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The Albemarle Sequence of the Carolina Terrane in Central North Carolina: Geologic and Metallogenic Analysis with an alternative model

and

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

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

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Abstract

One of the most studied and best defined components of the Carolina terrane is the Albemarle Sequence in central North Carolina. It consists of the basal late Ediacaran age Uwharrie Formation, a felsic-dominated bimodal volcanic sequence up to 5 kilometers thick, and the conformably overlying 8-10 kilometers thick clastic sediment and volcanic dominated late Ediacaran to early Cambrian Albemarle Group, consisting of the Tillery, Cid, Floyd Church, and Yadkin formations. The Uwharrie Formation and Albemarle Group are compositionally distinct and accumulated in very different depositional environments. The Albemarle Group has a restricted distribution in south-central North Carolina and north-central South Carolina; however, the Uwharrie Formation may have originally been much more widely distributed across the older Hyco arc and Virgilina formations to the east and northeast.

In Randolph and Montgomery counties, the Uwharrie Formation consists of overlapping and stacked felsic eruption centers with domes and flows grading laterally into pyroclastic and epiclastic sequences. It was deposited in a largely shallow marine but locally emergent environment. To the northeast and east early Uwharrie magmatism may have focused along north and east stepping *en echelon* transtensional fault zones that host alignments of large, variably mineralized zoned advanced argillic epithermal alteration systems (AES) that may be higher level expressions of intrusion-centered Au-Cu-Mo porphyry systems at depth. Many are strongly anomalous in fluorine and some have associated epithermal Au, Cu, and Mo mineralization.

The Albemarle Group outcrops over a roughly rectangular area of about 35 x 130 kilometers and accumulated in the arc-rift Albemarle Basin. It is characterized by abrupt subsidence during the waning stage of Uwharrie volcanism and slow deep marine accumulation of the Tillery Formation, followed by active rifting and rapid deposition of the Cid Formation accompanied by mafic-dominated volcanism in the Mudstone Member and felsic-dominated volcanism in the Flat Swamp Member. The Floyd Church and Yadkin formations appear to represent relatively passive post-rift basin filling accompanied by mafic magmatism that continued until at least 528 Ma.

Active arc rifting was largely focused in the northern half of the basin and may have begun ca. 547 Ma during deposition of the Mudstone Member of the Cid Formation, culminating ca. 541 Ma during a period of intense felsic-dominated submarine volcanism represented by the Flat Swamp Member of the Cid Formation, which hosts VMS deposits in the Cid and Gold Hill mining districts.

Known low tonnage but high-grade VMS deposits of the Flat Swamp Member are Bimodal-Felsic Class deposits and attractive exploration targets, especially where they cluster. The presence of often large and extensive mafic and felsic units interpreted as volcanic in the middle to upper Tillery Formation and throughout the Mudstone Member of the Cid Formation suggests the potential for similar styles of VMS mineralization. The absence of this mineralization and recent chemical analysis and new geochronological data for felsic units in the basin stratigraphy necessitate a review and reevaluation of the character and timing of basin magmatism and associated mineralization.

The Uwharrie, Tillery, and Cid Mudstone member in the northern part of the Albemarle Basin are intruded by numerous plugs, dikes, and sills of Morrow Mountain rhyodacite. Morrow Mountain rhyodacite is similar in age to Flat Swamp Member volcanism, which largely ended felsic magmatism in the basin. Skarn-like polymetallic mineralization at the Scarlett Mine in Asheboro and related skarn-like assemblages at Dave's Mountain suggest that polymetallic sulfide mineralization is specifically associated with Morrow Mountain rhyodacite magmatism.

Intrusions of Stony Mountain gabbro are present throughout the Albemarle Sequence but most abundant in the northern part of the Albemarle Basin. Stony Mountain gabbro is formed from mantle-derived magma and ranges in age from at least 445 Ma to around 528 Ma. It may be linked with mafic volcanism in the Tillery, Cid, Floyd Church, and Yadkin formations or there may be two distinct mafic magmatic events and sources.

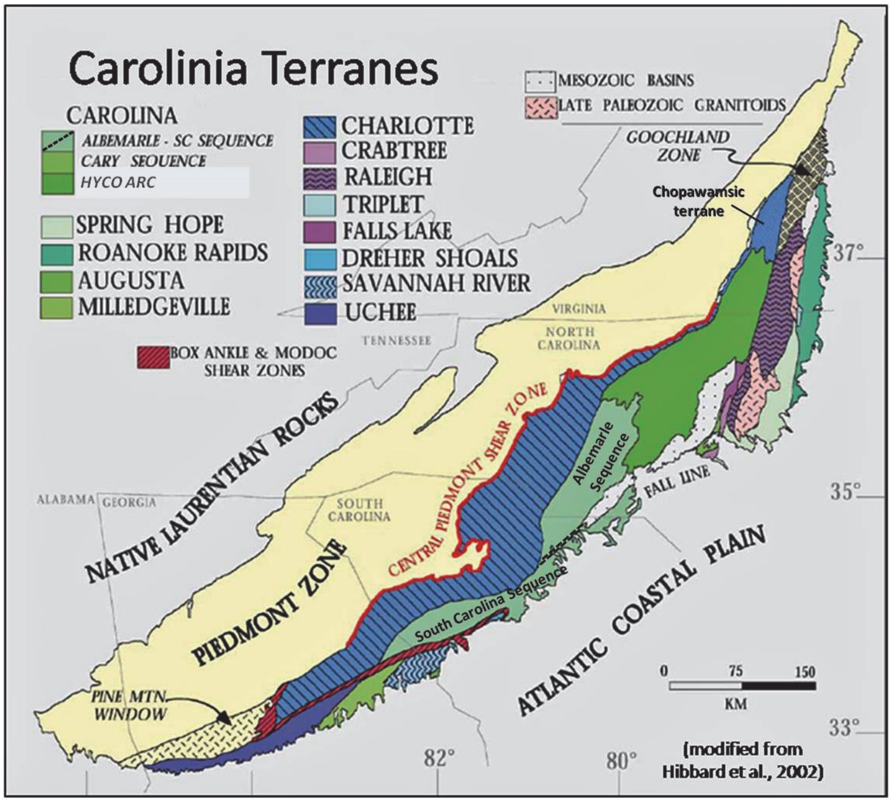
Uwharrie Formation magmatism is broadly synchronous with the Persimmon Fork Formation of the South Carolina Sequence of the Carolina terrane but the two are compositionally very different. Arc-rifting of the Carolina terrane, represented by the Albemarle Basin in central North Carolina, appears to post-date collision and suturing of the Carolina and Charlotte volcanic arc terranes in central South Carolina. It is also broadly synchronous with arc-rifting of the adjacent Charlotte terrane.

Introduction

This analysis of the Albemarle Sequence (**Fig. 1**) builds on the work of **Moye *et al.* (2017)** with the North Carolina Geological Survey on VMS deposits of the Albemarle Basin. It is part of a larger, long-term research project analyzing the metallogenesis of the Carolina terrane. The intent is a comprehensive, detailed, and holistic classification of all recognized types of precious and base metal sulfide deposits and associated hydrothermal alteration systems and their relationship to specific stages and events in the tectonic evolution of the terrane. These deposits are classified by mode of formation and expression, lithologic and structural controls, possible igneous associations, and mineral deposit model type.

The lithotectonic framework for the project is based on a broad range of studies published in journals, bulletins, reports, books, maps, field trip guides, MS and PhD theses, conference abstracts, and other sources made available through the public domain over the past 200 years. Most importantly, this project is made possible by a series of milestones in understanding the stratigraphy, structure, and tectonic history of the Carolina terrane over the past three decades. These are acknowledged as referenced works throughout the report.

The analysis incorporates information on Carolina terrane mineral deposits from a similarly broad range of sources, synthesized through the author's extensive experience in geologic mapping, precious and base metal exploration, and prospect evaluation in the Carolina terrane and adjacent terranes across North Carolina, South Carolina, and Georgia. It also benefits from the experience and perspectives of 40 years in exploration and ore deposit geology across three continents.



(modified from Hibbard et al., 2002)

Fig. 1: Location of the Albemarle Sequence in Carolinia

Ore deposits formed by hydrothermal systems are often local-scale products of regional-scale geologic events that result in the formation and movement of fluids through the upper crust. These include regional and district-scale metamorphism and deformation and magma generation, fractionation, and emplacement in a variety of tectonic environments. Many hydrothermal ore deposit types are represented by well constrained genetic models with strong indicators of the character of the tectonic environments in which they form. These ore deposit models can be used to as a check on interpretations of the tectonic environment of host lithologic sequences, complementary to stratigraphic, structural, petrologic, lithogeochemical, geochronological, and isotopic studies.

Among the potentially economic mineral deposit types associated with the Albemarle Sequence of the Carolina terrane are high-grade polymetallic volcanogenic massive sulfide deposits (VMS) and large advanced argillic epithermal alteration systems (AES) with significant potential for the discovery of epithermal gold mineralization and a possible association with large-tonnage intrusive-centered porphyry-type precious and base metal sulfide deposits. Each of these deposit types appears to be associated with specific tectonic events, geologic environments, and geographically constrained lithologic and/or structural elements that characterize the formation of the Albemarle Sequence.

Contrasting stratigraphic models for the Albemarle Sequence

Geochronological data from detrital zircon U-Pb studies (**Pollock, 2007**; **Pollock *et al.*, 2010**), new zircon U-Pb data from the Flat Swamp Member of the Cid Formation (**Hibbard *et al.*, 2012**; **Hibbard *et al.*, 2013**), and new U-Pb zircon ages and chemical studies of Morrow Mountain rhyodacite units in the Uwharrie, Tillery, and Cid formations appear inconsistent with the classic sequential and conformable stratigraphic model for the Albemarle Sequence (**Stromquist and Sundelius, 1969**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Butler and Secor, 1991**; **Hibbard *et al.*, 2002**).

An alternative stratigraphic model is proposed (**Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**) suggesting that the Tillery and Cid Formations are lateral facies equivalents of the upper Uwharrie Formation. This interpretation has major implications for the timing, character, distribution, and tectonic environment of Ediacaran arc volcanism and arc-rifting in the Carolina terrane in central North Carolina.

The present analysis is a comprehensive review of lithologic, stratigraphic, and geochronological studies of the component formations of the Albemarle Sequence combined with an analysis of concurrent magmatism and associated styles of hydrothermal alteration and precious and base metal mineralization. It is intended to fully evaluate the strengths of the contrasting stratigraphic models and better constrain the timing and character of arc-rifting of the Carolina terrane in central North Carolina, better defining the stratigraphic distribution of known VMS deposits within the Albemarle Sequence and the potential for additional discoveries. Additional ore deposits types that characterize the Albemarle Sequence are also reviewed as tectonic constraints, especially large, often intrusion-related advanced argillic epithermal alteration systems (AES) that appear to be associated with Uwharrie felsic magmatism (**Moye, 2013**).

The classic model of Albemarle Sequence stratigraphy

Regional and local stratigraphic and structural studies (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Seiders, 1981**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Butler and Secor, 1991**; **Brenan, 2009**; **Kurek, 2010**) suggest that the Albemarle Sequence is a continuous, upright stratigraphic succession with conformable and gradational contacts between the Uwharrie, Tillery, Cid, Floyd Church, and Yadkin formations (**Fig. 2**). The component formations and members are distinguished by variations in sedimentological character and the composition and proportions of interbedded volcanic units and igneous intrusions.

Published U-Pb zircon ages for the Albemarle Sequence are consistent with this interpretation. U-Pb zircon ages for the Uwharrie Formation in central North Carolina include 568 ± 6 and 558 ± 8 Ma (**Kozuch, 1994**), 554 ± 15 Ma (**Ingle *et al.*, 2003**), and 551 ± 8 Ma (**Ingle, 1999**; **Ingle-Jenkins *et al.*, 1998**). The data of **Kozuch** (**1994**) are not widely accepted.

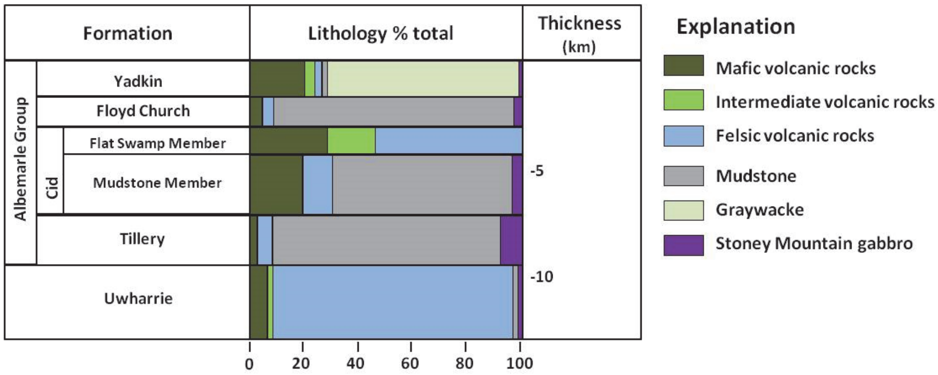


Fig. 2: Classic Albemarle stratigraphy and lithology (modified from Wright and Seiders 1980)

Kozuch (**1994**) reports poorly constrained U-Pb zircon ages of 554 ± 14 Ma for rhyolite from the lower Tillery Formation near Asheboro and 542 ± 14 Ma from a rhyolite unit within the Mudstone Member of the Cid Formation. In the type area near Denton in Davidson County, the Flat Swamp Member of the Cid Formation has yielded zircon U-Pb ages of 540 ± 1.2 Ma (**Ingle *et al.*, 2003**) and 547 ± 2 Ma (**Hibbard *et al.*, 2009**). Additionally, **Hibbard *et al.*** (**2012**) report a TIMS U-Pb zircon age of 542 +8/-5.5 for felsic quartz-feldspar phyric tuff, probably correlative with the Flat Swamp Member, within the Gold Hill Fault Zone west of the town of Silver Hill.

Detrital zircon U-Pb ages for samples from the Tillery, Cid (Mudstone Member), and Yadkin formations provide maximum ages of deposition for these units that are consistent with the classic stratigraphic model (**Pollock, 2007**; **Pollock *et al.*, 2010**). Detrital zircon U-Pb ages from the Tillery (**Pollock, 2007**) show a major peak at about 550 Ma from a range of 541 ± 9 to 591 ± 10 Ma (26 analyses) and a secondary peak at about 630 Ma from a range of 598 to 698 Ma (21 analyses). **Pollock** (**2007**) suggests a maximum age of around 552 Ma for the Tillery Formation.

Ninety-three percent of detrital zircon analyses from a sample of the Mudstone Member of the Cid Formation returned U-Pb ages of 539 ± 12 to 567 ± 15 Ma, with a prominent peak at 550 Ma on the cumulative probability plot (**Pollock, 2007**). This sample was collected from the Jacob's Creek Quarry north of Baden Lake, which has also yielded the Ediacaran body fossil *Aspidella*. The Floyd Church Formation has yielded specimens of both *Aspidella* and *Pteridinium* (**Hibbard *et al.*, 2009**; **Weaver *et al.*, 2006**).

Detrital zircon grain U-Pb analyses from the Yadkin (**Pollock, 2007**) include a strong peak at about 560 Ma in a cluster of 72 samples ranging from 528 ± 7 Ma to 636 ± 9 Ma, and a minor peak at around 650 Ma. The youngest U-Pb ages for detrital zircons obtained by **Pollock** (**2007**) from the Yadkin Formation range from 541 ± 16 Ma to 528 ± 8 Ma.

The existing "layer cake" stratigraphic model is consistent with possibly arc-related, felsic-dominated bimodal Uwharrie magmatism from ca. 555 Ma to ca. 551 Ma, followed by arc-rifting and deposition of the Albemarle Group with concurrent associated rift magmatism from ca. 550 Ma to at ca. 528 Ma.

The Lateral Facies Equivalence Model for the Albemarle Sequence

The alternative lateral facies equivalence stratigraphic model (**Fig. 3**) for the Albemarle Sequence (**Pollock, 2007**; **Pollock *et al.*, 2010**; **Hibbard *et al.*, 2012**) is based in part on U-Pb ages for three detrital zircon grains obtained from a sample of the Erect Member at the base of the Uwharrie Formation in the USGS Erect 7.5' Quadrangle. The sample was collected 1.1 kilometers west of the intersection of Fork Creek with Fork Creek Mill Road near Yow Mill, on a branch of Mill Creek (**Hibbard *et al.*, 2013 - Stop S-5, p. 29**).

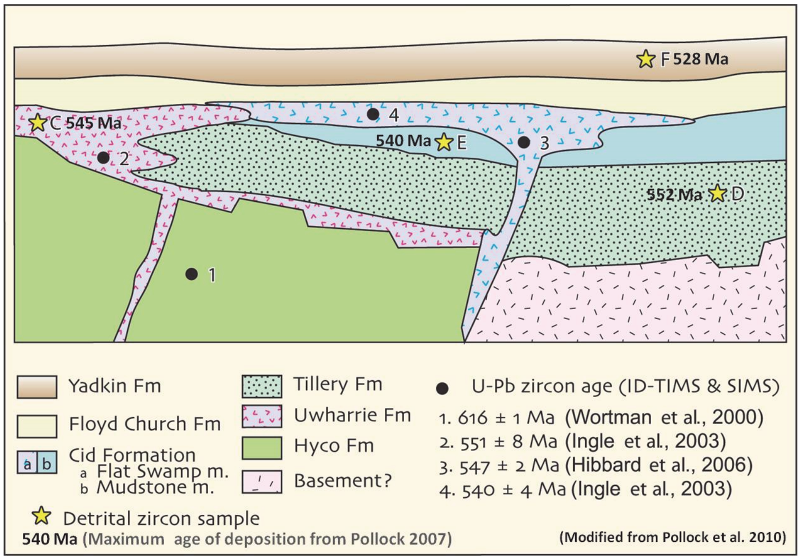


Fig. 3: Albemarle Sequence lateral facies equivalence model

The Erect Member is interpreted to lay below the base of the Uwharrie Formation in the USGS Erect 7.5' Quadrangle and consists of quartz-rich clastic sediments that include fine- to coarse-grained sandstone, pebbly sandstone, and conglomerate, and locally contains clasts of felsic volcanic rock (**Pollock, 2007**). The member strikes northeast, dips steeply northwest along the base of the Uwharrie Formation, and varies dramatically in thickness from 100 to around 1000 meters (**Hibbard *et al.*, 2013**).

Pollock (**2007**) reports 64 analyses of detrital zircons from the sample that yielded LAN-ICP-MS U-Pb ages of between 545 ± 7 Ma and 593 ± 9 Ma with a unimodal peak at about 560 Ma. The youngest concordant zircons from the sample are 545 ± 7 Ma, 545 ± 9 Ma, and 546 ± 7 Ma, interpreted to suggest a minimum age of deposition of ca. 545 Ma (**Pollock, 2007**; **Pollock *et al.*, 2010**). This result suggests that the base of the Uwharrie Formation is diachronous with the zircon U-Pb ages for the Uwharrie and similar in age to the Flat Swamp Member of the Cid Formation in the Albemarle Group to the west (**Fig. 3**). This assumes that the Uwharrie Formation is the source of the detritus and that there are no younger units present between the Uwharrie Formation and the Erect member.

The Erect Member overlies the Hyco Arc Formation on the geologic map of **Carpenter** (**1999**), consistent with a location above the basal unconformity of the Albemarle Sequence. The Erect Member is presumably composed of detritus from erosion of the older Hyco Arc and possibly the Virgilina Sequence and diverse igneous intrusions. It appears unlikely that it would contain detrital zircons that are younger than the overlying Uwharrie Formation, from which it may be separated by a significant period of time.

The small number of younger detrital zircon U-Pb age dates from the sample represents an extraordinary challenge to the well-documented standard stratigraphic model. In the absence of better constraints, evaluation of the stratigraphic equivalence model must depend on stratigraphic relationships constrained by age dates and fossil evidence within the Albemarle Sequence.

Additional support for the alternative stratigraphic model is suggested by felsic magmatism that appears to link the upper Uwharrie Formation, the Tillery Formation, and the Cid Formation (**Boorman *et al.*, 2013**). Rhyodacite of the Morrow Mountain complex intruding the upper part of the Tillery Formation returned a U-Pb zircon age of 539 ± 6 Ma (**Ingle, 1999**). Based on similarities of lithology and chemical composition, **Boorman *et al.*** (**2013**) suggest that domes, flows, dikes, and plugs of Morrow Mountain rhyodacite are present in the upper Uwharrie Formation, the Tillery Formation, and the Mudstone Member of the Cid Formation; and that they may be correlative with Flat Swamp Member volcanism.

The Albemarle volcanic arc

The Albemarle Sequence forms the northern part of the Neoproterozoic-early Paleozoic Albemarle Arc (**Hibbard *et al.*, 2013**), which extends from central North Carolina to northeast Georgia (**Fig. 4**). It is the youngest, most extensive component of the Carolina terrane (**Hibbard *et al.*, 2002**). It has been divided into the Albemarle Sequence in central North Carolina and the South Carolina Sequence in South Carolina and Georgia (**Hibbard *et al.*, 2002**). Although broadly coeval, these two sequences are separated by a NNE-trending zone of faults (**Dallmeyer, 1991**), many reactivated as basin-bounding structures during the early Mesozoic (**Fig. 4**). Direct correlation of Carolina terrane sequences across this fault zone is uncertain. The Albemarle and

South Carolina sequences are *en echelon*, possibly as a result of tectonic translation. Alternatively, these sequences represent separate and independent lithotectonic domains.

The Uwharrie Formation of the Albemarle Sequence and the Persimmon Fork Formation of the South Carolina Sequence are largely contemporaneous with broad lithologic similarities (**Hibbard *et al.*, 2002**), but with significant compositional and lithofacies differences. There are even more significant compositional, temporal, and lithofacies contrasts between the often correlated (**Hibbard *et al.*, 2002**) Albemarle Group and the Richtex and Asbill Pond formations of the South Carolina Sequence that suggest very different tectonic environments, histories, and metallogenic associations.

The Albemarle Sequence is estimated to be 12.7 to 15 kilometers thick (**Stromquist and Sundelius, 1969; Butler and Secor, 1991**), up to 50 kilometers wide, and extends for about 180 kilometers from central North Carolina into north central South Carolina (**Fig. 4**). It lies unconformably on the older Hyco Arc and Virgilina Formation to the east and north and is truncated to the west by the Gold Hill Fault. The Albemarle Sequence consists of the approximately 4500 meters thick basal strongly bimodal 80% felsic volcanic Uwharrie Formation and the overlying Albemarle Group, an up to 10 kilometers thick sedimentary-volcanic sequence deposited in a large arc-rift basin.

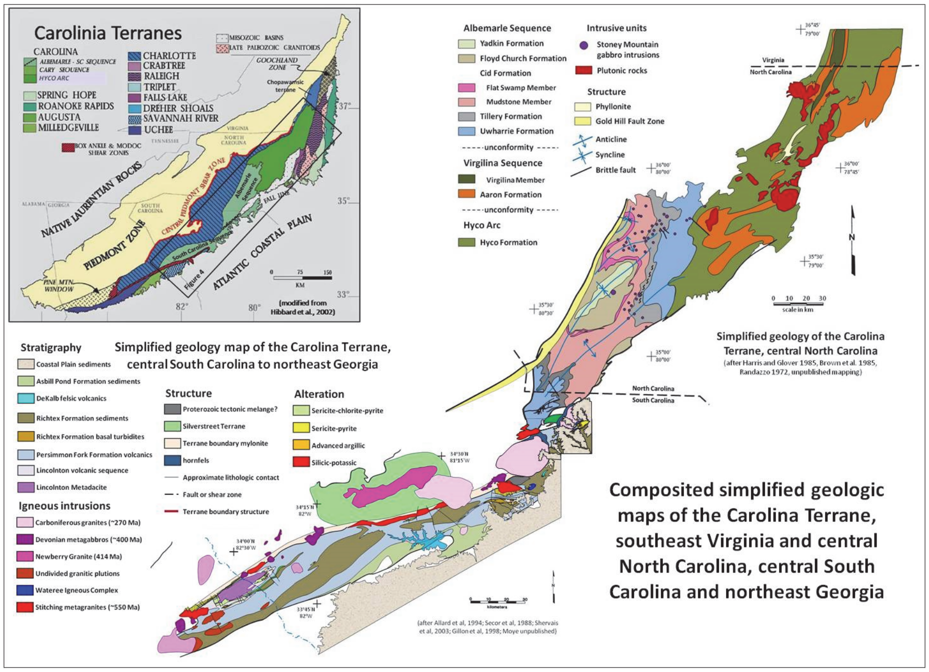


Fig. 4: Simplified geologic map of the Carolina terrane

The South Carolina Sequence is estimated at 6-10 kilometers thick and is typically 20-25 kilometers wide (**Secor and Wagner, 1968**; **Secor and Snoke, 1978**; **Secor, 1988**; **Hibbard *et al.*, 2002**). It is traced for around 260 kilometers from south central North Carolina to the termination in northeast Georgia (**Fig. 4**), but extends northeast into south-central North Carolina in Anson County. In central South Carolina and northeast Georgia it is and bounded by zones of intense transpressional ductile-brittle deformation; the Proterozoic sutured boundary with the Charlotte Terrane to the northwest and the Paleozoic Modoc Zone boundary with the Savannah Terrane to the southeast. The sequence consists of the ~ 5 kilometers thick basal volcanic Persimmon Fork Formation and the overlying Tillery, Emory, and Asbill Pond sedimentary formations (**Hibbard *et al.*, 2002**).

The Emory Formation may be a lateral facies equivalent to the Richtex Formation and of similar age. Both may have been deposited in a series of small inter-arc rift basins rather than as a continuous cover sequence (**Gillon *et al.*, 1998**). The unconformably overlying Asbill Pond Formation is dated by fossil evidence to the Middle Cambrian and may occupy a late successor basin (**Secor and Wagner, 1968**; **Secor and Snoke, 1978**; **Secor, 1988**).

Persimmon Fork volcanic arc felsic to intermediate-dominated calc-alkaline magmatism is dated to around 557-551 Ma (**Barker *et al.*, 1998**, **Ayuso *et al.*, 2005**), coeval with the Uwharrie Formation. Metavolcanic rocks of felsic and intermediate composition form more than 80% of the Persimmon Fork Formation, and compositionally range continuously from 49 wt% to 75 wt% SiO_2 without evidence of gaps or bimodality (**Shervais *et al.*, 1996**). The Persimmon Fork Formation formed in a mature volcanic arc constructed on a basement of either tectonically thinned continental crust or an older, mature intra-oceanic arc terrane (**Shervais *et al.*, 1996**).

The Persimmon Fork formation conformably overlies the older, chemically distinct (**Clark *et al.*, 1999**) Lincolnton sequence along the South Carolina-Georgia border region. The Lincolnton sequence consists of the large Lincolnton Metadacite intrusive-extrusive complex, dated by zircon U-Pb to 566 ± 15 Ma (**Carpenter et al., 1982**), and comagmatic pyroclastic, volcaniclastic, and epiclastic sedimentary units. The presence of associated VMS deposits suggests that the Lincolnton sequence originated in a rift environment that predates the Persimmon Fork volcanic arc.

The Albemarle Sequence

The Albemarle Sequence outcrops within a roughly rectangular, NNE-trending area of approximately 140 by 40 kilometers in central North Carolina and adjacent areas of north-central South Carolina (**Fig. 5**). It may be up to 12-15 kilometers thick (**Butler and Secor, 1991**) in Randolph and Davidson counties but thins to the southwest to around 5350 meters in Union County. It consists of the basal volcanic-dominated Uwharrie Formation and the younger or partly contemporaneous sediment-dominated Albemarle Group (**Hibbard *et al.*, 2002**; **Hibbard *et al.*, 2008**). Voluminous, strongly felsic-dominated bimodal Uwharrie magmatism began by ca. 554 Ma (**Ingle *et al.*, 2003**), although localized, lower volume magmatism may have begun earlier (**Kozuch, 1994**).

The Albemarle Sequence is in unconformable contact with the older Hyco arc and Virgilina sequence to the east and northeast (**Harris and Glover, 1988**) and truncated by faults or lost under Mesozoic basin cover to the southeast. The northern contact is largely obscured by younger intrusive rocks. The nature of the contact to the southwest is uncertain, but may be structural or an unconformity. The Albemarle Sequence is truncated to the west against the Gold Hill Fault, a steeply west-dipping reverse-sinistral ductile-brittle fault about 120 kilometers long with and estimated 12 kilometers of stratigraphic offset (**Hibbard, 2000**; **Hibbard *et al.*, 2012**).

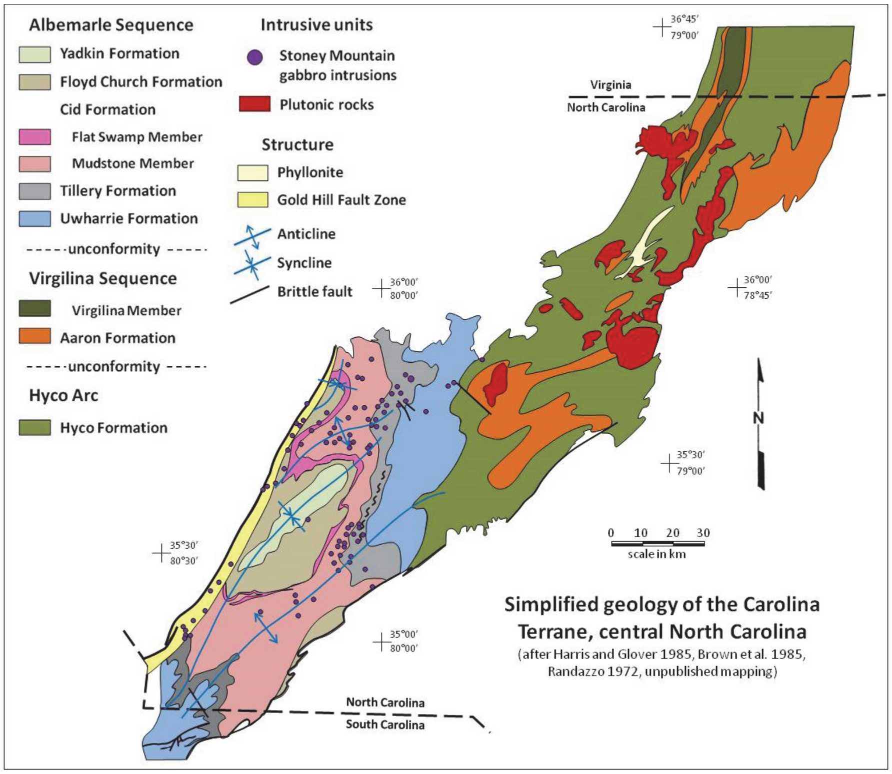


Fig. 5: Simplified geologic map of the Carolina terrane in North Carolina

The western limbs of large, first order *en echelon* folds that dominate outcrop patterns of the Albemarle Group in central North Carolina are appressed and truncated in the footwall of the Gold Hill Fault (**Hibbard *et al.*, 2008**). Both these folds and the Gold Hill Fault Zone formed during late Ordovician to early Silurian docking of Carolinia with the Laurentian margin as the Cherokee Orogeny (**Hibbard *et al.*, 2008**; **Hibbard *et al.*, 2012**). Volcanic rocks correlated with the older Hyco Arc of the Carolina terrane are present in the hangingwall of the Gold Hill Fault (**Standard, 2003**; **Allen, 2005**; **Hibbard *et al.*, 2008**). The nature of the contact between the Carolina and Charlotte terranes in North Carolina has not been established.

The Uwharrie Formation

The Uwharrie Formation outcrops stratigraphically below the Albemarle Group over a total area of around 180 by 50 kilometers; divided into an approximately 70 by 15-20 kilometer, NNE-trending area of central North Carolina, and in an irregular 30 by 8-12 kilometer area along the North Carolina-South Carolina state line (**Fig. 5**). Most detailed descriptions of the rocks are based on work in central North Carolina (**Conley, 1962**; **Upchurch, 1968**; **Stromquist and Sundelius, 1969**; **Seiders, 1978**; **Seiders, 1981**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Harris and Glover, 1988**), with more limited work to the south in Union County, North Carolina (**Randazzo, 1972**; **Allen, 2005**).

Conley (**1962**) suggests that the Uwharrie Formation could be up to 6000 meters thick. Based on an assumed homoclinal section, **Seiders** (**1981**) estimated the maximum thickness of the Uwharrie Formation in the Asheboro area at around 11,000 meters. However, **Harris and Glover** (**1988**) recognized large-scale fold repetition and revised this estimate to around 3000 meters. The thickness of the Uwharrie Formation is often estimated at around 4500 meters (**Hibbard *et al.*, 2002**). The lithology appears to be dominated by numerous irregularly distributed stacked and overlapping felsic intrusive-extrusive complexes and associated proximal to distal volcaniclastic facies. The Uwharrie Formation thins to the south in Union County to around 1000 meters and appears to be dominated by finer-grained volcaniclastic units distal from major eruptive centers (**Randazzo, 1972**).

The Uwharrie Formation has not been described along the north-western margin of the Albemarle Sequence, largely obscured by younger plutons, or along the western margin of the sequence, where is may be tectonically removed by large-scale oblique-reverse displacement on the Gold Hill Fault (**Hibbard *et al.*, 2012**). Previously more extensive distribution of the Uwharrie Formation to the east and northeast is suggested by possible local preservation in grabens and by intrusions of similar age (**Schmidt *et al.*, 2006**; **Moye, 2013**).

The Uwharrie Formation in central North Carolina

The Uwharrie Formation in central North Carolina (**Figs. 5-7**) is a felsic-dominated, strongly bimodal metavolcanic sequence estimated to be approximately 4500 meters thick (**Hibbard *et al.*, 2002**). It is composed largely of felsic flows and volcaniclastic units, dome complexes, and hypabyssal intrusions with subordinate intercalated intermediate to mafic flows and volcaniclastic units and epiclastic sediments (**Conley, 1962**; **Black, 1978**; **Butler and Ragland, 1969**; **Seiders, 1981**; **Milton, 1984**; **Harris, 1982**; **Harris and Glover, 1988**). Although locally interbedded with metasedimentary units, **Seiders and Wright** (**1977**) suggest both subaerial and submarine deposition. Isotopic data from intrusion-centered hydrothermal alteration systems suggest extensive subaerial conditions around emergent volcanic centers (**Feiss *et al.*, 1993**).

The Uwharrie Formation in the Asheboro area (**Fig. 6**) is estimated to be 80% felsic, 17% mafic, and 3% intermediate (**Seiders, 1978**). Based on the mapping of **Seiders** (**1981**), felsic volcaniclastic units may represent over 50% of the sequence. They are mostly thin to thick-bedded crystal tuff, crystal-lapilli tuff, crystal-lithic tuff, and tuff breccia with clasts dominated by massive to flow-banded felsite and probable pumice fragments. Fine-grained to aphanitic felsite units may form 20-30% of the sequence and include flows, domes, sills, dikes, and volcanic necks (**Seiders, 1981**). They are light to dark grey, locally flow banded and/or spherulitic, and typically albite ± quartz phyric.

