeckeite, chamosite, cobaltarthurite, pyrite, and others. Abundances of white mica also increase in this zone of silicification, causing the rock fabric to change from slaty to phyllitic. Feldspar alteration to sericite has been observed in thin section (Fig. 31) in the silicification zone as well.

The aphanitic rhyolites in both the Cid and Tillery formations exhibit a composition of quartz and albite, with varying amounts of muscovite. The similar composition between the two volcanic units suggests both rhyolites may have formed in the same magmatic environment, as Boorman et al. (2013) have found with the “Morrow Mountain rhyodacites”. They use this term for a volcanic unit observed in the Uwharrie, Tillery, and Cid formations that magmatically links members of the Albemarle Group. More analysis in our area is needed to confirm if the aphanitic rhyolites from the Tillery and Cid formations we observed are indeed part of the same geochemical grouping of volcanic rocks.

The mafic volcanics observed in the area were greenstones found as blobs in the Cid and Tillery rhyolites. Ferro-pargasite, clinochlore, and anorthite dominate these rocks, along with varying amounts of epidote (Stromquist and Sundelius, 1969) (sample 340, Fig. 30). This collection of minerals is characteristic of mafic basalts at greenschist facies (Fyfe et al., 1958).

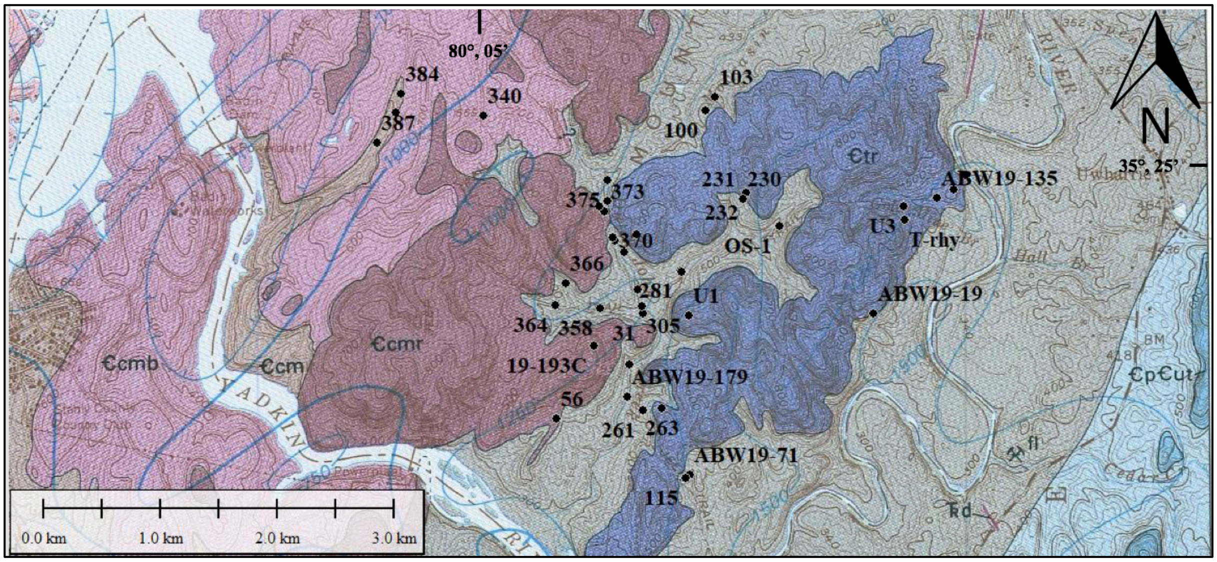

Figure 29 – Locations of X-ray analyzed samples in comparison to Stromquist and Henderson (1985) contacts.

Sample	Rock type	Mineral 1	Mineral 2	Mineral 3	Mineral 4
230	Argillite/tuff	Quartz	Albite	Muscovite	Clinochlore
OS-1	Tillery rhyolite	Quartz	Albite	Muscovite	
366	Silicified argillite	Quartz	Albite	Muscovite	
373	Silicified rhyolite	Quartz	Albite	Clinochlore	
370	Silicified rhyolite	Quartz	Friedrichbeckeite	Muscovite	
375	Silicified argillite	Albite	Quartz	Muscovite	
368	Silicified argillite	Quartz	Clinochlore	Cobaltarthurite	
372	Silicified volcanic	Quartz	Labadorite		
374	Silicified argillite	Quartz	Muscovite	Clinochlore	
364	Phylitic argillite	Quartz	Albite	Muscovite	
358	Argillite	Quartz	Orthoclase	Muscovite	Chlorite
384	Rhyodacite?	Quartz	Muscovite	Orthopyroxene	
340	Greenstone	Ferro-pargasite	Chlorite	Anorthite	
ABW19-71	Tillery rhyolite	Quartz	Albite		
231	Silicified argillite	Quartz	Muscovite		
115	Tuffaceous sandstone	Quartz	Sanidine		
103	Argillite	Quartz	Chlorite	Muscovite	
100	Silicified argillite	Quartz	Clinochlore	Muscovite	Saponite
056	Mafic blob in Cid rhyolite	Clinochlore	Quartz	Fergusonite	Chamosite
226	Argillite	Quartz	Clinochlore	Muscovite	
031	Silicified argillite	Quartz	Muscovite	Wolframite	
371	Silicified argillite	Quartz	Muscovite	Friedrichbeckeite	
ABW19-135	Tillery silicified rhyolite	Albite	Quartz	Unknown aluminosilicate	
305	Argillite	Clinochlore	Quartz	Albite	Muscovite
261	Tillery silicified rhyolite	Quartz	Albite		
ABW19-19	Tillery rhyolite	Quartz	Albite	Muscovite	
377	Greenstone	Clinochlore	Anorthite		
TRhy	Tillery rhyolite	Quartz	Albite	Muscovite	
ABW19-193 (5 samples)	Cid rhyolite	Quartz	Albite		
19-274	Argillite	Quartz	Clinochlore	Muscovite	
493	Argillite	Quartz	Clinochlore	Muscovite	

Figure 30 – Compilation of X-Ray analyzed samples and their major mineral components from the field site, Uwharrie National Forest, North Carolina.

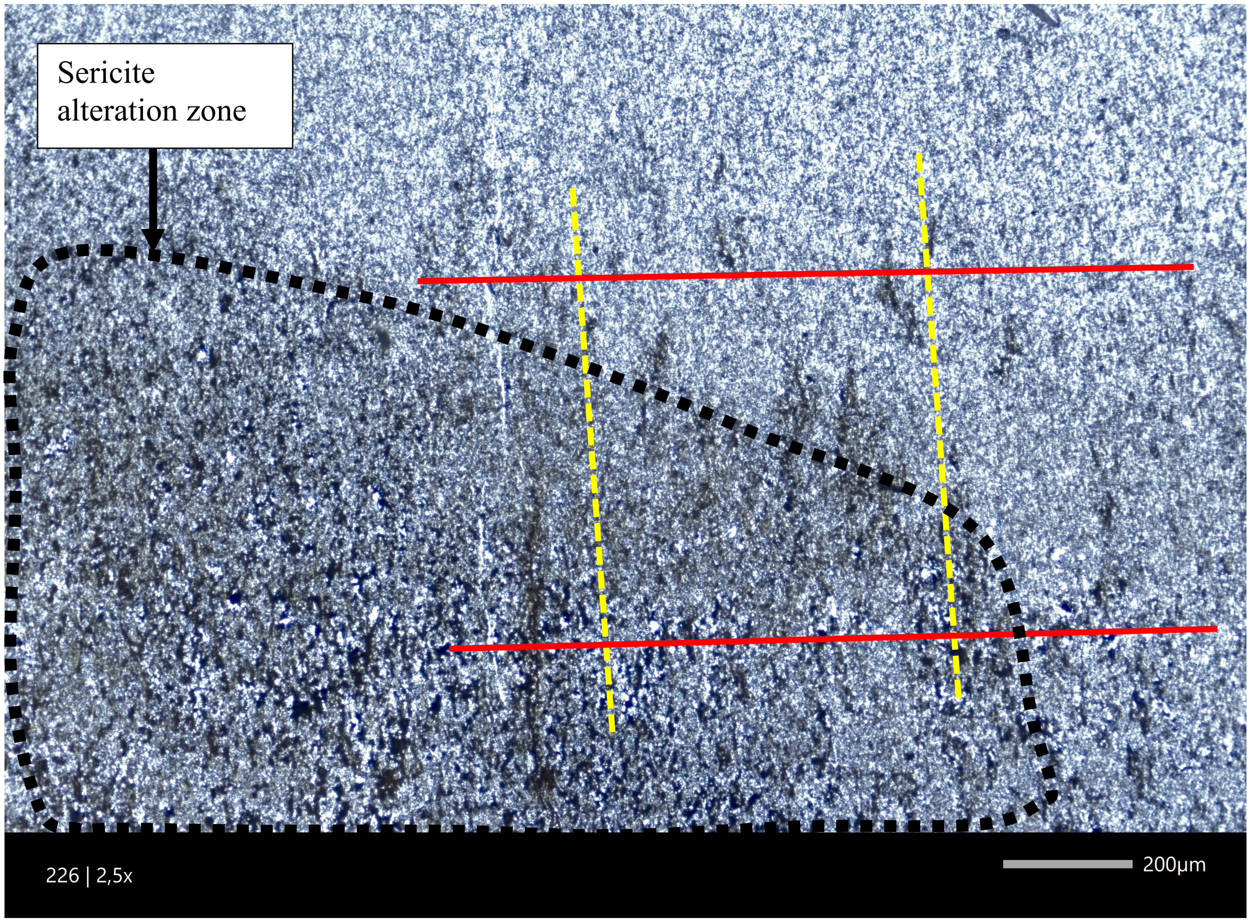

Figure 31 – Argillite with sericite alteration (outlined) at 2.5x and uncrossed polars. Alignment of grains due to axial planar cleavage (yellow dashed lines), with bedding in red solid lines. Opaque minerals are most likely pyrite. Quartz veins run along cleavage, which formed during hydrothermal activity near the main silicified zone between formation and metamorphism.