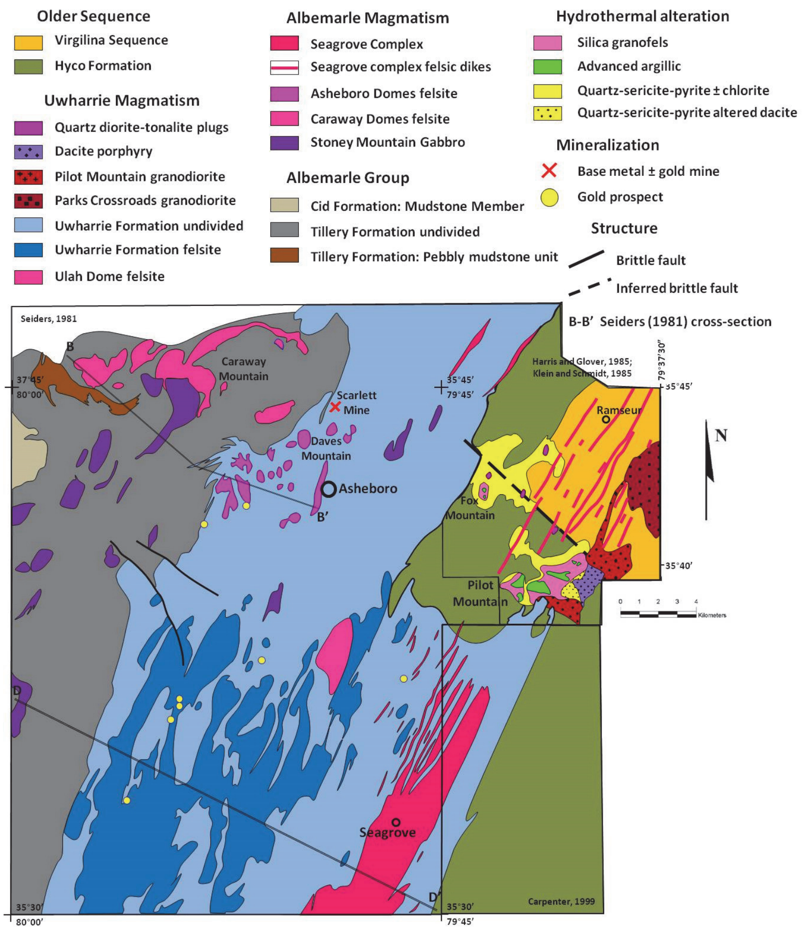


Fig. 6: Simplified geologic map of the Asheboro-Ramseur-Seagrove area NC (modified from Seiders, 1981; Harris and Glover, 1985; Klein and Schmidt, 1985; and Carpenter, 1999)

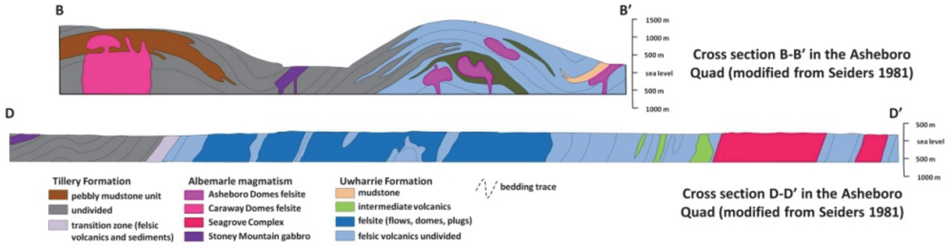


Fig. 7: Seiders (1981) Asheboro Quadrangle cross-sections B-B' and D-D' (see Fig. 6)

Upchurch (**1968**) reports that the Uwharrie Formation near the axis of the Troy Anticlinorium in Montgomery County is dominated by feldspar- and quartz-phyric felsite units, many flow-banded, with phenocrysts that range from small and sparse to 40-50% by volume and up to 3-millimeters in diameter. Phenocrysts include albite, orthoclase or sanidine, and quartz.

Lithic tuffs composed of 30-60% clast up to several centimeters in size predominate near the upper contact of the Uwharrie with the Tillery Formation, but are interbedded with often strongly laminated, locally spherulitic felsite units. Similar units were mapped in the upper Uwharrie Formation along the western limb of the Troy Anticlinorium by **Conley** (**1962**).

The contact of the Uwharrie with the Tillery Formation is folded around the SSW-plunging axis of the Troy Anticlinorium in central Montgomery County (**Fig. 5**), and possibly around a small, more tightly folded syncline to the southeast (**Upchurch, 1968**; **Burt, 1981**) before it is lost under the Deep River Mesozoic Basin to the south. The Uwharrie Formation does not appear to outcrop along the western margins of the Wadesboro Mesozoic Basin.

Published U-Pb zircon ages for the Uwharrie Formation in central North Carolina include 586 ± 10 Ma (**Wright and Seiders, 1980**), 568 ± 6 and 558 ± 8 Ma (**Kozuch, 1994**), 551 ± 8 Ma (**Ingle, 1999**; **Ingle-Jenkins *et al.*, 1998**), and a SHRIMP age of 554 ± 15 Ma (**Ingle *et al.*, 2003**). The older data is considered suspect by ***Hibbard et al.*** (**2002**) and the age of the Uwharrie is generally considered as 554-551 Ma.

The Uwharrie Formation in Union County, North Carolina

Rhyolite to rhyodacite crystal tuffs and crystal lapilli tuffs dominate the Uwharrie Formation at the southern end of the Albemarle Sequence in Union County, North Carolina (**Fig. 5**), with subordinate felsite and minor interbedded massive- to thinly-bedded mudstone, siltstone and sandstone (**Randazzo, 1972**; **Allen, 2005**). Felsite units are aphanitic to albite ± quartz phyric with local flow banding and spherulites (**Randazzo, 1972**). **Randazzo** (**1972**) interpreted the Uwharrie Formation in this area as generally distal from eruptive centers. The base of the Uwharrie Formation and contact relationships with rocks to the southwest are uncertain, but **Randazzo** (**1972**) suggests a thickness of at least 1000 meters. To the northwest, Uwharrie Formation equivalent strata is strongly sheared and truncated in the footwall of the Gold Hill Fault (**Allen, 2005**).

The Uwharrie Formation in this area is described by **Allen** (**2005**) as felsic volcanic units of his Twelve Mile sequence. Felsic volcaniclastic units are about 60% massive, homogenous crystal tuffs and 30% crystal-lapilli tuffs with minor (≤10%) coarser-grained crystal lithic tuffs. Phenocrysts of albite-oligoclase and quartz with subordinate, microcline, sanidine, and biotite are commonly 1-3 millimeters long, but range up to 5 millimeters in the crystal-lapilli tuffs (**Allen, 2005**). Lapilli and lithic fragments are 5-10 millimeters across (**Allen, 2005**) and **Randazzo** (**1972**) locally observed possible collapsed pumice clasts.

Compared to the type area in central North Carolina, the Uwharrie Formation in the North Carolina-South Carolina border region appears thinner, finer-grained, and largely dominated by volcaniclastic units deposited distal from major eruptive centers. This parallels thinning and fining of the Tillery and Cid Formations from north to south, and a general decrease in the abundance of interbedded volcanic units and related intrusions.

Uwharrie Formation stratigraphy and facies architecture

There is no published stratigraphy for the Uwharrie Formation and limited volcanic facies mapping and analysis. The main body of the Uwharrie Formation is described by **Conley** (**1962**), **Seiders** (**1981**), and **Harris** (**1982**). As mapped by **Seiders** (**1981**), much of the Uwharrie Formation appears to be characterized by abundant, irregularly elongated, broadly conformable felsite flows, domes, or cryptodomes that may be eruptive centers for and/or intrude the enclosing volcaniclastic units (**Fig. 5-7**). These intrusive-extrusive complexes and associated volcaniclastic facies may form much of the main body of the Uwharrie Formation in central North Carolina. Examples may include the distinctive 4 x 1.5 kilometer Ulah felsite (**Seiders, 1981**), located about 7-kilometers south of Asheboro (**Fig. 5**), and the irregularly shaped, northeast-elongated felsite units (**Fig. 6**) that form the main hills and ridges of the Uwharrie Mountains in Randolph and Montgomery counties (**Seiders, 1981**; **Conley, 1962**).

In the western Ramseur Quadrangle, **Harris** (**1982**) mapped a stratified sequence of lapilli crystal tuff, tuff-breccia, crystal tuff, and vitric tuff with interbedded or intruded units of porphyritic to flow-layered and spherulitic rhyolite. He interpreted lack of welding in pumice-rich units, the presence of sedimentary structures and normal grading in fine-grained units, and the absence of significant sorting in pyroclastic flows as indicating deposition in a relatively shallow marine environment. Pyroclastic units in this area are often composed largely of quartz and feldspar crystals and vitriclasts with minor pumice lapilli (**Harris, 1982**). Clasts are dominantly locally derived porphyritic to flow-layered rhyodacite, mafic lava, spherulites, and pumice lapilli.

The upper portion of the Uwharrie Formation in central North Carolina appears to be largely composed of thin to thick-bedded felsic volcaniclastic and epiclastic units, banded rhyolite flows, and rare intermediate and mafic volcaniclastic units (**Conley, 1962**; **Upchurch, 1968**; **Gibson and Teeter, 1984**; **Seiders, 1981**; **Kurek, 2010**; **Boorman *et al.*, 2013**). The Uwharrie Formation grades conformably upward into the Tillery Formation with increasing interbedded tuffaceous mudstone and siltstone over an interval of up to 500 meters (**Conley, 1962**; **Upchurch, 1968**; **Gibson and Teeter, 1984**; **Seiders, 1981**; **Kurek, 2010**; **Boorman *et al.*, 2013**). **Conley** (**1962**) noted thin interbedded units of crystal-lithic tuff extending into the lower Tillery Formation and evidence of sedimentary slump. **Seiders** (**1981**) mapped extensive sequences of felsite and felsic volcaniclastic units interbedded with thinly-bedded siltstone and mudstone along the transition zone in the Asheboro Quadrangle.

Locally, the transition into the Tillery Formation is relatively abrupt and the lower 50 meters of the Tillery is characterized by turbidite beds grading from sand composed largely of euhedral feldspar and quartz crystal into siltstone, cut by polylithic conglomeratic channel deposits and intraformational breccias with mudstone and siltstone rip-up clasts (**Gibson and Teeter, 1984**). West of the town of Albemarle, **Gibson and Teeter** (**1984**) note extensive evidence for reworking in the uppermost Uwharrie Formation with clasts-supported to matrix-supported conglomerates and breccias with rounded to angular clasts. Normal and reverse graded bedding is common in finer-grained sediments, with limited cross-bedding and cross-lamination (**Gibson and Teeter, 1984**). **Gibson and Teeter** (**1984**) suggest that the transition from the Uwharrie to the Tillery represents submarine fan deposits transitional from a locally emergent volcanic highland into a basin environment.

Regional extent and character of Uwharrie magmatism

Preserved Uwharrie magmatism appears to have been largely focused in the area between Asheboro, Randolph County and Troy, Montgomery County (**Fig. 5**, **Fig. 6**), as the Uwharrie Formation is thinner and finer-grained in Union County (**Fig. 5**) to the southeast (**Randazzo, 1972**). The absence of the Uwharrie Formation to the north, northeast, and east may be the result or removal by erosion of Uwharrie strata that are thin by comparison with those in the Asheboro area. Alternatively, the formation is largely preserved by subsidence within the Albemarle Basin.

The wider distribution of Uwharrie-age magmatism beyond the present extent of the Uwharrie Formation is suggested by Uwharrie-age subvolcanic intrusions, dike swarms, volcanic units preserved in grabens, and alignments of advanced argillic epithermal alteration systems or AES (**Moye, 2013**). Possible Uwharrie-equivalent volcanic rocks are also present in the Glendon and Robbins areas of Moore County (**Powers, 1993**), closely associated with the AES alignments (**Fig. 8**).

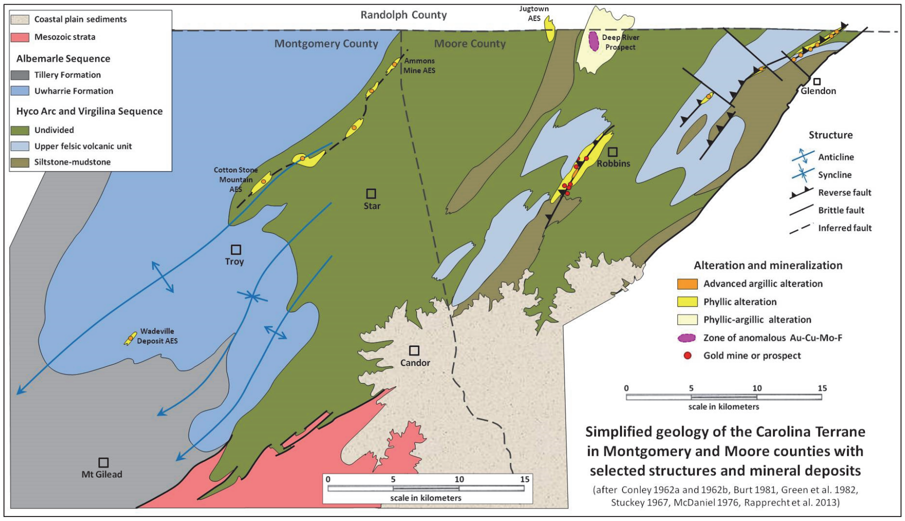


Fig. 8: Simplified geology of part of Montgomery and Moore counties NC showing areas of hydrothermal alteration, AES alignments, and areas of possible Uwharrie Formation

The 275 meters thick upper felsic volcanic unit (**Green *et al.*, 1982**; **Powers, 1993**) previously assigned to the Hyco Formation is in sharp contact with the underlying intermediate volcanics and distinct from stratigraphically deeper Hyco felsic volcanic units (**Green *et al.*, 1982**). This unit is largely volcaniclastic but with flow banded and locally spherulitic lava units and forms the host for the AES in the Glendon area (**Green *et al.*, 1982**). Deposited under subaerial to shallow marine conditions, this felsic sequence is overlain by thinly laminated bluish-gray mudstone and siltstone up to 460 meters thick with possible tuffaceous intervals near the base (**Green *et al.*, 1982**). These sediments grade upward into sandstones with graded bedding (**Green *et al.*, 1982**). The sequence suggests the Uwharrie Formation and the transition into the Albemarle Group (**Powers, 1993**).

Porphyry-style Au-Cu-Mo-F mineralization at the Deep River Prospect (**Fig. 8**) in the southeast corner of Randolph County (**Capps *et al.*, 1997**; **Rapprecht *et al.*, 2013**) is associated with a ca. 547-550 Ma felsic dike, and may also be an expression of Uwharrie magmatism (**Rapprecht *et al.*, 2013**). A large area of pyritic silicic and phyllic alteration and an extensive Au-Cu-Mo-F soil geochemical anomaly are centered on a series of porphyritic quartz and feldspar phyric andesitic or dacitic intrusions (**Capps *et al.*, 1997**). The adjacent Jugtown AES occurrence may also be an epithermal expression of Uwharrie magmatism.

Early Uwharrie magmatism, fault zones, and AES alignments

Uwharrie magmatism is represented by proxy in often *en echelon* alignments of faults, small intrusive complexes, dike swarms, and large (1-20 km^2), concentrically zoned, high sulfidation advanced argillic epithermal alteration systems (AES) that post-date the Virgilina Deformation but predate the Cherokee Orogeny. AES are often intrusion-related, typically anomalous in fluorine, and often host Au ± Ag ± Cu ± Mo mineralization, suggesting that they may be shallow crustal expressions of porphyry-style Cu-Mo-Au mineralization at depth (**Schmidt, 1985**; **Moye, 2013**). These alignments occur exclusively where the Uwharrie Formation is absent through erosion or non-deposition, exposing the older Hyco Formation and Virgilina Sequence.

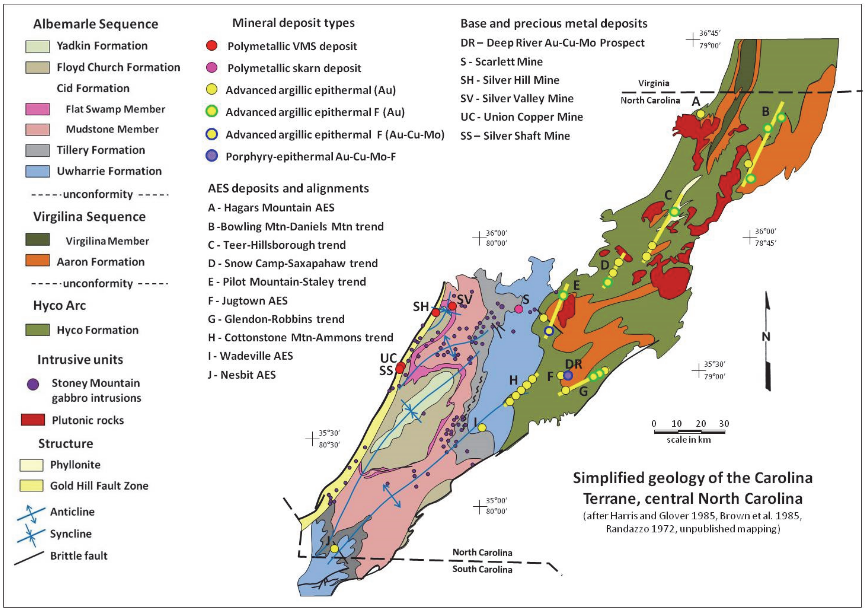


Fig. 9: Mineral deposits of the Albemarle Sequence and related magmatism

There are four recognized 20-40 km long *en echelon* alignments of AES that step north and east across the Carolina Terrane in central North Carolina (**Fig. 9**); Pilot Mountain-Staley (Randolph County), Snow Camp-Saxapahaw (Alamance County), Teer-Hillsborough (Orange County), and Bowlings Mountain-Daniels Mountain (Granville County). All cut across Virgilina Deformation structures and fabrics (**Schmidt, 1983**; **Schmidt, 1985a**; **Schmidt *et al.*, 2006**; **Moye, 2013**).

A fifth alignment (Cottonstone Mountain-Ammons) trends about 045° near the axis of the Troy Anticlinorium in Montgomery County (**Fig. 9**) and is also hosted by the Hyco Formation. The sixth alignment (**Fig. 9**) is the *en echelon* Glendon-Robbins trend in Moore County, oriented about 060° and traced for over 20 km along the Robbins and Glendon faults. Both alignments may have been rotated into their current orientation by large-scale folding during the Cherokee Orogeny with reverse reactivation of the associated faults.

Age relationships are best constrained in the Pilot Mountain-Staley (**Fig. 6**) and Snow Camp-Saxapahaw alignments east and northeast of Asheboro (**Fig. 10**). Stratigraphic equivalents of the Uwharrie Formation, locally preserved in small grabens (**Fig. 10**), appear to unconformably overlie AES in the Pilot Mountain and Snow Camp-Saxapahaw areas (**Schmidt, 1983**; **Schmidt, 1985**; **Schmidt *et al.*, 2006**; **Moye, 2013**); apparently post-dating alteration and mineralization. This suggests that early Uwharrie magmatism and AES formation along these *en echelon* transtensional fault zones pre-dates the main stage of Uwharrie volcanism. Many additional AES alignment to the northeast and south (**Fig. 9**) appear to be of similar age, with similar associations and controls.

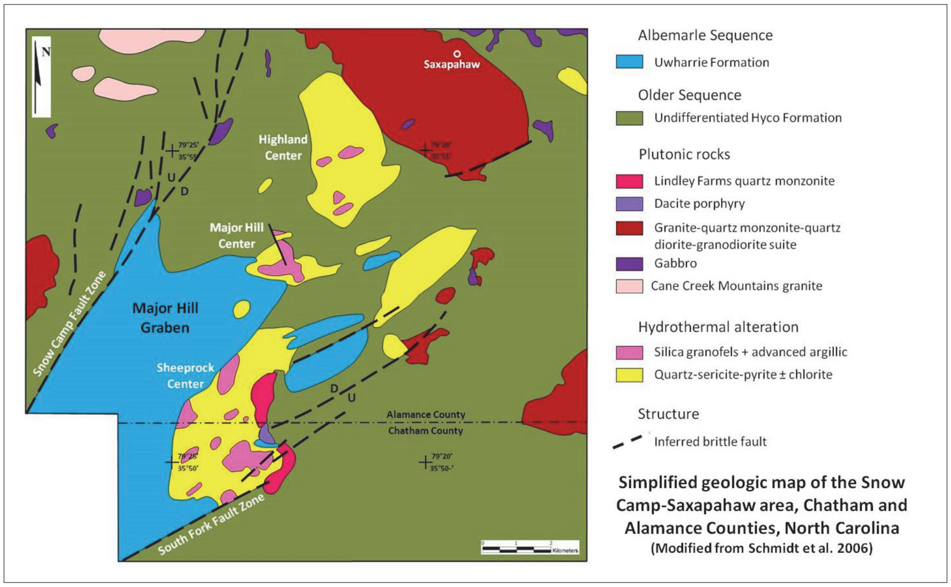


Fig. 10: Uwharrie magmatism in the Snow Camp-Saxapahaw AES area

The Seagrove Complex (**Fig. 6**) felsic intrusive-extrusive complex (**Seiders, 1981**; **Moye, 2013**) and related Ramseur dike swarm (**Harris, 1982**; **Harris and Glover, 1985**) intrude the Uwharrie Formation and appear to have developed along the same major fault zone that passes through the Pilot Mountain and Staley AES (**Moye, 2013**). Relationships in this area suggest three phases of Uwharrie magmatism; **1**) early magmatism and AES formation along *en echelon* transtensional fault zones, **2**) main stage Uwharrie volcanism ca. 554-551 Ma, and **3**) emplacement of the Seagrove Complex. This will be discussed in detail in a subsequent section.

The character, timing, and distribution of AES alignments suggest that early, relatively low-volume Uwharrie magmatism may have occurred along *en echelon* transtensional fault zones throughout much of the Carolina terrane in central North Carolina (**Moye, 2013**). Possible Uwharrie-equivalent strata may have been lost to erosion or are unrecognized due to deformation and metamorphism during the Cherokee Orogeny. Subsequent high-volume eruption of felsic-dominated magmas to form the Uwharrie Formation may have largely been focused in a more confined area adjacent to the future site of arc-rifting and deposition of the Albemarle Group.

The Wadeville AES in Montgomery County (**Burt, 1981**) and the Nesbit AES in Monroe County (**Randazzo, 1972**; **McKee, 1985a**; **McKee, 1985b**) are isolated occurrences hosted by the Uwharrie Formation (**Fig. 9**). They suggest that formation of these hydrothermal systems continued locally throughout deposition of the Uwharrie Formation, but with greatly reduced intensity. No AES have been identified in any member of the Albemarle Group, and it appears that their genesis was specifically associated with Uwharrie magmatism, volcanism, or conditions of deposition.

AES may be specifically developed under subaerial or shallow marine conditions in association with emergent Uwharrie magmatic centers, and unable to form under the deeper marine conditions represented by the Tillery and Cid formations. Subaerial or shallow marine settings have previously been suggested for several AES occurrences (**Feiss, 1982**; **Klein and Schmidt, 1985**; **Feiss and Wesolowski, 1986**; **Criss and Klein, 1986**; **Hughes, 1987**; **Klein and Criss, 1988**; **Schmidt *et al.*, 2006**).

Advanced argillic epithermal alteration systems (AES)

The most conspicuous form of hydrothermal alteration and mineralization associated with Uwharrie magmatism is the alignments of AES across the Carolina terrane in central North Carolina (**Fig. 9**). Associated subeconomic precious and base metal sulfide mineralization are most strongly expressed in the Pilot Mountain AES (**Schmidt, 1983**; **Schmidt, 1985a**; **Moye, 2013**). It is associated with a suite of small quartz diorite-tonalite-dacite plugs (**Fig. 6**) that predate main-stage Uwharrie volcanism (**Harris, 1982**; **Klein and Schmidt, 1985**)

The core of the Pilot Mountain AES is a 3.5 x 1 kilometers area of intense silicic and advanced argillic alteration with a 1 x 1 kilometer area of similar character located immediately to the west (**Fig. 6**). Topaz-bearing zones up to several meters thick are present in the larger silicic alteration zone, where local irregularly-shaped fragmental textures have possible clasts with bleached rims replaced by quartz and topaz. These may represent late fluorine-rich breccia pipes cutting the quartz granofels cap (**Klein and Schmidt, 1985**).

Coherent and coincident soil Mo, Cu, Au, B, and Sn geochemical anomalies are centered on the silicic-advanced argillic core of the Pilot Mountain hydrothermal alteration system (M**ilton *et al*., 1983**; **Schmidt, 1985a**; and **Klein and Schmidt, 1985**). Copper values are typically 30-100 ppm and a value of 1200 ppm Cu was obtained from drill core (**Klein and Schmidt, 1985**). Anomalous Mo values reach 400 ppm and Sn is up to 360 ppm, although both generally range from 20-50 ppm. A small plug of dacite porphyry with 2-5 millimeter quartz phenocrysts on the northeast side of Pilot Mountain is intensely altered to quartz granofels with accessory pyrophyllite and sericite (**Klein and Schmidt, 1985**). Samples of this rock contain up to 200 ppm As, 180 ppm Cu, 46 ppm Mo, 18 ppm Sn, and 0.5 ppm Ag (**Klein and Schmidt, 1985**).

Over a dozen historic Au mines and prospects are present within the Pilot Mountain AES. The most prominent is the Pine Mountain Mine, located at the contact between a dacite porphyry plug and Hyco Formation metavolcanic rocks, both altered to quartz granofels (**Klein and Schmidt, 1985**). Two mine shafts are centered on a soil Au-B-Mo anomaly up to 150 meters wide that extends northeast for at least 500 meters (**Klein and Schmidt, 1985**). The soil Au anomaly ranges from 0.1 to >1.0 ppm and appears to be located near the porphyry contact. Samples of spoil from the mine shafts contain traces of copper carbonate and molybdenite, and composite grab samples contained up to 10 ppm Au and 2200 ppm Cu (**Klein and Schmidt, 1985**).

Atypical of many AES in North Carolina, the aluminosilicate-rich advanced argillic alteration core of the Pilot Mountain system may be locally overprinted by silica-dominated assemblages with possible topaz-rich breccia pipes and strongly anomalous Mo-Sn-Cu-Au-B mineralization, suggesting multiple hydrothermal events sourced from a large felsic igneous reservoir at depth. These overprinting hydrothermal events may be associated with the rise of small dacitic stocks from the magmatic center below.

Aluminosilicate-rich advanced argillic alteration zones often develop in the transition from potassic porphyry alteration and mineralization to the epithermal environment of the lithocap (**Hedenquist and Arribas, 2022**). The formation of overprinting silicic alteration suggests the locally focused influx of magmatic volatiles and extreme acid leaching, followed by mineralizing magmatic brines with anomalous ore metals. This downward telescoping of epithermal events usually associated with a higher level lithocap (**Hedenquist and Arribas, 2022**) suggests rapid unroofing of the Pilot Mountain system during its magmatic and hydrothermal evolution.

Anomalous gold ± base metal ± Mo mineralization is present locally in many of the more than 20 AES in the Carolina Terrane in North Carolina, and many have been prospected both historically and in the modern era. Extensive though subeconomic gold mineralization is associated with the Nesbitt AES and geochemically anomalous gold is present in most of the AES in the Cottonstone Mountain- Ammons trend in northeast Montgomery County (**Fig. 8**).

Phelps Dodge Exploration East identified significant intervals of subeconomic gold mineralization (≥ 1 ppm) associated with silicic and silicic-phyllic alteration at the Ammons Pyrophyllite Mine in the late 1970s. This mineralization is consistent with the character and occurrence of gold mineralization associated with the Pilot Mountain AES in Randolph County (**Schmidt, 1985**).

The economic potential for associated porphyry-style mineralization at depth below AES systems is supported by porphyry-style Au-Cu-Mo-F mineralization at the Deep River Prospect (**Fig. 8**) in the southeast corner of Randolph County (**Capps *et al.*, 1997**; **Rapprecht *et al.*, 2013**). An extensive Au-Cu-Mo-F soil geochemical anomaly and locally stockwork Cu + Mo-bearing quartz veins are present with a large area of pyritic silicic and phyllic alteration that are centered on a series of porphyritic quartz and feldspar phyric andesitic or dacitic intrusions (**Capps *et al.*, 1997**). The association of mineralization with a felsic dike dated to ca. 547-550 Ma (**Rapprecht *et al.*, 2013**) suggests that the Deep River Prospect may be an expression of Uwharrie magmatism and mineralization.

Possible Uwharrie low-sulfidation epithermal gold mineralization

Additional forms of mineralization apparently associated with Uwharrie magmatism include small shear zone hosted auriferous silicic-phyllic mineralization. Although poorly documented, irregularly developed zones of silicic to phyllic alteration with disseminated pyrite are associated with many hypabyssal felsic intrusive or intrusive-extrusive centers of the central Uwharrie Formation in Randolph and Montgomery counties (**Conley, 1962**). None appear to carry significant gold or base metal mineralization, but may have contributed to numerous small placer gold deposits in the tributaries of the Uwharrie River.

Around 20 historic gold mines and prospects occur in rocks of the Uwharrie Formation in Randolph and Montgomery counties (**Carpenter, 1976**). Many are hosted by porphyritic felsite units and most appear to be products of low-sulfidation epithermal alteration focused along faults or shear zones. All are characterized by silicic and phyllic alteration, with accessory disseminated hydrothermal biotite, sericite, and pyrite. Shallow surface workings are typically more extensive than underground workings, and development at all locations suggests limited, short-term production. No historic gold deposits with significant production have been identified within the Uwharrie Formation. These occurrences may be products of small-scale hydrothermal systems related to Uwharrie magmatism, or may be associated with deformation and metamorphism during the Cherokee Orogeny (**Hibbard *et al.*, 2012**).

The Black Ankle Au Mine in northern Montgomery County lies six kilometers southwest of Seagrove, on strike to the south of the Seagrove Complex. Quartz stringer veins and silicic and phyllic alteration with disseminated pyrite along shear zones cut porphyritic felsite. The historic Dowd, Gluyas, and Rush gold mines are aligned on a 025°-030° trend for about 2.4 kilometers in southwestern Randolph County (**Carpenter, 1976**). The Dowd prospect consists of biotite-muscovite altered shear zones in a flow-banded feldspar phyric rhyolite. A kilometer to the southwest, strongly silicic alteration in felsic lithic-crystal tuff at the Gluyas Mine grades outward into sericite-chlorite phyllic alteration. The Rush Mine is 0.5 kilometer southwest of the Gluyas Mine, and characterized by strongly silicified sheared and brecciated porphyritic rhyolite with biotite-sericite-pyrite alteration.

The Albemarle Group

The Albemarle Group of the Albemarle Sequence outcrops over a roughly rectangular area of about 35 x 130 kilometers in central North Carolina and adjacent northern South Carolina (**Fig. 4**, **Fig. 5**). In the type area near the town of Albemarle, the Albemarle Group consists of four conformable, apparently gradational stratigraphic sequences that are, oldest to youngest (**Fig. 2**), the Tillery, Cid, Floyd Church, and Yadkin Formations (**Milton, 1984**; **Stromquist and Sundelius, 1969**; **Hibbard *et al.*, 2002**; **Boorman *et al.*, 2013**). The Cid Formation is divided into the lower Mudstone Member and the distinctive upper Flat Swamp Member.

These formations are distinguished by variations in sediment composition and grain size, sedimentary structures, and the character and abundance of interbedded metavolcanic units (**Fig. 2**). Total thickness of the Albemarle Group in the type Albemarle area is estimated at 7650-8500 meters (**Stromquist and Sundelius, 1969**). The sequence appears to thin to the south and southeast to around 5000 meters in Union County, North Carolina with a corresponding fining in the grain size of sediments in most units (**Randazzo, 1972**).

The component formations of the Albemarle Group appear to represent three distinct phases of basin development, sedimentation, and associated magmatism. The Tillery Formation appears to represent generally low energy, fine-grained epiclastic sedimentation in a generally deep marine depositional basin following the decline of Uwharrie volcanism. The abrupt gradation into the Cid Formation is associated with widespread, locally voluminous and sustained mafic volcanism, culminating in the explosive submarine felsic-dominated bimodal volcanism that characterizes the Flat Swamp Member of the Cid Formation.

This felsic-dominated volcanic member was deposited at a rate that overwhelmed quiescent basin sedimentation and may represent a geologically brief period of time. It represents the culmination of active arc-rift felsic magmatism. The Floyd Church and Yadkin formations appear to represent upward coarsening, increasingly shallow water clastic sedimentation as passive basin fill accompanied by greatly reduced mafic-dominated magmatism in the basin.

Bulbous to lenticular to tabular bodies of rhyodacite are widespread throughout the Tillery and Cid mudstone member. Previously interpreted as representing volcanic necks, domes, cryptodomes, flows, volcaniclastic units, and sills; these bodies may be largely intrusive in character and possibly associated with Flat Swamp Member volcanism. These Morrow Mountain-type rhyodacite bodies (**Boorman *et al.*, 2013**) appear to be absent from the Floyd Church and Yadkin formations. Plugs, sills, and dikes of Stony Mountain gabbro, interpreted as mantle-derived magma associated with arc-rifting, intrude all portions of the Albemarle Sequence, but are most abundant and widespread in the Tillery and Cid formations.

The original geographic extent, depth, and geometry of the depositional basin where the Albemarle Group accumulated are uncertain. This basin is informally referred to as the Albemarle Basin. Outcrop of Albemarle Group units is largely controlled by four broad, northeast-trending, *en echelon* first-order folds (**Stromquist and Sundelius, 1969**) formed by oblique reverse-sinistral transpression during the Cherokee Orogeny (**Hibbard *et al.*, 2012**). The amplitude and tightness of these folds is greatest in the northern and west-central portion of the Albemarle Group area (**Fig. 5**), and decreases to the east and south.

These folds are, from northwest to southeast, the Silver Valley Syncline, the Denton Anticlinorium, the New London Synclinorium, and the Troy Anticlinorium (**Stromquist and Sundelius, 1969**). Folds are strongly appressed and sheared in the lower portion of the Gold Hill Fault Zone (**Standard, 2003**; **Allen, 2005**). A fifth fold to the southeast, a syncline paired with the Troy Anticlinorium, is indicated by the work of **Randazzo** (**1972**) in Union County and **Conley** (**1962**) and **Upchurch** (**1968**) in Montgomery County. Named the Peachland Syncline by **Randazzo** (**1972**), much of this structure is lost under the Mesozoic Wadesboro Basin.

The rifted-arc model for the Albemarle Group

While working for Amselco Exploration (BP Minerals/Rio Tinto-Kennecott) in 1985, the author suggested that the Albemarle Group represents a rift basin with a thick sequence of marine sediments and associated bimodal volcanism with significant potential for VMS and possibly SEDEX styles of mineralization. Geological compilation and analysis was followed by a large-scale geochemical survey program. The effort failed to identify any base metal sulfide or related mineralization apart from the known VMS deposits of the Gold Hill and Silver Hill mining districts. This result was incongruous with the geologic environment as interpreted from existing stratigraphic models (**Stromquist and Sundelius, 1969**; **Milton, 1984**; **Gibson and Teeter, 1984**).

Moye and Stoddard (**1987**) propose deposition of the Albemarle Group in an arc-rift basin during sinistral transtension. **Harris and Glover** (**1988**) suggest a possible intra-arc rift environment for deposition of the Virgilina Sequence with the Uwharrie Formation representing renewed volcanism in a possible intra-arc transtensional basin. Based on whole-rock $\delta^{18}O$ isotopic data, **Feiss *et al.*** (**1993**) suggest Neoproterozoic to Middle Cambrian arc-rifting of the Carolina Terrane in central North Carolina.

Recent studies of the depositional history and tectonic setting of the Albemarle Group also support an arc-rift or back-arc rift environment (**Pollock, 2007**; **Pollock *et al.*, 2010**; **Hibbard *et al.*, 2012**; **Hibbard *et al.*, 2013**), possibly related to the separation of Carolinia and Gondwana with opening of the Rheic Ocean. Suggested modern analogues for the tectonic environment of the Albemarle Sequence include the Sea of Japan, Okinawa Trough, and Lau Basin (**Pollock *et al.*, 2010**); all areas of active rifting and widespread seafloor hydrothermal vents and polymetallic sulfide deposition.