4.4 Structure

Three main methods were used in the structural analysis of the field area: 1) spatial zonation of bedding and cleavage measurements based on coherence of orientations within each zone and location relative to the proposed larger fold, 2) creation of total bedding and total cleavage stereonets for description of the overarching structure of the area, and 3) generation of geologic cross sections based on mapped bedding attitudes for visualization of the underlying structure.

4.4.1 Mesoscopic Folds

Exposures of complete mesoscopic fold closures are rare in the study area. A few road and stream bed exposures of folds, however, allow measurement of bedding attitudes, axial planes or axial plane cleavage, and rarely fold hinge lines. These observations permit characterizations of mesoscopic fold attitudes and approximations of their geometries. Max eigenvector great circles are shown in most stereonets, which in this case display the mean lineation direction (densest cluster of points) of the data set. Due to the variation in bedding orientations from across the area, this analysis will not result in an accurate fold axis orientation for those plots.

Figure 32 shows one of these visible fold closures. Bedding measurements taken from the fold dip shallowly NW-SE around 30° and strike SW-NW, with the main fold hinge striking 030° and plunging 25°. Axial plane cleavage taken from the fold dips steeply 80° to the NW and strikes 230°. A compilation of bedding attitudes taken from observed mesoscopic folds is shown in Figure 33. Two main concentrations of bedding attitudes emerge from this stereonet: One which dips moderately to the NW and strikes SW, and one which dips steeply to the SE and strikes NW. The maximum eigenvector great circle displays a main concentration of attitudes with an average axial plane that trends NE-SW at about 225° and dips NW at 75°. Cleavage measurements taken from mesoscopic folds confirm this trend (Fig. 34), with a main orientation which dips steeply NW at 75° and strikes NE-SW at 225°. These visible fold structures, though sparse, allow for characterization of a visibly unobservable mesoscopic fold(s) across the site.

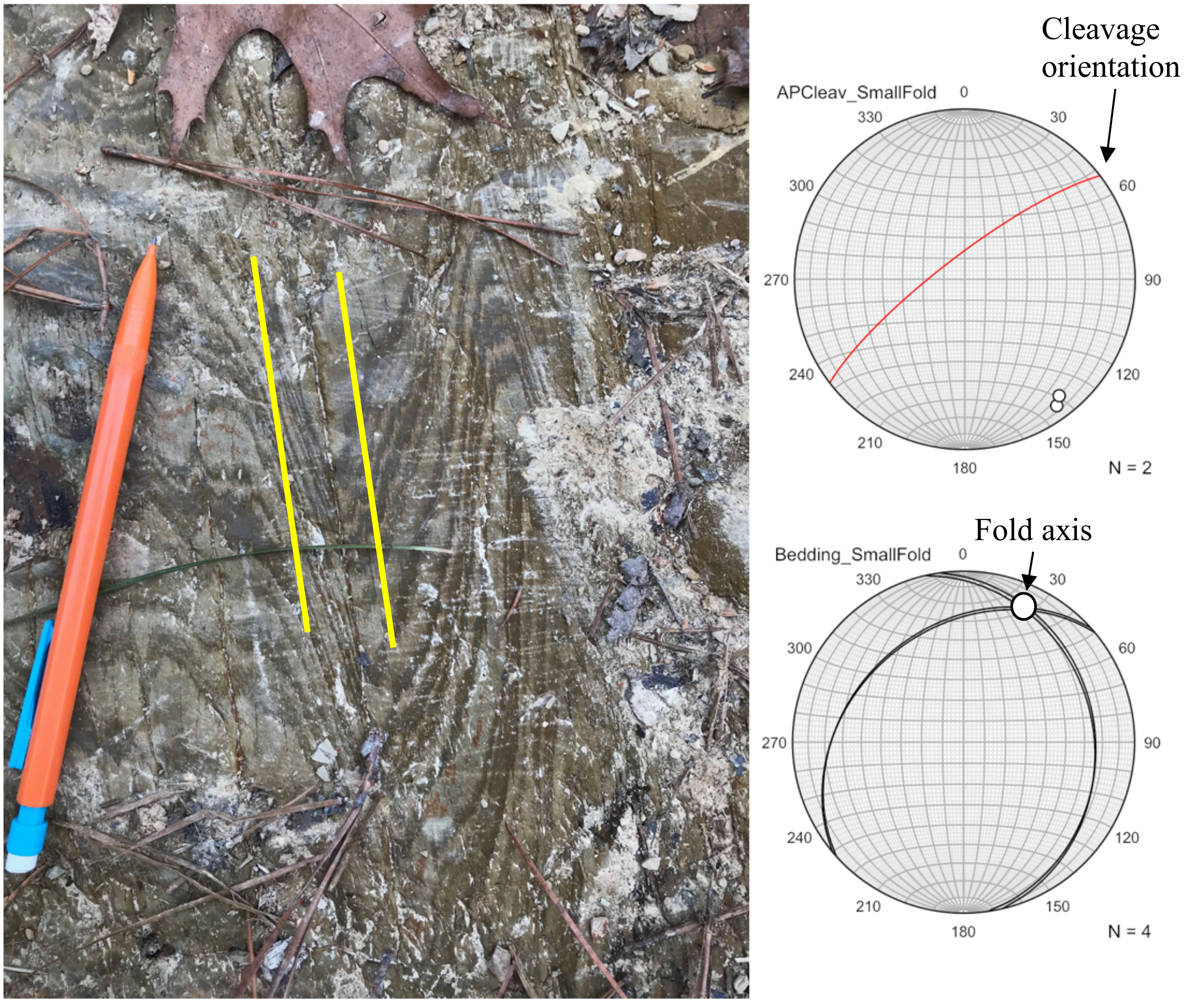

Figure 32 – Mesoscopic fold in Tillery argillite with bedding and axial plane cleavage (trace highlighted in yellow) measured and displayed in stereonets with their associated great circles. The outcrop surface is horizontal. Cleavage (top right) dips steeply northwest at 80° and strikes about 232° based on the max eigenvector great circle. Bedding (bottom right) dips shallowly NW-SE across the fold and strikes generally northeast. The estimated fold hinge from beta analysis plunges about 25° toward 030° and the axial planes are oriented about 030°, 75°.

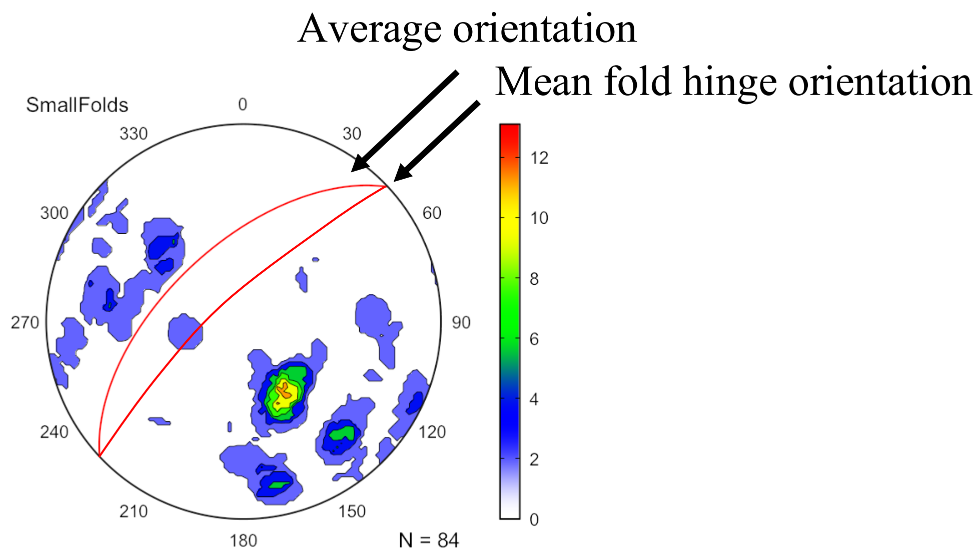

Figure 33 – Compilation of observed mesoscopic folds and their associated bedding attitudes from across the site in Tillery argillite. Two concentrations of bedding measurements can be seen: One that dips moderately NW and strikes SW (using right hand rule, RHR), and the other dipping steeply SE and striking NE, displaying the geometry of folding across the site. The associated max eigenvector great circle in this case displays an average axial plane that trends SW-NE at about 225° and dips moderately NW at 60°. The mean fold hinge orientation has a similar strike, but dips more steeply at about 80°.