The Tillery Formation

The Tillery Formation (**Fig. 2**, **Fig. 5**) is characterized by thin-bedded, fine-grained epiclastic metasedimentary rocks dominated by laterally persistent 1-3 millimeter thick beds that typically grade from silt to clay, suggesting deep marine quiescent deposition (**Conley and Bain, 1965**; **Seiders and Wright, 1977**; **Gibson and Teeter, 1984**). Interbedded units of andesitic basalt are rare in the lower and central portions of the formation, but become more widespread in the upper portion of the Tillery (**Conley and Bain, 1965**; **Seiders and Wright, 1977**; **Seiders, 1981**; **Gibson and Teeter, 1984**). Although considered to include subordinate interbedded felsic volcanic rocks, most of the felsic units appear to be intrusive in character. The thickness of the Tillery is estimated at about 1500 meters in the central Albemarle Basin (**Stromquist and Sundelius, 1969**) and a maximum of 750 meters to the south in Union County (**Randazzo, 1972**).

The basal Tillery Formation appears to be in conformable and gradational contact with the Uwharrie Formation to the east and south (**Conley, 1962**; **Randazzo, 1972**; **Seiders, 1981**; **Gibson and Teeter, 1984**; **Boorman *et al.*, 2013**) and in fault and unconformable contact with Mesozoic sediments of the Wadesboro Basin to the southeast. To the north, the relationship of the Albemarle Group to the Hyco arc is poorly described and often obscured by younger intrusive bodies. In the southwestern part of the Albemarle Basin, the Tillery Formation is juxtaposed to the west across the Gold Hill Fault against rocks equivalent to the Hyco arc (**Standard, 2003**; **Allen, 2005**; **Hibbard *et al.*, 2012**).

Although recently interpreted as in part a lateral facies equivalent of the Uwharrie Formation in central North Carolina (**Pollock, 2007**; **Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**), everywhere directly observed the Tillery conformably overlies the Uwharrie Formation across a gradational and locally interfingering 100-500 meters thick stratigraphic transition. **Gibson and Teeter** (**1984**) report arenaceous units, matrix supported conglomerate and intraformational breccias in the lower 50 meters of the Tillery, suggesting an initially higher energy depositional environment.

Based on the mapping of **Conley** (**1962**) and **Seiders** (**1981**), thin, laterally extensive felsic volcaniclastic units similar to the Uwharrie Formation are interbedded with siltstone and mudstone in the lower 500 meters of the Tillery Formation in the Albemarle and Asheboro quadrangles. Similarly, **Randazzo** (**1972**) indicates a transition zone around 500 meters thick in Union County, North Carolina. The interdigitation of Uwharrie felsic volcaniclastic units into the lower Tillery Formation is exposed on the western flank of a north-striking anticline immediately west of the city of Asheboro (**Figs. 6, 7**). These Uwharrie interbeds are estimated to be around 100 meters thick and present over an estimated 500-1000 meters of stratigraphic section (**Seiders, 1981**).

Kozuch (**1994**) reports a U-Pb zircon age of 554 ± 14 Ma for metarhyolite from the lower Tillery Formation near Asheboro. Rhyolite of the Morrow Mountain complex in the upper part of the Tillery Formation has a U-Pb zircon age of 539 ± 6 Ma (**Ingle, 1999**). Detrital zircon

U-Pb ages from the Tillery (**Pollock, 2007**) show a major peak at about 550 Ma from a range of 541 ± 9 to 591 ± 10 Ma (26 analyses) with a secondary peak at about 630 Ma from a range of 598 to 698 Ma (21 analyses). **Pollock** (**2007**) suggests a maximum age of around 552 Ma for the Tillery Formation.

Small bodies of Morrow Mountain rhyodacite are present in the upper Uwharrie and lower Tillery formations (**Boorman *et al.*, 2013**). These bodies become larger and more numerous in the middle to upper Tillery Formation. Emplacement of the Shepherd Mountain rhyodacite plug, dome, or cryptodome into the Tillery Formation formed a peripheral unit composed of lenses of pebbly to conglomeratic mudstone containing sparse clasts of rhyodacite (**Seiders, 1981**). These clastic lenses are interbedded with laminated mudstone with possible synsedimentary isoclinal folding (**Seiders, 1981**).

Additionally, stocks and sills of the Stony Mountain gabbro are locally abundant intruding the middle to upper Tillery Formation, one dated to ca. 545 Ma (**DeDecker *et al.*, 2013**). The Morrow Mountain rhyodacite and Stony Mountain gabbro will be discussed in more detail in later sections.

Mineralization in the Tillery Formation

Gold mineralization hosted by the Tillery Formation at the Russell Mine in northern Montgomery County has been interpreted as a structurally remobilized auriferous massive sulfide deposit (**Klein *et al.*, 2007**) associated with the Russell Dome, a small rhyolite or rhyodacite dome or cryptodome located deep within the stratigraphic footwall northeast of the Russell Mine. The Russell Dome is an elongate 0.6 × 2 kilometers Morrow Mountain rhyolite or rhyodacite dome or cryptodome (**Fig. 11**) striking 021° and apparently conformable within the central part of the Tillery Formation stratigraphy. It straddles the Montgomery-Randolph county line near the center of the Tillery Formation. The Russell Mine workings are located about 1.1 kilometers to the southwest near the top of the Tillery Formation (**Fig. 11**).

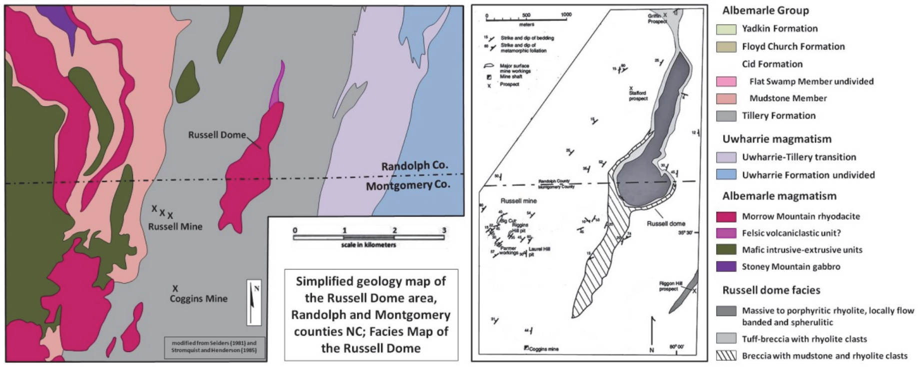


Fig. 11: Russell Dome geology location and facies (modified from Klein *et al.*, 2007)

This felsic body is sparsely feldspar-biotite-almandine phyric, massive to flow banded with one millimeter thick laminae, and locally spherulitic near the margins (**Klein *et al.*, 2007**). It is mantled by a 3-4 meter thick fragmental unit interpreted as tuff breccia with rhyolite clasts (**Klein *et al.*, 2007**) that may be hyaloclastite breccia. A unit interpreted as felsic volcaniclastic rocks extends in an arcuate band northwest from the northern end of the Russell Dome (**Maddry *et al.*, 1992**), and appears to be a continuation of the tuff breccia unit mapped by **Klein *et al.*** (**2007**) mantling the dome (**Fig. 11**). The tuff breccia is in turn mantled by a unit with clasts and blocks of laminated siltstones up to a meter in diameter in a siltstone matrix, and includes an interval with spherulitic rhyolite clasts (**Klein *et al.*, 2007**). This unit extends for 1.5 kilometers to the southwest of the dome (**Fig. 11**).

Although interpreted as a dome emplaced synchronous with sedimentation (**Klein *et al.*, 2007**), it is more likely that the Russell Dome is a cryptodome emplaced into the water-saturated semi-consolidated sediments of the Tillery Formation. The present geometry of the Russell Dome and associated units may be in part a product of compression associated with the Cherokee Orogeny in the late Ordovician to early Silurian.

The Russell Dome is cut by two sets of quartz veins; one set strikes 050° and dips 65°-70° SE and is composed of 1.5-4.0 centimeters thick pale gray vitreous quartz with up to 1% pyrite (**Klein *et al.*, 2007**). These veins are cut by a younger set of 0.5-1.5 centimeter thick veins with only trace pyrite that strike 005° and dip 80° SE. The 45° angle between the strikes of these veins sets, almost bisected by the 021° strike of the dome, suggests that they are conjugate tension fractures. The Tillery metasediments adjacent to the unit of breccias that extend to the southwest of the dome (**Klein *et al.*, 2007**) are sheared and mineralized with disseminated pyrite and stockwork quartz-carbonate veinlets (**Maddry *et al.*, 1992**).

Rock-chip samples from this 4.5-6 meter thick Contact Lead (**Maddry *et al.*, 1992**) contain gold values of 0.1-0.8 g/t (maximum 0.03 oz/t Au) along a strike length of one hundred meters. It is likely that the conjugate extensional quartz vein sets formed within the rheologically competent rhyolite dome during the Cherokee Orogeny (**Hibbard *et al.*, 2012**), synchronous with shearing-related mineralization of the Contact Lead along the contact with the rheologically incompetent adjacent metasediments.

The Russell Gold Mine and the Coggins Gold Mine to the south-southwest are, along with the Sawyer-Jones Keystone gold deposits in northwest Randolph County, a special class of mesozonal orogenic gold deposits formed during the Cherokee Orogeny (**Moye, 2018a**; **Moye, 2018b**). The Sawyer-Russell type orogenic gold deposits are broad, often multiple zones of low total sulfide, base metal poor Au-Ag-As mineralization in pyritic silicic and phyllic alteration hosted by shear zones and meso-scale folds associated with reverse faults (**Moye, 2018a**; **Moye, 2018b**).

The gold deposits of the Sawyer-Keystone trend lie along a 065° alignment that extends for 21 kilometers across northwest Randolph County, North Carolina (**Moye, 2018b**). These deposits include the Jones-Keystone, Lofflin, Parrish-Kindley, Sawyer, and New Sawyer mines. The mineralized trend and the host structures cut across the stratigraphy of the Albemarle Group and major regional-scale folds associated with the early stages of the Cherokee Orogeny (**Hibbard et al., 2012**). The Jones-Keystone, Southern Homestake, Lofflin, Parrish, and Kindley mines are hosted by the Mudstone Member of the Cid Formation. The Sawyer deposit occurs in the Tillery Formation, and the New Sawyer deposit is hosted by the Uwharrie Formation (**Moye, 2018b**).

Most of the numerous small to medium-sized lode gold deposits present throughout the Albemarle Group in central North Carolina, including the classic orogenic lode gold deposits along the Gold Hill Fault Zone, formed during the Cherokee Orogeny (**LaPoint and Moye, 2013**; **Moye, 2016**; **Hibbard *et al.*, 2012**).

The Cid Formation

In the type area near the town of Albemarle, the Cid Formation consists of the lower Mudstone Member and the upper Flat Swamp Member (**Fig. 2**) with a combined thickness of around 4200 meters (**Stromquist and Sundelius, 1969**; **Gibson and Teeter, 1984**). The Flat Swamp Member is not identified in the southern portion of the basin (**Fig. 5**), and the combined Cid Formation and Floyd Church Formation have an estimated maximum thickness of about 3600 meters (**Randazzo, 1972**).

The Mudstone Member of the Cid Formation

The Mudstone Member continues the accumulation of fine-grained clastic sediment-dominated fill in the Albemarle Basin, although with distinct sedimentological changes. It is about 3000 meters thick in the type area and composed of generally massive to thickly bedded (30-60 centimeters) mudstones with intermittent units of rhythmically interbedded siltstone and mudstone and contains numerous conformable felsic and mafic igneous units (**Stromquist and Sundelius, 1969**; **Gibson and Teeter, 1984**; **Pollock, 2007**). Synchronous volcanism is characterized by andesitic basalt flows and volcaniclastic units termed Baden Greenstone (**Conley, 1962a**) that locally compose much of the Mudstone Member and are laterally interbedded with the sedimentary sequence (**Fig. 12**). Massive to flow-banded rhyolite to rhyodacite bodies largely conformable with stratigraphy may be Morrow Mountain rhyodacite of largely intrusive origin.

Gibson and Teeter (**1984**) note the presence of a sequence of siltstones, sandstones, and matrix-supported to clast-supported fine-pebble breccias and conglomerates between the finely laminated mudstone of the Tillery Formation and the more massive mudstone of the Mudstone Member of the Cid Formation. Lithic clasts in breccia and conglomerate are angular to sub-rounded and derived from a volcanic source. Siltstones and sandstones in this interval are typically well-sorted and sedimentary features suggest a range in the energy of the depositional environment (**Gibson and Teeter, 1984**).

Stromquist and Sundelius (**1969**) note the presence of numerous lenses and layers of felsic volcaniclastic or epiclastic material at the base of the member and the presence of 30-60 centimeter thick beds of bluish-grey, blocky tuffaceous mudstone that weathers white in color. **Brennan** (**2009**) notes that ellipsoidal to tabular carbonate concretions are common along bedding planes. However, **Ingram** (**1999**) records no distinct sedimentological change from the Tillery into the Cid Formation in the Morrow Mountain area, and defines the contact on the basis of the first occurrence of mafic volcanic units.

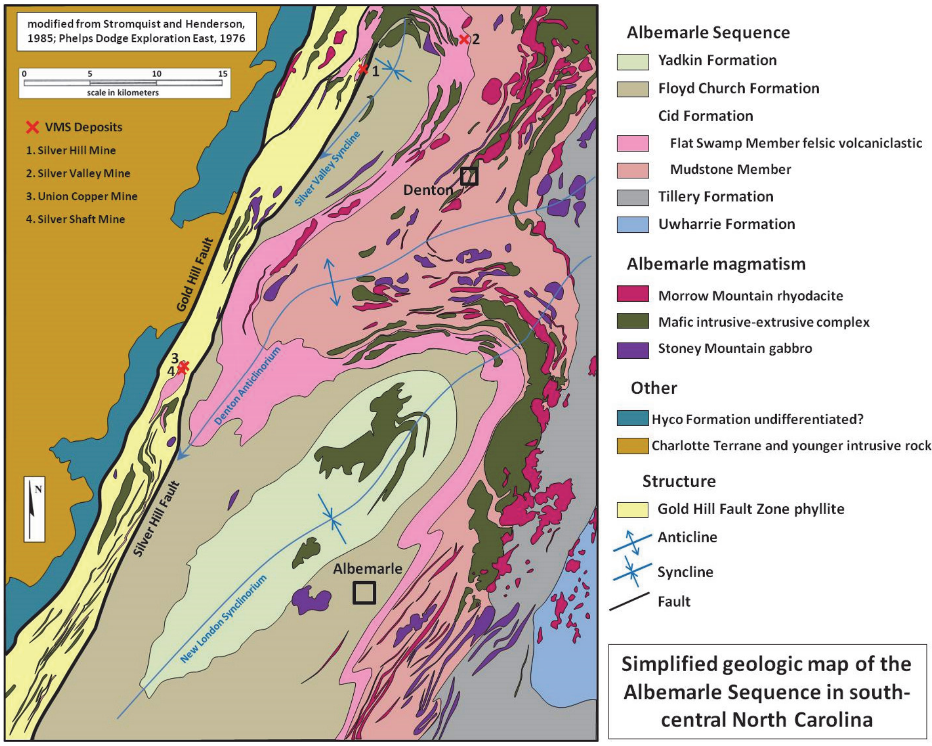


Fig. 12: Simplified geologic map of the Albemarle Sequence in south-central North Carolina illustrating distribution of felsic and mafic intrusive-extrusive centers and occurrence of Stony Mountain gabbro

The Ediacaran fossil *Aspidella* is locally present in the Mudstone Member of the Cid Formation (**Hibbard *et. al.*, 2006**; **Weaver *et al.*, 2006**). **Kozuch** (**1994**) reports a U-Pb zircon age of 542 ± 14 Ma from an interbedded metarhyolite unit. **Pollock** (**2007**) estimates a minimum age of ca. 540 Ma for the Mudstone Member, based on detrital zircons in a sample collected from the Jacobs Creek Quarry, located south of the town of Denton in Davidson County.

Felsic and mafic igneous units represent a significant proportion by volume of the Mudstone Member of the Cid Formation, ranging from an estimated 20-60% (**Fig. 2**) and averaging about 30% (**Wright and Seiders, 1980**). Mafic volcanic units compose about 20% of the Mudstone Member (**Fig. 2**, **Fig. 12**), although they locally dominate much of the thickness of the Mudstone Member in northwest Montgomery County (**Fig. 12**).

Major lithologies include vesicular to amygdular lava flows, agglomeratic lapilli tuff, crystal-lithic tuff breccia, massive and bedded tuff, and epiclastic sandstone and siltstone (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Stromquist *et al.*, 1971**; **Stromquist and Henderson, 1985**). Most of the mafic sequence is andesitic basalt (**Stromquist and Sundelius, 1969**) composed of faintly bedded lithic-crystal tuff with clasts from a few millimeters to over 20 centimeters long (**Conley, 1962**).

Large areas of mafic volcanic rocks compose much of the Mudstone Member in the Albemarle area, where they are intruded by large bodies of Morrow Mountain rhyodacite (**Fig. 12**). Basal units of greenish-gray epiclastic sediments contain deformed, angular rip-up clast of the underlying mudstone and show slump structures (**Stromquist and Sundelius, 1969**). At the base of the mafic sequence near Morrow Mountain in Stanley County **Conley** (**1962**) notes the presence of a fragmental unit with mafic clasts and rounded mudstone pebbles in a matrix of fine-grained mafic tuff. Amygdular mafic flows are also reported from the basal section, some with possible columnar jointing (**Conley, 1962**), but these may be sills.

Felsic igneous units compose around 10% of the Mudstone Member (**Fig. 2**, **Fig. 12**) and are typically conformable feldspar-phyric porphyry and vitrophyre. They form steep-sided hills and ridges and have been interpreted as volcanic plugs, domes, cryptodomes, sills, and possible lava flows (**Stromquist *et al.*, 1971**). Many are oval to elongate bodies with lensoidal cross-sections and irregular margins. Most measure 0.5-2 kilometers along strike, but some are continuous for up to 8-10 kilometers. Flow banding is common, and the rocks are typically medium-gray in color with albite crystals up to three millimeters long in an aphanitic groundmass (**Stromquist *et al.*, 1971**). Some albite grains are intergrown with 5-90% patchy microcline, and variable disseminated biotite, rutile, pyrite, pyrrhotite, and magnetite are common (**Stromquist *et al.*, 1971**).

Large felsic magmatic bodies, including the Morrow Mountain rhyodacite complex (**Ingram, 1999**; **Boorman *et al.*, 2013**), become much more abundant across the contact with the Tillery Formation and throughout the lower Cid Formation. These felsic complexes (**Fig. 11**) are often spatially associated with voluminous mafic volcanic centers (**Stromquist and Sundelius, 1969**) which are absent from the Tillery Formation. Like those of the Tillery Formation, these felsic bodies may be largely intrusive in character and post-date sedimentation and synchronous mafic volcanism. Additionally, the Mudstone Member is widely intruded by bodies of the Stony Mountain gabbro, although they are not as abundant as in the Tillery Formation (**Fig. 2**, **Fig. 5**, **Fig. 12**).

Although felsic and mafic igneous units of the Mudstone Member suggest a strongly bimodal magmatic environment, only the mafic units appear to be the result of mafic volcanism synchronous with sedimentation with subsequent intrusion of conformable felsic bodies. This synchronous mafic-dominated magmatism extends throughout the Mudstone Member, and is interrupted by the intense felsic-dominated bimodality in the Flat Swamp Member of the Cid Formation. Mafic volcanism continues through the Floyd Church and Yadkin formations.

Mafic and felsic units decrease in abundance towards the top of the Mudstone Member (**Gibson and Teeter, 1984**) and more quiescent deposition is suggested by 1-10 millimeter thick laminations (**Stromquist and Sundelius, 1969**). **Stromquist and Sundelius** (**1969**) report flattened limestone concretions 15-20 centimeters across in the upper part of the Mudstone Member, and possible conformable carbonate units in the Mudstone Member have been reported by **Conley** (**1962**) in the Albemarle area and by **Randazzo** (**1972**) in Union County, North Carolina.

Like the Uwharrie and Tillery formations, the Cid Formation thins to the south. At the southern end of the Albemarle Basin in Union County **Randazzo** (**1972**) combined the entire Cid Formation and the Floyd Church Formation into a single ~3600 meters sequence. The Flat Swamp Member is largely absent, and the Mudstone Member is characterized by the same metasedimentary sequence described to the north (**Stromquist and Sundelius, 1969**; **Gibson and Teeter, 1984**; **Pollock, 2007**). However, interbedded felsic and mafic units appear to be far less abundant or absent (**Randazzo, 1972**).

Flat Swamp Member of the Cid Formation

The distinctive Flat Swamp Member of the Cid Formation is up to 1200 meters thick in the Denton area of Davidson County and characterized by often coarse-grained rhyolite to rhyodacite pyroclastic and volcaniclastic rocks with subordinate interbedded felsic flows and domes, intermediate to mafic flows and volcaniclastic units, and epiclastic sedimentary sequences (**Stromquist and Sundelius, 1969**; **Gibson and Teeter, 1984**). Although locally dominated by felsic volcanic units similar to the Uwharrie Formation, it is compositionally more diverse with approximately 55% felsic, 30% mafic, and 15% intermediate units. The Flat Swamp Member is exposed over a northeast-trending area measuring about 2000 km^2 in the northern portion of the Albemarle Basin and forms a prominent marker horizon around the limbs of the Silver Valley Syncline, Denton Anticlinorium, and New London Synclinorium (**Fig. 5**, **Fig. 12**).

The thickest portion of the Flat Swamp Member lies in the Denton area, in a 22.5 by 40 kilometers area on the limbs of the Silver Valley Syncline and Denton Anticlinorium (**Fig. 5**, **Fig. 12**). Felsic volcanic and volcaniclastic facies proximal to eruption centers appear to dominate the northern portion of this area, especially in the limbs of the Silver Valley Synclinorium. **Stromquist and Henderson** (**1985**) suggest the presence of eruption centers at Flat Swamp Mountain, Grist Mountain, and Wildcat Mountain on the southeast limb of the Silver Valley Synclinorium, coincident with extensive units of rhyolite to rhyodacite flows, domes and/or cryptodomes, dikes, and sills.

Flat Swamp Ridge is composed of coherent, locally flow-laminated rhyolite that is orthoclase, albite-oligoclase, and quartz phyric with minor disseminated pyrite and pyrrhotite (**Pogue, 1910**). **Pogue** (**1910**) describes continuous lateral and vertical facies gradations from coherent rhyolite flows or domes through coarse-grained, monomict rhyolite breccia, to increasingly finer-grained rhyolite crystal-lithic volcaniclastic facies with decreasing rhyolite clast size; with clasts increasingly mixed with clasts of mafic volcanic rocks and fine-grained siltstone. The interbedding of felsic units with basaltic andesite volcaniclastic units and massive to thinly-bedded siltstone sequences suggests simultaneous felsic and mafic volcanism in a generally quiescent marine environment (**Pogue, 1910**) with localized eruption centers rather than large, centralized volcanic constructs.

Andesitic basalt volcanic rocks of the Flat Swamp Member of the Cid Formation are amygdaloidal lava and pyroclastic and volcaniclastic facies including crystal-lithic tuff breccia, agglomeratic lapilli tuff and scoriaceous units, and coarse to fine-grained massive to bedded tuffs (**Stromquist and Sundelius, 1969**; **Stromquist and Henderson, 1985**). **Stromquist and Sundelius** (**1969**) note the occurrence of an autobrecciated andesitic basalt flow.

The Flat Swamp Member is locally recognized within the Gold Hill Fault Zone to the west, hangingwall to the Silver Hill Fault that forms the floor of the fault zone duplex (**Hibbard et *al.*, 2013**). **Indorf** (**1981**) traced the Flat Swamp Member on the western limb of the Silver Valley Syncline westward across the projected trace of the Silver Hill Fault with little evidence of displacement. **Standard** (**2003**) suggests that the Gold Hill Fault veers east through the town of Silver Hill and merges into the Silver Hill Fault, terminating the fault zone duplex.

However, detailed geologic mapping by Phelps Dodge Exploration East in 1975-1976 (**Fig. 13**) supports the interpretation of **Indorf** (**1981**) and suggests that the Flat Swamp Member hosts the Silver Hill VMS deposit of the Cid District in Davidson County. The Silver Hill Mine appears to be situated hangingwall to the Silver Hill Fault, which may die out in the hinge of the Silver Hill Syncline (**Fig. 13**). Rather than merging with the Silver Hill Fault, the Gold Hill Fault appears to continue along a northeast strike to the west of the Silver Hill area.

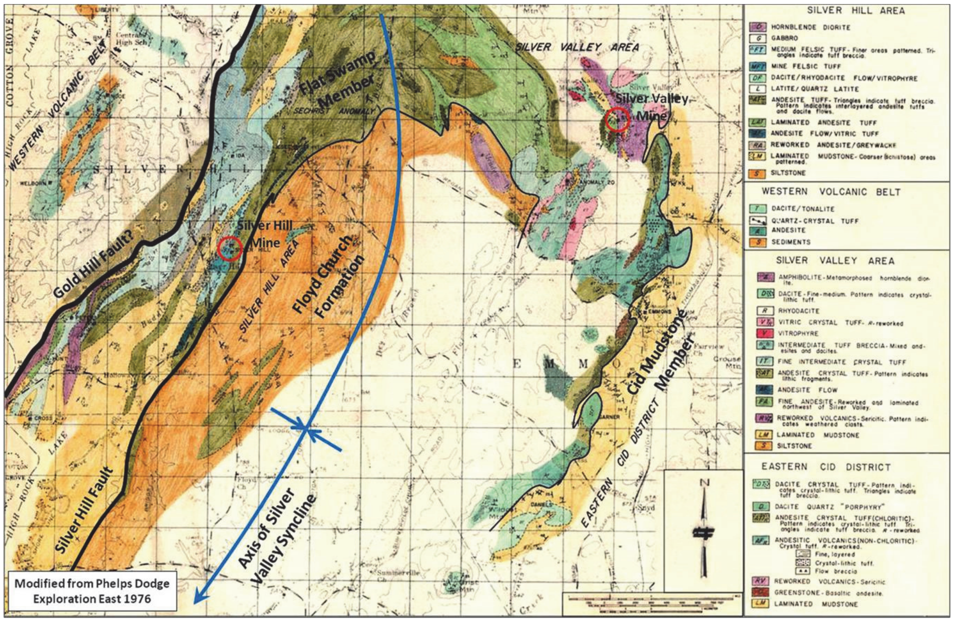


Fig. 13: Geologic map of the Cid Mining District, Davidson County, North Carolina

Ledger (**1978**), **Unger** (**1982**), and **Moye *et al.*** (**2017**) conclude that the Union Copper and Silver Shaft VMS deposits of the Gold Hill District of Rowan and Cabarrus counties are also hosted by units of the Flat Swamp Member within the Gold Hill Fault Zone. These units may be part of the faulted western limb of the Denton Anticlinorium or a dismembered extension of the Silver Valley Syncline. All known VMS deposits hosted by the Albemarle Sequence appear to be associated with the Flat Swamp Member.

Butler (**1995**) interprets the Flat Swamp Member in the Albemarle area as 1200-1800 meter thick intra-caldera facies, composed of mudflow breccias, tuffs, pyroclastic flows, and lava flows. The Flat Swam Member appears to thin rapidly south of the Albemarle area, and **Butler** (**1994**) suggests a transition into extra-caldera facies less than 150 meters thick composed of coarse- to fine-grained crystal-rich tuffs with an upper unit of extremely fine-grained devitrified vitric tuffs. The thickness and average grain size of the unit decrease to the south and east, losing identity in a continuation of the thick sequence of fine-grained well- bedded metasediments of the upper Mudstone Member of the Cid Formation. The Flat Swamp Member is not recognized in the south-eastern portion of the Albemarle Basin (**Randazzo, 1972**; **Gibson and Teeter, 1984**).

Ingle *et al.* (**2003**) report a ^{207}Pb/^{206}Pb TIMS age of 540.6 + 1.2 Ma for two multigrain zircon fractions from the Flat Swamp Member west of the town of Denton. **Hibbard *et al.*** (**2009**) obtained an ID-TIMS zircon U-Pb age of 547 ± 2 Ma from a dacite flow near High Rock on the Yadkin River southwest of the town of Denton. **Hibbard *et al.*** (**2012**) report a TIMS U-Pb zircon age of 542 +8/-5.5 for felsic quartz-feldspar phyric tuff within the Gold Hill Fault Zone west of the town of Silver Hill, and apparently correlative with the Flat Swamp Member. Like the Mudstone Member, the Flat Swamp Member of the Cid Formation may have been deposited in a geologically short period of time, possibly as little as 1-2 Ma.

The Flat Swamp Member of the Cid Formation is a magmatic and metallogenic anomaly within the dominantly quiescent sedimentary record of the Albemarle Group. It represents a period of dramatically increased felsic-dominated bimodal magmatism and effusive to explosive volcanism within the Albemarle Basin ca. 540-542 or possibly 547 Ma (**Ingle *et al.*, 2003**; **Hibbard *et al.*, 2009**; **Hibbard *et al.*, 2012**). It contrasts with the localized quiescent magmatism of the Tillery Formation and the Mudstone Member of the Cid Formation. It is followed by an abrupt change in the style and composition of sedimentation and magmatism in the Albemarle Group.

Mineralization in the Cid Formation

There is no significant hydrothermal alteration or mineralization genetically associated with any portion of the Albemarle Group other than the Flat Swamp Member of the Cid Formation. The high-grade polymetallic VMS deposits in the Cid and Gold Hill mining districts (**Indorf, 1981**; **Moye *et al.*, 2017**) are hosted by the Flat Swamp Member of the Cid Formation (**Fig. 12**, **Fig. 13**). Although VMS ore bodies in the Cid and Gold Hill districts are relatively small in size and tonnage, they are typically part of much larger zones of footwall and hangingwall hydrothermal alteration and laterally equivalent distinctive chemical sedimentary units (banded Fe-formations, baritic units, manganiferous units, chert, etc.).

Average run of mine for the Silver Hill ore body in the Cid District was 59.2% sphalerite, 21.9% galena, 17.1% pyrite, and 1.8% chalcopyrite (**Pogue, 1910**), yielding 40% Zn and 19% Pb. The galena is argentiferous, and supergene Pb-carbonate was intergrown with plates of native Ag (**Pogue, 1910**). The Silver Valley deposit in the same district is Ag-Pb-Zn rich but probably a footwall silicic alteration and stringer zone to VMS mineralization that has not been located or lost to erosion. The historic Emmons and Cid prospects and other occurrences in the area may also represent VMS related footwall alteration and stringer zones. Multiple VMS associated hydrothermal systems are indicated in the Cid District.

The Union Copper ore body in the Gold Hill district produced five million pounds of Cu and almost 20,000 ounces of Au from a 350,000 metric ton VMS deposit centered above a strongly zoned silicic and chloritic footwall alteration zone (**Fig. 14**) with an extensive sulfide stringer zone (**Unger, 1982**). It is part of a larger zone of hydrothermal alteration with disseminated, vein, and stringer base metal sulfide mineralization that extends for over 1000 meters along strike across a stratigraphic section over 100 meters thick (**Fig. 15**). Hangingwall to the Union Copper ore body, this mineralized interval hosts a series of smaller zinc and Ag-rich ore bodies (**Unger, 1982**; **Moye *et al.*, 2017**).

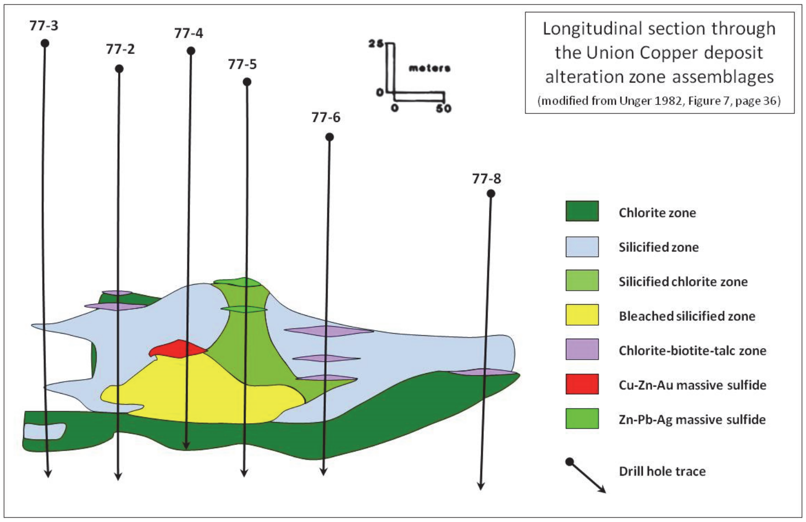


Fig. 14: Alteration facies at the Union Copper Mine, Rowan County NC

The largest of these is the Silver Shaft or McMakin Mine (**Fig. 15**) where two ore lenses are present. The main lode was 1-3 meters thick and assayed around 14-53 oz/t Ag (**Kerr and Hanna, 1888**). It is composed of pale yellow sphalerite, galena, Ag-bearing tetrahedrite, pyrite, and chalcopyrite, with a gangue of quartz, calcite, barite, rhodochrosite, and talc (**Genth 1891, p. 90**). Samples of ore collected in 1980 assayed 11.4% Pb, 25.2% Zn, and 28.68 oz/t Ag (**Smart and Moye, 1982**).

The deposit was worked for around 275 meters along strike and mined underground through three shafts over a length of 60 meters to a maximum depth of 55 meters (**Kerr and Hanna, 1888**; **Nitze and Hanna, 1896**). About 15 meters north of the main shaft, a 1980 Phelps Dodge core drill hole intersected 7.3 meters averaging 8.88 oz/t Ag and 1.113% Zn at a vertical depth of 91.4 meters. This largely disseminated mineralization is peripheral to the more massive sulfide-rich lenses exploited by historic mining.

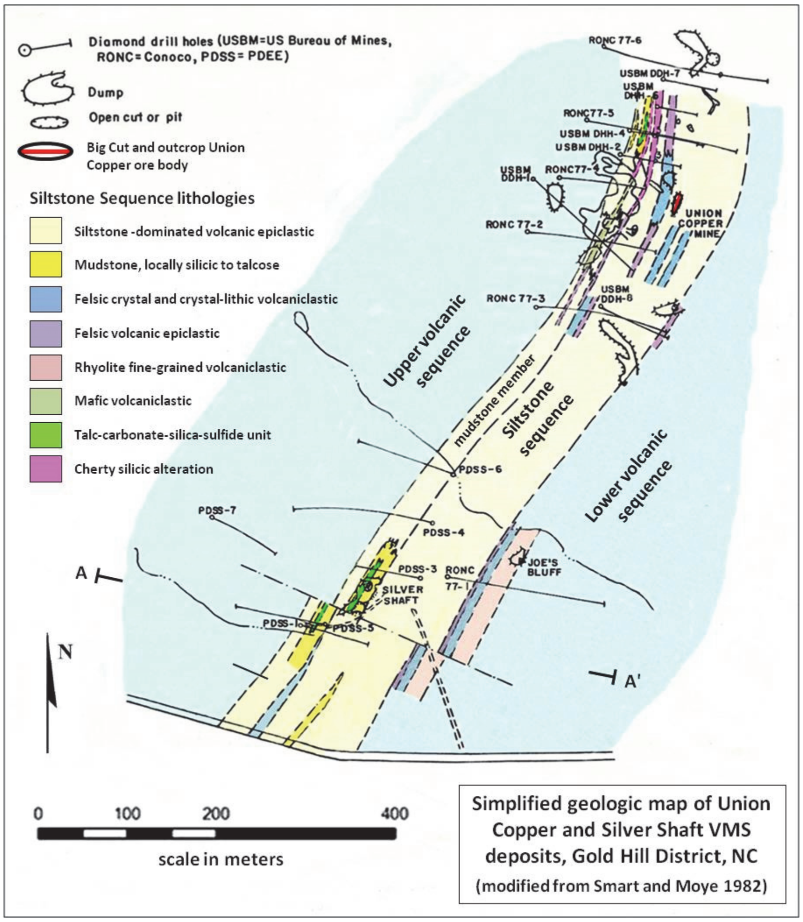


Fig. 15: Geologic map of the Union Copper Mine area, Rowan County NC

Multiple intervals of similar mineralization were intersected by drill holes at several locations (**Fig. 15**) about 60 meters into the hanging wall of the Union Copper Mine ore body (**Unger, 1982**). Bureau of Mines drill holes DDH01 and DDH02 intersected a 5-meter thick zone of sphalerite and galena mineralization. Conoco drill hole RONC-77-2 intersected 3.7 meters (true thickness) of 4.91 oz/t Ag and 1.17% Zn. Drill hole RONC-77-5 intersected 2.7 meters of 1.02 oz/t Ag and 5.10% Zn within a 7.6 meter zone that averaged 3.59% Zn. Tennessee Copper drill hole No. 2 intersected 2.1 meters (true thickness) of 3.7 oz/t Ag and 1.74 % Zn.