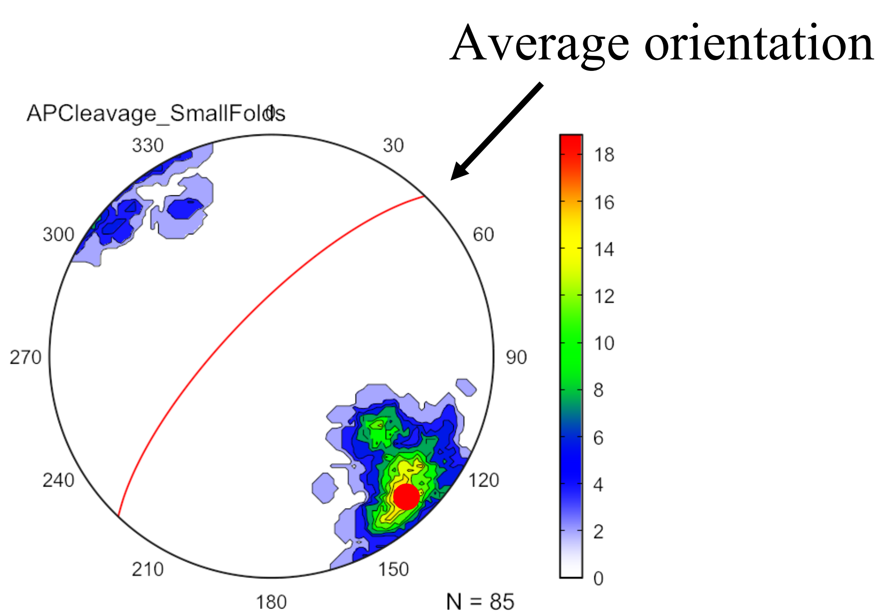

Figure 34 – Compilation of cleavage axial planar to visible mesoscopic folds in Tillery argillite. Main concentration (red circle, associated great circle) of attitudes dips steeply to the NW at 75° and strikes 225° (RHR).

4.4.2 Bedding Orientations

The total bedding stereonet (Figs. 35, 36) shows three main concentrations of attitudes. The largest is a grouping that dips to the northwest about 50° (area 1) and strikes 225°. A smaller concentration dips steeply southeast at 80° and strikes 045° (area 3), and a third grouping is nearly horizontal or dipping gently southeast (area 2). Area 1 has the largest and most dispersed concentration of points, while area 3 is more concentrated and steeply dipping. Based on the total bedding stereonet and bedding attitudes from Figure 36, this pattern is indicative of an asymmetric anticline (Fig. 37). Area 1 represents the more shallowly dipping and spread out northwestern limb, and area 3 the more steeply dipping southeastern limb of the fold. Similar to the parasitic folds in Figure 33, the main fold hinge in Figure 38 strikes 225°, with its axial plane dipping 80° NW. Due to the large distribution in bedding orientations in Figure 38, the max eigenvector of total bedding more closely displays the average orientation of attitudes as opposed to the actual hinge line, which have a similar strike to the hinge but a more moderate dip of around 60° toward 315°.

Clusters of bedding attitudes in the southwestern and northeastern quadrant of the stereonet represent possible closures and plunges in the fold (Fig 37, dotted circles). These areas are outlined in yellow in Figure 36 in the northeast and southwest portions of the fold. The concentrations are roughly orthogonal to the main fold axis, dipping moderately NE-SW and striking NW-SE. This difference in orientation from the main limbs of the fold (which dip more steeply NW-SE) is suggestive of a doubly plunging anticline across the site (Figs. 39, 40).

Zonal stereonet plots (Figs. 41, 42) show the variability in local bedding orientations due to folding. For example, zone 3 (B3) displays one limb of the larger anticline dipping moderately to the northwest and striking southwest-northeast. Zone 1 on the other hand has concentrations that show bedding planes dipping northwest-southeast. Zone 1 is indicative of the structure of the main anticlinal fold. Furthermore, zone 2 exhibits similar features, though bedding is more moderately dipping. This grouping of attitudes is near the possible hinge of the main anticlinal fold across the field site, with shallow dips and a northeast-southwest strike.

In the northeast and southwest parts of the map area, contacts between Tillery Formation sedimentary rocks and Tillery or Cid formation volcanic rocks are likely fold closures of the doubly plunging anticline (Fig. 41). Bedding stereonets from zones 7 through 9 show this geometry (Fig. 42), striking NW-SE as opposed to the limbs of the main anticline which strike NE-SW, which most of the other zones show.

The wide variation in attitudes outside of the three main concentrations in the total bedding stereonet in Figure 35 is likely caused by the mesoscopic parasitic folds on the limbs of the main anticline discussed in figures 32 and 33. For example, zones 4 and 5 (Fig. 42) are on the southeast dipping limb of the main anticline but exhibit full folding structures themselves. Parasitic folds are present in zones 2 and 3 as well. These folds, which locally may differ from the geometry of the macroscopic doubly plunging anticline, when combined display a similar geometry to the main fold as seen in Figure 33. It is also possible that later folding has rotated both bedding and cleavage from the main phase of deformation.

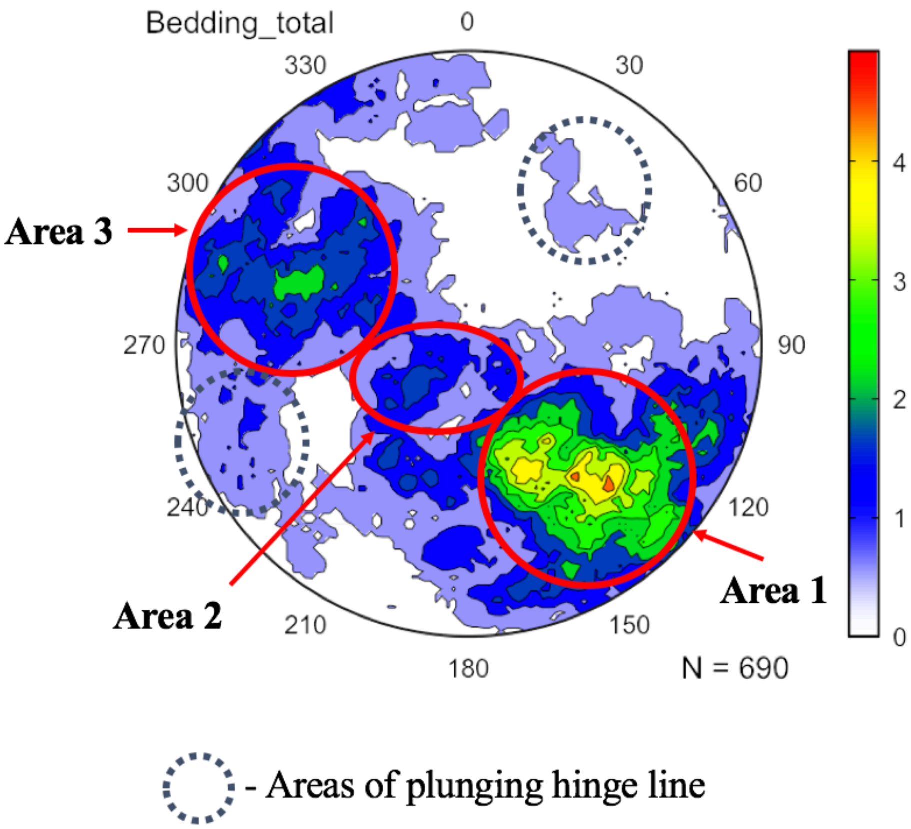

Figure 35 – Stereonet of bedding measured in the study site in Uwharrie National Forest, NC using the modified Schmidt projection. Circles indicate concentrations of bedding attitudes.

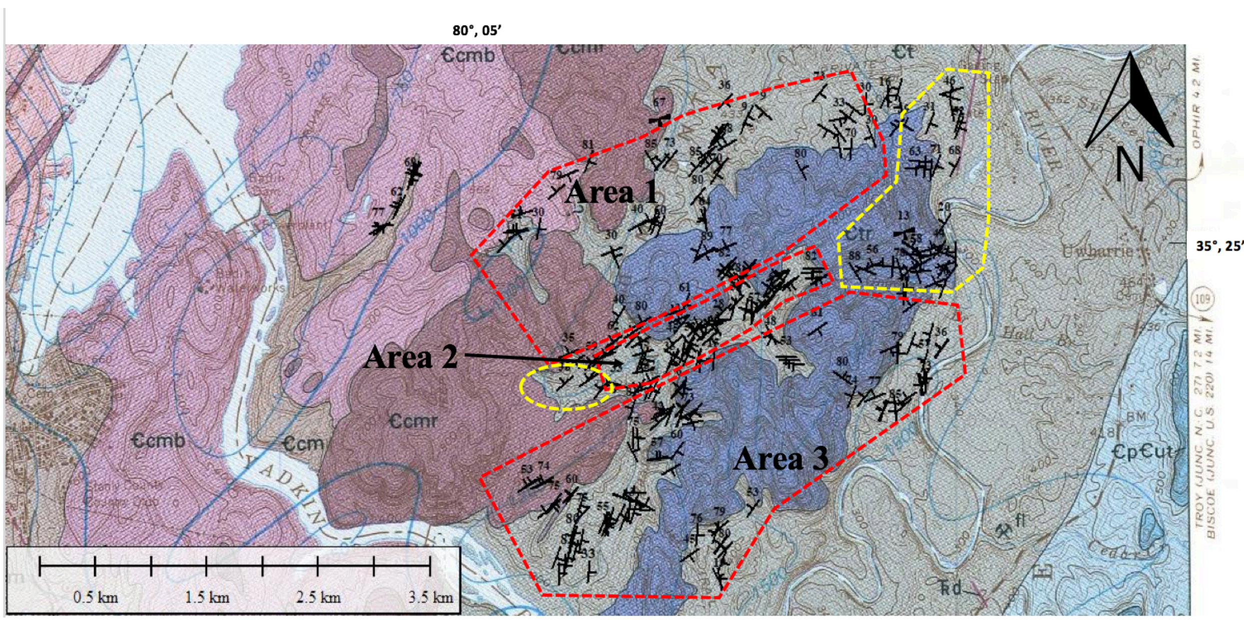

Figure 36 – Locations of attitudes from Figure 35. Three main areas outlined and labelled in red, areas of plunging hinge line are outlined in yellow.

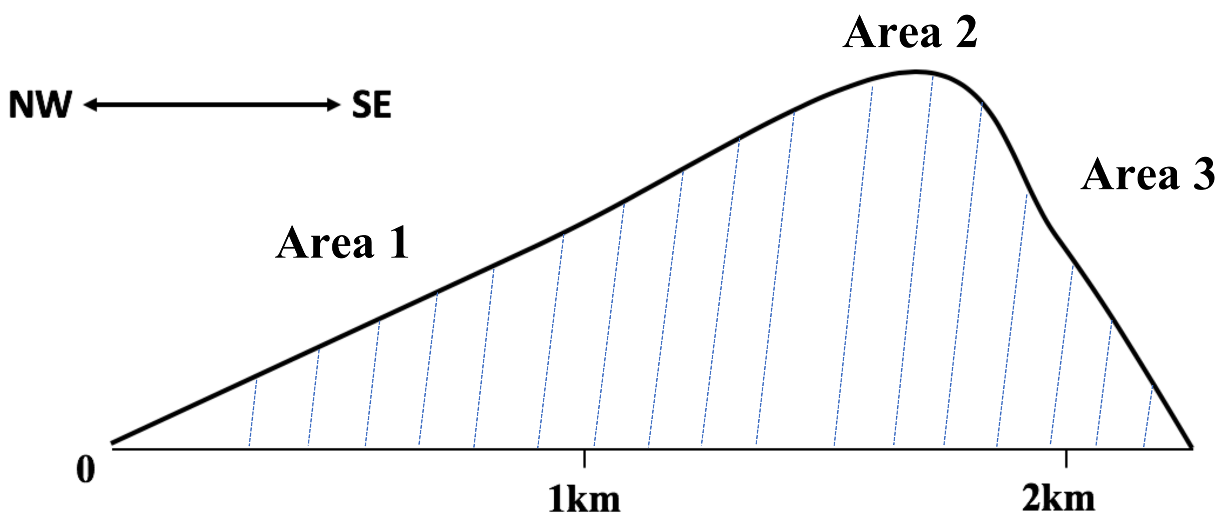

Figure 37 – Visualization of main asymmetric anticline, with the limb in area 1 dipping 50°, and area 3 80°. Used for the purposes of visualizing the differences between the northwestern and southeastern limbs of the main fold from Figure 35. Dotted lines represent the axial plane of the fold, dipping 80° northwest. Accurate representations of the geometries of folding are shown in later cross sections.

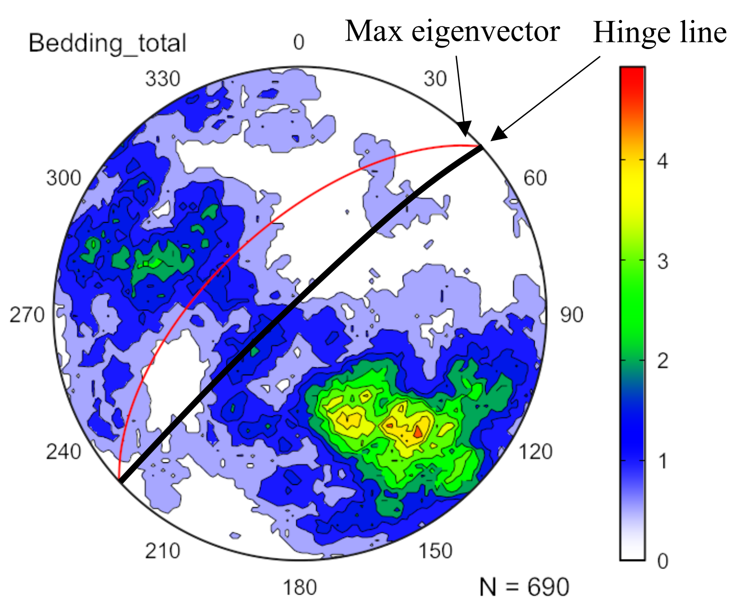

Figure 38 – Stereonet of all bedding measurements collected from across the site. Great circle of max eigenvector represents the average orientation of attitudes, which strike 225° and dip 60° NW. The hinge line of the main fold similarly strikes 225° SW, but its associated axial plane dips more steeply at about 80° NW.

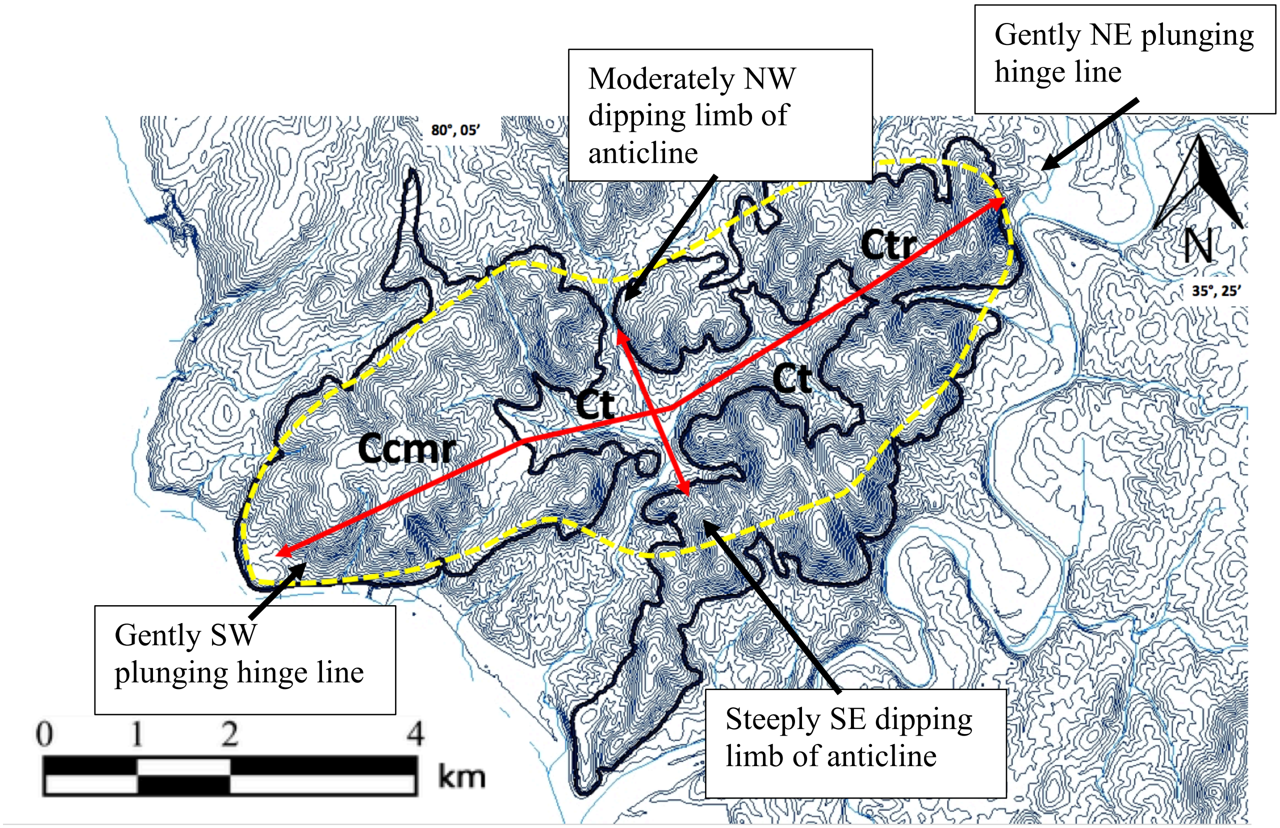

Figure 39 – Outline of main fold structure shown in yellow, with hinge and limbs outlined in red.