The series of hangingwall Zn-Pb-Ag VMS lenses that extend southwest from the Union Copper Mine to the McMakin Mine may have been exploited by a series of poorly known surface working located west of the main line of lode at the Union Copper Mine. They appear to form segments of the “Silver Vein” of **Nitze and Hanna** (**1896**, Plate VI).

The Union Copper-McMakin VMS hydrothermal system in the Gold Hill district is laterally and vertically extensive and was long-lived, forming multiple ore bodies at various stratigraphic positions. This is an underexplored system, especially at depth, with significant potential for additional discoveries. There is significant potential for the presence of additional VMS mineralization in both the Gold Hill and Cid mining districts. Additionally the geographic extent of the host Flat Swamp Member suggests significant potential for additional discoveries of VMS mineralization in less well explored areas, especially within the Gold Hill Fault Zone between the Cid and Gold Hill districts.

Volcanogenic massive sulfide (VMS) deposits form in extensional tectonic regimes, typically in active rift environments, including mid-ocean ridges, back-arc basins, intra-oceanic arc rifts, and continental arc rifts (e.g. **Swinden, 1991**; **Hannington *et al.*, 1995**; **Scott 1997**; **Syme *et al.*, 1999**; **Barrett *et al.*, 2001**; **Piercey *et al.*, 2001**; **Dusel-Bacon *et al.*, 2004**). VMS deposits of the Cid and Gold Hill districts strongly support an arc-rift setting for the Flat Swamp Member of the Cid Formation. The metal budgets of the deposits (Zn-Pb-Cu) are consistent with an evolved tectonic-magmatic rift environment involving input from both continental crust and the asthenosphere (**Barrie and Hannington, 1999**; **Franklin *et al.*, 2005**; **Piercey, 2010**).

The Flat Swamp Member is lithologically consistent with the Bimodal-Felsic Class of VMS deposits (**Barrie and Hannington, 1999**; **Franklin *et al.*, 2005**; **Piercey, 2010**), and similar to deposits of the Kuroko District in Japan, the Buchans District in Canada, and the Skellefte District of Sweden.

Floyd Church Formation

The Floyd Church Formation (**Figs. 2, 5, and 12**) is estimated at between 900 and 1800 meters thick and characterized by greenish-grey metamudstone with local units of mafic metavolcanics (**Stromquist and Sundelius, 1969**). Metasediments are typically moderately graded in the lower part of the sequence, but more massive and increasingly interbedded with minor volcanic epiclastic sandstone and siltstone in the upper portion. Lenses of upward-fining argillaceous tuff breccia with scoured bases are present in the lower portion of the sequence, and contain clasts of primary and reworked felsic volcanic rocks and siltstone rip-up clasts (**Stromquist and Sundelius, 1969**). A general upward coarsening of sedimentary input begins in the upper part of the Floyd Church and continues in the Yadkin Formation. The Ediacaran fossil *Pteridinium* is present in the lower portion of the Floyd Church Formation (**Gibson and Teeter, 1984**) suggesting that the age is late Ediacaran.

Decreasing mafic volcanism accompanied deposition of the Floyd Church Formation (**Stromquist and Sundelius, 1969**). A light-gray, fine-grained volcaniclastic unit composed of clasts < 4 millimeters in diameter and small feldspar fragments in an aphanitic groundmass is identified in the lower portion of the Floyd Church Formation in the northern portion of the

Silver Valley Synclinorium (**Stromquist *et al.*, 1971**; **Stromquist and Henderson, 1985**), the same area where the Flat Swamp Member reaches maximum thickness.

In Union County, **Randazzo** (**1972**) did not recognize significant changes in sedimentation style and composition from the Mudstone Member of the Cid Formation through the Floyd Church Formation. He combined them as the McManus Formation with a maximum estimated thickness of 3600 meters.

Yadkin Formation

The Yadkin Formation (**Fig. 2**, **Fig. 5**) is about 900 to 750 meters thick and composed largely of dark colored, thin to thickly interbedded, poorly sorted greywacke and well-sorted arenaceous siltstone and sandstone layers (**Stromquist and Sundelius; 1969**, **Gibson and Teeter, 1984**; **Pollock, 2007**) that are locally interbedded with metamorphosed andesitic basalt flows and pyroclastic units (**Stromquist and Sundelius, 1969**). There is a distinct shift towards more voluminous, mafic dominated magmatism relative to the Floyd Church Formation. Sedimentary structures suggest an upward shoaling marine depositional environment dominated by wind, waves and tides (**Pollock, 2007**).

Andesitic basalt forms up to 30% by volume of the exposed Yadkin Formation (**Wright and Seiders, 1980**). Mafic volcanism in the Yadkin Formation is largely restricted to a large volcanic complex that appears to interfinger with the host greywacke in the northern portion of the New London Synclinorium (**Fig. 12**). Mafic volcanic units in the Yadkin Formation are fine to coarse-grained, green to gray-green andesitic basalt, and include tuff and locally scoriaceous tuff breccia (**Stromquist and Henderson, 1985**). Clasts of scoriaceous material range from 0.15 to 10 centimeters, and many are flow banded (**Conley, 1962**). Flattened scoriaceous clasts comprise up to 60% of the rock, and flattened pumice clasts are also reported (**Conley, 1962**).

Black (**1978**) reports a Rb/Sr whole rock age of 540 ± 7 Ma from mafic metavolcanic rocks of the Yadkin Formation. Detrital zircon grain U-Pb analyses from the Yadkin (**Pollock, 2007**) include a strong peak at about 560 Ma in a cluster of 72 samples ranging from 528 ± 7 Ma to 636 ± 9 Ma, and a minor peak at around 650 Ma. The youngest U-Pb ages for detrital zircons obtained by **Pollock** (**2007**) from the Yadkin Formation range from 541 ± 16 Ma to 528 ± 8 Ma.

The Yadkin Formation, as a definable unit, does not appear to extend into the southeastern portion of the Albemarle Basin (**Randazzo, 1972**). However, **Randazzo** (**1972**) describes a sequence of massive to laminated mudstone and siltstone with 20-30% interbedded greywacke sandstone units, often in graded beds that fine upwards into siltstone and mudstone. This sequence is gradational with the underlying McManus (combined Cid and Floyd Church) Formation and fines to the southeast.

Randazzo (**1972**) interprets this sequence as finer-grained but stratigraphically equivalent to the Yadkin Formation, and suggests that it occupies a syncline that underlies the Mesozoic Wadesboro Basin in southeastern Union County (Fig. 2). He suggests that the syncline, informally named the Peachland Syncline, is also present to the southeast of the

Wadesboro Basin and extends south into adjacent South Carolina. However, other compilations variously show this strata as Cid Formation (**Goldsmith *et al.*, 1988**), Tillery Formation (**Hibbard *et al.*, 2002**), or Floyd Church Formation (**Brennan, 2009**).

Albemarle Group felsic magmatism reconsidered

Magmatism associated with the Albemarle Group of the Carolina terrane appears to be distinct from Uwharrie magmatism (**Fig. 2**), which is expressed as voluminous, strongly felsic-dominated bimodal volcanism, as well as localized felsic to intermediate plutonic units exposed in the older Hyco Formation and Virgilina Sequence to the east and northeast along transtensional faults. Uwharrie volcanic rocks in the Asheboro area are estimated to be 80% felsic and 17% mafic (**Seiders, 1978**).

The character of Albemarle Group magmatism expressed as both volcanic and plutonic units is distinctly bimodal, but with a general parity in the abundance of felsic and mafic units (**Fig. 2**). There is an overall mafic dominance if units of the Stony Mountain gabbro are also considered. Additionally, the character of magmatism, the proportion of felsic to mafic units, and the distribution of both appear to change throughout the Albemarle Group.

Most importantly, recognition of the chemical similarity and widespread occurrence of Morrow Mountain rhyodacite units in the upper Uwharrie, Tillery, and Cid Mudstone Member sequence (**Boorman *et al.*, 2013**) requires reevaluation of the age and character of this magmatism, especially as constrained by the U-Pb zircon TIMS analysis at 539 ± 5 Ma (**Ingle *et al.*, 2003**) for the Morrow Mountain rhyodacite body near the Tillery-Cid formation contact. There is significant evidence for the widespread distribution of Morrow Mountain felsic magmatism throughout the Albemarle Sequence below the Flat Swamp Member of the Cid Formation. Essentially all felsic magmatism in the basin ceases with the end of this singular volcanic episode.

Review and analysis of available physical descriptions for units of Morrow Mountain rhyodacite suggests that past assumptions regarding the character and timing of emplacement for many of these bodies may be open to reevaluation. There appears to be a strong circumstantial case for the absence of felsic volcanism synchronous with sedimentation in the Tillery Formation and Cid Mudstone Member but widespread intrusion of Morrow Mountain rhyodacite units ca. 547-539 Ma.

The missing VMS consideration

The absence of VMS mineralization from the Tillery and Cid Mudstone Member despite the apparent presence of widespread felsic and mafic volcanic units is puzzling. Bimodal volcanism in a marine inter-arc rift environment should be conducive to the formation of extensive polymetallic sulfide mineralization. There appears, however, to be a complete absence of exhalative chemical sediments (sulfides, BIF, and manganiferous, baritic or siliceous sedimentary units). Additionally there are no areas of significant hydrothermal alteration or disseminated and stockwork sulfide mineralization that would suggest the activity of VMS-related hydrothermal systems.

The presence of VMS mineralization only in association with the Flat Swamp Member suggests that even large felsic units in the lower units of the Albemarle Group, interpreted as intrusive-extrusive complexes and domes, failed to generate any of the expected hydrothermal activity in this otherwise apparently fertile environment. Predicated on the apparent fertility of a bimodal rift environment, Amselco Exploration (BP Minerals/Kennecott Exploration) conducted an extensive geologic and geochemical reconnaissance of the Albemarle Basin for base metal sulfide mineralization ca. 1984-85. The results were entirely negative.

Although largely ignored by many studies of the Albemarle Sequence, hydrothermal alteration systems and associate precious or base metal mineralization are a major constraint on geologic interpretation of stratigraphy, concurrent magmatism, and dynamic processes associated with the evolving tectonic environment. The absence of VMS mineralization in association with even large felsic units in the Cid Mudstone Member, the Tillery Formation, and in the transition from the Tillery to the Uwharrie Formation is a possible red flag.

The ambiguity of textures in submarine felsic flows, domes, cryptodomes, and sills

Although commonly interpreted as flows, domes, cryptodomes, or sills on the basis of stratigraphic conformity, apparent morphology, and the presence or absence of flow banding, spherulites, lithophysae, and amygdales (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Seiders, 1981**; **Ingram, 1999**; **Klein *et al.*, 2007**; **Kurek, 2010**; **Boorman *et al.*, 2013**), most units of Morrow Mountain rhyodacite lack adequate detailed observations to classify their mode of emplacement with confidence. Additionally, published literature on felsic flows, domes, cryptodomes, and sills (**Minakami *et al.*, 1951**; **Goto and McPhie, 1998**; **Dadd and Wagoner, 2002**; **Skilling *et al.*, 2002**; **Stewart and McPhie, 2003**; **Orth and McPhie, 2003**) suggests significant ambiguity in interpretation and classification without extensive and detailed analysis of morphology, textural features, facies associations, and contact relationships.

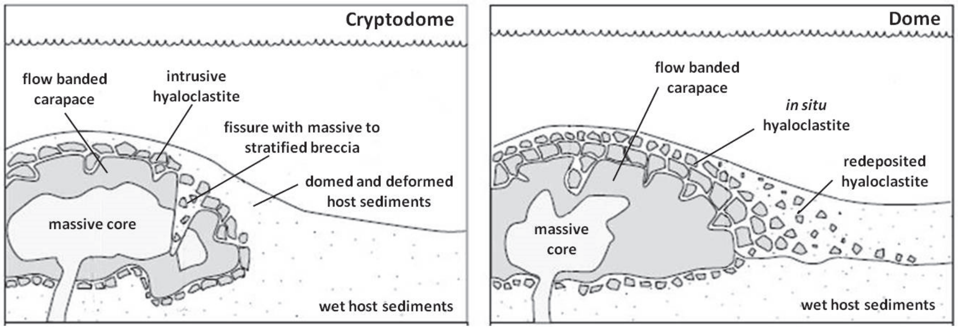


Fig. 16: Characteristics of domes and cryptodomes (modified from **Stewart and McPhie, 2003)**

Felsic lava domes are surface extrusion of magma while cryptodomes are intrusions of magma at shallow depths below the surface that results in doming of the overlying strata (**Minakami *et al.*, 1951**). Submarine felsic lava domes and equivalent cryptodomes (**Fig. 16**) may have similar morphology, textural facies, and internal structures (**Stewart and McPhie, 2003**). Submarine cryptodomes are distinguished from submarine domes by coherent facies, well-developed concentric textural zones, and the absence of transported and redeposited peripheral autoclastic facies (**Stewart and McPhie, 2003**). Submarine domes are distinguished by the presence of both *in situ* and redeposited autoclastic facies (**Stewart and McPhie, 2003**). Additionally, the upper contact of a cryptodome with the host sedimentary sequence will be intrusive and commonly characterized by the occurrence of peperite.

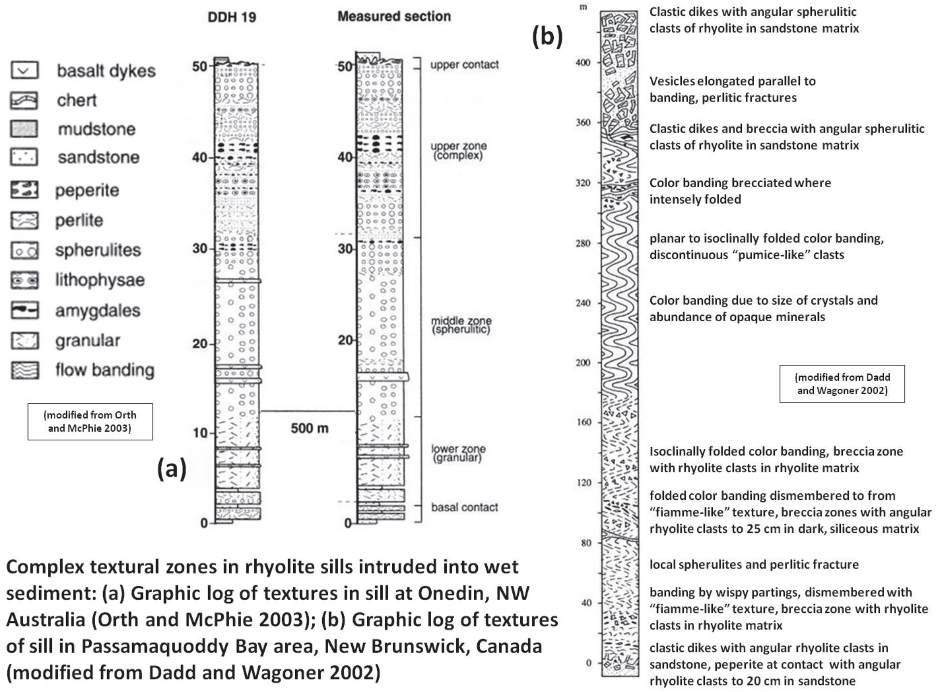
Evidence of shallow subsurface emplacement of cryptodomes may include bulbous cross-sections with flattened bases and domed tops with truncated to compressionally deformed bedding in the enclosing sedimentary host (**Goto and McPhie, 1998**; **Stewart and McPhie, 2003**). Small cryptodomes intruded at shallow depths may show strongly developed radial columnar jointing, strongly laminated and locally vesicular rims, contact breccia with angular clasts of the intrusive in a finer-grained cogenetic matrix, and adjacent peperite with angular clasts of the intrusive in a matrix of the host sediment (**Goto and McPhie, 1998**; **Stewart and McPhie, 2003**). **Stewart and McPhie** (**2003**) conclude that cryptodomes in older rock sequences can be easily mistaken for extrusive domes.

Stewart and McPhie (**2003**) note the local presence of contact-parallel units of monomict, variably stratified breccia in large tension fractures in the Kalogeros cryptodome on Milos Island, Greece. Similar deposits could easily be mistaken for pyroclastic or volcaniclastic facies in older successions; however, they are the result of brittle mechanical processes restricted to the immediate periphery of the cryptodome and do not show evidence of transport and redeposition.

More deeply emplaced conformable felsic bodies may share variations of the same concentric structure and contact relationships that characterize cryptodomes, but with increasingly planar morphologies that transition into sills. However, there appears to be little literature on the transition from the morphology, facies, and contact relationships of cryptodomes to that of sills formed at greater depth and higher confining pressures.

Orth and McPhie (**2003**) observe complex textural stratification in a Palaeoproterozoic rhyolite sill 52 meters thick with a strike of three kilometers, emplaced into water saturated, unconsolidated sediments of the Koongie Park Formation at Onedin in northwestern Australia (**Fig. 17a**). The estimated depth of emplacement is some hundreds of meters below the sediment surface at a water depth below wave base (**Orth and McPhie, 2003**). The length to thickness ratio of 30:1for this sill further serves to distinguish it from a felsic flow.

A thin (1-2 meterss thick) zone of basal peperite is transitional through an interval of abundant spherulites into fine-grained central zone of granular rhyolite (**Orth and McPhie, 2003**). The upper portion of the central zone becomes increasingly rich in spherulites and amygdales and grades sharply into a 20 meters thick upper zone with alternating layers with abundant irregular to rounded amygdales, abundant spherulites, numerous lithophysae, massive rhyolite, and perlite formed by laminar shear (**Orth and McPhie, 2003**). The upper contact is characterized by 2-3 centimeters thick pumiceous layer and a 1-2 meters thick interval of peperite.



Complex textural zones in rhyolite sills intruded into wet sediment: (a) Graphic log of textures in sill at Onedin, NW Australia (Orth and McPhie 2003); (b) Graphic log of textures of sill in Passamaquoddy Bay area, New Brunswick, Canada (modified from Dadd and Wagoner 2002)

Fig. 17: Complex textures in rhyolite sills intruded into wet sediments

Dadd and Wagoner (**2002**) describe a 435 meter thick Silurian rhyolite sill that intruded wet siltstone and sandstone in the Passamaquoddy Bay area of southwestern New Brunswick, Canada (**Fig. 17b**). Peperite is present along the footwall and hangingwall contacts. Clastic dikes of sandstone with rhyolite clasts, formed as large quench fractures, are present in the upper 80 meters of the sill with vesicles, perlitic fracturing, spherulites, and lithophysae developed in the adjacent rhyolite (**Dadd and Wagoner, 2002**). The sill interior is characterized by sparsely feldspar phyric rhyolite with strongly developed flow foliation banding that is commonly moderately to isoclinally flow-folded (**Dadd and Wagoner, 2002**). This foliation banding is locally dismembered to form "false fiamme" or autobrecciated with angular rhyolite clasts in a dark colored, siliceous matrix (**Dadd and Wagoner, 2002**).

Based on these studies and observations, morphological and textural evidence suggests that many of the Morrow Mountain rhyodacite bodies present in the upper Uwharrie Formation, the Tillery Formation, and the Mudstone Member of the Cid Formation may be intrusive in origin. If this is the case, then the morphology of various units of Morrow Mountain rhyodacite should reflect depth of emplacement and local stratigraphic controls on the vertical and horizontal movement of magma. Additionally, rather than a protracted magmatic event throughout deposition of the lower Albemarle Group, Morrow Mountain rhyodacite magmatism may represent a relatively brief period of geologic time in the evolution of the Albemarle Basin.

Younger felsite domes or cryptodomes of the upper Uwharrie Formation

Locally numerous small, often equant felsic bodies interpreted as domes and/or cryptodomes, plugs, and possible necks characterize the upper Uwharrie Formation in the Asheboro area (**Seiders, 1981**; **Kurek, 2010**). They are typically rounded to oval or irregularly lobate in form and intrude stratigraphic units of felsic and mafic volcaniclastic rocks and thinly bedded ash-rich mudstone of the uppermost Uwharrie Formation (**Fig. 18**). They are distinct from the earlier stratigraphic units of similar Uwharrie Formation felsite and appear to post-date the main phase of voluminous Uwharrie magmatism, possibly representing a younger phase of felsic magmatism.

This cluster of younger felsic intrusions is informally termed the Asheboro Domes. They include Dave's Mountain (**Fig 6**, **Fig. 18**), a prominent hill formed by a 750-1000 meter diameter felsic dome or cryptodome (**Kurek, 2010**). Dave's Mountain is dominantly a dark gray massive, coherent plagioclase-phyric dacite to rhyodacite body with 1-3 millimeter albite phenocrysts in a matrix composed of around 50% quartz, 40% feldspar, 5% sericite, 5% chlorite, and minor biotite and zoisite (**Kurek, 2010**). The central mass is at least locally enclosed by border phases of possible hyaloclastite breccia that contains angular clasts of the felsite to >10 centimeters across in a black mudstone matrix (**Kurek, 2010**). Additionally, bedded crystal-lithic tuffs with large clasts of the central felsite are present near the base (**Kurek, 2010**). Although interpreted as a dome (**Kurek, 2010**), the characteristics of the Dave's Mountain body are also consistent with a cryptodome.

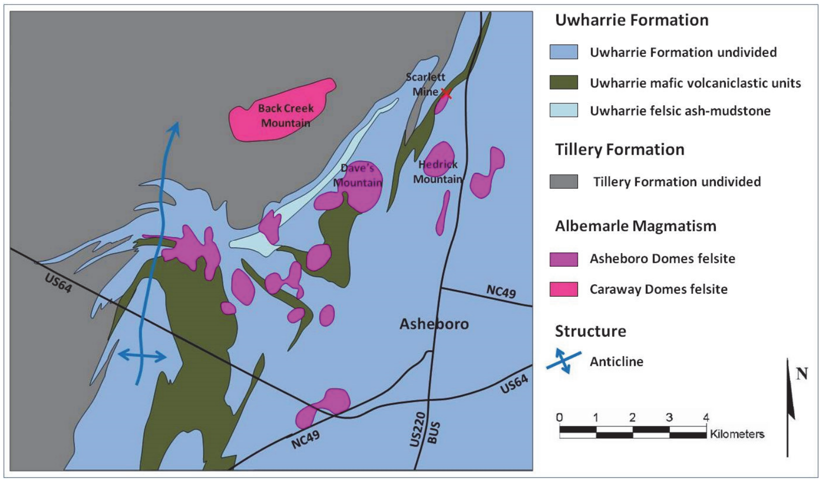


Fig. 18: Asheboro Domes and surrounding area (modified from Seiders, 1981)

An atypical feature of the Asheboro Domes is the skarn-like polymetallic sulfide mineralization at the Scarlett Mine (**Fig. 18**), located at the contact between a small rhyodacite intrusion and an altered mafic volcaniclastic unit, suggesting localized hydrothermal metasomatism. Calc-silicate alteration of the mafic volcaniclastic rocks in the hangingwall is composed largely of epidote, biotite, and quartz in a finer-grained matrix of chlorite and actinolite (**Kline and Dosh, 1949**).

Possibly similar epidote-rich assemblages are described by **Kurek** (**2010**) proximal to the contact of the Dave's Mountain domes and along the Uwharrie-Tillery formation contact at several locations in the Asheboro area (**Kurek, 2010**). This metasomatism and sulfide mineralization appear to be unique to the Asheboro Domes area of younger rhyodacite magmatism and has not been recognized in association with similar rhyodacite bodies in the upper Uwharrie Formation to the south in Montgomery County (**Conley, 1962**; **Ingram, 1999**; **Boorman et *al.*, 2013**) or in the Tillery Formation or the Mudstone Member of the Cid Formation.

The Scarlett Mine Cu-Zn-Pb sulfide deposit

The Scarlett Mine is a small polymetallic base metal sulfide deposit located in northern Asheboro (**Fig. 6**, **Fig. 18**). Originally opened on gossan as a gold mine about 1882; it operated as a copper mine from 1899 to 1915 (**Carpenter, 1976**). Three small sulfide ore bodies are located along the contact between a footwall rhyodacite dome, part of the Asheboro cluster, and a hangingwall mafic unit at least 50 meters thick, described as epidosite (**Kline and Dosh, 1949**) and mapped by **Seiders** (**1981**) as mafic volcaniclastic rocks.

Sulfides occur as disseminations, on fractures, as stringers, as stockwork veins, and as narrow semi-massive to massive intervals (**Kline and Dosh, 1949**). Principal ore minerals are pyrite, sphalerite, chalcopyrite, and minor galena with quartz, chlorite, and amphibole gangue. Alteration associated with mineralization is silicic to phyllic (quartz-sericite-chlorite-sulfide ± epidote). The footwall rhyodacite is locally intensely silicic altered and consists largely of quartz (**Kline and Dosh, 1949**).

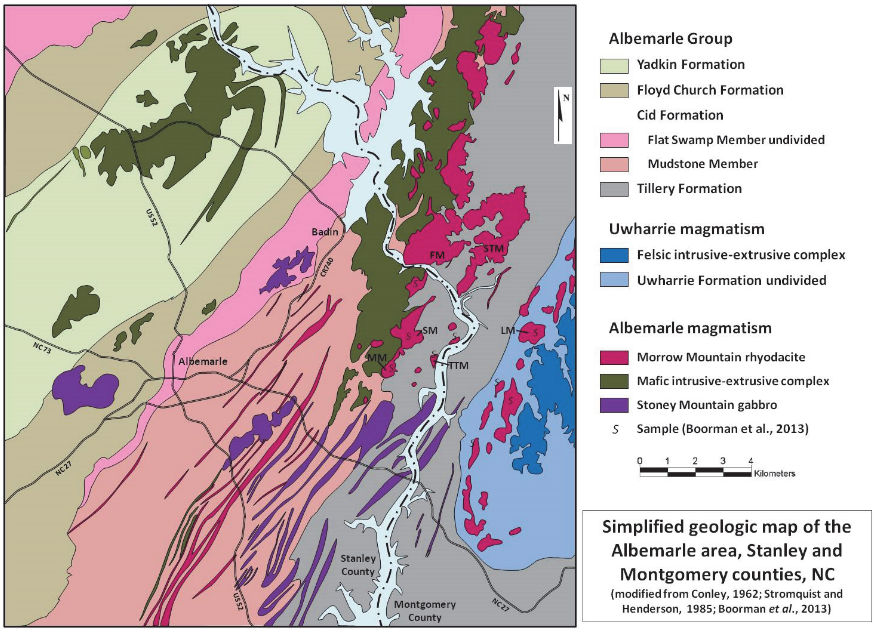
Mineralization, although discordant, appears to be "stratabound" to the lithologic contact between an altered mafic volcaniclastic unit and the felsic dome. However, it is uncertain whether this contact is depositional, intrusive, or structural. The Scarlett Mine may be a structurally modified and strongly remobilized VMS deposit or a polymetallic shear zone hosted deposit, but is most probably a metasomatic skarn-like occurrence along an intrusive contact, as suggested by **Pardee and Park** (**1948**). Available information is not adequate to fully resolve the Scarlett Mine deposit model.

The epidosite alteration at the Scarlett Mine is composed largely of epidote, biotite, and quartz in a finer-grained matrix of chlorite and actinolite (**Kline and Dosh, 1949**). A compositionally similar epidote-rich volcaniclastic unit is described by **Kurek** (**2010**) peripheral to Dave's Mountain, another of the Asheboro Domes cluster. It is also present along the Uwharrie-Tillery formation contact at several locations in the Asheboro area (**Kurek, 2010**). Although mapped as mafic or intermediate volcaniclastic units (**Seiders, 1981**; **Kurek, 2010**), association with polymetallic sulfide mineralization at the Scarlett Mine suggests that this unique lithology may represent zones of hydrothermal alteration.

This style of alteration and mineralization is atypical of the Uwharrie Formation, and appears to be highly localized to the uppermost Uwharrie Formation and the contact with the Tillery Formation in the Asheboro area. The Scarlett Mine and similar zones of calc-silicate alteration occur proximal to the unique cluster of small felsic bodies that comprise the Asheboro Domes, suggesting a genetic relationship. These occurrences do not appear to be generally consistent with Uwharrie metallogeny and may represent a separate and distinct event, possibly synchronous with Morrow Mountain rhyodacite magmatism (**Boorman *et al.*, 2013**).

Morrow Mountain rhyodacite in the Albemarle area

Bodies of Morrow Mountain rhyodacite (MMR) intruding the upper Uwharrie Formation in Montgomery County (**Fig. 19**) are interpreted as intrusive-extrusive in character, possibly forming plugs, domes, or cryptodomes (**Ingram, 1999**; **Boorman *et al.*, 2013**). At Lick Mountain in the upper Uwharrie Formation (**Fig. 19**) breccia with angular clasts of dark rhyodacite in aphyric grey rhyodacite is overlain by nodular facies (spherulites or lithophysae) and locally flow-banded rhyodacite (**Ingram, 1999**; **Boorman *et al.*, 2013**).



Simplified geologic map of the Albemarle area, Stanley and Montgomery counties, NC
(modified from Conley, 1962; Stromquist and Henderson, 1985; Boorman *et al.*, 2013)

Fig. 19: Morrow Mountain rhyodacite occurrences in Montgomery County with Boorman *et al.* (2013) rhyodacite bodies sampled for analysis (FM-Falls Mountain, STM-Shingle Trap Mountain, SM-Sugarloaf Mountain, MM-Morrow Mountain, TTM-Tater Top Mountain, LM- Lick Mountain

The nodular rhyodacite encloses areas of intercalated turbulent flow-banded and laminar flow-banded rhyodacite. The flow banded rhyodacite encloses enclaves of massive rhyodacite, overlain by hydromagmatic rhyodacite breccia. Whole rock analyses (**Ingram, 1999**) suggest that variable hydrothermal Si ± K alteration with small-scale quartz veins and vein stockworks is common.

The occurrence and character of the numerous small bodies of Morrow Mountain rhyodacite intruding the upper Uwharrie Formation in Montgomery County is very similar to the Asheboro Domes in Randolph County to the north near Asheboro (**Fig. 6 and 18**). This suggests that the emplacement of small intrusions of Morrow Mountain rhyodacite into the upper Uwharrie Formation is widespread but localized into clusters.

Boorman *et al.* (2013) report a sill of Morrow Mountain rhyodacite intruding the conformable contact between the Uwharrie Formation and Tillery Formation on Cedar Creek north of Lick Mountain (**Fig. 19**). Although the presence of black rhyolite cobbles in the basal volcanic conglomerate of the Tillery Formation is suggested to imply simultaneous intrusion, erosion, and deposition or Morrow Mountain rhyodacite (**Boorman *et al.,* 2013**), black rhyolite forms flows, domes, and plugs throughout the Uwharrie Formation and these cobbles should not be assumed to be Morrow Mountain rhyodacite.

Numerous bodies of Morrow Mountain rhyodacite are present in the Tillery Formation. Larger bodies include Morrow Mountain, Falls Mountain, and Shingle Trap Mountain in the Albemarle area (**Fig. 19**), and the Caraway Domes west of Asheboro (**Fig. 6**). The Caraway Domes that intrude the Tillery Formation west of Asheboro in Randolph County are compositionally similar to the Morrow Mountain rhyodacite in Montgomery County and broadly cluster with the Asheboro Domes of the upper Uwharrie Formation.

Kurek (2010) interprets the Back Creek Mountain body as a felsic volcaniclastic sequence. However, the Caraway Mountain, Shepherd Mountain, and Back Creek Mountain bodies (**Fig. 6**) appear to be intrusive into the Tillery Formation sediments (**Seiders, 1980**). This roughly east-west trending series of irregular bodies of light to dark-grey rhyodacite intrude the thinly laminated metasediments of the central Tillery Formation near the northern limit of the Albemarle Sequence, forming high-relief hills and ridges.

All are variably quartz and albite phyric and locally flow banded to spherulitic (**Seiders, 1981**). As interpreted by **Seiders (1981)**, these bodies were emplaced a shallow levels, possibly locally emergent, and represent possible flows, domes, necks, and dikes. A highly localized unit of pebbly mudstone and mudstone clast conglomerate with sparse felsite clasts and possible penecontemporaneous deformation (**Fig. 6**, **Fig. 7**) may have formed during emplacement of the Shepherd Mountain dome (**Seiders, 1981**). Although interpreted as the products of volcanism synchronous with sedimentation, the Caraway Domes consistently appear to be intrusive into the Tillery Formation, locally disrupting and deforming bedding in the subsurface.

Evaluating the character and mode of emplacement for Morrow Mountain rhyodacite units within the Albemarle Sequence and their relationship to main stage Uwharrie Formation magmatism is hindered by the lack of detailed descriptions of textures, facies, and contact relationships, petrography, chemistry, and accurate isotopic age dates for all but a few occurrences. These include Dave's Mountain in Asheboro and Lick Mountain in Montgomery

County, both in the uppermost Uwharrie Formation. There is also the small Russell Dome (previously discussed) and the large Morrow Mountain complex in the Tillery Formation.

Morrow Mountain rhyodacite in the upper Tillery and lower Cid formations

Felsic volcaniclastic units, present in the Uwharrie to Tillery transition zone, appear to be largely absent from the middle and upper portions of the Tillery Formation. Felsic units in most of the Tillery are isolated masses with central coherent cores and often spherulitic to fragmental peripheral phases. Bodies of Morrow Mountain rhyodacite were previously interpreted as a volcanic member of the Tillery Formation (**Milton, 1984**) and as intrusive plugs into the Tillery Formation (**Stromquist and Sundelius, 1969**). Morrow Mountain is the southernmost of a series of similar bodies present for over 15 kilometers along the contact between the Tillery and Cid formations, but also locally clustering in the central portion of the Tillery Formation (**Fig. 19**).

There is little detailed descriptive information on the internal structure of the Morrow Mountain body. The unit is finely flow-banded with variable abundance of 0.5-2 millimeter orthoclase, quartz, and plagioclase phenocrysts; however, fragmental textures with clasts 0.5-7.5 centimeters long are present near the contacts (**Conley, 1962a**). The Morrow Mountain rhyodacite body is dated by U-Pb zircon TIMS analysis at 539 ± 5 Ma (**Ingle *et al.*, 2003**).

Boorman *et al.* (**2013**) report that dark gray to black aphanitic, massive to flow-banded Morrow Mountain rhyodacite occurs as dikes, stocks, and flows that often form topographic highs in the Albemarle Quadrangle, but without details of their internal structure or contact relationships. The rhyodacite is often plagioclase-phyric with elongate phenocrysts up to 10 millimeters long, but quartz-phyric rhyodacite is rare.

There appears to be consistent facies architecture in Morrow Mountain rhyodacite bodies where description are available, as illustrated by Lick Mountain (**Boorman *et al.*, 2013**). A basal fragmental unit consists of angular black rhyodacite clasts up to 3 centimeters across in a matrix of aphyric gray rhyodacite. This is overlain by a zone of nodular or spherulitic rhyodacite that encloses a core of massive laminar to contorted flow-banded rhyolite, possibly overlain by rhyodacite breccia with quartz cement (**Boorman *et al.*, 2013**).