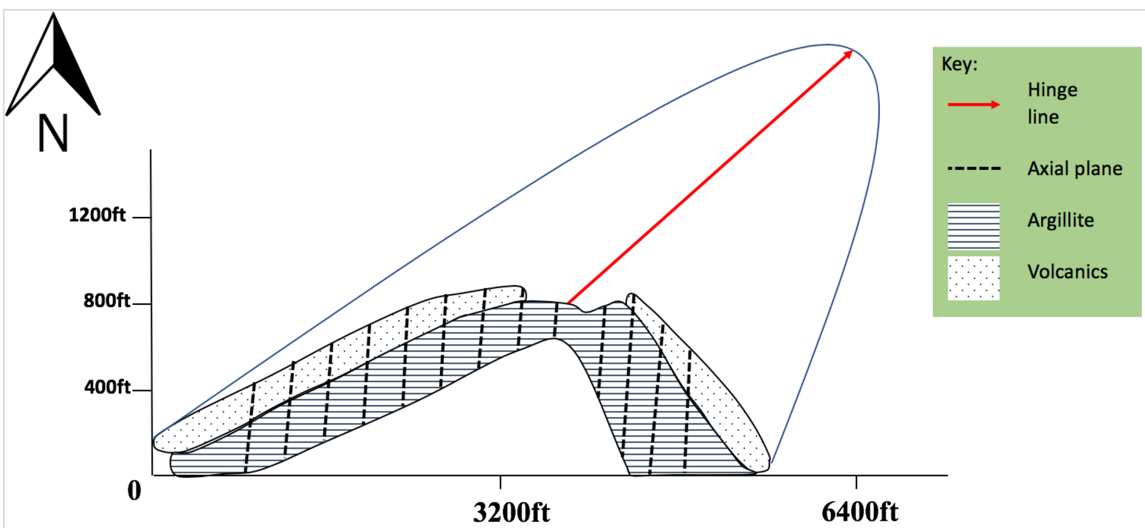

Figure 40 – Three-dimensional cross section of the northeastern half of the proposed doubly plunging anticline. The hinge of the fold has been weathered out to expose the stratigraphically lower argillite underneath as seen in Figure 39. Stratigraphic thicknesses not to scale.

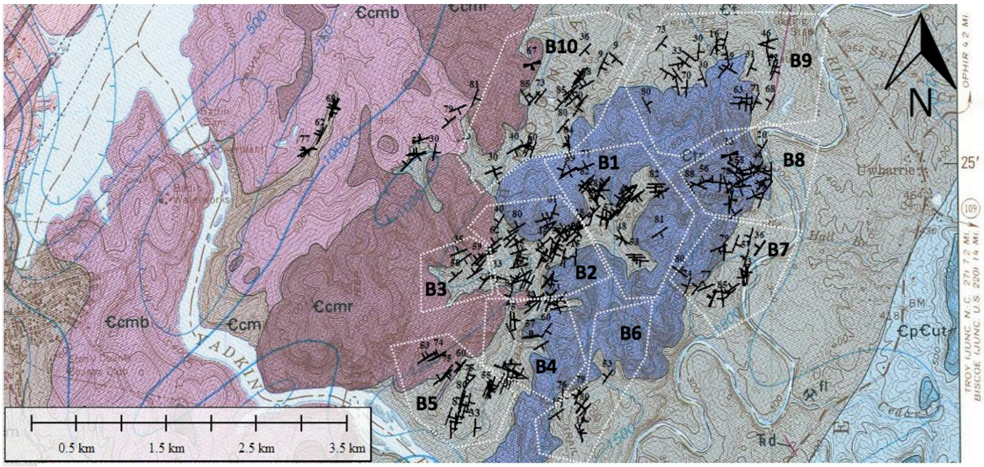

Figure 41 – Bedding measurements across the fold divided into marked zones for further stereonet analysis. B1 = Zone 1. Stromquist and Henderson (1985) map used as the base.

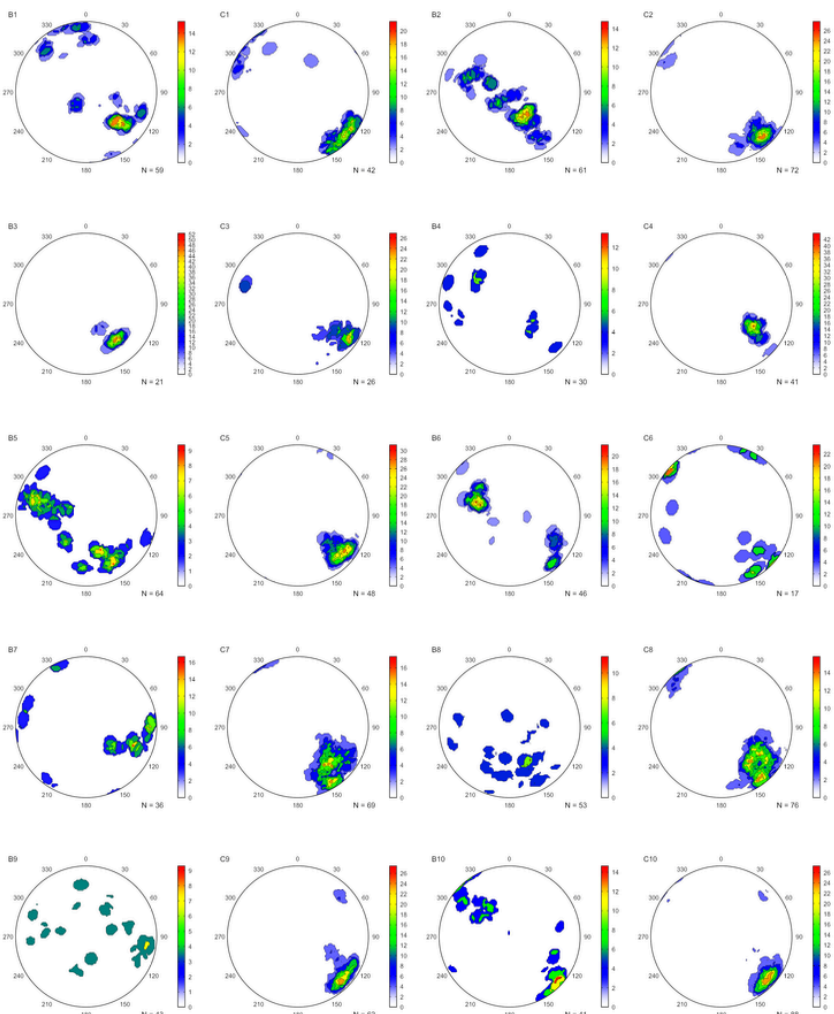

Figure 42 – Bedding and cleavage stereonets with their associated zones marked in the map above. B = bedding with its corresponding zone number, C = cleavage with its corresponding zone number. Ex: B1 = bedding in zone 1.

4.4.3 Cleavage

The total cleavage diagram in Figure 43 displays a main concentration of attitudes dipping steeply 80° and striking 225° (RHR). Although the concentration of poles to cleavage is tight, there is a faint suggestion of pole distributions along the same great circle as shown by bedding. It's possible that there is some overlap in bedding and cleavage orientations resulting from difficulty in distinguishing cleavage from bedding in some outcrops. This is most problematic where cleavage and bedding are close to the same strike and in poorly exposed outcrops.

Close examination of the contours in Figure 43 also suggest possible rotation of cleavage planes about folds that plunge moderately to steeply northwest. Some of the scatter in bedding orientations (Fig. 38) may show similar distributions. We have observed kink folds in several outcrops (Fig. 44) that may account for this variation in bedding and cleavage if there are larger folds of similar orientation. These folds appear to have their own set of spaced axial planar cleavage or joints. This set of cleavage dips 80-85° NE and strikes 330° (Fig. 45). Kink axial planes often are dilational with quartz veins in the voids.

4.4.4 Main Structure

The main doubly plunging anticline is elongated northeast-southwest (Fig. 39). Cross section A in figures 46 and 47 show the main asymmetric anticline inclined to slightly overturned to the southeast, with a prominent parasitic fold in the center. Cross section B, which runs along the hinge of the fold, depicts the gently doubly plunging fold closures to the NE-SW. Lastly, cross section C runs across an area of the asymmetric anticline with several parasitic folds. Parasitic folds occur across the site and are not limited to the areas shown, more may even occur in the cross-section areas but are not visible in observed outcrops. Together, these sections display the main, gently NE-SW plunging and trending, slightly overturned to the southeast, asymmetric doubly plunging anticline with numerous parasitic folds throughout.