Rhyodacite nodules average about one centimeter in diameter but range as large as 3-4 centimeters, characterized as radiating aggregates of fibrous quartz and plagioclase consistent with devitrification spherulites. Some nodules are formed from concentric bands of mineral growth consistent with lithophysae, interpreted to represent shallow intrusive to extrusive emplacement (**Boorman *et al.*, 2013**).

This textural architecture is similar to that of the Russell dome (**Klein *et al.*, 2007**) and the Dave’s Mountain dome (**Kurek, 2010**), and suggests that the fragmental units, spherulitic units, and often contorted flow-banding are concentric zones around a central massive rhyodacite intrusion. Although sometimes interpreted as domes, this architecture may be more consistent with cryptodomes.

Morphology and emplacement of Morrow Mountain rhyodacite bodies

A significant feature of Morrow Mountain rhyodacite magmatism is the strong clustering of many of the larger, more equant to irregular bodies along the contact between the Tillery and Cid formations. One cluster is located in the Albemarle Quadrangle (**Fig. 12, Fig. 19**) and the other in the Denton Quadrangle (**Fig. 12**). Both are intimately associated with large, laterally extensive mafic volcanic complexes dominating large areas of the Mudstone Member of the Cid Formation. The Morrow Mountain plug and associated bodies located along the contact of the Cid and Tillery formations in Montgomery County intrude both Tillery and Mudstone member sediments and the voluminous mafic volcanic complex that extends for at least 30 kilometers along strike. This mafic complex is 2-5 kilometers wide and dominates much of the Mudstone Member in this area of the Albemarle Basin (**Fig. 12**, **Fig. 19**).

Where the base of this mafic volcanic sequence is located above the contact between the Tillery and Mudstone Member to the north (**Fig. 12**), rhyodacite intrusions continue to be localized along the base of the mafic sequence rather than following the formation contact. This suggests that the base of the mafic volcanic sequence may be a local control on the emplacement of Morrow Mountain rhyodacite magma.

Large equant to irregular bodies of Morrow Mountain rhyodacite appear to form where the magma rises through the Tillery Formation and encounters thick sequences of mafic volcanic units in the Mudstone Member, suggesting that intrusive Morrow Mountain rhyodacite magmatism is younger than synsedimentary mafic volcanism in the upper Tillery and in the Mudstone Member of the Cid Formation. This also suggests that rhyodacite magmas may locally be prevented from rising higher in the section by these thick mafic volcanic units.

In the Albemarle area, numerous narrow, laterally extensive units of felsite in the Mudstone Member of the Cid Formation are interpreted by **Conley** (**1962a**) as flows and tuffs (**Fig. 19**). These units range from 1-2 kilometers to over 10 kilometers in strike length and are often 100 to 300 meters thick. The largest is an anastomosing body interpreted as a sparsely orthoclase, plagioclase, quartz, and biotite phyric lava flow with "swirl flow banding" (**Stromquist and Conley, 1959**). The hangingwall and footwall are formed by units interpreted as felsic tuff with locally strongly developed fragmental textures (**Stromquist and Conley, 1959**). The remarkable strike length of this unit (>10 kilometers) and uniform thickness (200-300 meters) yield a length to width ratio of over 30:1. Although possibly elongated by regional tectonism, it is highly unlikely that this unit originated as a viscous rhyodacite flow, and suggests instead a sill or dike with quench-fragmented contacts developed during intrusion into water-saturated sediments.

Conley (**1962a**) indicates that many units interpreted as vitric tuff in the Albemarle area commonly contain thin laminations, enhanced by weathering, which are almost certainly flow laminae, and that these units can be underlain by thin units of lithic tuff, which may represent the quench-fragmented base of a sill. **Butler and Ragland** (**1969**) suggest that the "vitric tuffs" have experienced metasomatic alteration, consistent with intrusion of a sill into seawater-saturated sediments. Bedded volcanic or tuffaceous units described by **Conley** (**1962a**) are interpreted by **Stromquist and Henderson** (**1985**) as epiclastic strata typical of the Cid Mudstone Member.

The thinner, less laterally extensive units described as felsic vitric tuff in the Albemarle area are also discrete isolated tabular bodies with uniform thickness and length to width ratios of around 30:1. These fragmental units are characterized by aphanitic felsic clast up to three centimeters long with 1-3 millimeter feldspar crystals, with correspondingly smaller clasts in the finer-grained units (**Conley, 1962a**). There is no mention of stratification or sorting in these units. Like the larger tabular rhyodacite bodies, there is a high likelihood that these are quench-fragmented sills and dikes emplaced into water-saturated sediments.

Similar units of rhyolite to rhyodacite composition were mapped in the Denton Quadrangle to the north (**Fig. 12**) and occur from the Tillery Formation contact upward throughout the Mudstone Member of the Cid and into the basal portion of the Flat Swamp Member (**Stromquist *et al.*, 1971**; **Stromquist and Henderson, 1985**); some interpreted as domes or flows and some as volcaniclastic units. There is no distinction among these units in published maps, and it is uncertain which are massive to flow banded and which have fragmental textures. Some of the larger felsic bodies, including Crouse Mountain and Steep Rock Mountain, are described as vitrophyre and interpreted as volcanic plugs and “fissure fillings” (**Stromquist and Henderson, 1985**). Flow banding is reported in many felsic bodies and chaotic, swirled flow banding is reported at Bald Mountain (**Stromquist and Henderson, 1985**).

Rhyodacitic units interpreted as volcaniclastic rocks (**Butler and Ragland, 1969**; **Stromquist and Henderson, 1985**; **Stromquist *et al.*, 1971**) within the central portion of the Mudstone Member are composed of <10% to 50% angular to subrounded quartz and feldspar crystals, generally less than 3 millimeters in diameter, and <10% to 60% lithic fragments up to 20 millimeters in diameter (**Brennan, 2009**). As in the Albemarle Quadrangle to the south, there is no mention of stratification or reworking. While the presence of felsic volcaniclastic units cannot be entirely discounted, it is possible that many of the units mapped by **Stromquist *et al.*** (**1971**) as volcaniclastic units in the Mudstone Member are also sills and dikes with quench fragmentation textures.

There is a clear dichotomy in the morphology of Morrow Mountain rhyodacite intrusions in the Cid Mudstone member. Where intrusive into the base of extensive mafic volcanic complexes they generally form bulbous to irregular masses, most concentrated along the base of this sequence (**Fig. 19**). Along strike to the northeast and southwest (**Fig. 12**, **Fig. 19**), Morrow Mountain rhyodacite appears to be largely expressed as highly elongated sills conformable with stratigraphy in the Mudstone Member. The presence of large mafic volcanic complexes may have hindered the formation of Morrow Mountain rhyodacite sills, favoring the formation of more equant plugs instead.

It appears highly likely that the compositionally and texturally uniform felsic units widespread throughout the Mudstone Member of the Cid Formation are Morrow Mountain rhyodacite and that essentially all are intrusive into the sequence. Local stratigraphic controls may be largely responsible for the morphology of these intrusive units.

If units of the Morrow Mountain rhyodacite are largely intrusive into the uppermost Uwharrie Formation, the Tillery Formation, and the Mudstone Member of the Cid Formation, then volcanism throughout this portion of the Albemarle Sequence is not bimodal but strongly mafic dominated. Mafic and felsic magmatism in the Albemarle Group is coincident in space but apparently separated in time.

Morrow Mountain rhyodacite magmatism in the Albemarle Group appears to essentially end with the eruption of felsic magmas to form the Flat Swamp Member of the Cid Formation. This suggests that Morrow Mountain rhyodacite intrusive units in the Mudstone Member of the Cid Formation may have been feeders for Flat Swamp Member volcanism.

The Seagrove Complex and Ramseur dike swarm

The Seagrove Complex (**Seiders, 1981**; **Harris, 1982**; **Moye, 2013**) is a 3-5 kilometer wide felsic intrusive-extrusive complex centered on the town of Seagrove in south-central Randolph County along the eastern edge of the Uwharrie Formation (**Fig. 6**). The main body trends 030° for over 11 kilometers and continues northeast as a major dike swarm for another 20 kilometers beyond the erosional limit of the Uwharrie Formation. The extent of this unit to the southwest is not established.

This complex either intrudes the entire thickness of the Uwharrie Formation or forms the eastern border of the sequence. Either way, it post-dates the main stage of Uwharrie volcanism. The associated dike swarm to the northeast post-dates the early Uwharrie Pilot Mountain AES. The southern part of the complex has been deformed by large-scale regional folding during the Cherokee Orogeny in the late Ordovician.

Like most Uwharrie Formation felsite units and Morrow Mountain rhyodacite intrusions, Seagrove Complex intrusive and extrusive phases are albite ± quartz phyric, often flow banded, and locally spherulitic. **Seiders** (**1981**) identified a three kilometer wide sequence of felsic volcaniclastic rocks along the western flank of the Seagrove Complex that appear to be rich in pumice clasts and lack interbedded laminated tuffs. **Seiders** (**1981**) interprets this sequence as possible mass flow deposits comagmatic with the Seagrove Complex.

However, if the Seagrove Complex post-dates the main stage of Uwharrie magmatism, then the associated comagmatic volcaniclastic sequence would also be younger and overlay Uwharrie strata. If similar comagmatic volcaniclastic units are present along the eastern margin of the complex, they would also be younger than the Uwharrie Formation. Rather than forming the base of the Uwharrie Formation, the potentially diachronous Erect Member **(Pollock *et al.*, 2010**; **Hibbard *et al.*, 2012**) may actually be a detrital facies of the younger Seagrove Complex. Like older Uwharrie volcanic facies, volcaniclastic and epiclastic rocks associated with the Seagrove Complex magmatic center may have originally spread over a wide area to the east.

The Seagrove Complex and dike swarm developed along an older fault zone with a strike length of 45-50 kilometers that post-dates Virgilina Deformation but pre-dates the main phase of Uwharrie magmatism. This is one of the series of *en echelon* fault zones that may have controlled the earliest phases of Uwharrie magmatism (**Moye, 2013**). This reactivated structure may represent the eastern boundary fault of the Albemarle Basin.

If the Seagrove Complex is younger than both early fault-controlled Uwharrie magmatism and main stage Uwharrie volcanism, then it potentially represents the youngest phase of Uwharrie magmatism or a separate magmatic event. If the youngest detrital zircons from the Erect Member originated from Seagrove Complex rocks, this magmatism may date to ca. 545 Ma and form part of the Morrow Mountain magmatic event.

Reinterpreting Albemarle Group felsic magmatism

A comprehensive review of available published data and observations suggests that many of the felsic units present throughout much of the Albemarle Group may be intrusive in origin and separated in time from the deposition of these sediments, dramatically altering the purported significance of syndeposition felsic volcanism. If correct, then volcanism synchronous with sedimentation in the Tillery Formation and the Mudstone Member of the Cid Formation is overwhelmingly mafic.

Mafic volcanic units form ≤ 2-3% in the Tillery Formation and are largely confined to the upper 300-500 meters of the sequence. Mafic volcanism increases dramatically to average about 20% in the Mudstone and Flat Swamp members of the Cid Formation. If intrusions of Stony Ridge gabbro are included, the mafic igneous content of the Tillery increases to around 10% and to around 25-30% of the Cid Mudstone Member.

In addition to significant stratigraphic and local geographic variations in the distribution of both felsic and mafic igneous units within the Tillery and Cid formations, there is a distinct concentration of these units in the northern half of the Albemarle Basin and a marked paucity in the southern half. There appear to be no occurrences of Stony Mountain gabbro in central and southern Union County (**Fig. 5**). The overall thinning and fining of the Albemarle Sequence and the decrease in felsic and mafic igneous components in the southern portion of the Albemarle Basin suggest that subsidence and both mafic and felsic magma generation are strongly focused in the northern portion.

Constraints on the timing of Morrow Mountain rhyodacite magmatism

There are limited direct geochronologic constraints on the age of Morrow Mountain rhyodacite magmatism in the Albemarle Sequence. The only body directly dated is the zircon U-Pb age of 539 ± 5 Ma for the Morrow Mountain rhyodacite intrusion (**Ingle *et al.*, 2003**). **Kozuch** (**1994**) reports a U-Pb zircon age of 554 ± 14 Ma for metarhyolite from the lower Tillery Formation near Asheboro, which may represent either Uwharrie or Morrow Mountain magmatism. **Kozuch** (**1994**) also reports a U-Pb zircon age of 542 ± 14 Ma from an interbedded metarhyolite unit in the Mudstone Member of the Cid Formation, which may be an intrusive unit of Morrow Mountain rhyodacite.

Geochronological ages for the Flat Swamp Member of the Cid Formation include 540.6 + 1.2 Ma (**Ingle *et al.*, 2003**), 542 +8/-5.5 Ma (**Hibbard *et al.*, 2012**), and 547 ± 2 Ma (**Hibbard *et al.*, 2009**). These age constraints suggest that the Flat Swamp Member was deposited between about 547 Ma and 540 Ma. Flat Swamp Member volcanism appears to represent the effective end of felsic magmatism in the Albemarle Group.

A single unit interpreted as felsic volcanic in origin has been identified in the lower portion of the Floyd Church Formation in the northern portion of the Silver Valley Synclinorium (**Stromquist *et al.*, 1971**; **Stromquist and Henderson, 1985**), the same area where the Flat Swamp Member reaches maximum thickness. It is described as a light-gray, fine-grained volcaniclastic unit composed of clasts < 4 millimeters in diameter and small feldspar fragments in an aphanitic groundmass.

The presence of the Ediacaran fossils *Pteridinium carolinaensis* and *Sekwia excentrica* in the stratigraphically younger Floyd Church Formation (**Gibson and Teeter, 1984**; **Weaver *et al.*, 2008**) constrain the minimum age for the end of felsic volcanism in the Albemarle Group, possibly fed by Morrow Mountain rhyodacite magmas, to the latest Ediacaran. The 539 ± 5 Ma age of the Morrow Mountain rhyodacite body (**Ingle *et al.*, 2003**), intrusive on the Cid-Tillery formation boundary, is within error of the probable end of Flat Swamp Member volcanism and any units in the basal Floyd Church.

If all units of Morrow Mountain rhyodacite magma are intrusive into the upper Uwharrie and Tillery formations and the Mudstone Member of the Cid Formation, then that stratigraphic sequence must have be present at the beginning of the MMR magmatic event. In the absence of other age constraints, the timing of Morrow Mountain rhyodacite magmatism may be constrained to the age of Flat Swamp Member volcanism. This age range for MMR magmatism ranges from ca. 540 Ma to 547 Ma, with possible decreased magmatism until as late as ca. 539 Ma.

This interpretation is consistent with the suggestion that Morrow Mountain rhyodacite magmatism affecting the Uwharrie, Tillery, and Cid formations is the result of a single, short-lived magmatic event (**Ingram, 1999**; **Boorman *et al.*, 2013**). If MMR magmatism is only eruptive in the Flat Swamp Member and intrusive into the underlying portions of the Albemarle Sequence, then the classic stratigraphic framework is preserved and the lateral facies equivalence model, which conflicts with established stratigraphic observations, is unnecessary.

Morrow Mountain rhyodacite magma chemistry

Trace element data suggest that Morrow Mountain rhyodacite in the Albemarle area represents two distinct but compositionally similar magma groups (**Ingram, 1999**; **Boorman *et al.*, 2013**). There is no stratigraphic or geographic partitioning between the two groups, suggesting that magmas from both groups were emplaced into the upper Uwharrie, Tillery, and lower Cid formations (**Ingram, 1999**; **Boorman *et al.*, 2013**), linking them through continuity of magmatic processes. **Ingram** (**1999**) suggests that the Morrow Mountain rhyodacite bodies in all three formations in both groups are similar in age.

Boorman *et al.* (**2013**) analyzed 14 samples collected from 9 separate rhyodacite bodies; 9 samples total from 4 bodies in the Uwharrie Formation (6 from a single body), and one sample each from 2 bodies in the Tillery Formation and from 3 bodies along the Tillery-Cid (Mudstone Member) contact. They conclude that the five rhyodacite bodies within the upper Tillery and lower Cid formations, including Morrow Mountain, appear to have originated from a single magma reservoir and are linked through magma differentiation.

Similar associations may account for the apparent clustering of many rhyodacite bodies in the Uwharrie, Tillery, and Cid formations. **Ingram** (**1999**) suggests that the two rhyodacite magma groups may represent two different magma generation processes, one with an island arc magmatic signature and the other with an intraplate magmatic affinity, possibly indicative of arc-rifting. However, both could also indicate an island arc setting that experiences rifting (**Ingram, 1999**).

Albemarle Group mafic magmatism

Mafic magmatism associated with deposition of the Albemarle Group appears to be largely basalt to andesitic basalt volcanism and also includes emplacement of stocks, sills, and dikes of Stony Mountain gabbro. Both show distinct geographic and stratigraphic variations in distribution. Mafic volcanic rocks occur throughout the Albemarle Group, although their abundance varies significantly geographically and stratigraphically (**Fig. 12**). They characteristically occur as thick, lenticular to irregular bodies that are generally conformable with stratigraphy and may interfinger with the host sedimentary units (**Stromquist and Sundelius, 1969**). Almost all mafic volcanic rocks in the Albemarle Group appear to be andesitic basalt in composition (**Stromquist and Sundelius, 1969**) with similar coherent and volcaniclastic facies present in most occurrences. All were metamorphosed to the greenschist facies and deformed during the Cherokee Orogeny (**Hibbard *et al.*, 2012**).

The apparent consistency in composition and mode of occurrence for andesitic basalt volcanic rocks throughout deposition of the Albemarle Group suggest a long-lived mafic magmatic event. A broadly similar geographic and stratigraphic distribution of Stony Mountain gabbro throughout the Albemarle Group suggests a possible association. The mafic volcanism is informally referred to as Baden greenstone (**Conley, 1962a**; **Ingram, 1999**) and the gabbroic intrusions as the Stony Mountain gabbro.

The Stony Mountain gabbro

All members of the Albemarle Sequence are intruded by stocks, laccoliths, sills, and dikes of Stony Mountain gabbro (**Figs. 2**, **5**, **12**, and **19**) composed of typically equigranular, medium- to course-grained, dark green to greenish-grey metagabbro (**Pollock and Hibbard,**

2010). The parent magmas are sub-alkaline low-K to medium-K tholeiitic basalts interpreted as the product of mantle-derived basaltic magmatism associated with probable arc-rifting (**Pollock and Hibbard, 2010**; **DeDecker *et al.*, 2013**). **Pollock and Hibbard** (**2010**) suggest a mixing of magma formed through partial melting of depleted NMORB lithospheric mantle, decompression melting of upwelling enriched asthenospheric mantle, and fluids formed by dehydration of subducted oceanic crust. They suggest back-arc rifting and magmatism that may be associated with the opening of the Rheic Ocean along the western margin of Gondwana (**Pollock and Hibbard, 2010**).

Although present throughout the Albemarle Sequence, intrusions of Stony Mountain gabbro are not randomly distributed. They are most abundant (**Figs. 2**, **5**, **12**, and **19**) in the middle to upper Tillery Formation with the second highest abundance in the Mudstone Member of the Cid Formation (**Wright and Seiders, 1980**). Only a few plugs intrude the Uwharrie, the Floyd Church, and the Yadkin formations. Numerous occurrences of Stony Mountain gabbro within the Gold Hill Fault Zone are probably part of the heterogeneously deformed Tillery and Cid formations.

There also appears to be a distinct geographic bias in the distribution of Stony Mountain gabbro intrusions. In the Tillery and Cid formations they often appear to cluster in specific domains (**Fig. 12**). Within the Tillery Formation there is a paucity of Stony Mountain gabbro intrusions into the Tillery Formation between about 35’35”N and 35’20”N but a remarkable abundance of large oval to equant gabbro bodies to the north and large gabbro sills to the south (see **Seiders, 1971**; **Stromquist and Henderson, 1985**). There is a similar gap in gabbro occurrences in the Cid Mudstone Member between about 35’32”N and 35’20”N, with numerous sills to the south and to the north but decreasing significantly north of 35’35”N (see **Stromquist and Henderson, 1985**).

This gabbro gap in both formations is broadly correlated with the largest mafic volcanic complex in the Mudstone Member of the Cid Formation (**Figs. 12 and 14**). South of this gap numerous gabbro sills show no association with mafic volcanic members of the Mudstone Member. North of the gap, there is a distinct association of gabbro sills and plugs with mafic volcanic units and sills and plugs of Morrow Mountain rhyodacite (**Fig. 12**).

Additionally, occurrences of Stony Mountain gabbro are most abundant in the northern half of the outcrop area of the Albemarle Sequence (**Fig. 5**) with significantly fewer occurrences in the southern portion of the area. Gabbro bodies south of about 35’10”N are infrequent and small. This suggests that like Morrow Mountain rhyodacite magmatism, mafic magmatism was dominantly confined to the northern part of the Albemarle Basin.

In the Albemarle area, **Conley** (**1962**) reports that gabbro sills intruding the Tillery Formation and the Mudstone Member of the Cid have contact metamorphic or metasomatic aureoles less than a meter wide adjacent to smaller bodies increasing to as much at 10 meters around the larger sills. However, **Brennan** (**2009**) suggests that conformable gabbro sills or laccoliths intruding the Mudstone Member of the Cid Formation near the town of Denton lack evidence of contact metamorphism. A sill partly discordant to bedding on NC Highway 27 near the Pee Dee River east of Albemarle appears to show decreased grain-size near the contacts (**Stromquist and Conley, 1959**) suggesting more rapid cooling. A large gabbro sill intruding the central Tillery Formation south of Caraway Mountain in Randolph County has a basal zone rich in serpentine pseudomorphs after olivine and comb-layering along the upper contact suggesting post-emplacement differentiation (**Seiders and Wright, 1977**).

Stony Mountain gabbro units in the Albemarle area have an ophitic texture with amphibole phenocrysts and amygdales are reported in some sills (**Conley, 1962**). **Stromquist and Conley** (**1959**) and **Conley** (**1962**) suggest that the largest bodies, including Stony Mountain, are laccoliths that domed the overlying sediments during intrusion. **Conley** (**1962**) reports two bodies intruded by hornblende (40%) plus plagioclase (60%) pegmatite and metamorphosed basaltic dikes in the area may be feeders for some of the sills.

As Stony Mountain gabbro is intrusive into the Albemarle Sequence, the age of individual units relative to stratigraphy is conjectural. The youngest gabbro bodies post-date deposition of the youngest detrital zircons of the Yadkin Formation ca. 528 Ma (**Pollock, 2007**) and pre-date ca. 456 Ma deformation and metamorphism of the Albemarle Sequence (**Offield *et al.*, 1995**; **Hibbard *et al.*, 2012**), suggesting that they are Early Cambrian to Late Ordovician in age (**Pollock and Hibbard, 2010**).

Stony Mountain gabbro intruding the Tillery Formation at Ridges Mountain in Randolph County yielded a U-Pb zircon TIMS age of 544.81 ± 0.55 Ma (**DeDecker *et al.*, 2013**). Accurate age dating of Stony Mountain gabbro units intruding other portions of the Albemarle Sequence stratigraphy is needed to determine whether their emplacement is continuous over a period of around 17 million years or episodic.

If Stony Mountain gabbro is a product of arc-rifting (**Pollock and Hibbard, 2010**), then mafic magmatism associated with arc-rifting of the Carolina terrane extends from at least 545 Ma until after 528 Ma (**DeDecker *et al.*, 2013**), encompassing deposition of the Cid, Floyd Church, and Yadkin formations. This suggests that Stony Mountain mafic magmatism was broadly contemporaneous with mafic volcanism in the Albemarle Group and with Morrow Mountain rhyodacite intrusive magmatism and Flat Swamp Member volcanism.

Emplacement of Stony Mountain gabbro units

Southeast of Albemarle (**Fig. 12**, **Fig. 14**), a swarm of over a dozen sills of Stony Mountain gabbro ranging from 50 centimeters to over 300 meters thick (**Ingram, 1999**) are present in the upper Tillery Formation and lower Mudstone Member of the Cid Formation. **Conley** (**1962a**) suggests that these sills may represent the magmas that formed the Baden Greenstone mafic volcanic units in the overlying Cid Formation. Gabbro bodies in the middle Mudstone Member locally appear to intrude and overprint rhyodacite sills. This extensive area of conformable rhyodacite and gabbro units occurs immediately to the south and generally along strike from the large mafic volcanic complex intruded by Morrow Mountain and similar large rhyodacite bodies (**Fig. 12**). The probable felsic sills in the same area are largely present in the middle to upper Mudstone Member.

A similar distribution of rhyodacite and gabbro units flanks the large felsic and mafic complex to the north (**Fig. 12**) in the Denton Quadrangle around the nose and northwest limb of the New London Synclinorium. A similar association is present on the northwest limb of the Denton Anticlinorium northeast of the town of Denton (**Fig. 12**), where numerous mafic volcanic units and possible rhyodacite sills occupy much of the lower to middle Mudstone Member with numerous gabbro sills present in the adjacent upper Tillery Formation (**Fig. 12**).

These observations suggest that, like Morrow Mountain rhyodacite magmas, the intrusion of Stony Mountain gabbro magmas may have been influenced by the presence of stratigraphic impediments such as thick mafic volcanic units. Additionally, there may be a link between the rise of mantle-derived mafic magmas into the lower part of the rift and the generation of Morrow Mountain rhyodacite magma.

Post-rift Albemarle Group sedimentation and magmatism

Albemarle magmatism waned rapidly and became entirely mafic-dominated following deposition of the Flat Swamp Member of the Cid Formation. Metasediments of the lower Floyd Church Formation are moderately graded in the lower part of the sequence, but more massive and increasingly interbedded with minor volcanic-derived epiclastic sandstone and siltstone in the upper portion. Lenses of upward-fining argillaceous tuff breccia with scoured bases in the lower portion of the Floyd Church sequence contain clasts of primary and reworked felsic volcanic rocks and siltstone rip-up clasts (**Stromquist and Sundelius, 1969**). This suggests the waning stages of Flat Swamp Member magmatic activity and concurrent large-scale mass wasting, possibly associated with locally significant basin floor topographic relief.

A general upward coarsening of sedimentary input to the Albemarle Basin begins in the upper part of the Floyd Church and continues through the Yadkin Formation. Poorly sorted greywacke and well-sorted arenaceous siltstone and sandstone in the Yadkin Formation, locally interbedded with andesitic basalt flows and volcaniclastic units (**Stromquist and Sundelius, 1969**; **Gibson and Teeter, 1984**; **Pollock, 2007**) suggest the end of felsic magmatism but continued low volume mafic magmatism. This included the emplacement of a body of Stony Mountain gabbro across the Floyd Church-Yadkin formation contact. Sedimentary structures suggest an upward shoaling marine depositional environment for the Yadkin Formation, dominated by wind, waves and tides (**Pollock, 2007**).

The youngest U-Pb ages for detrital zircons obtained by **Pollock** (**2007**) from the Yadkin Formation range from 541 ± 16 Ma to 528 ± 8 Ma, marking the end of documented sedimentation in the Albemarle Basin. The Floyd Church and Yadkin formations may represent largely passive erosional sedimentation in the Albemarle Basin following the end of active arc-rifting. Clastic sediment may have been sourced from areas internal and external to the Albemarle Sequence, including the adjacent sutured Charlotte terrane.

Discussion

The stratigraphic and magmatic relationships among the Uwharrie, Tillery, and Cid formations of the Albemarle Sequence form the basis for contention between the conventional stratigraphic model (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Seiders, 1981**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Butler and Secor, 1991**; **Hibbard *et al.*, 2002**) and the newly proposed stratigraphic facies equivalence model (**Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**). The proposition that the Tillery and Cid formations are lateral facies equivalents to part of the Uwharrie Formation is based largely upon two factors; **1**) the ca. 545 Ma U-Pb age for 3 detrital zircons from the Erect member, interpreted to be footwall to the Uwharrie Formation on the eastern margin of the Albemarle Sequence, and **2**) the possible synchronous emplacement of extrusive units of Morrow Mountain rhyodacite into the Uwharrie, Tillery, and Cid formations (**Boorman *et al.*, 2013**).

The validity and significance of such a small number of detrital zircon age data points is debatable. In the absence of better constraints and supporting evidence this cannot be accept as strong evidence for a ca. 545 Ma age for a portion of the Uwharrie Formation. The youngest non-detrital U-Pb zircon age date for the Uwharrie Formation is 551 ± 8 Ma (**Ingle, 1999**; **Ingle-Jenkins *et al.*, 1998**). The problem is eliminated if the Erect Member is actually in contact with volcaniclastic units of the Seagrove Complex, which is younger than the Uwharrie Formation and may be part of the Morrow Mountain felsic magmatic event.

Everywhere observed, the contacts between the Uwharrie-Tillery and the Tillery-Cid formations, and the contact between the Mudstone Member and the Flat Swamp Member are conformable and gradational. **Hibbard *et al.*** (**2013**) concluded from the detrital zircon studies of **Pollock** (**2007**) that "*the maximum ages of deposition of the Albemarle Group formations became younger in an order consistent with the stratigraphy of the group as interpreted by **Milton (1984)***".

Weighing the evidence

There is no published stratigraphic evidence for the presence of felsic pyroclastic or volcaniclastic units consistent with Uwharrie Formation volcanism within the Albemarle Group above the Uwharrie-Tillery transition. Reported felsic volcanic units in the Tillery Formation and the Mudstone Member of the Cid Formation appear to be coherent intrusive units of Morrow Mountain rhyodacite (**Boorman *et al.*, 2013**).

The Flat Swamp Member of the Cid Formation, although similar to the Uwharrie Formation in the abundance of felsic pyroclastic and volcaniclastic facies, is compositionally distinct and stratigraphically isolated from the Uwharrie Formation (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Randazzo, 1972**; **Seiders, 1981**; **Milton, 1984**; **Gibson and Teeter, 1984**). Additionally, the Flat Swamp Member thickens to the northwest, where numerous small intrusive-extrusive centers suggest a local focus for volcanism (**Pogue, 1910**) that is well removed from the Uwharrie Formation stratigraphically and geographically.

The evidence for a felsic magmatic linkage among the Uwharrie, Tillery, and Cid formations is compelling given the widespread presence of compositionally and chemically similar bodies of Morrow Mountain rhyodacite (**Boorman *et al.*, 2013**). However, the morphology of these felsic units is not consistent with eruptive emplacement synchronous with sedimentation. Instead bodies of Morrow Mountain rhyodacite appear to be intrusive as dikes, sills, cryptodomes, and laccoliths.

The remarkably consistent pattern of concentric textural domains in the larger, better documented bodies of MMR (**Ingram, 1999**; **Klein *et al.*, 2007**; **Kurek, 2010**; **Boorman *et al.*, 2013**) are consistent with intrusion of felsic magma into water-saturated sediments under hypabyssal conditions. The Asheboro domes, probable Morrow Mountain intrusions, are demonstrably intrusive into the upper Uwharrie Formation. The Russell dome and Caraway-Shepherd domes are intrusive into the Tillery Formation. The intrusive character of Morrow Mountain magmas is reinforced by apparent "ponding" at the base of thick mafic volcanic sequences in the lower Cid Formation to form many of the larger intrusions.

Where not stratigraphically confined, Morrow Mountain rhyodacite typically forms relatively thin, highly elongated units throughout the Mudstone Member of the Cid Formation. Although often interpreted as lava flows where laminar to contorted flow banding is present, the 30:1 length to width ratios of these units are more consistent with sills and dikes, as are the quench-fragmented contacts of these units. Thinner units interpreted as volcaniclastic in origin may be sills or dikes with pervasive quench fragmentation, especially where the coarseness of the textures is apparently proportional to the thickness of the unit (**Stromquist and Conley, 1959**; **Conley, 1962a**; **Stromquist and Sundelius, 1969**; **Stromquist *et al.*, 1971**; **Stromquist and Henderson, 1985**).

The Uwharrie, Tillery, and Cid formations are not linked by synchronous felsic volcanism as suggested by the facies equivalence model and Morrow Mountain rhyodacite magmatism is not a continuation of Uwharrie magmatism. It is a younger and chemically distinct igneous event associated with arc-rifting. Morrow Mountain rhyodacite magma intrusive into the upper Uwharrie and Tillery formations and the Mudstone Member of the Cid Formation is the likely source of Flat Swamp Member felsic volcanism.

Although there is strong evidence for both mafic plutonism and volcanism throughout the evolution of the Albemarle Basin, rift-related felsic magmatism is confined to a relatively brief but voluminous episode ca. 547-539 Ma that produced a single but intense period of basin volcanism to form the Flat Swamp member of the Cid Formation.

This interpretation also negates an important aspect of the traditional stratigraphic model for the Albemarle Sequence (**Stromquist and Sundelius, 1969**; **Wright and Seiders, 1980**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Butler and Secor, 1991**; **Hibbard *et al.*, 2002**). If the felsic units throughout the Albemarle Group are intrusions of Morrow Mountain rhyodacite, then coeval volcanism in the sequence is not compositionally bimodal but is entirely or overwhelmingly mafic.

Additionally, the possibly widespread intrusion of Morrow Mountain rhyodacite into the Uwharrie Formation significantly complicates interpretations of stratigraphy and geochronologic constraints on age. Morrow Mountain rhyodacite intrusions into the upper Uwharrie Formation include the Asheboro Domes in the Asheboro area and Lick Mountain and similar bodies to the south. The extensive Seagrove Complex intrudes and forms the eastern boundary of the Uwharrie Formation. Associated volcaniclastic and epiclastic units may have spread across the Hyco Arc to the east and the Uwharrie Formation and Albemarle Group to the west. Additional intrusions of MMR into the Uwharrie may be unrecognized.

Constraints on the character and timing of basin magmatism

Age constraints on the inception and duration of Morrow Mountain rhyodacite magmatism in the Albemarle Basin include the zircon U-Pb age of 539 ± 5 Ma for the Morrow Mountain rhyodacite intrusion (**Ingle *et al.*, 2003**) and age dates from the Flat Swamp Member of the Cid Formation of 540.6 + 1.2 Ma (**Ingle *et al.*, 2003**), 547 ± 2 Ma **(Hibbard *et al.*, 2009**), and 542 +8/-5.5 Ma (**Hibbard *et al.*, 2012**).

Morrow Mountain rhyodacite magmatism may slightly precede and post-date formation of the Flat Swamp Member, but is likely to date to between about 547 Ma (**Hibbard *et al.*, 2009**) and 539 Ma (**Ingle *et al.*, 2003**). This magmatic event appears to be largely focused within the northern portion of the Albemarle Group, especially in the area occupied by the Cid Formation where the Flat Swamp Member is present. This magmatism may be largely absent from the southern portion of the Albemarle Basin, where formations of the Albemarle Sequence are thinner, finer-grained, and contain reduced volcanic and intrusive units.

Mafic magmatism appears to accompany the entire ca. 550-528 Ma history of the Albemarle Basin. Syndeposition mafic volcanism extends from the lower Tillery Formation through the Yadkin Formation and is especially voluminous in the Mudstone Member of the Cid Formation. The highest volume of mafic magmatism may have preceded or accompanied the Morrow Mountain rhyodacite magmatic event during the period of most active arc-rifting.

Intrusive units of Stony Mountain gabbro may represent the same magmatic event responsible for mafic volcanism in the Tillery, Cid, Floyd Church, and Yadkin formations. Alternatively, they may represent a separate and distinct mafic magmatic event. The only available age constraints on the timing of Stony Mountain magmatism are the U-Pb zircon TIMS age of 544.81 ± 0.55 Ma for the Ridges Mountain gabbro intrusion into the central Tillery Formation west of Asheboro in Randolph County (**DeDecker *et al.*, 2013**) and the presence of gabbro intrusions in the ca. 528 Ma Yadkin Formation.

The distribution of gabbro sills and laccoliths in the upper Tillery and lower to middle Cid formations suggests that gabbroic magma was often emplaced lower in the stratigraphic sequence than many rhyodacite sills (see **Stromquist and Henderson, 1985**). Gabbro sills are locally seen to intrude and cut-across sills of Morrow Mountain rhyodacite, but rhyodacite is not seen to intrude or cross-cut gabbro sills (see **Stromquist and Henderson, 1985**). A large gabbro body appears to intrude the Caraway Mountain rhyodacite body in the Tillery Formation west of Asheboro (see **Seiders, 1971**), but a smaller units of rhyodacite may be intrusive into this body.