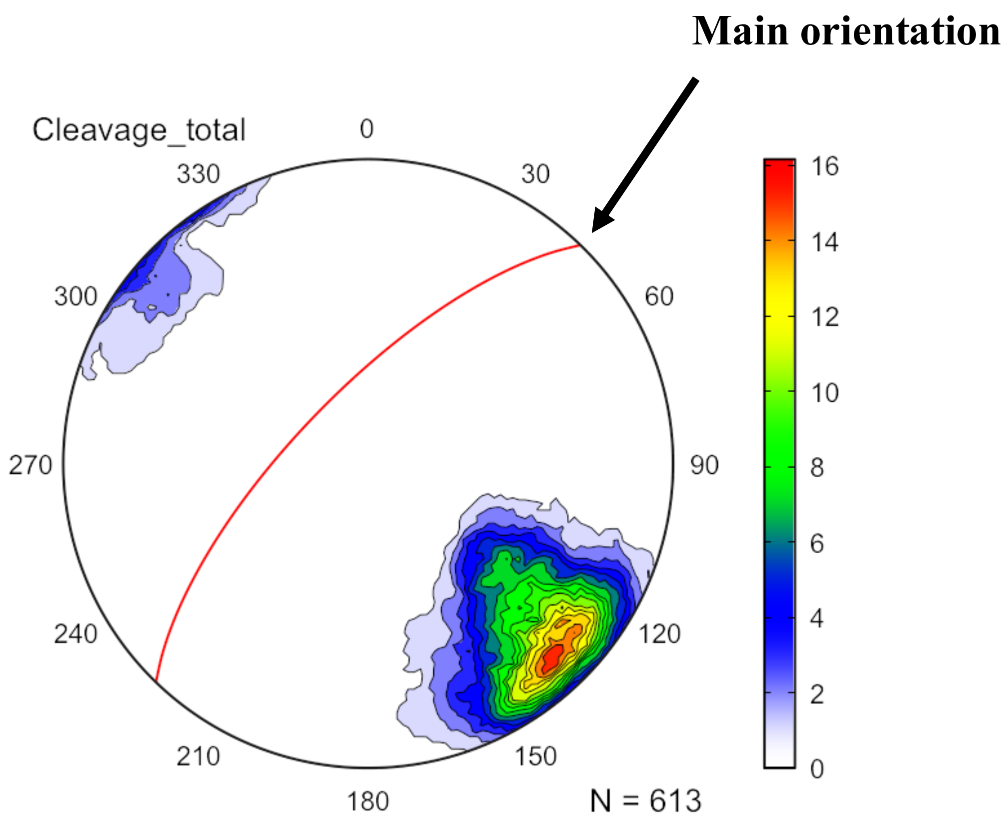

Figure 43 - Secondary kink folds in Tillery Formation argillite. Fold axial planes shown in yellow. Inset – Within the kink bedding dips steeply westerly and strikes southwest, with slight variation across the fold (Kamb contours). The cleavage measurement taken from this location had a strike of 340° and dip of 79° (RHR).

Figure 44 – Secondary kink folds in Tillery Formation argillite, Uwahrrie National Forest, NC. Fold axial planes shown in yellow. Inset – Within the kink bedding dips steeply W-NW and strikes southwest, with slight variation across the fold. Kamb contours. The cleavage measurement taken from this location had a strike of 340° and dip of 79° (right hand rule).

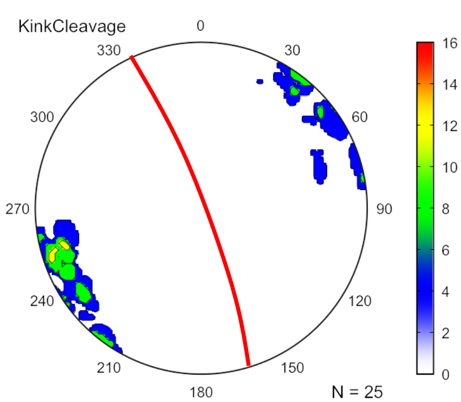

Figure 45 – Stereonet of cleavage axial planar to secondary kink folds. The best fit great circle strikes 330° NW and dips 80-85° NE, similar to the cleavage measurement in figure 44.

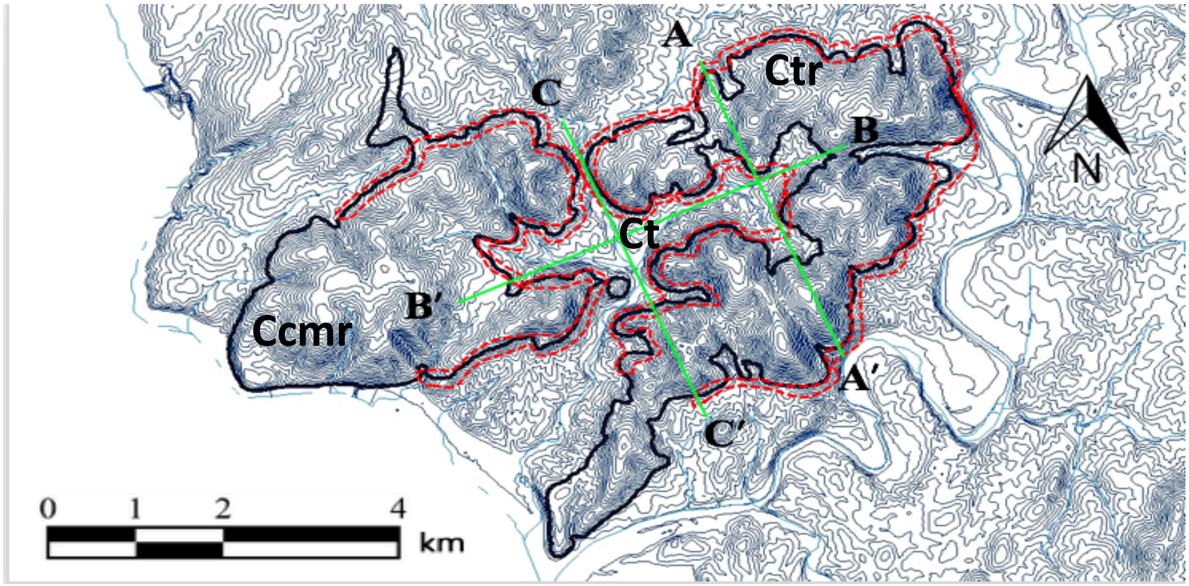

Figure 46 – Locations of cross sections (shown in green) with remapped contacts.