Generally, Morrow Mountain rhyodacite magmatism and Stony Mountain gabbroic magmatism may initially intrude the Albemarle Sequence at a similar time, possibly ca. 547 Ma and both may be products of active arc-rifting. Although Morrow Mountain rhyodacite magmatism abruptly ends by ca. 539 Ma, both basaltic volcanism and Stony Mountain gabbro plutonism continue through deposition of the Yadkin Formation.

Character of the Albemarle arc-rift basin

Known VMS deposits and associated footwall or peripheral alteration and mineralization in the Albemarle Sequence (**Fig. 11**) are exclusively hosted by the Flat Swamp Member of the Cid Formation and may have formed during the waning stages of volcanism or during hiatuses in local eruptive activity. Volcanogenic massive sulfide deposits typically form in extensional tectonic regimes, usually in active rift environments, including mid-ocean ridges, back-arc basins, intra-oceanic arc rifts, and continental arc rifts (e.g. **Swinden, 1991**; **Hannington *et al.*, 1995**; **Scott, 1997**; **Syme *et al.*, 1999**; **Barrett *et al.*, 2001**; **Piercey *et al.*, 2001**; **Dusel-Bacon *et al.*, 2004**). VMS deposit environments include extensional and trans-tensional grabens, calderas, and synvolcanic and synsedimentary faults bounding basins (e.g. **Gibson, 1989**; **Allen, 1992**; **McPhie and Allen, 1992**; **Setterfield *et al.*, 1995**; **Allen *et al.*, 1996**; **Gibson *et al.*, 1999**; **Stix *et al.*, 2003**; **Gibson, 2005**).

The association with VMS deposits is consistent with formation of the Flat Swamp Member of the Cid Formation in an active rift environment. If the Morrow Mountain rhyodacite is the source of Flat Swamp Member felsic volcanism, then these magmas are a product of rifting ca. 547-539 Ma (**Ingle *et al.*, 2003**; **Hibbard *et al.*, 2009; Hibbard *et al.*, 2012**). Consequently, all areas intruded by Morrow Mountain rhyodacite probably lie within or peripheral to the area of active rifting.

The Flat Swamp member represents a transformative event in the evolution of the Albemarle Basin. The volume of mostly felsic magma erupting completely overwhelms the slow, quiescent sedimentation that characterize the Mudstone Member and the Tillery Formation. The end of Flat Swamp volcanism is abrupt and rapidly replaced by a completely different phase of basin evolution and sedimentation.

The interpretation of Stony Mountain gabbro basaltic magmatism as a product of mantle partial melting is also consistent with arc-rifting (**Pollock and Hibbard, 2010**; **DeDecker *et al.*, 2013**) and suggests that rifting begins at least as early as ca. 544 Ma (**DeDecker *et al.*, 2013**). Along with Morrow Mountain felsic bodies, these magmas were emplaced within or peripheral to the rift zone. The coincidence of Stony Mountain gabbro magmatism with Morrow Mountain rhyodacite magmatism in time and space is consistent with an arc-rift association for both magmatic events.

Although both mafic and felsic rift-related magma generation may have initiated at about the same time, the process that generated Stony Mountain mafic magmatism was much longer-lived. If the mafic magmatism is the product of mantle partial melting, then Morrow Mountain felsic magmatism may be either the result of differentiation or mixing product of mafic magmatism or magmas formed by partial melting of possible Mesoproterozoic lithosphere or other rocks in the basement (**Wortman *et al.*, 2000**). Although very similar in composition, the chemistry of multiple Morrow Mountain rhyodacite bodies suggests two possible sources of magma (**Boorman *et al.*, 2013**).

The tectonic, sedimentological, and magmatic evolution of the Albemarle arc-rift basin appears to consist of four stages: **1**) subsidence and deep marine deposition of the Tillery Formation beginning ca. 552 Ma (**Pollock, 2007**) with the possible onset of initial mafic volcanism; **2**) initial arc-rifting and intense mafic volcanism during deposition of the Cid Mudstone member; **3**) main-stage arc-rifting ca. 547-540 Ma with intense Morrow Mountain felsic magmatism culminating in deposition of the Flat Swamp member (**Ingle *et al.*, 2003**; **Hibbard *et al.*, 2009**; **Hibbard *et al.*, 2012**) with accompanying Stony Ridge gabbroic magmatism (**DeDecker *et al.*, 2013**); and **4**) post-rifting period with the end of felsic magmatism and passive basin fill sedimentation accompanied by diminishing mafic magmatism in the Floyd Church and Yadkin formations.

There is a striking contrast between the explosive volcanism, rapid deposition, and largely shallow to locally emergent marine deposition of the Uwharrie Formation (**Seiders, 1978**; **Harris and Glover, 1988**; **Feiss, 1982**; **Klein and Schmidt, 1985**; **Feiss and Wesolowski, 1986**) and the quiescent, deep marine deposition of the Tillery Formation. The gradational boundary between the Uwharrie Formation and the Tillery Formation is consistent with waning Uwharrie volcanism and a transition to basin subsidence.

The waning of Uwharrie magmatism after around 551 Ma (**Ingle, 1999**; **Ingle-Jenkins *et al.*, 1998**) is consistent with the end of subduction-related magmatism in the Persimmon Fork Formation of the South Carolina Sequence prior to collision and final suturing of the Carolina and Charlotte terranes ca. 550 Ma (**Barker *et al.*, 1998**; **Dallmeyer *et al.*, 1986**). Subsequent localized arc-rifting and formation of the Albemarle Basin largely post-dates arc-arc collision and amalgamation and is unlikely to be associated with plate subduction.

Albemarle Sequence architecture and extent

The distribution of extant Uwharrie Formation strata along the eastern and southern sides of the Albemarle Group and possible preservation of Uwharrie correlative strata and related intrusions for up to 30 kilometers to the east and 60 kilometers to the northeast suggests that an unknown thickness of Uwharrie Formation strata may have been present continuously or locally across much of the Carolina Terrane in North Carolina (**Fig. 20**). Stratigraphic units associated with Albemarle felsic magmatism associated with the Seagrove Complex may also have covered a significant area to the east, unconformably overlaying more distal Uwharrie units.

The presence of an estimated thickness of 3000 to 6000 meters of the Uwharrie Formation in Randolph and Montgomery counties (**Conley, 1962**; **Harris and Glover, 1988**) thinning to around 1000 meters in Union County (**Randazzo, 1972**; **Allen, 2005**) may be due to preservation within the Albemarle rift basin. The Albemarle Group may also have originally been more extensive, although the distribution of rift-related Stony Mountain and Morrow Mountain intrusive units suggests that much of the central rifted basin area is intact with variable loss of younger stratigraphic units to erosion.

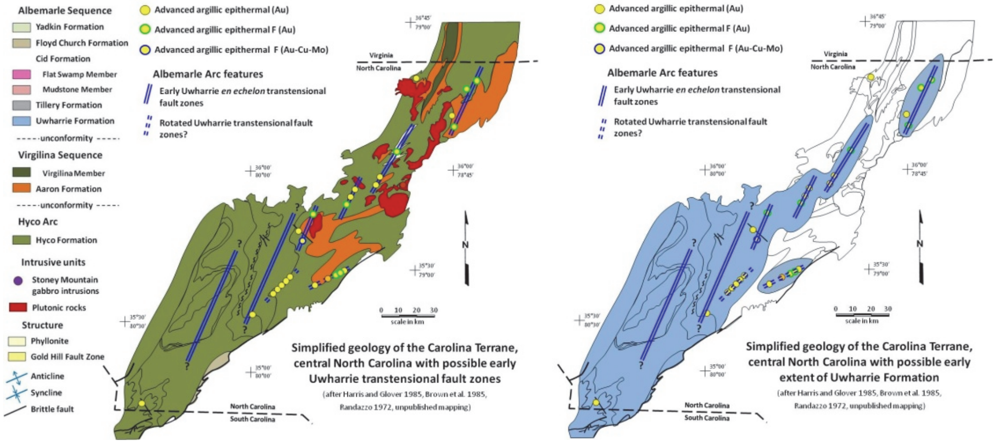


Fig. 20: Hypothetical origin of the Uwharrie Formation as intrusive and eruptive centers along right-stepping NNE-striking transtensional fault zones and possible original extent

Systematic variations in the thickness of all members of the Albemarle Sequence and the distribution of rift-related intrusive and extrusive igneous units suggest that arc-rifting was focused in the northern portion of the Albemarle Basin, with largely passive sedimentation and limited magmatism in the southern portion. The original basin geometry is uncertain, due to the truncation of the sequence to the west by large-scale reverse movement on the Gold Hill Fault during the Cherokee Orogeny (**Hibbard *et al.*, 2012**) and the uncertain limits of the sequence to the north and south.

The greater thickness of the Flat Swamp Member, the presence of numerous felsic eruption centers, and the occurrence of associated VMS deposits northwest of Denton in the limbs and nose of the Silver Valley Synclinorium, along with VMS deposits in the Gold Hill District to the southwest, suggest that the basin may have been asymmetric, deepening to the west and north.

The locations of the boundary faults of the Albemarle inter-arc rift basin are not well established. The western boundary, possibly the most active fault zone, was almost certainly overthrust by the Gold Hill Fault during the Cherokee Orogeny (**Fig. 21**). The presence of volcanic units possibly equivalent to the Hyco Arc in the hangingwall of the Gold Hill Fault

(**Hibbard *et al.*, 2012**) is consistent with this suggestion. It is possible that the Gold Hill Fault in part developed along the eastward-rotated and reactivated western basin fault boundary zone.

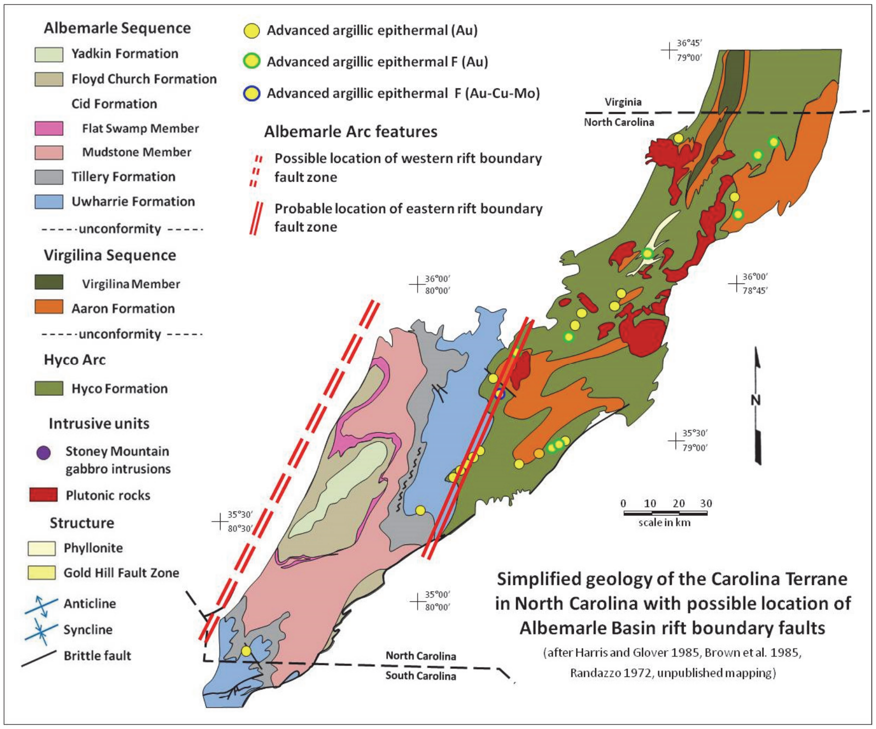


Fig. 21: Possible location of Albemarle rift basin boundary faults

The eastern boundary fault of the basin is occupied by the Seagrove Complex and associated Ramseur dike swarm at the eastern margin of the Uwharrie Formation in Randolph County NC (**Fig. 6**, **Fig. 21**). Fault displacement was probably normal and down on the west side, preserving the Uwharrie Formation as basement to the Albemarle Group. The Seagrove Complex is probably part of the Morrow Mountain rhyodacite magmatic event. The eastern boundary fault appears to reactivate the older, early Uwharrie fault zone that hosts the Pilot Mountain-Staley AES alignment (**Fig. 6, Fig. 10**, and **Fig. 21**). The Cottonstone Mountain-Ammons AES alignment **(Fig. 10**, **Fig. 21)** may be a continuation to the south, but rotated clockwise by large-scale Cherokee Orogeny formation of the Troy Anticlinorium.

Tectonic constraints on the evolution of the Albemarle Basin

A rift environment for the Albemarle Group has been previously proposed (**Moye and Stoddard, 1987**; **Harris and Glover, 1988**; **Feiss *et al.*, 1993**), and is supported by the work of **Pollock and Hibbard** (**2010**), **Pollock *et al.*** (**2010**), and **Hibbard *et al.*** (**2013**). Tectonic models for the collision and suturing of the Carolina and Charlotte volcanic arc terranes in the Ediacaran Period (**Shervais *et al.*, 1996**; **Dennis and Wright, 1997**) suggest that formation of the

Albemarle Basin by arc-rifting ca. 550-540 Ma is part of a broader pattern of rifting events within both the Carolina and Charlotte terranes in the late Ediacaran to early Cambrian.

Dennis and Wright (**1997**) propose Proterozoic to Early Cambrian intra-arc rifting of the Charlotte terrane concurrent with regional deformation and metamorphism between about 560 Ma and 535 Ma; the result of over-riding an oceanic spreading center. Final collision and suturing of the Carolina and Charlotte volcanic arc terranes in central South Carolina is dated by granitic stitching plutons to around 550 Ma (**Barker *et al.*, 1998**; **Dallmeyer *et al.*, 1986**). This event and associated D_1 and D_2 tectonism may have ended rifting in the southern part of the Charlotte terrane at this time, but arc-rifting may have continued in north-central South Carolina and central North Carolina (**Dennis and Wright, 1997**).

Dennis and Wright (**1997**) suggest deposition of the Tillery Formation of the Albemarle Group and the Richtex Formation of the South Carolina Sequence of the Carolina terrane in intra-arc basins coeval with Charlotte terrane rifting. **Shervais *et al.*** (**1996**) and **Gillon *et al.*** (**1998**) support deposition of the Richtex Formation in faulted basins during rifting of the Persimmon Fork Formation volcanic arc, however this event pre-dates D_1 and D_2 tectonism and is older than ca. 550 Ma.

Arc-rifting of the Charlotte terrane in north-central South Carolina (**Dennis and Wright, 1997**) ca. 560-535 Ma and arc-rifting to form the Albemarle Basin in the Carolina terrane in south-central North Carolina are broadly synchronous, although possibly resulting from different mechanism. Arc-rifting of the Charlotte terrane (**Fig. 22**) may be the result of over-riding and subduction of an oceanic spreading center during the convergence of the Charlotte and Carolina volcanic arcs prior to collision and suturing (**Dennis and Wright, 1997**; **Hibbard *et al.*, 2002**; **Shervais *et al.*, 2003**). The arc-rifting is characterized by the emplacement of large zoned mafic-ultramafic magmatic complexes into the older primitive arc volcanic sequence (**Dennis and Wright, 1997**).

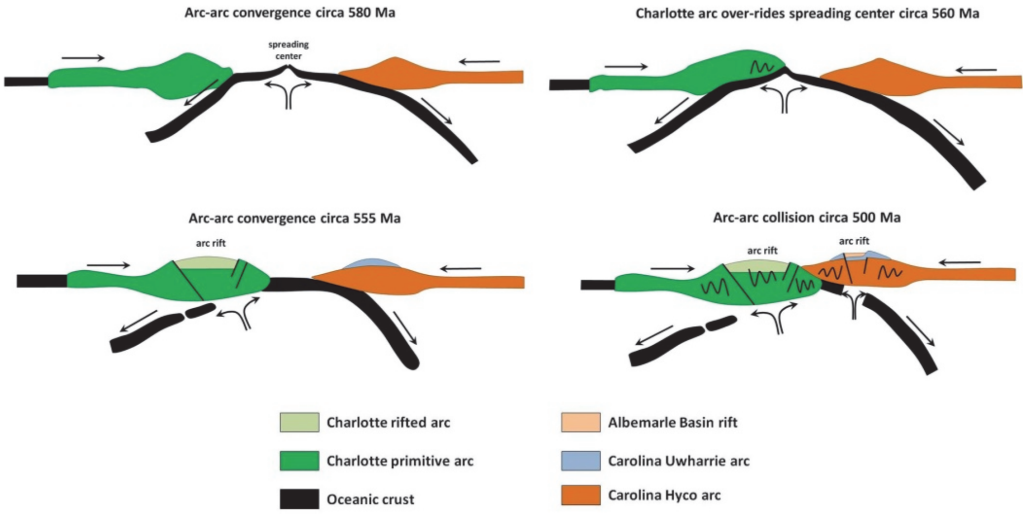


Fig. 22: Model for collision and rifting of the Charlotte and Carolina arcs (modified from Shervais *et al.*, 2003)

This tectonic model includes break-off the subducted oceanic lithosphere beneath the Carolina terrane arc (**Fig. 22**), followed by tectonic rebound uplift of the Charlotte terrane (**Shervais *et al.*, 2003**). Arc-rifting of the Carolina terrane to form the Albemarle Basin, with associated mantle-derived mafic magmatism (**Pollock and Hibbard, 2010**; **DeDecker *et al.*, 2013**), is potentially associated with this suggested subducted slab break-off and asthenosphere upwelling ca. 550 Ma.

The Gold Hill Fault and the Albemarle Basin

Unlike the well-defined ca. 550 Ma suture zone between the Charlotte terrane and the South Carolina sequence of the Carolina terrane to the south, the tectonic contact between the Carolina and Charlotte terranes west of the Albemarle Basin has not been identified (**Hibbard *et al.*, 2012**) and the timing and nature of their juxtaposition is unclear. The docking of the Carolina and Charlotte terranes here may have been very different from that in central South Carolina. The presence of Hyco-equivalent metavolcanic units in the hangingwall of the Gold Hill Fault (**Hibbard *et al.*, 2012**) indicates that the Gold Hill Fault is not the terrane boundary.

Hibbard *et al.* (**2008**) suggest a complex history for the Gold Hill Fault Zone, possibly extending from the latest Ediacaran into the late Paleozoic. **Feiss *et al.*** (**1993**) suggest that deformation along the boundary between the Charlotte and Carolina terranes in central North Carolina may result from a combination of faulting along the margin of a Neoproterozoic to Cambrian rift basin, reactivation during docking of Carolinia with Laurentia, and subsequent minor reactivation during the Devonian and Carboniferous. If the ancestral Gold Hill Fault Zone was initially part of the western faulted margin of the Albemarle Basin, the history of the structure may extend back to ca. 550 Ma.

Allen (**2005**) has interpreted emplacement of the granitic Waxhaw Pluton as synkinematic with deformation along the southwestern portion of the Gold Hill Fault Zone. A U-Pb zircon age of 539.4 + 1.4 Ma for the Waxhaw Pluton, along with ca. 541-542 Ma zircon U-Pb ages for granitic plutons in the hangingwall of the Gold Hill Fault to the north (**Hibbard *et al.*, 2012**) suggests dextral-reverse transpression along this portion of the fault zone in the latest Ediacaran, displacing Hyco-equivalent strata to the west over Uwharrie-equivalent strata and the Albemarle Group to the east.

Ediacaran transpression and felsic plutonism along the Gold Hill Fault Zone are broadly synchronous with Morrow Mountain rhyodacite magmatism and deposition of the Flat Swamp member (**Ingle *et al.*, 2003; Hibbard *et al.*, 2012**), marking the end of rift-related felsic magmatism and active rifting in the Albemarle Basin. This transpressional event along the western margin of the Albemarle Basin may be associated with the end of active arc- rifting and the transition to passive basin filling.

Subsequent mega-scale reverse-sinistral displacement along the Gold Hill Fault and mega-scale folding and regional greenschist facies metamorphism of the Albemarle Sequence accompanied the docking of Carolinia with Laurentia during the Cherokee Orogeny in the Late Ordovician to Early Silurian (**Hibbard *et al.*, 2012**). The earlier Ediacaran portion of the Gold Hill Fault Zone may have been greatly modified or largely obliterated during this event.

The potential for VMS-style and related mineralization in the Albemarle Basin

All known deposits of VMS mineralization in the Albemarle Basin are directly associated with the Flat Swamp Member of the Cid Formation. Although relatively small (≤ 0.5 Mt), the base metal content of the ore bodies is typically very high with significant gold and silver credits. Additionally, there is evidence for clustering of these deposits in the Cid and Gold Hill mining districts.

Multiple VMS systems are indicated in the Cid District, with the very high-grade Silver Hill deposit (40% Zn + 19% Pb + Ag) and footwall alteration and stringer mineralization at the Silver Valley, Emmons, and Cid prospects. Additional areas of probable VMS related footwall or peripheral alteration and mineralization are present in the district (**Fig. 16**).

In addition to Cu, the Union Copper VMS ore body in the Gold Hill District produced almost 20,000 ounces of Au. The 350,000 metric ton massive sulfide body is enclosed by an extensive peripheral and footwall halo of lower-grade stringer and disseminated polymetallic mineralization. The high Au content of the Union Copper ore body and the apparent intense silicic alteration overprint of the footwall alteration zone suggest an evolving hydrothermal system and the involvement of multiple fluids, possibly with a significant igneous contribution. It is also part of a larger zone of hydrothermal alteration with disseminated, vein, and stringer base metal sulfide mineralization that extends for over 1000 meters along strike across a stratigraphic section over 100 meters thick.

Hangingwall to the Union Copper ore body, this mineralized section hosts the series of smaller Zn + Pb + Ag-rich ore bodies that include the McMakin Mine, with 1-3 meters thick lenses of massive high-grade mineralization (up to > 35% combined Pb + Zn and 50 oz/t Ag) enclosed by up to 7.3 meters of disseminated mineralization averaging 9 oz/t Ag and more than a percent Zn (**Moye *et al.*, 2017**). This lower temperature Zn-Pb-Ag dominated mineralization with talc, carbonate, and barite gangue suggest that the Union Copper-McMakin hydrothermal system was very long-lived.

The Union Copper-McMakin VMS hydrothermal system in the Gold Hill district is laterally and vertically extensive and long-lived, forming multiple ore bodies at various stratigraphic positions. This is an underexplored system, especially at depth, with significant potential for additional discoveries. There remains significant potential for the presence of additional VMS mineralization in both the Gold Hill and Cid mining districts. Additionally, the geographic extent of the host Flat Swamp Member suggests significant potential for additional discoveries of VMS mineralization in less well explored areas, especially within the Gold Hill Fault Zone between the Cid and Gold Hill districts.

In contrast, there is no evidence for VMS-related or other forms of base or precious metal sulfide mineralization in the Mudstone Member of the Cid Formation and the Tillery Formation. The composition of these sequences is broadly consistent with Mafic-Siliclastic type VMS deposit environments, characterized by subequal proportions of mafic ± ultramafic and siliclastic sediments ± minor felsic volcanic units (**Barrie and Hannington, 1999**; **Franklin *et al.*, 2005**; **Piercey, 2010**). This is especially true of the Cid Mudstone member.

However, the mafic volcanism that accompanied deposition of the Albemarle Group was apparently of limited metallogenic potential and there is no evidence for extensive associated hydrothermal systems. This may result from the tholeiitic chemistry of the magmas as opposed to boninite, MORB, and alkalic mafic magmas characteristic of many VMS environments (**Piercey, 2010**). Synchronous mineralization is also not recognized in the post-rifting Floyd Church and Yadkin formations.

The skarn-like polymetallic sulfide mineralization at the Scarlett Mine in Asheboro is associated with a possible small cryptodome of Morrow Mountain-type rhyodacite emplaced into mafic volcanic rocks. Although not VMS-type mineralization, this may suggest the potential of similar sulfide mineralization associated with other Morrow Mountain intrusions. The numerous large MMR intrusions emplaced into large expanses of mafic volcanic rocks in the lower Cid Formation would be the most likely targets to test this possibility.

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The potential for Uwharrie epithermal and porphyry mineralization

There is significant potential for the discovery of economic epithermal and porphyry style base and precious metal mineralization in association with Uwharrie magmatism as occurrences and alignments (**Fig. 9**) of large advanced argillic epithermal alteration systems (AES). A number of these occurrences host known epithermal gold, silver, copper, and molybdenum mineralization that suggest the possible presence of intrusion-centered porphyry style mineralization at depth.

Recognized precious and base metal sulfide mineralization is most strongly expressed in the Pilot Mountain AES (**Schmidt, 1983**; **Schmidt, 1985a**; **Moye, 2013**) where locally abundant topaz indicates a fluorine-rich hydrothermal fluid with possible F-rich breccia pipes cutting through the quartz granofels cap (**Klein and Schmidt, 1985**). Coincident soil Mo, Cu, Au, B, and Sn geochemical anomalies are centered on this area (**Milton *et al.*, 1983**; **Schmidt, 1985a**; and **Klein and Schmidt, 1985**). The historic Pine Mountain gold mine, with samples that assay up to 10 ppm Au and 2200 ppm Cu, is centered on a soil Au-B-Mo anomaly up to 150 meters wide that extends northeast for at least 500 meters (**Klein and Schmidt, 1985**).

The Pilot Mountain AES may have formed at the transition from the magmatic-porphyry environment to the epithermal environment of the lithocap (**Hedenquist and Arribas, 2022**) and is associated with a cluster of evolved intermediate to felsic intrusive phases. Overprinting silicic alteration with locally abundant topaz, possible hydrothermal breccias, and associated Au-Cu-

Mo-Sn mineralization suggests a long-lived and evolving magmatic-hydrothermal system that may be linked to magmatic-hydrothermal reservoir at depth (**Schmidt, 1983**; **Schmidt, 1985a**).

The porphyry-style Au-Cu-Mo-F mineralization at the Deep River Prospect (**Fig. 8**) is characterized by stockwork Cu + Mo-bearing quartz veins within a large area of pyritic silicic and phyllic alteration enclosed by an extensive soil geochemical anomaly. The hydrothermal system is centered on a series of porphyritic quartz and feldspar phyric andesitic or dacitic intrusions (**Capps *et al.*, 1997**) similar to those at Pilot Mountain. The mineralization is also associated with a felsic dike dated to ca. 547-550 Ma (**Rapprecht *et al.*, 2013**).

The AES mineralization at Pilot Mountain may represent the epithermal expression of intrusion-centered Au-Cu-Mo porphyry mineralization similar to that at the Deep River Prospect. Similar porphyry-type mineralization may be associated with others of the more than 20 known AES occurrences in the Carolina Terrane in central North Carolina (**Fig. 9**). Those with strongly anomalous F ± Mo are likely candidates and include the Staley deposit on the same trend with Pilot Mountain, the Snow Camp and Hillsborough AES, the deposits along the Bowling Mountain-Daniels Mountain alignment, and the Robbins and Glendon AES in Moore County.

The Pilot Mountain AES and associated Au-Cu-Mo-F mineralization has similarities to the Brewer Mine in South Carolina. The Brewer Mine Cu-Au deposit is an F-rich (topaz) epithermal high sulfidation polyphase hydrothermal breccia deposit cutting through a strongly zoned silicic-advanced argillic alteration lithocap two kilometers in diameter. This is surrounded by a zone of phyllic alteration that measures 2.5 x 7 kilometers and hosts numerous zones of disseminated pyritic gold mineralization.

The Brewer metallic element association of Cu-Au-As-Sb-Sn-Ag-Bi-Mo (**Scheetz, 1991**) is similar to that of the Pilot Mountain mineralization. Brewer Cu-Au bearing hydrothermal breccias are associated with a series of felsic porphyry apophyses, probably sourced from a larger intrusive body at depth, and may represent the high-level epithermal expression of a porphyry Cu-Au-Mo deposit (**Schmidt, 1985**; **Zwaschka and Scheetz, 1995**). These porphyry apophyses have a high-precision zircon U/Pb date of 550 ± 3 Ma (**Ayuso *et al.*, 2005**).

Although similar in character and age, the Pilot Mountain and Brewer Mine deposits formed in very different tectonic environments. Pilot Mountain is centered on a cluster of small hypabyssal felsic to intermediate intrusions that lies along the 030° oriented 3-5 km wide, 35-40 km long early Uwharrie (ca. 554 Ma?) transtension fault zone (**Fig. 6**) that includes the Staley AES to the north-northeast.

The Brewer Mine deposit is part of the Kershaw Gold District that includes the Haile and Ridgeway gold mines and over a dozen smaller deposits of similar character along with over 50 zones of related hydrothermal alteration. Apart from the epithermal Brewer deposit, these are largely mesozonal orogenic gold deposits associated with 2nd order reverse faults in a localized area of felsic magmatism formed about 550 Ma during the final suturing of the Carolina and Charlotte volcanic arc terranes in central South Carolina.

Conclusions

The results of this analysis, illustrated graphically in **Fig. 23**, support the classic stratigraphic model for the Albemarle Sequence of the Carolina Terrane. This conclusion is supported by overwhelming direct sedimentological evidence (**Conley, 1962**; **Stromquist and Sundelius, 1969**; **Seiders, 1981**; **Milton, 1984**; **Gibson and Teeter, 1984**; **Butler and Secor, 1991**; **Brenan, 2009**; **Kurek, 2010**) that is nowhere violated. Additionally, it is consistent with both detrital and non-detrital zircon U/Pb age dates for the component formations (**Ingle, 1999**; **Ingle-Jenkins *et al.*, 1998**; **Pollock, 2007**; **Hibbard *et al.*, 2009**; **Hibbard *et al.*, 2013**).

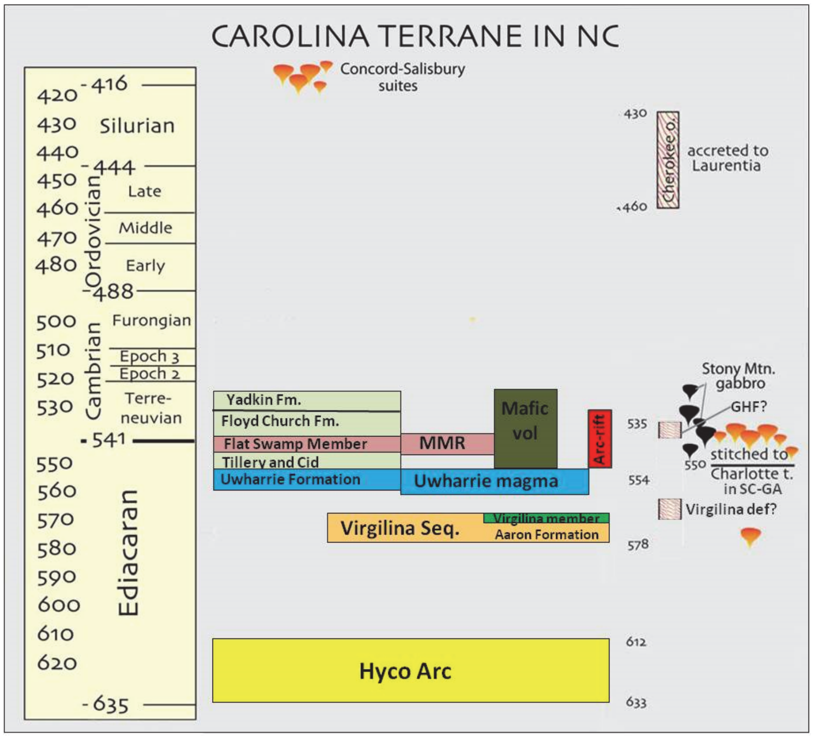

Fig. 23: Components and events diagram for the Carolina terrane in North Carolina; Uwharrie magma = Uwharrie magmatism, MMR = Morrow Mountain felsic magmatism, Mafic vol = mafic volcanism, GHF = ancestral Gold Hill Fault (modified from Hibbard *et al.*, 2013)

The ca. 545 Ma U/Pb age detrital zircons from the Erect Member, interpreted as basal to the Uwharrie Formation (**Pollock, 2007**; **Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013**), may be sourced from the younger Seagrove Complex that bounds the Uwharrie on the east (**Fig. 6**). This potentially MMR-associated body intrudes the eastern normal border fault of the Albemarle Basin, a reactivation of an early Uwharrie-age transtensional fault zone that hosts the Pilot Mountain-Staley AES alignment (**Fig. 10**).

The presence of Uwharrie Formation strata up to 6 kilometers thick in Randolph and Montgomery counties and 1000 meters thick in Union County, when it is largely removed by erosion across most of the Carolina Terrane in North Carolina, is due to subsidence and preservation within the Albemarle arc-rift basin.

The recognition that felsic bodies present in the upper Uwharrie and Tillery formations and the Cid Mudstone Member have comparable compositions and chemistry (**Boorman *et al.*, 2013**) and an age of ca. 539 Ma for one of these bodies (**Ingle *et al.*, 2003**) requires modification of the classic stratigraphic model. The narrow range of zircon U-Pb age dates for units of Morrow Mountain rhyodacite and the Flat Swamp Member of the Cid Formation (**Ingle *et al.*, 2003**; **Hibbard *et al.*, 2009**; **Hibbard *et al.*, 2012**) suggest that they are products of the same felsic magmatic event. This event has a basin wide distribution but was of relatively brief duration ca. 547-539 Ma.

The classic stratigraphic model for the Albemarle Sequence is preserved with the recognition that Morrow Mountain rhyodacite units stratigraphically below the Flat Swamp member are largely intrusive as dikes, sill, cryptodomes, and laccoliths. The possibility of eruptive Morrow Mountain rhyodacite units in the upper Uwharrie, Tillery, and lower Cid formations cannot be fully dismissed without more comprehensive geologic and petrographic examinations and accurate isotopic age dates.

However, the absence of any evidence of VMS-style mineralization in association with units of Morrow Mountain rhyodacite in this part of the stratigraphy is consistent with an intrusive interpretation of their emplacement. Morrow Mountain magmatism only erupted at the basin surface as the Flat Swamp Member of the Cid Formation, consistent with the associated VMS deposits (**Fig. 24**).

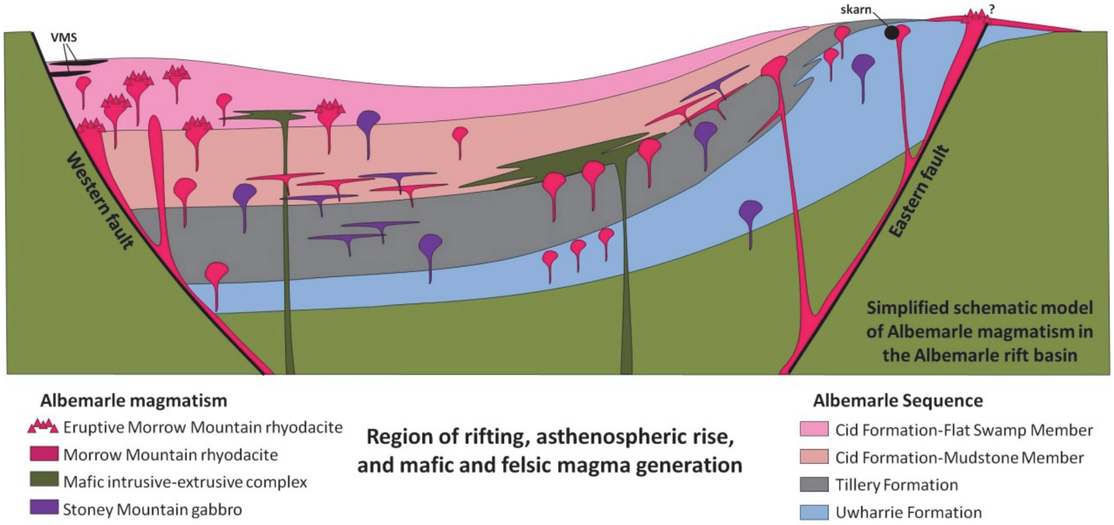

Fig. 24: Schematic model of the Albemarle rift basin and associated magmatism ca. 541 Ma

The Morrow Mountain magmatic event is associated with active arc-rifting and was accompanied by Stony Mountain gabbroic magmatism that continued until at least ca. 528 Ma (**Fig. 23**). Mafic magmatism and associated volcanism apparently extended throughout the ca. 550-528 Ma evolution of the Albemarle Basin, and was most voluminous accompanying deposition of the Mudstone Member of the Cid Formation (**Fig. 23**). The relationship between Albemarle Basin mafic volcanism and Stony Mountain gabbroic plutonism is uncertain.

The initiation of arc-rifting and formation of the Albemarle Basin may be the result of subducted oceanic slab break-off and asthenosphere upwelling beneath the Carolina terrane (**Fig. 20**). Albemarle arc-rifting post-dates the collision and suturing of the Carolina and Charlotte volcanic arc terranes in central South Carolina ca. 550 Ma, consistent with this interpretation.

Basin magmatism is strongly bimodal, characterized by compositionally uniform but chemically diverse Morrow Mountain rhyodacite magmatism between around 547-539 Ma and mafic plutonism and volcanism beginning no later than about 550 Ma and continuing until at least around 528 Ma. Albemarle mafic volcanism, Stony Mountain gabbro, and MMR magmas may have been generated by separate mechanisms and sources.

Mafic magmatism in the Albemarle Group is characterized by basaltic andesite volcanism throughout the sequence and the emplacement of intrusive stocks, laccoliths, sills and dikes of Stony Mountain gabbro (**Fig. 24**). Although present locally in the Tillery Formation, mafic volcanism becomes increasingly abundant and widespread (20-30%) throughout the Cid Formation. Mafic volcanism continues in diminished volume through deposition of the Floyd Church Formation and is again locally abundant in the Yadkin Formation. Intrusions of Stony Mountain gabbro are present throughout the entire Albemarle Sequence (**Fig. 23**), but are most abundant in the Tillery and Cid formations in the northern portion of the Albemarle Group.

Arc-rifting and formation of the Albemarle Basin is one of a number of Carolinia arc-rifting events between ca. 560 and 530 Ma. Arc-rifting of the Charlotte terrane primitive oceanic arc continued until around 530 Ma west of the Albemarle Basin (**Dennis and Wright, 1997**). Active arc rifting in both terranes diminishes and ends following latest Ediacaran transpression and plutonism along a possible ancestral Gold Hill Fault Zone ca. 539-542 Ma (**Allen, 2005**; **Hibbard *et al.*, 2012**). In the Albemarle Basin there is a transition to upward-coarsening detrital fill accompanied by diminishing mafic magmatism ca. 540 Ma **(Pollock, 2007**).

Additionally, localized uplift and erosion of the Emory Formation on the southern margin of the South Carolina Sequence was followed by Middle Cambrian deposition of the Asbill Pond Formation as a possible successor basin (**Secor and Wagner, 1968**; **Secor and Snoke, 1978**; **Secor, 1988**). These scattered events suggest that widespread but localized deformation of the Carolina and Charlotte terranes continued for up to 20 Ma after collision and suturing ca. 550 MA. This deformation may have been largely restricted to the terrane boundaries.

The Uwharrie Formation is not a typical subduction-related magmatic arc and not an extension of Persimmon Fork arc magmatism, but may have similarities with the Taupo Volcanic Zone in New Zealand. The apparent transition to Albemarle arc-rifting is consistent with this interpretation. Early Uwharrie-age *en echelon* alignments of advanced argillic epithermal alteration systems (AES) across the Carolina terrane in central North Carolina offer exploration potential for both epithermal and porphyry Au-Cu-Mo mineralization. Isolated AES are associated with the Persimmon Fork volcanic arc of the South Carolina sequence to the south, but similar alignments and associated mineralization potential are not indicated.

VMS mineralization associated with Albemarle arc-rifting may be limited to the Flat Swamp member of the Cid Formation, and especially to the thicker portion of the sequence in the northwestern part of the basin. However, there is evidence for clustering of these often high-grade base and precious metal sulfide deposits and some known occurrences in the Cid and Gold Hill mining districts are part of under-explored larger hydrothermal systems. Additionally, the deformed and variably dismembered Flat Swamp sequence within the Gold Hill Fault Zone between these two districts is poorly defined and under-explored with significant additional potential for new discoveries.

Recommendations

The conclusions of this study are provisional pending additional constraints on the stratigraphic and age relationships of the Erect Member to the Seagrove Complex and the Uwharrie Formation, the age and chemistry of the Seagrove Complex and its extent to the south, and the mechanisms of emplacement for units of Morrow Mountain rhyodacite in the Uwharrie, Tillery, and Cid formations.

Paramount is accurate age dating of felsic units throughout the Albemarle Sequence combined with whole rock chemistry. There is also a need for additional regional and detailed geologic mapping to confirm earlier maps and clarify the character of felsic units in the Albemarle Group. Detailed geologic mapping and structural analysis to determine the nature of the geologic boundary at the north and south ends of the Albemarle Basin would be useful. Finally, felsic volcanic sequences that may be Uwharrie or Morrow Mountain correlatives throughout the Carolina terrane in VA, NC, and northern SC should be investigated. Priority areas are those within and adjacent to alignments of AES.

Detailed mapping of the Gold Hill Fault Zone between the Gold Hill and Cid mining districts is recommended to identify intact portions of the Flat Swamp Member and examine possible evidence of VMS style mineralization and associated hydrothermal footwall alteration and mineralized feeder zones. Renewed exploration of the known areas of VMS mineralization in the Cid district should focus on the Flat Swamp Member on the eastern limb and nose of the Silver Valley Synclinorium. The extensive Union Copper-McMakin VMS hydrothermal system in the Gold Hill district is under-explored, especially at depth and along the line of Zn-Pb-Ag deposits hangingwall to the Union Copper ore body.

If correct, the conclusions of this report may justify a change in stratigraphic nomenclature for the Albemarle Group. If felsic units within the Cid Mudstone member are exclusively intrusive, then perhaps the formation should be divided into the Cid Formation (formerly the lower member) and the Flat Swamp Formation (formerly the upper member).

Additionally, formation of the Albemarle Sequence and the South Carolina Sequence of the Carolina terrane is broadly coeval, but in very different tectonic environments. While the character of the South Carolina Sequence is consistent with a subduction-related volcanic arc, the Uwharrie Formation appears to represent transtensional rifting of the older Hyco volcanic arc.

Additionally, the Uwharrie Sequence includes the Albemarle arc-rift basin, which post-dates both the Uwharrie "arc" and the Persimmon Fork arc of the South Carolina Sequence.

Under the circumstances, it is perhaps not appropriate to refer to these three tectonic elements as the Albemarle Arc as proposed by **Hibbard *et al.*** (**2013**). Perhaps they should be termed the South Carolina Arc, the Uwharrie Arc, and the Albemarle Basin of the Carolina terrane. Given the apparently different character and timing of interactions of the South Carolina Sequence and the Albemarle Sequence with the Charlotte terrane, it is likely that the Hyco-Virgilina-Albemarle portion of the Carolina terrane in North Carolina (and the border areas of VA and SC) acted as an independent tectonic block from the South Carolina sequence-Lincolnton sequence in SC and GA during their evolution and interactions.

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

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Abstract

Recognized styles of precious and base metal sulfide mineralization accompanying hydrothermal alteration systems characteristic of the Charlotte terrane include: **1**) small tonnage low-grade to barren VMS-type stratabound Fe ± Mn ± Si ± Ba ± polymetallic sulfide ± precious metal mineralization with footwall alteration zones; **2**) large epizonal to possibly epithermal hydrothermal alteration systems zoned from silicic-advanced argillic to phyllic assemblages with associated precious metal ± base metal sulfide mineralization; **3**) intrusion-centered deposits including ring dike hosted Au-Ag-Cu-Ba mineralization with alteration zoned from silicic-advanced argillic to propylitic, porphyry Cu-Mo mineralization, and REE-rich skarns; and **4**) orogenic low sulfidation quartz vein deposits with Au ± Cu ± W mineralization.

Understanding the character, associations, and genesis of these occurrences helps to constrain interpretations of the lithostratigraphy and tectonic evolution of the Charlotte terrane. VMS-type mineralization appears to be associated with localized rifting ± felsic to intermediate volcanism concurrent with the formation of large mafic intrusive-extrusive magmatic centers that interfinger with surrounding sequences of immature epiclastic sediments. This earliest stage in the development of the Charlotte terrane is interpreted as a primitive peri-Gondwanan supra-subduction volcanic arc complex built on oceanic lithosphere prior to ca. 579 Ma.

This Primitive Arc sequence is strongly deformed and metamorphosed during D_1 tectonism; probably associated with subduction of an oceanic spreading center followed by collision and suturing with the Carolina terrane ca. 550 Ma. The D_1 tectonic event was preceded by the widespread intrusion of diorite, granodiorite, and tonalite plutons as early as ca. 579 Ma. Large, possibly fault-hosted zoned epizonal hydrothermal alteration systems are associated with synchronous deformation and arc-rifting of the Charlotte terrane between ca. 570 Ma and 535 Ma, characterized by the formation of large zoned plutonic complexes that are intrusive into the older mafic-dominated Primitive Arc sequence.

Associated with these zoned plutonic complexes are suites of comagmatic volcanic rocks dominated by basalt or basaltic andesite, with subordinate andesite, dacite, and rhyodacite that generally decrease in volume with increasing silica content. These younger, Rifted Arc volcanic sequences and associated sedimentary rocks are commonly less deformed and only metamorphosed to the lower to middle greenschist facies in Georgia and southwest South Carolina.

Only a few examples of intrusion-centered mineralization have been identified in the Charlotte terrane. The Stoney Ridge Au-Ag-Cu-Ba deposit in Washington County GA is

associated with an extensive silicic-advanced argillic alteration system formed along a ring dike encircling a Proterozoic granodiorite pluton. The Newell Cu-Mo porphyry deposit in Cabarrus County NC is associated with an evolved Devonian diorite-monzonite-granite intrusive complex of the Salisbury plutonic suite. Many of these plutons host localized Mo mineralization and are often enriched in F, Be, Nb, Th, U, Y, and Zr. The Propst REE-rich skarn on the southeast margin of one pluton also host molybdenite, barite, and base metal sulfides. The adjacent Hamby Branch vein swarm hosts Au-Cu-W-Ba mineralization. Extensive small but sometimes high-grade orogenic Au lode gold deposits of the Charlotte terrane in North Carolina, many centered in the Charlotte area, may have formed during the Ordovician-Silurian Cherokee Orogeny and during early Devonian tectonism.

Introduction

Numerous occurrences of silicic, advanced argillic and phyllic hydrothermal alteration zones are present in the metaintrusive, metavolcanic, and metasedimentary domains of the Charlotte terrane. Some are characterized by tabular to podiform silicic and advanced argillic core areas enclosed by broad haloes of phyllic alteration, others consist largely of phyllic alteration, and many are characterized by the heterogeneous presence of disseminated rutile and pyrite or iron oxides.

All are deformed and metamorphosed, with grade ranging from middle greenschist to middle amphibolite facies. These alteration zones typically have strike lengths of kilometers, may be hundreds of meters wide, and are typically parallel and conformable with the local tectonic fabric. Many of these alteration zones are the focus of historic gold prospects and small-scale gold mines, as well as extensive exploration and evaluation during the 1970s to 1990s.

The Charlotte terrane is the second largest component of Carolinia (**Hibbard *et al,* 2002**; **Hibbard *et al.,* 2007**), but less well studied and understood compared to the adjacent Carolina terrane. Detailed geologic mapping, petrographic and chemical studies, and zircon U-Pb age dates in the Charlotte terrane in north-central South Carolina (**Dennis and Shervais, 1991; Dennis and Shervais, 1996**; **Dennis and Wright, 1997**) provide the best available constraints on the magmatic and tectonic history of this peri-Gondwanan oceanic volcanic arc. Additional constraints on the geologic character and evolution of the Charlotte terrane are provided by studies of the type area of the terrane in north-central South Carolina near the border with North Carolina (**Butler, 1984; Butler, 1991**; **Brazell, 1984**).

Much of the work in both areas has focused on multiple generations of plutons, ranging from granite to gabbro in composition, which dominate large areas of the Charlotte terrane (**King, 1955**; **Butler and Fullagar, 1978**). Metavolcanic and metasedimentary sequences of the Charlotte terrane are less well studied and generally poorly preserved or absent over large areas.

However, these stratigraphic sequences are more widely preserved over large areas of the Charlotte terrane in northeast Georgia and adjacent areas of South Carolina where there appear to be two separate and distinct lithostratigraphic sequences present; the Primitive Arc sequence and the Rifted Arc sequence. These two sequences differ in composition, associated plutonic phases, degree of deformation and metamorphism, and associated styles of base metal sulfide and precious metal mineralization. These metallic mineral occurrences were the focus of extensive exploration and evaluation by dozens of mining companies throughout the 1970s and 1980s.

This study is in significant part the product of extensive reconnaissance and detailed geologic mapping and gold and base metal sulfide exploration and prospect evaluation by the author for Phelps Dodge Exploration East (1979-1981) and Amselco Minerals/BP Minerals/Kennecott Exploration (1982-1987) in the South domain of the Charlotte terrane (Georgia and adjacent areas of South Carolina) and limited examinations in the North domain.

Unfortunately, the original field maps and geologic notes, data relating to prospect and project evaluations, and numerous memos and reports are only extant as hard copies and archived in the storage facilities of the relevant mining companies where they are not readily accessible. Much of the information included in this study comes from published resources and a few surviving copies of maps, notes, and reports and from memory.

The results of this work help to constrain interpretations of geology, the history of magmatism and deformation, and metallogeny and exploration potential of the North domain of the Charlotte terrane (North Carolina and north-central South Carolina). The assignment of metamorphosed plutonic, volcanic, an sedimentary rock units in the North domain to the Primitive Arc or Rifted Arc suites is based on their comparison and correlation with similar units in the South Domain and their association with specific styles of mineralization. There is a significant margin for error in these interpretations in the absence of more widespread high-precision geochronological data.

Acknowledgements

This study has benefitted greatly from the review and analysis of MS theses on geologic studies of various areas of the Charlotte terrane in Georgia and South Carolina available from the University of Georgia in Athens, as well as discussions with the students and their supervisors. I am especially grateful to Gil Allard of the University of Georgia in Athens for his friendship, guidance, encouragement, and his dedication to the study and understanding of the geology and mineral deposits of the Charlotte and Carolina terranes.

Numerous maps and publications available through the North Carolina, South Carolina, and Georgia geological surveys and the US Geological Survey have also been an essential resource to the present study.

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

Geologic framework of the Charlotte terrane

The Charlotte terrane, as defined by **Hibbard** ***et al.*** (**2002**) and modified by **Hibbard** ***et al.*** (**2007**), is the second largest component of peri-Gondwanan Carolinia (**Fig. 1**). It generally corresponds to the western portion of the Carolina terrane of **Secor** ***et al.*** (**1983**), the Charlotte Belt of **King** (**1955**), and includes the Juliette terrane of ***Horton et al.*** (**1989**).

The Charlotte terrane can be divided into three domains based on recognized lithologies, structure, history of magmatism and deformation, and the grade of regional metamorphism; **1**) the North domain from central North Carolina to north-central South Carolina, **2**) the Silverstreet domain in central South Carolina, and **3**) the South domain in southwest South Carolina and northeast Georgia (**Fig. 1**). The North and Silverstreet domains are separated by the 10 kilometer wide Gold Hill Shear Zone (**Lawrence, 2008**; **Allen** ***et al.*****, 2008**). The nature of the contact between the Silverstreet domain and the South domain is uncertain. The North and South domains of the Charlotte terrane are geologically and metallogenically similar and will be the subject of this review and analysis.

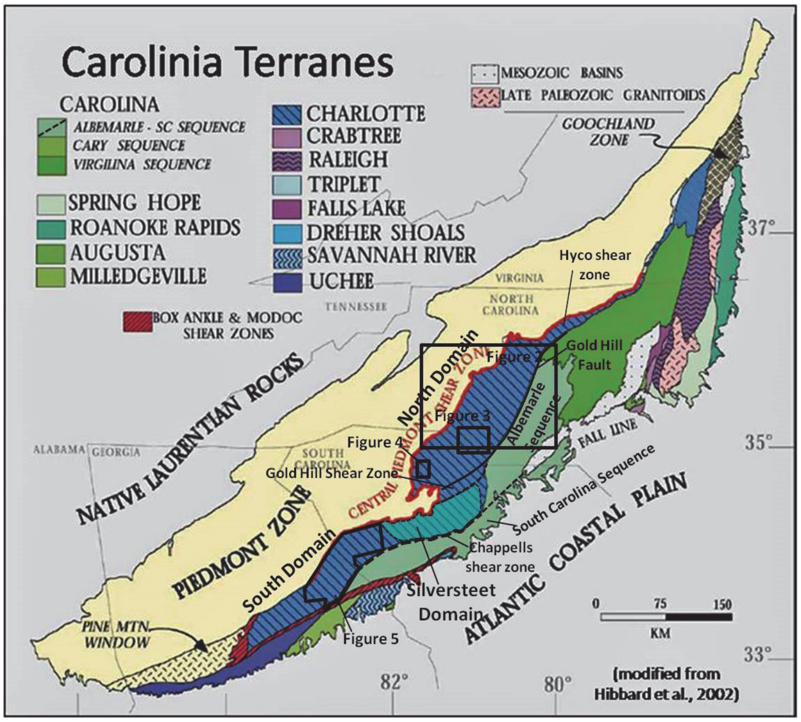


Fig. 1: Location and features of the Charlotte terrane in Carolinia

The Charlotte terrane collided and amalgamated with the Carolina terrane from northeast Georgia to central South Carolina ca. 550 Ma (**Barker** ***et al.*****, 1998**) along a suture zone overprinted by the Chappells shear zone, and both were accreted to the North American craton during the Late Ordovician-Early Silurian Cherokee Orogeny (**Hibbard** ***et al.*****, 2012**). The manner and timing of the collision and accretion of the Carolina and Charlotte terranes from northern South Carolina through North Carolina is less well constrained and complicated by inter-arc rifting of the Carolina terrane ca. 550 Ma with formation of the Albemarle Basin. Active rifting continued until ca. 540 Ma and may have ended coincident with latest Ediacaran deformation and magmatism along the Gold Hill Fault Zone (**Allen *et al.*, 2008**; **Hibbard *et al.*, 2012**) with subsequent largely passive upward-coarsening basin fill and diminishing mafic magmatism.

King (**1955**) and **Butler and Fullagar** (**1978**) emphasized the abundance and character of plutonic rocks composing the Charlotte terrane, which largely range from granite to dunite and commonly represent 50-100% of the exposure in all areas. Others (**Overstreet and Bell, 1965a**; **Overstreet and Bell, 1965b**; **Overstreet, 1970**; **Horton and Zullo, 1991**; **Allard and Whitney, 1994**; **Allard and Whitney, 1995**) have characterized the Charlotte terrane on the basis of dominantly amphibolite facies mineral assemblages in a heterogeneous, polydeformed sequence of quartzofeldspathic orthogneiss and paragneiss, amphibolite, hornblende gneiss, mica schist, quartzite, marble, and other metamorphic rock types.

All or a portion of the nonintrusive rocks of the Charlotte terrane have been interpreted as more strongly metamorphosed equivalents of Carolina terrane metavolcanic and metasedimentary rocks (**Secor and Wagener, 1968**; **Sundelius and Stromquist, 1978**; **Bourland and Farrar, 1980**; **Secor *et al.*, 1982**; **Hauck, 1984**; **Allard and Whitney, 1994**; **Allard and Whitney, 1995**; **Nelson *et al.*, 1998**). However, significant differences in the composition and character of nonintrusive and intrusive lithologies in each terrane have been noted (**Dennis and Shervais, 1996**; **Hibbard *et al.*, 2002**). Divergence in age, isotopic evolution, and contrasting styles and intensity of deformation (**Offield, 1995**; **Offield *et al.*, 1995**; **Hibbard *et al.*, 2002**; **Shervais *et al.*, 2003**) and metamorphism (**Butler, 1991**; **Shervais *et al.*, 2003**) further distinguish the Charlotte terrane from other Carolinia component terranes.

The Charlotte terrane is interpreted as a peri-Gondwanan supra-subduction volcanic arc complex built on oceanic lithosphere (**Dennis and Shervais, 1996**; **Dennis and Wright, 1997**; **Fullagar *et al.*, 1997**; **Shervais *et al.*, 2003**). Two main phases of development are distinguished. Initial mafic-dominated Primitive Arc magmatism pre-dates ca. 579 Ma, and is followed by apparently synchronous D_1 deformation, regional metamorphism, and Rifted Arc magmatism between ca. 571 and 535 Ma (**Dennis and Wright, 1997**). Rifting was associated with possible subduction of an oceanic spreading center, enabling the rapid rise of unfractionated mantle-derived mafic and ultramafic magmas into the upper crust (**Dennis and Wright, 1997**; **Shervais *et al.*, 2003**). The D_1 deformation event may be associated with the collision and amalgamation of the Charlotte and Carolina terranes that largely ended ca. 550 Ma in the South and Silverstreet domains (**Barker *et al.*, 1998**; **Secor et al., 1998**; **Shervais *et al.*, 2003**) but continued until at least 540 Ma in the North domain (**Dennis and Wright, 1997**).

A suggested general increase in the metamorphic grade and the relative volume of plutonic rocks from northwest to southeast across the Charlotte terrane in the North domain has been interpreted to reflect deeper levels of exposure in the volcanic arc terrane (**Dennis and Shervais, 1991**). This trend is consistent with the model of arc-arc collision, partial subduction of the Charlotte terrane beneath the Carolina terrane, and rebound of the Charlotte terrane following slab break-off (**Shervais *et al.*, 2003**). A similar pattern is present in South domain of the Charlotte terrane. However, this general pattern is not present in central South Carolina, dominated by more deeply exposed levels of the Charlotte arc in the Silverstreet domain (**Shervais *et al.*, 2003**).

Metaplutonic-metavolcanic complexes of the Charlotte terrane

Extensive mafic-dominated metaplutonic-metavolcanic sequences of the Primitive Arc are the oldest rocks recognized in any area of the Charlotte terrane (**Bates and Bell, 1965**; **Butler, 1966**; **Butler, 1984**; **Butler, 1989**; **Griffin, 1978**; **Griffin, 1979**; **Secor *et al.*, 1982**; **Taylor, 1982**; **Butler and Secor, 1991**; **Allard and Whitney, 1995**; **Dennis, 1995**; **Dennis and Wright, 1997**). Many of these older magmatic centers are intruded by younger zoned ultramafic-mafic- intermediate-felsic plutonic associations of the Rifted Arc association (**Dennis, 1995**; **Dennis and Wright, 1997**) to form large composite plutonic-volcanic complexes.

These composite igneous centers commonly range in area from 100 km^2 to more than 500 km^2 and include the Mocksville Complex in central North Carolina (**Taylor, 1982**; **Butler, 1989**; **Butler and Secor, 1991**); the Barber-Farmington, Concord, and Mecklenburg-Weddington complexes in south-central North Carolina (**McSween *et al.*, 1984**); the York-Chester Complex in northern South Carolina (**Wagener, 1974**; **Butler, 1988**; **Dennis and Shervais, 1991**); the Mean Crossroads Complex (**Dennis, 1988**; **Dennis and Shervais, 1991**; **Dennis and Shervais, 1992**; **Dennis and Shervais, 1996**) and Wildcat Branch Complex (**Horkowitz, 1984**; **Dennis and Shervais, 1991**; **Dennis and Shervais, 1992**; **Dennis and Shervais, 1996**) in northeast South Carolina; the Heardmont-Latimer Complex across the South Carolina-Georgia border region (**Griffin, 1978**; **Griffin, 1979**; **Weisenfluh and Snoke, 1978**; **Allard and Whitney, 1994**; **Allard and Whitney, 1995**); and the Eastern Oglethorpe County (**Davidson, 1981**) and Berner complexes in Georgia (**Hooper, 1986**; **Hooper and Hatcher, 1989**).

Differentiating the products of Primitive Arc versus Rifted Arc magmatism in these igneous complexes can be challenging, especially in the North domain. Primitive Arc magmatism is dominantly basaltic to andesitic in composition and intrusive to extrusive in character with extensive interbedded sequences of immature epiclastic sediments. Rifted Arc magmatism ranges from ultramafic to felsic in composition with generally lower volumes of associated volcanic, volcaniclastic, and epiclastic sedimentary units (**Griffin, 1978**; **Weisenfluh and Snoke, 1978**; **Griffin, 1979**; **Davidson, 1981**; **Butler, 1984**; **Brazell, 1984**; **Butler, 1991**; **Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**; **Dennis and Wright, 1997**).

Among the best documented examples of the relationships between the older Primitive Arc association and the younger Rifted Arc association are found in the Wildcat Branch and Mean Crossroads (**Fig. 4**) complexes in the southwestern part of the North domain (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1992**; **Dennis and Shervais, 1996**; **Dennis and Wright, 1997**) and the Eastern Oglethorpe complex in the South domain (**Fig. 5**).

The Charlotte terrane in the North domain

The geology of the North domain of the Charlotte terrane is best known from studies which includes the type area of **Butler** (**1984; 1991**), the integrated geological, structural, geochemical, and geophysical studies of **Goldsmith *et al.*** (**1989**) for the Charlotte 1° x 2° Quadrangle, and detailed studies of the Wildcat Branch and Mean Crossroads zoned mafic plutonic complexes (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**) in northwest South Carolina (**Fig. 1**, **Fig. 2, Fig. 3**).

The North domain in North Carolina (**Fig. 2**, **Fig. 3**) is dominated by a central Rifted Arc metaplutonic complex that ranges from ultramafic and gabbro, to quartz diorite and tonalite, to granodiorite and measures around 80 x 40 kilometers, almost twice the size of the Heardmont-Latimer complex in the South domain. It is enclosed by areas of the Primitive Arc sequence to the NE, SE, and SW, including the large Mocksville mafic complex to the north. Extensive areas of mafic metavolcanic rocks of uncertain affinity (probably Primitive Arc) are exposed along the southeast side of the North domain (**Fig. 2**, **Fig. 3**).

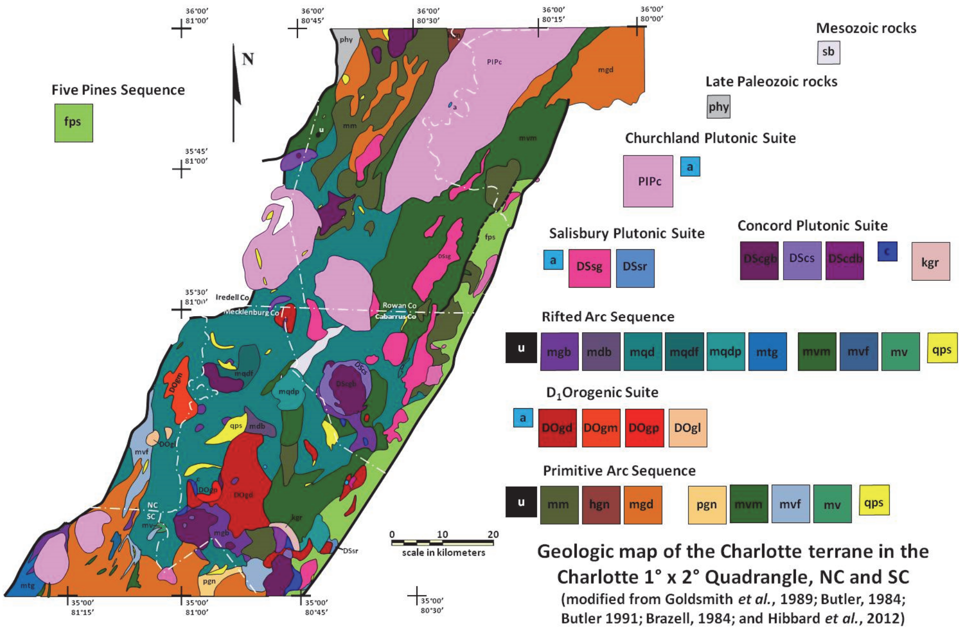


Fig. 2: Geology of the North domain of the Charlotte terrane in the Charlotte 1° x 2° Quadrangle

Legend for Fig. 2

Primitive Arc Sequence (> ca. 579 Ma)

Metamorphosed Mafic Complex (mm): The metamorphosed mafic complex that occurs along the eastern and northwest Charlotte terrane in the Charlotte 1° x 2° map includes amphibolite facies metamorphosed equivalents of gabbroic and ultramafic intrusive and hypabyssal and probably extrusive basalts. This unit is probably a basal pre-metamorphic unit and could include ophiolitic associations (**Goldsmith *et al.*, 1989**). This unit represents the mafic magmatism-dominated Charlotte primitive ocean volcanic arc prior to rifting.

Hornblende gneiss (hgn): Coarse-grained, strongly foliated hornblende plagioclase gneiss and hornblende diopside-microcline gneiss (**Goldsmith *et al.*, 1989**).

Undivided paragneiss (pgn): Sequences of immature arkosic sediments that interfinger with the periphery of metamorphosed mafic complexes (mm) and may contain interbedded mafic flows, volcaniclastic units, and small-scale intrusions **(Butler, 1991)**.

Metagranodiorite and related metagranitoids (mgd): Dominating the Charlotte terrane in the northern and southern part of the Charlotte 1° x 2° map area is light-gray to yellow-gray, fine- to coarse-grained, inequigranular, massive to distinctly foliated metamorphosed plutonic rocks ranging from monzogranite to leucodiorite (**Goldsmith *et al.*, 1989**). They are composed mostly of plagioclase, quartz, potassium feldspar, biotite and smaller amounts of epidote, sericite, and opaque minerals. Like similar sequences in Georgia, this is a mixed sequence of orthogneiss and paragneiss that may represent the lateral immature arkosic sediments peripheral to the primitive arc mafic magmatic centers and pretectonic intrusions.

Mafic and Intermediate Metavolcanic Rocks (mvm): This lithology is characterized by fine- to medium-grained, locally coarse-grained or agglomeratic rocks of basaltic, andesitic and dacitic composition with local areas of interbedded or dominant felsic metavolcanic rocks (**Goldsmith *et al.*, 1989**). Mostly sequences are largely volcaniclastic, but may include flows and perhaps hypabyssal intrusions. These rocks are metamorphosed to the epidote amphibolite facies in the Charlotte terrane. This lithology may be associated with both the Primitive and Rifted Arc sequences.

Felsic Metavolcanic Rocks (mvf): Sequence of fine- to medium-grained, locally coarse-grained or agglomeratic rhyolitic and rhyodacitic metatuffs that may include some hypabyssal intrusives (**Goldsmith *et al.*, 1989**). These sequences may also contain minor intermediate and mafic metavolcanic rocks. This lithology appears to be associated with both the Primitive Arc sequence.

Metavolcanic Rocks undivided (mv): Rocks of either felsic (mvf) or mafic to intermediate (mvm) metavolcanic units, both commonly interbedded (**Goldsmith *et al.*, 1989**). This lithology may be associated with either the Primitive or Rifted Arc sequences.

Metamorphosed hydrothermal alteration zones (qms): Often elongate to lenticular zones of fine- to medium-grained schists and phyllite composed largely of muscovite and quartz, with or without minor feldspar, biotite, pyrite, sillimanite, and opaque minerals including pyrite and rutile (**Goldsmith *et al.*, 1989**). They are interbedded with or gradational into quartzite with accessory andalusite, kyanite, or sillimanite, and minor chloritoid, pyrite (or hematite), accessory rutile, and locally minor gahnite and aluminum phosphates (**Goldsmith *et al.*, 1989**). These are phyllic to silicic and locally advanced argillic alteration zones. Some felsic metavolcanic units are misinterpreted as phyllic alteration. Some portions of these zones may be auriferous. Occurrences may include alteration footwall to VMS mineralization in the Primitive Arc Sequence and mesozonal to epizonal alteration along faults and shear zones in the Rifted Arc Sequence.

D_1 Orogenic Suite (< ca. 580 Ma > ca. 535 Ma)

Granodiorite and related granitoids (DOgd): These are gray, medium-grained, massive to weakly foliated intrusions composed of plagioclase and quartz with accessory potassium feldspar and biotite ± hornblende (**Goldsmith *et al.*, 1989**). This is volumetrically the dominant lithology of the suite and includes the large pluton centered on the city of Charlotte. It is described as a bluish-gray, generally fine-grained biotite granite composed largely of K-feldspar (orthoclase and microcline) with only minor plagioclase.

Metagranite and metagranodiorite (DOgm): These are light gray to pinkish gray, medium to coarse-grained, foliated, metamorphosed biotite granite, biotite granodiorite, and hornblende biotite granite present at Mountain Island, NC (**Goldsmith *et al.*, 1989**). A coarse-grained phase is characterized by euhedral, zoned plagioclase crystals and mosaics of highly sutured quartz grains.

Porphyritic granodiorite (DOgp): Similar to granodiorite and other related granitoids (DOgd) but inequigranular, with plagioclase phenocrysts and small biotite phenocrysts in a fine-grained matrix (**Goldsmith *et al.*, 1989**).

Biotite metagranodiorite (DObg): This is very light gray, medium- to coarse-grained, foliated to massive, metamorphosed biotite granodiorite and leucogranite found at Denver, N C (**Goldsmith *et al.*, 1989**).

Gneissic metagranite (DOg): This is a light-gray to light-greenish-gray, medium- to coarse-grained, gneissic biotite granite with biotite largely replaced by chlorite and accessory sphene (**Goldsmith *et al.*, 1989**). The metagranite is weakly foliated to augen gneiss or blastomylonite and locally brecciated.

Biotite monzogranite and leucogranite (DOgl): Small bodies of very gray to yellowish-gray, medium to coarse-grained, massive to very weakly foliated biotite monzogranite and leucogranite found southwest of Mt Holly, N C (**Goldsmith *et al.*, 1989**). Plagloclase is variably saussuritized, fractured, and strained.

Aplite (a): This lithology is cryptocrystalline with a conchoidal fracture. Small light to dark gray quartz phenocrysts with doubly terminated pyramidal faces are irregularly distributed in a holocrystalline groundmass of feldspar and quartz with accessory sericite and occasional inclusions of prismatic apatite and zircon. Aplite dikes with spots and streaks of Mn + Fe oxides occur at several places in the Charlotte area and are colloquially called leopardite. It appears to be associated with D_1 orogenic granodiorite (DOgd) and granite of the Churchland Plutonic Suite (PlPc).

Rifted Arc Sequence (< ca. 580 Ma < 535 Ma)

Metagabbro (mgb): These are dark, coarse-grained rocks with olivine and pyroxene largely replaced by abundant amphiboles (**Goldsmith *et al.*, 1989**). Plagioclase is subordinate to mafic minerals, epidote is common, and biotite and spinel may be present.

Metasyenite (msy): Grayish-pink, coarse-grained hornblende-biotite syenite with biotite and hornblende defining a strong foliation (**Goldsmith *et al.*, 1989**).

Metadiabase (mdb): Units with composition and mineral phases equivalent to amphibolitic and mafic metavolcanic rocks (mvm) or metagabbro (mgb), but with relict plagioclase phenocrysts in a fine-grained groundmass and traces of an original ophitic texture suggest emplacement as hypabyssal intrusions (**Goldsmith *et al.*, 1989**). They are more strongly recrystallized than younger metadiabase (DScdb). This unit also occurs as unmapped dikes cutting metamorphosed quartz diorite and tonalite (mqd) and metagranodiorite and related metagranitoids (mgd). They are particularly abundant near Charlotte, NC, and locally volumetrically equal to the host rock.