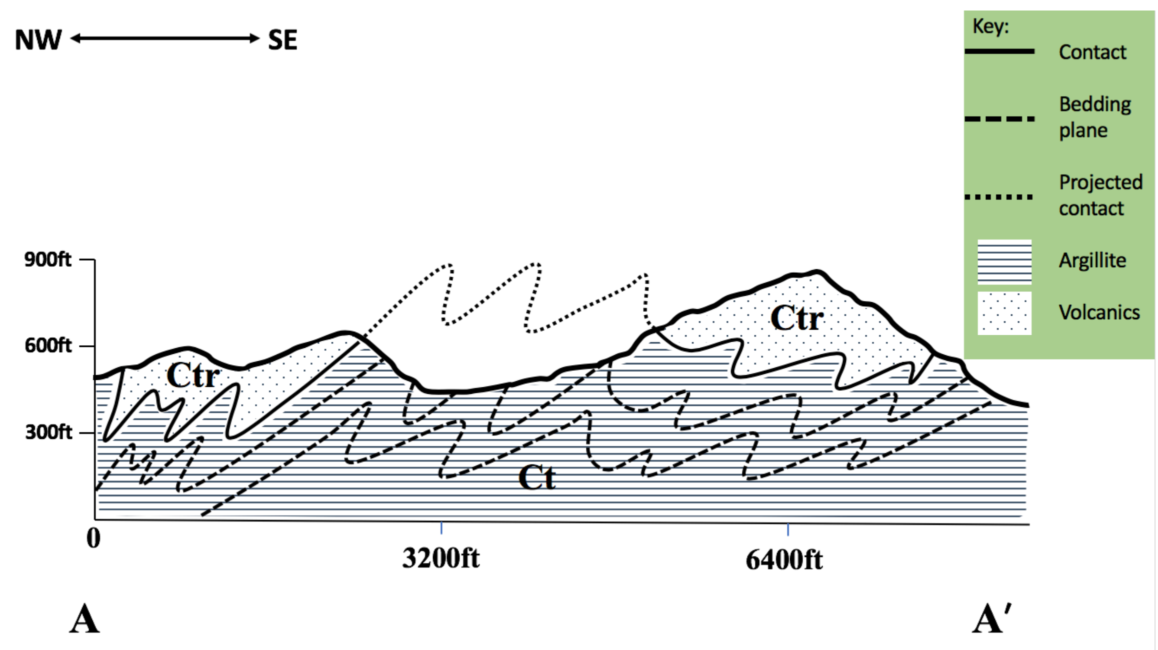

Figure 47A

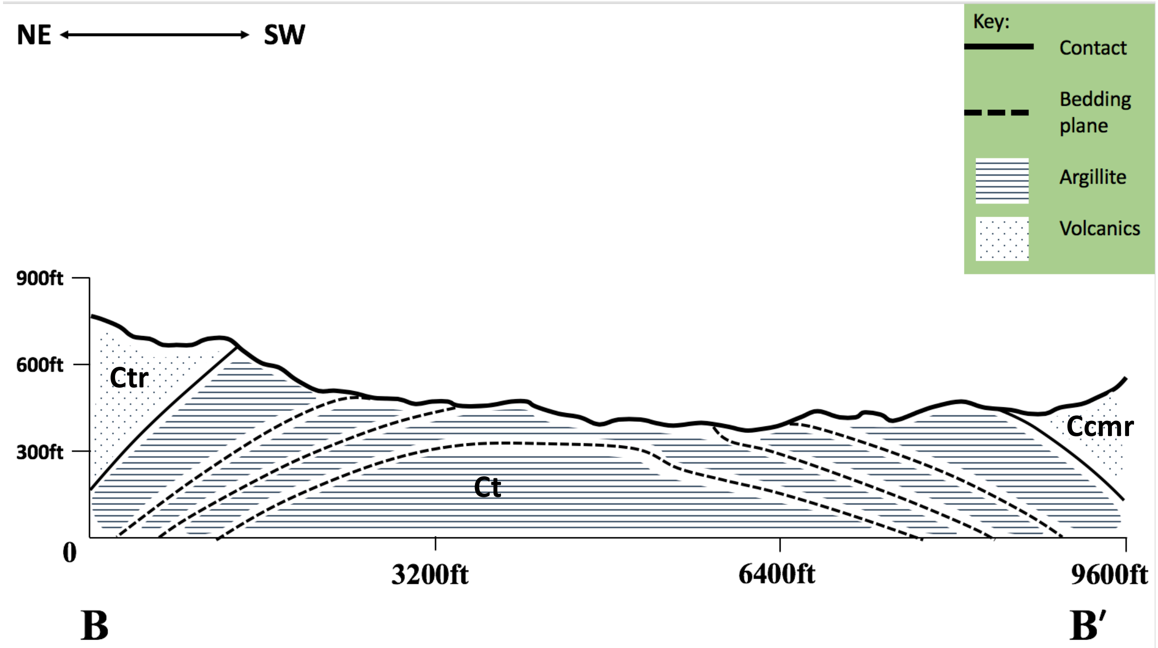

Figure 47B

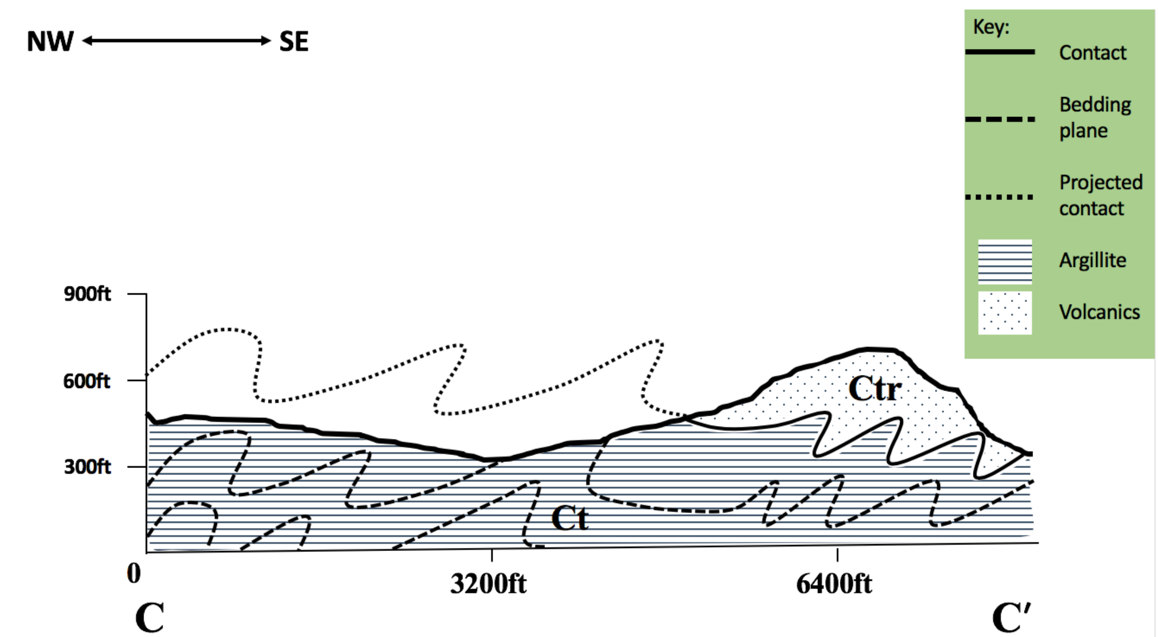

Figure 47C

Figure 47 – Cross sections (A, B, and C) of estimated bedding based on measured attitudes on visible surface outcrops. More parasitic folds in the areas of these cross sections are most likely present but were not observed at the surface or measured. Naming conventions are from Stromquist and Henderson (1985).

5 DISCUSSION

5.1 Timing of Events

The rhyolite and encompassing argillite in the area were deposited during the late Neoproterozoic to Cambrian as part of the Albemarle Arc - a volcanic island arc within the larger Carolina terrane (Hibbard et al., 2013). We hypothesize that the silicification of rocks due to hydrothermal alteration near the contact between the argillite and rhyolite occurred sometime between deposition of those rocks and regional metamorphism, as rocks in this zone exhibit the same metamorphic and deformational features as the rest of the area. This event lead to the formation of the ore-rich hydrothermal alteration and economic minerals found in the volcanics and associated sedimentary rocks in the silicified zone described in the area and throughout this section of the Carolina terrane (Klein et al., 2007).

Folding and metamorphism occurred during the middle Paleozoic Cherokee orogeny, that marked the collision of peri-Gondwanan components and Laurentia, marking the closure of the Iapetus (Hibbard et al., 2013). This event created the main series of folds in the central part of the Carolina terrane including the proposed doubly plunging anticline in the current study. This anticline is on the southeastern limb of the New London synclinorium (Figs. 1, 39), itself a doubly-plunging structure. Similarly, smaller parasitic folds throughout the study area and the prominent northwest dipping, axial planar cleavage formed at this time.

It has been proposed that southeast sinistral transpression along the Gold Hill shear zone during the Cherokee orogeny caused the doubly plunging fold structure characteristic of folds in the Carolina terrane (Hibbard et al., 2012). In the study area, the antiformal hinge region of the proposed fold has been eroded to expose the stratigraphically lower Tillery Formation sedimentary rocks in the core of the fold. Subsequent differential erosion inverted the topography with regards to bedrock structural facing.

The Cherokee orogeny was also responsible for the remobilization and concentration of gold ore bodies throughout the larger central Piedmont area in the core of some anticlinal folds (Klein et al., 2007). The extent of ore enrichment is unknown in the study area, though gold prospects present near the silicification zone (Fig. 28, dashed lines) have been observed. Silicification and ore enrichment is noted in roughly similar stratigraphically positioned folds throughout the central North Carolina area of the Carolina Terrane (Klein et al., 2007; LaPoint and Moye, 2013; Challener, 2016).

As noted earlier, a second set of folds with their own associated axial planar cleavage (or closely spaced joints) are found in the study area (Fig. 45). This cleavage differs in orientation from that of the primary folds, striking northwest-southeast as opposed to northeast-southwest. We believe these folds occurred during a later deformational event. Elsewhere in the terrane, Alleghenian deformation is recognized in discrete shear zones (Klein et al., 2007, Miller, 2013; Hibbard et al., 2013;). It is possible that these kink folds could be related to this later deformational event, though more analysis is needed. After this, Triassic or Jurassic diabase dikes (Rapprecht et al., 2013) intruded all rock layers in the area.

6 CONCLUSIONS

Interpretations of field data collected in Uwharrie National Forest, including contact locations and rock types, geochemistry, and structural analysis, lead to the following conclusions regarding the structural geology of the sedimentary and volcanic rocks of the area.

1) Previous mapping of the lower contact(s) between metavolcanic and metasedimentary rocks often show this contact following topographic contours, suggesting low dip angles (Conley and Bain, 1965; Stromquist and Henderson, 1985). Our remapped contact shows that in many locations the contact can be moved farther upslope in ephemeral stream valleys and thus changes map projections to better represent dips controlled by folding. It is possible for the contact to be locally horizontal where the contact coincides with fold hinges, however. The rhyolite unit in the Tillery Formation is far less extensive than previously mapped, as rhyolite colluvium dominates some hillslopes but is not *in situ* in these areas. Here, outcrops and tree tip-ups of weathered argillite can still be found. Mudstone similar to the Cid mudstone unit mapped by Stromquist and Henderson (1985) to the north has been observed in the field area as well, usually near the argillite rhyolite contact. However, outcroppings are rarely found for more than a few meters, and are difficult to map as a separate unit.

2) An area of silicification was observed mainly in the Tillery formation sedimentary rocks near the contact between sedimentary rocks and rhyolitic volcanic rocks. The silicified zone contains highly altered argillites, abundant quartz veins, and may contain singular rhyolite layers. Ore rich hydrothermal and metamorphic alteration minerals are concentrated in this area. Very fine-grained siliceous layers are intercalated

with distinguishable sedimentary protoliths and these layers may be purely hydrothermal in origin. This zone is roughly in the same stratigraphic position of known gold-bearing ores within the Tillery Formation to the northeast noted by Klein et al., (2007). Silicification most likely pre-dates regional metamorphism.

3) We believe the Cid and Tillery aphanitic rhyolites in the field area to be part of the same formation based on structural and mineralogic data (Fig. 30). Stratigraphically above this aphanitic rhyolite on the western side of the site is a zone of pyroclastic rocks. It is possible that the pyroclastics are associated with the aphanitic rhyolites below and form a volcanic dome, with the pyroclastics to the west representing a near vent volcanic facies of a volcanic center. However, this remains a hypothesis as geochemistry and geochronology were not the focus of this study. A similar lava dome has been postulated by Klein et al. (2007) at Russell Mine, northeast of the field area.

4) The main set of folds in the study area are a doubly-plunging anticline on the southeastern limb of the (doubly-plunging) New London synclinorium and parasitic folds of multiple wavelengths within the anticline. The larger anticlinal fold is slightly inclined to the southeast and trends roughly 045° northeast-southwest. Folding occurred during the mid-Paleozoic Cherokee orogeny (Hibbard et al., 2013) and is marked by lower greenschist facies metamorphism (LaPoint and Moye, 2013) and generally northwest-dipping slaty or phyllitic axial planar cleavage. Parasitic folds are common on the limbs of the main anticline. These smaller folds explain the local, sometimes sharp variations in bedding attitudes.

5) A set of kink folds and minor reverse faults have been observed in the field area as well. These folds have a separate set of axial planar cleavage or closely spaced

joints which dip steeply SW-NE, compared to the mainly NW dip of the main set of cleavage. Although we believe these to be from a later deformational event, possibly Alleghenian, more work is needed to confirm this theory.

While we consider there to be only one volcanic unit in the field area, detrital zircon dating is needed to confirm this hypothesis. Additional geochemical work with an ICP-MS would allow us to further categorize the volcanics and silicified zone observed in this area. Thanks to an abundance of white micas, future plans also include adding solid age dates to the deformation history of these rocks in the Albemarle Group through muscovite Ar-Ar dating. Finally, more work is needed collecting data and structurally analyzing the secondary kink folds in the area. This work will be used to compare the observed kink folds to later deformation described by Klein et al. (2007) and others in the Carolina terrane.

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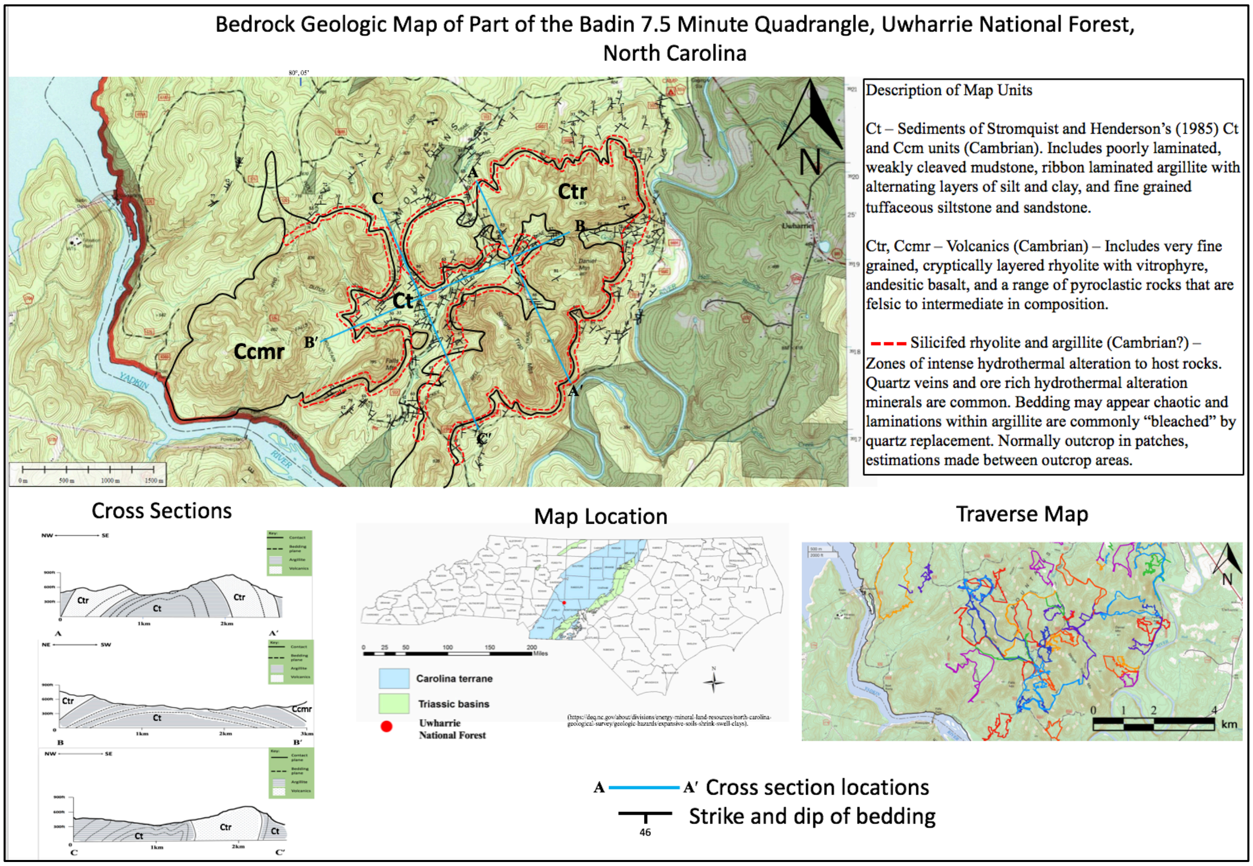
APPENDIX - PLATES

Plate 1 - Bedrock Geologic Maps

Bedrock Geologic Map with Bedding Attitudes



Bedrock Geologic Map with Cleavage Attitudes

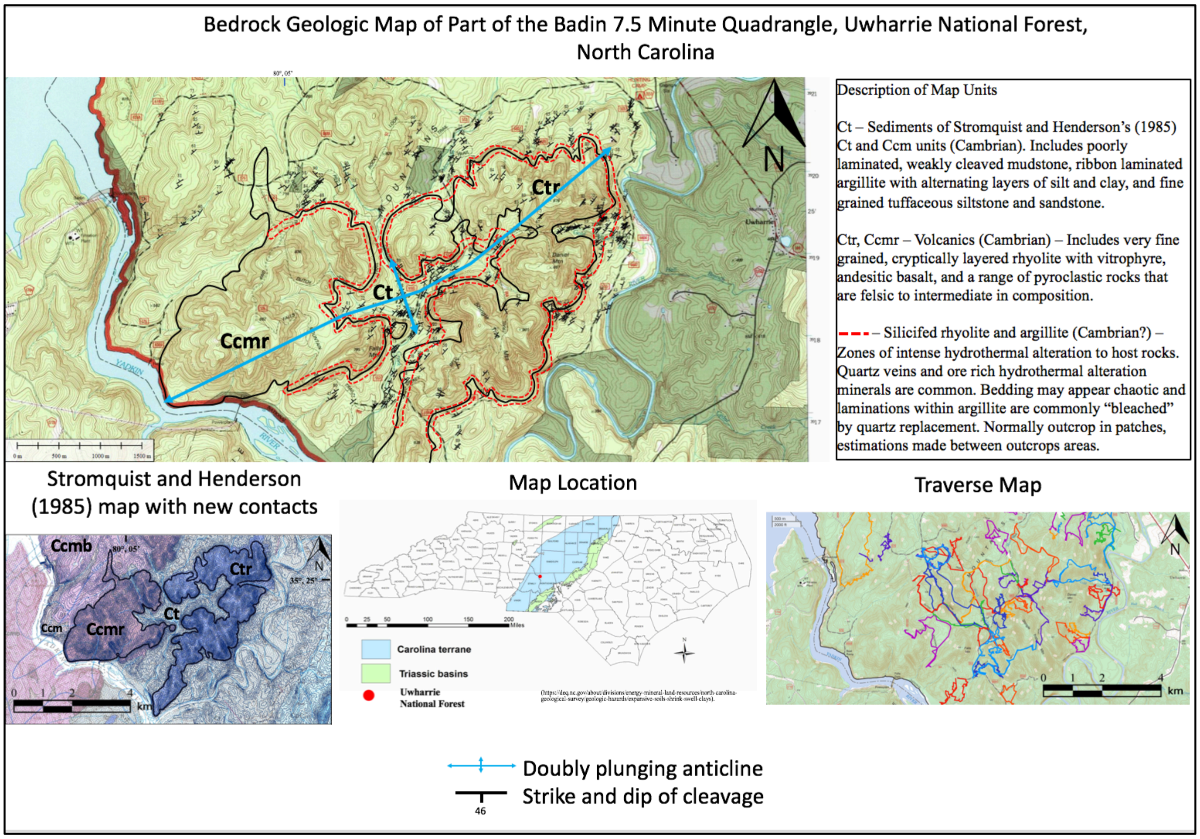


Plate 2 - Structural Geologic Map with Associated Stereonets