Metamorphosed quartz diorite and tonalite (mqd): Gray, usually medium- to coarse-grained, generally foliated rocks composed dominantly of plagioclase, quartz, biotite, hornblende, and epidote (**Goldsmith *et al.*, 1989**). Biotite hornblende, and epidote are commonly associated in clots replacing original mafic phenocrysts; clots may be smeared out into the foliation.

Metamorphosed tonalite porphyry (mqdp): Composed of plagioclase and less abundant quartz grains and biotite clots similar to those in metamorphosed quartz diorite and tonalite (mqd), set in a much finer grained matrix of the same minerals (**Goldsmith *et al.*, 1989**). This may be a metamorphosed hypabyssal intrusion.

Fine grained metamorphosed biotite tonalite (mqdf): This body is similar to metamorphosed quartz diorite and tonalite (mqd), but finer grained and generally lacks hornblende (**Goldsmith *et al.*, 1989**). Biotite flakes define a strong foliation.

Biotite metatonalite and metagranodiorite (mtg): Very light gray to yellowish-gray medium to coarse grained, inequigranular, foliated to massive metamorphosed biotite tonalite, biotite granodiorite, and some rare trondhjemite (**Goldsmith *et al.*, 1989**). Locally contains hornblende; epidote is common.

Salisbury Plutonic Suite (ca. 415 Ma)

Granite (DSsg): This includes light gray, locally pink, medium- to coarse-grained leucocratic granite and some quartz monzonite that is weakly foliated with mortar texture common (**Goldsmith *et al.*, 1989**). Rb-Sr whole rock ages suggest and age of 400 Ma (**Butler and Fullagar, 1978**).

Porphyritic rhyolite (DSsr): This unit is characterized by quartz and feldspar phenocrysts in a fine-grained groundmass of quartz and feldspar, locally with minor biotite or chlorite and very minor epidote (**Goldsmith *et al.*, 1989**). It forms border facies to some granite plutons in the eastern Charlotte terrane.

Concord Plutonic Suite (ca. 400-408 Ma)

Gabbro (DScgb): This is an intrusive suite that includes gabbro, norite, gabbronorite, and hornblende gabbro (**Goldsmith *et al.*, 1989**). They are largely composed of plagioc1ase, clinopyroxene and orthopyroxene, hornblende, biotite, and olivine or quartz. Hornblende ^{40}Ar-^{39}Ar age spectra plateau are 406 ± 4 Ma for the Farmington pluton and 408 ± 1 Ma for the Weddington pluton (**Sutter *et al.*, 1983**).

Syenite (DScs): This includes gray, coarse-grained, mostly augite syenite with subsidiary hornblende and biotite in Cabarrus County and medium to coarse-grained biotite hornblende syenite and monzonite with or without accessory augite in Mecklenburg County (**Goldsmith *et al.*, 1989**).

Metadiabase (DScdb): Fine to medium-grained undeformed ophitic texture with original pyroxene almost completely replaced by amphibole (**Goldsmith *et al.*, 1989**). Probably a hypabyssal intrusive cogenetic with gabbro (DScgb). Probably related are unmapped basaltic dikes with little modified igneous features that cut metamorphosed quartz diorite and tonalite (mqd) and metagranodiorite and related metagranitoids (mgd), less abundant than the more recrystallized dikes correlative with metadiabase (mdb).

Potash feldspar-rich granite (kgr): This unique, strongly sheared fine- to medium-grained, typically porphyritic unit contains abundant potassium feldspar (**Goldsmith *et al.*, 1989**). It may have formed by K-metasomatism of granodiorite or related granitoids. It is associated with an aeromagnetic high and a very strong aeroradioactivity anomaly (**Miller, 1983**) and possibly formed in association with Concord Plutonic Suite magmatism.

Contact metamorphic rocks (c): Largely present southwest of Charlotte, NC on the periphery of a large composite intrusive mass. The rock is composed largely of albite or sodic oligoclase and hedenbergite, with or without amphibole, andradite, orthoclase, and sphene. It is probably originally metagranodiorite and related metagranitoids (mgd) metasomatized in the aureole of gabbro (DScgb) and perhaps of granodiorite and related granitoids (DOgd). Southeast of Charlotte, quartzofeldspathic hornfels variously contain cordierite, sillimanite, or hedenbergite. Olivine-amphibole-chlorite-spinel rock (probably hornfelsed serpentinite) and anorthite-quartz-clinopyroxene-orthopyroxene-amphibole-magnetite rock (mafic hornfels?) are present near Harrisburg, NC.

Churchland Plutonic Suite (ca. 290 Ma)

Churchland Granite (PlPc): Biotite monzogranite, typically porphyritic, but with fine-grained phases (**Goldsmith *et al.*, 1989**). This suite also includes minor quartz monzonite and hornblende-bearing phases. A weak flow foliation is locally recognized. Rb-Sr whole rock ages are 282 ± 6 Ma for the Churchland pluton, 292 ± 29 Ma for the Landis pluton, and 322 ± 6 Ma for the York pluton (**Fullagar and Butler, 1979**).

Late Paleozoic rocks

Phyllonite (phy): Quartzofeldspathic rocks characterized by strong ductile deformation locally overprinted by brittle deformation. Feldspar is typically sericitized or saussuritized. Protoliths are felsic volcanic and granitic rocks (**Goldsmith *et al.*, 1989**).

Mesozoic rocks

Silicified breccia (sb): Tabular, steeply dipping bodies of cohesive silicified fault breccia composed mostly of fine-grained quartz (**Goldsmith *et al.*, 1989**). Broader zones in the Charlotte belt are commonly pyritic.

Five Pines Sequence (ca. 613 Ma)

Generally well-bedded, greenschist-facies sequence of dominantly mafic to intermediate volcanic and volcaniclastic rocks and phyllite with an outcrop thickness of ~4 km in the immediate hangingwall of the Gold Hill Fault that is correlated with the Hyco Arc of the Carolina terrane (**Hibbard *et al.*, 2012**).

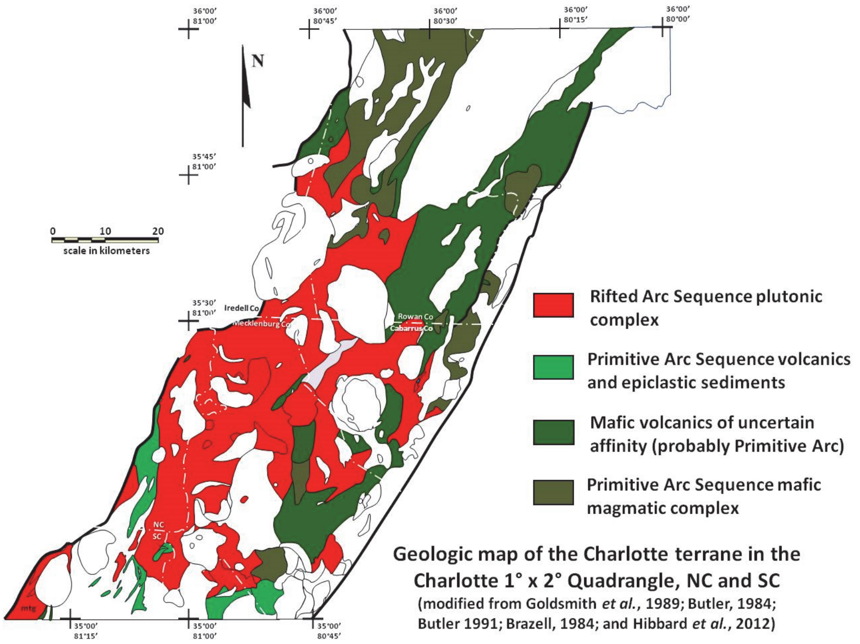


Fig. 3: Primitive Arc and Rifted Arc domains of the Charlotte terrane in the Charlotte 1° x 2° Quadrangle

Distinguishing between Charlotte terrane intrusions and stratigraphic units associated with Primitive Arc magmatism and those associated with Rifted Arc magmatism is difficult in the North domain. This is due to the abundance of unrelated D_1 and Concord, Salisbury, and Churchland plutonic suite intrusions, uncertainty in the affiliation of metavolcanic and metasedimentary sequences (**Fig. 2**), and a general dearth of modern geochronological data. Extensive mafic metavolcanic sequences along the eastern portion of the North domain may be products of either magmatic episode, but their volume and extent suggest that they are part of the Primitive Arc sequence.

In the type area for the Charlotte terrane (**Fig. 4**) in northern York County, South Carolina, near the border with North Carolina, the character of the Primitive Arc stratigraphic sequence is locally preserved but Rifted Arc stratigraphic units appear to be absent. However, there is a clear demarcation between these two lithologic associations in the South domain of the Charlotte terrane that facilitates separation of these two lithologic associations in the North domain.

The Type Area of the Charlotte terrane

Butler (**1984; 1991**) and **Brazell** (**1984**) identified the earliest rocks present in the type area as a stratigraphic sequence of amphibolite and biotite gneiss, interpreted as a sequence of mafic flows and volcaniclastic units interbedded with epiclastic sedimentary rocks, with a localized domain of intermediate to felsic and subordinate mafic metavolcanic units (**Fig. 4**).

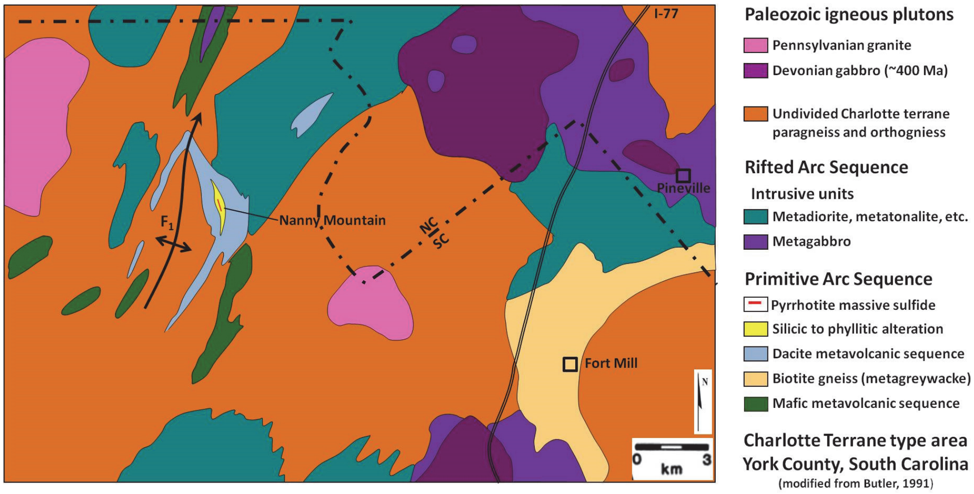


Fig. 4: Charlotte terrane type area, York County, South Carolina

This localized intermediate to felsic volcanic sequence is dominantly dacitic metavolcaniclastic units, with subordinate pillowed basalt flows and volumetrically minor rhyolite units which include a possible flow or dome and several sills or dikes of opaline blue quartz-phyric rhyolite porphyry (**Brazell, 1984**). Hydrothermal alteration and mineralization associated with the intermediate to felsic volcanic sequence include an extensive sericitic (phyllic) to silicic alteration zone, the small Nanny Mountain pyrrhotite-dominated VMS deposit, and cherty iron formation (**Brazell, 1984**). This association suggests formation of a seafloor VMS system contemporaneous with localized Primitive Arc rifting and intermediate to felsic volcanism (**Brazell, 1984**).

The entire stratigraphic sequence in this area is metamorphosed to the amphibolite facies and tightly folded around a large-scale, possibly refolded F_1 anticlinorium (**Fig. 4**) that plunges gently to the north (**Brazell, 1984**). The sequence is extensively intruded by a pre- to syn-D_1 plutonic suite dominated by metatonalite that grades into metagranodiorite and metagranite (**Butler, 1966**; **Brazell, 1984**). A metagranitoid of this intrusive suite at the Catawba Nuclear Plant site in northern York County SC near the North Carolina state line returned a zircon U-Pb age of 532 ± 15 Ma (**Gilbert *et al.*, 1982**).

This orogenic plutonic suite intrudes the mafic-dominated Primitive Arc volcanic-sedimentary sequence and the Mecklenburg metagabbro pluton, part of the Mecklenburg-Weddington intrusive complex (**Wagener, 1974**; **Butler, 1988**; **Dennis and Shervais, 1991**). The metagabbro and metatonalite appear to be associated with Rifted Arc magmatism, but no associated volcanic or sedimentary units are observed.

Structure in the type area for the Charlotte terrane around the North Carolina-South Carolina state line is interpreted by **Butler (1971)** and **Brazell (1984)** as D_1 synmetamorphic (M_1) large-scale isoclinal folding (F_1), with subvertical axial planes that strike northeast and fold hinges that plunge gently northeast or southwest. A strongly developed, steeply-dipping axial planar foliation (S_1) is locally overprinted by a younger crenulation cleavage (S_2) that is roughly coplanar to S_1.

Map patterns for nonintrusive rocks of the Charlotte terrane are dominated by first and second order F_1 folds, but variably obscured or deformed by the emplacement of pre-, syn-, and post-tectonic plutons (**Butler, 1971**; **Brazell, 1984**). Deformation fabrics are generally weakly developed in the interior of large metamorphosed plutons, but more strongly developed near the margins.

The Wildcat Branch and Mean Crossroads zoned mafic plutonic complexes

These plutonic complexes **(Fig. 5)** are ~10 kilometers in diameter and heterogeneously zoned (**Dennis and Shervais, 1996**) from meta-ultramafic cores up to two kilometers diameter (~15%-20% by area) enclosed by foliated, coarse-grained metagabbro and hornblende metagabbro (10%-15%), surrounded by coarse-grained metadiorite gneiss and quartz diorite (60%-70%). Ultramafic core rocks include coarse-grained meta-clinopyroxenite and hornblendite with local serpentinite. Cumulate pyroxene, hornblende, and plagioclase are present in the metagabbro bodies, but not as mappable layered intervals (**Dennis and Shervais, 1996**). The variations in the major- and trace-element compositions of the diorites, including a trend from 54 wt% SiO_2 to 66 wt% SiO_2, suggest a liquid line of descent from andesitic to dacitic composition.

The plutonic bodies of the complexes are intrusive into a sequence of dominantly mafic metavolcanic rocks with subordinate intermediate and felsic metavolcanic rocks and a ca. 570 Ma metagranodiorite. Four general groups of metavolcanic rocks (**Dennis and Shervais, 1996**) are recognized in the sequence intruded by the Mean Crossroads and Wildcat Branch zoned intrusive complexes; **1**) tholeiitic ankaramite, **2**) high-Mg basalt and basaltic porphyry, **3**) normal low-Mg basalt and basaltic andesite, and **4**) andesite, dacite, and rhyodacite.

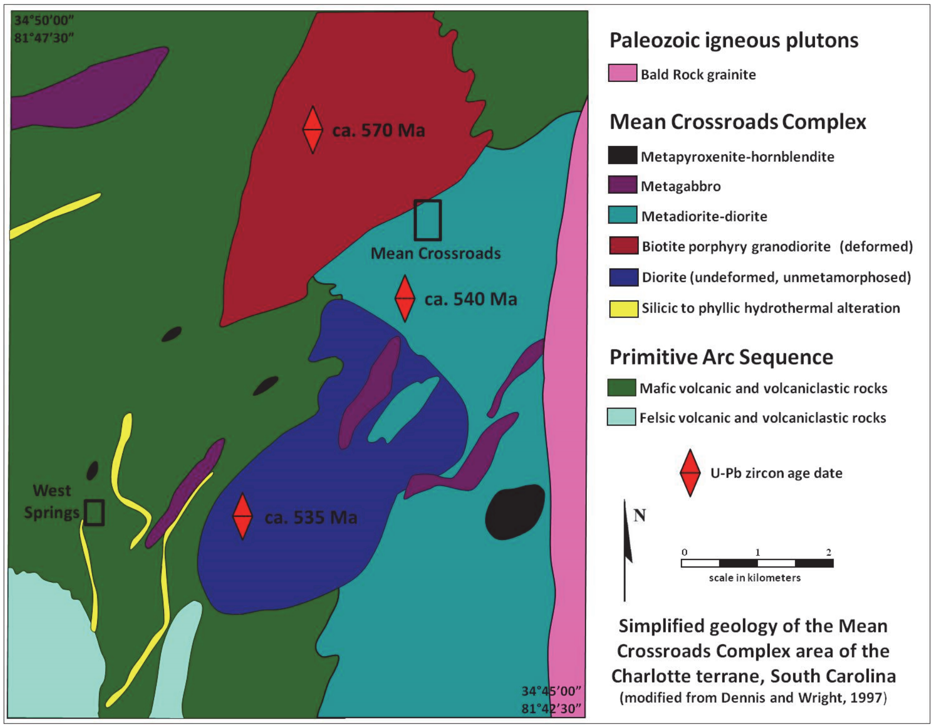


Fig. 5: Mean Crossroads zoned mafic plutonic complex

Pyroxene- and olivine-phyric tholeiitic ankaramite occurs as flows, dikes, volcanic breccias, and crystal-rich volcaniclastic units (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**). Flows and dikes modally contain up to 40% clinopyroxene phenocrysts 0.5 -1.5 centimeters in diameter, typically replaced by actinolitic amphibole (**Dennis and Shervais, 1996**). The most mafic ankaramite samples are interpreted as crystal-rich cumulates similar in composition to olivine pyroxenite of the zoned plutonic complexes (**Dennis and Shervais, 1996**). High-Mg basalt, characterized by 11-13% MgO, includes massive and augite- and hornblende-phyric flows. The composition of both the ankaramite and high-Mg basalt is related to the abundance of phenocrysts (**Dennis and Shervais, 1996**).

The most common rocks in the metavolcanic sequence are low-Mg basalt and basaltic andesite with chemical compositions typical of normal, arc-related basalts (**Dennis and Shervais, 1996**) and consistent with the Primitive Arc sequence. These units include actinolite amphibolite, banded amphibolite, amygdaloidal greenstone, and mafic lapilli tuff (**Dennis and Shervais, 1991**). Andesite, dacite, and rhyodacite flows and volcaniclastic units are subordinate to mafic volcanic rocks. These rocks are intruded by a ca. 570 Ma metagranodiorite pluton.

In general, the relative abundance of lithotypes decreases with increasing silica content (**Dennis and Shervais, 1996**). Mafic and felsic units are locally interlayered at scales of 1-10 meters (**Dennis and Shervais, 1991**), suggesting synchronous eruption and deposition. The compositions of these units appear to define a liquid line of descent from the more primitive basaltic magmas, and they appear chemically similar to the diorites of the Means Crossroad and Wildcat Branch complexes (**Dennis and Shervais, 1996**).

Mafic to intermediate metavolcanic units intruded by the Mean Crossroads plutonic complex are locally cut by zones of metamorphosed phyllic to advanced argillic alteration 10-150 meters wide (**Fig. 2**) that extend for several kilometers along strike (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**). These zones often carry heterogeneous concentrations of typically ~5% disseminated pyrite and/or magnetite and were the focus of historical gold prospecting and small-scale mining. Alteration appears to be cross-cutting, possibly along fault zones, and can be traced along strike into andesitic metavolcaniclastic units.

These hydrothermal alteration zones are crosscut by metamorphosed mafic and ultramafic dikes that are possible feeders for higher-level volcanism; this suggests that alteration was synchronous with deformation and contemporaneous with mafic and ultramafic magmatism (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**) of the Arc Rift Sequence. Metamorphosed ankaramite and picrite dikes intrude both metaplutonic and metavolcanic units and may represent parent magmas for the zoned plutonic complexes and comagmatic volcanic rocks (**Dennis and Shervais, 1996**).

There appear to be two separate and distinct associations present in the metavolcanic sequence intruded by the Wildcat Branch and Mean Crossroads zoned plutonic complexes. Much of the sequence is dominated by subduction-related low-Mg basalt and basaltic andesite of the Primitive Arc sequence. The smaller volume tholeiitic ankaramite and high-Mg basalt association has strong chemical affinities to the younger zoned plutonic phases of the Wildcat Branch and Mean Crossroads complexes, and appears to be associated with Rifted Arc magmatism. It is unclear whether the subordinate andesite, dacite, and rhyodacite metavolcanic units present in this area are part of the Primitive Arc sequence, the younger Rifted Arc event, or both. All are metamorphosed to the amphibolite facies and do not appear to have a distinct stratigraphic separation,

The older Primitive Arc mafic-dominated metavolcanic rocks intruded by the Wildcat Branch and Mean Crossroads zoned plutonic complexes were deformed and metamorphosed to amphibolite-facies after about 571 ± 16 Ma, the Rifted Arc-related zoned plutonic complexes and comagmatic metavolcanic rocks were emplaced synchronous with deformation no later than 538 ± 5 Ma, and both rifting and deformation in this area ended ca. 535 Ma (**Dennis and Wright, 1997**).

The timing of D_1 deformation and metamorphism in the Charlotte terrane of northeast South Carolina is constrained by **Dennis and Wright** (**1997**) to between about 571 and 535 Ma, and may have been a protracted, polyphase event. In addition to deformation, metamorphism, and arc-rifting of the Charlotte terrane, this period encompasses the collision and suturing of the Charlotte and Carolina terranes ca. 550 Ma in the South domain (**Barker *et al.*, 1998**; **Dallmeyer *et al.*, 1986**; **Shervais *et al.*, 2003**), as well as the initiation of arc-rifting of the Albemarle arc of the Carolina terrane in central North Carolina (**Hibbard *et al.*, 2013**) with mafic and felsic magmatism and deposition of the Albemarle Group until as late as 528 ± 8 Ma (**Pollock, 2007**).

Charlotte terrane Primitive Arc plutonic, volcanic, and sedimentary rocks in the North domain are characteristically metamorphosed to the middle to upper amphibolite facies during D_1 deformation. Undeformed felsic and mafic dikes cutting deformed plutons are also metamorphosed to amphibolite facies, suggesting that peak metamorphic conditions continued after the peak of D_1 deformation (**Dennis and Wright, 1997**).

The Concord and Salisbury Plutonic Suites

The Concord and Salisbury plutonic suites represent Devonian episodes of renewed magmatism in the Charlotte terrane. Gabbroic to syenite intrusions of the ca. 400-410 Ma Concord Plutonic Suite extend throughout the North and South domains of the Charlotte terrane, intruding Primitive and Rifted Arc magmatic complexes. However, monzonite and quartz monzonite to granite plutons of the ca. 415-417 Ma Salisbury Plutonic Suite appear to be unique to the North domain of the Charlotte terrane (**Fig. 2**). They show no spatial association with Concord Plutonic Suite plutons.

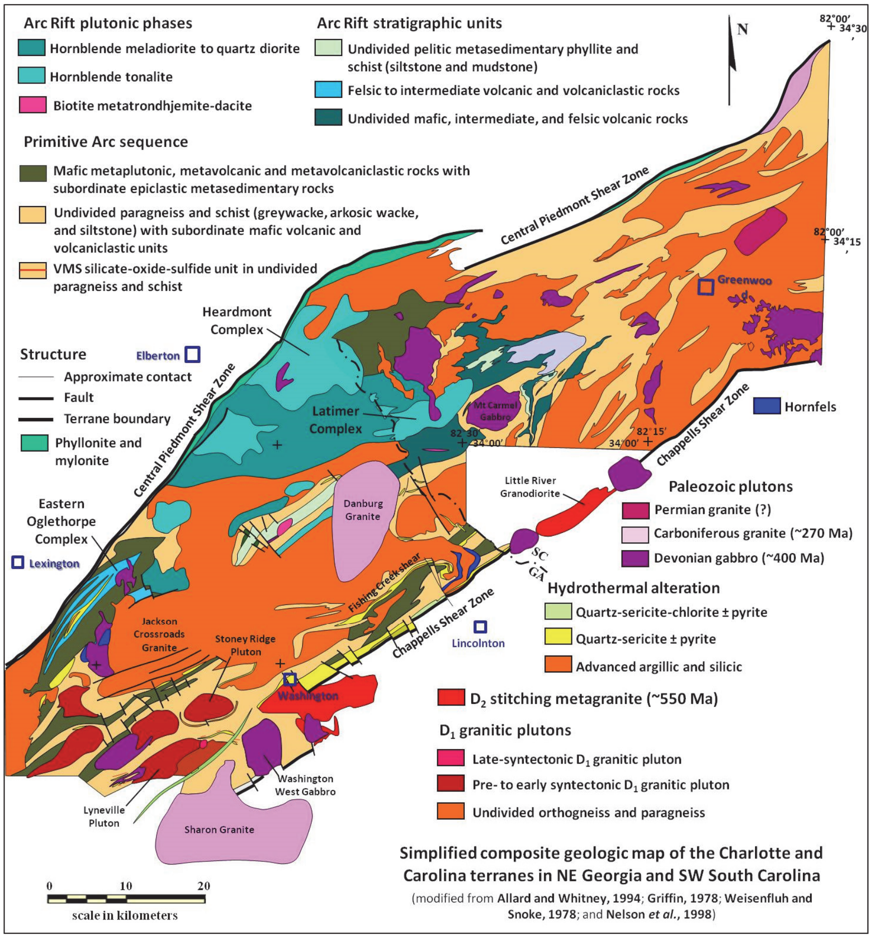
The 14 highly felsic plutons of the Salisbury suite are described as syntectonic granites by **Butler and Fullagar** (**1978**). They are abnormally rich in microcline, albite, and quartz which make up more than 95% of the rock (**Butler and Fullagar, 1978**) with whole rock MgO content typically less than 0.1% (**Goldsmith *et al.*, 1989**). Dark minerals, mainly biotite, form less than 3% and commonly less than 1% of the rock. Chlorite, muscovite, calcite, and garnet are common and probably were formed during greenschist facies metamorphism.

They represent a very felsic magma formed as a result of extreme differentiation or limited partial melting in the lower crust or mantle (**Butler and Fullagar, 1978**). The Salisbury pluton is characterized by anomalous concentrations of incompatible elements including Nb, Th, U, Y, and Zr (**Lemmon, 1969**; **Fullagar *et al.*, 1971.** Additionally, at least four of these plutons hosted localized molybdenite mineralization and an evolved monzonite body in the southern corner of Cabarrus County hosts the Newell porphyry type Cu-Mo deposit.

Many of these plutons are distributed along a linear NNE-trend that is subparallel to the contact between the Charlotte terrane and the Five Pines Sequence of metavolcanic and metasedimentary rocks that appear to be correlative with the Hyco Formation of the Carolina terrane (**Hibbard *et al.*, 2012**). This alignment may broadly correspond with the tectonic suture between the Charlotte and Carolina terranes at depth.

The Charlotte terrane in northeast Georgia and southeast South Carolina

Studies in the South domain of the Charlotte terrane in central and southwest South Carolina **(Secor and *et al.*, 1982**; **Halik, 1983**; **Hauck, 1984**; **Offield, 1995**) and northeast Georgia (**Thurmond, 1979**; **Davis, 1980**; **Davidson, 1981**; **Conway, 1986**; **Dunnagan, 1986**; **Allard and Whitney, 1994**) are broadly consistent with the observations and interpretations in the North Domain, suggesting a consistent pattern in the character of Primitive Arc and Rifted Arc sequences and regional D_1 tectonism and plutonism.



Simplified composite geologic map of the Charlotte and Carolina terranes in NE Georgia and SW South Carolina

(modified from Allard and Whitney, 1994; Griffin, 1978; Weisenfluh and Snoke, 1978; and Nelson *et al.*, 1998)

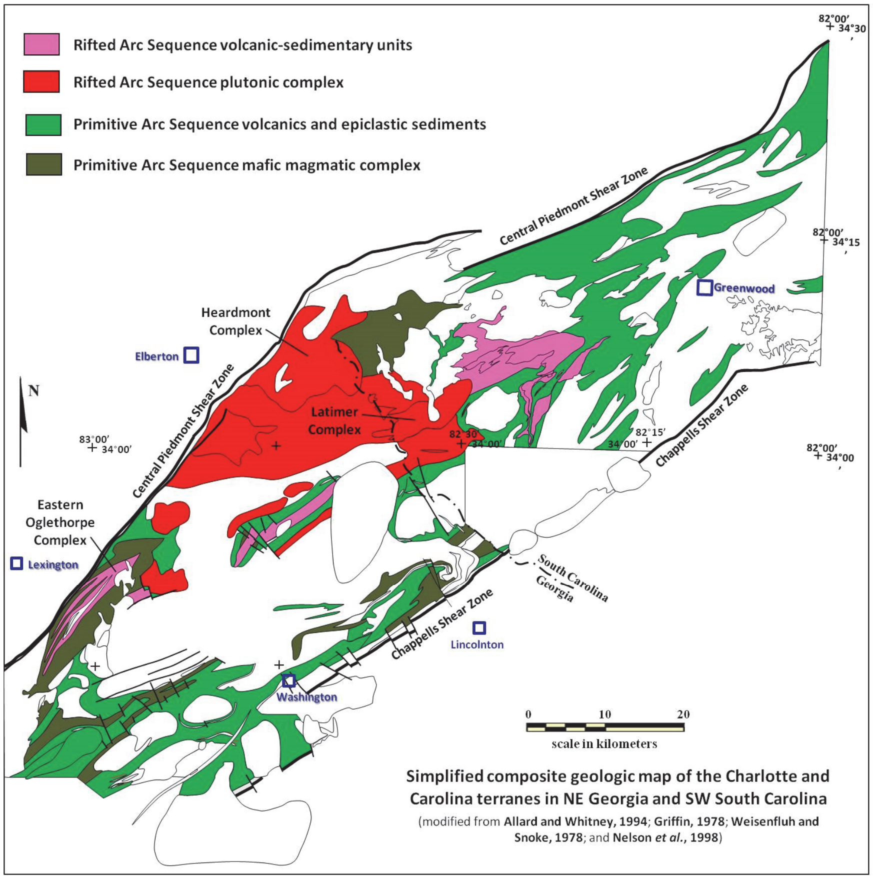
Fig. 6: Simplified geology of part of the South domain of the Charlotte terrane

The Charlotte terrane in the South domain (**Fig. 6**) can be divided into three general dominant rock associations: **1**) Primitive Arc metavolcanic and metasedimentary sequences are widely present along the southern margin of the terrane and northeast of the Latimer Complex, **2)** Rifted Arc intrusions and associated stratigraphic sequences of the Heardmont-Latimer Complex dominate much of the northwest portion of the terrane, and **3**) the central portion of the Charlotte terrane in Georgia is dominantly occupied by large syn- to post-tectonic granodiorite to granite plutons and undivided strongly deformed amphibolite facies orthogneiss and paragneiss, with major plutons including the late Proterozoic Jackson Crossroads metagranodiorite and the Pennsylvanian Danburg Granite.

The extensive preservation of stratigraphic sequences associated with both Primitive Arc and Rifted Arc magmatic centers in the South domain provides an opportunity to better constrain their character and relationship. Additionally, the occurrence of distinctive types of hydrothermal systems associated with each helps to define metallogenic distinctions.

The Primitive Arc Sequence of the Charlotte terrane in the South domain

The Primitive Arc Sequence in the South domain is characterized by thick sequences of mafic metaplutonic, metavolcanic and metavolcaniclastic units that interdigitate with immature epiclastic sedimentary rocks. This sequence is extensively preserved in an arcuate belt that extends south, east, and northeast from eastern Oglethorpe County through Greene, Taliaferro, Wilkes, and Lincoln counties, Georgia (**Fig. 6, Fig. 7**). It is also widely preserved to the northeast of the Heardmont-Latimer complex in South Carolina (**Fig. 6, Fig. 7**).



Simplified composite geologic map of the Charlotte and Carolina terranes in NE Georgia and SW South Carolina
(modified from Allard and Whitney, 1994; Griffin, 1978; Weisenfluh and Snoke, 1978; and Nelson *et al.*, 1998)

Fig. 7: Primitive Arc and Rifted Arc areas of the South domain

This is the most widely distributed stratigraphic component of the Charlotte terrane in the South domain and appears to be correlative with mafic-dominated intrusive-extrusive centers recognized as the oldest rocks in the Charlotte terrane. These basal mafic magmatic centers are intruded by portions of the Heardmont-Latimer Complex across the South Carolina-Georgia border region (**Griffin, 1978**; **Griffin, 1979**; **Weisenfluh and Snoke, 1978**; **Allard and Whitney, 1994**; **Allard and Whitney, 1995**) and the Eastern Oglethorpe County Complex (**Davidson, 1981**).

The Primitive Arc mafic volcanic portion of these magmatic complexes interfingers outward with thick, laterally extensive sequences of biotite gneiss and schist, hornblende gneiss, and amphibolite, interpreted as immature epiclastic sediments dominated by arkosic metagreywacke, and intercalated mafic volcanic flows and volcaniclastic units (**Griffin, 1978**; **Griffin, 1979**; **Davidson, 1981**).

This Primitive Arc mafic-dominated volcanic, volcaniclastic, and epiclastic sedimentary sequence was deposited as early as 579 ± 4 Ma (**Dennis and Wright, 1997**; **Hibbard *et al.*, 2002**) and is everywhere strongly deformed by D_1 tectonism and metamorphosed to the amphibolite facies (**Griffin, 1978**; **Griffin, 1979**; **Davidson, 1981**; **Thurmond, 1979**; **Davis, 1980**; **Davidson, 1981**; **Conway, 1986**; **Dunnagan, 1986**).

Mafic magmatic centers of the Primitive Arc Sequence in Georgia are best described in the Eastern Oglethorpe County complex (**Davidson, 1981**). The immature clastic sequence that interfingers with the mafic magmatic centers is best described in southern Wilkes County, Georgia southwest of Washington (**Fig. 6**).

Eastern Oglethorpe complex Primitive Arc mafic volcanic sequence

The Eastern Oglethorpe plutonic-volcanic complex (**Fig. 6**) covers an area of at least 100 km² west and southwest of the Rayle Pluton, which truncates the complex to the east and encloses a large pendant of the mafic metavolcanic sequence. Although not contiguous, the eastern Oglethorpe County magmatic complex is consistent in character and possibly a continuation of the adjacent Heardmont-Latimer magmatic complex.

The basal Primitive Arc sequence is dominated by amphibolites interpreted by **Davidson** (**1981**) as massive to amygdaloidal basalt to andesite flows interbedded with subordinate volcaniclastic units. Flows are unfoliated dark green massive units 0.25-92 meters thick, some traced for 2.7 kilometers along strike (**Davidson, 1981**).

Amygdules 1.5-15 millimeters in diameter are common, rounded to slightly flattened and elongated, and composed of various combinations of hornblende, quartz, and epidote. Larger amygdules are quartz with hornblende or epidote rims, and smaller amygdules are filled with anhedral epidote. **Davidson** (**1981**) cites the vesicularity versus depth curves of **Moore** (**1970**) to suggest eruption at depths of 1-1.5 kilometers below sea level.

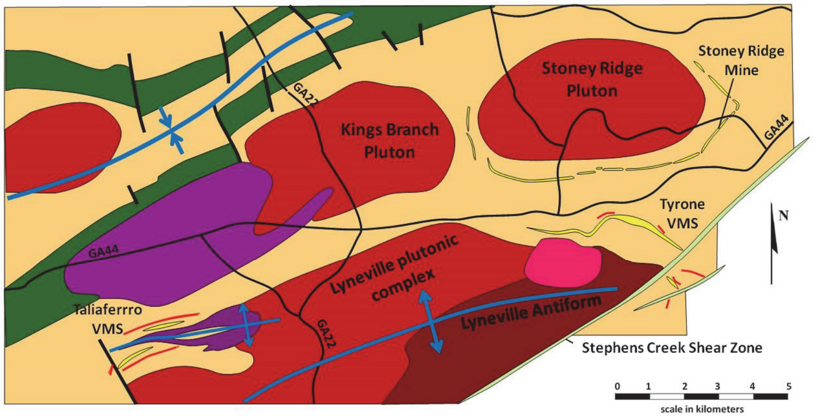
This basal mafic flow-dominated metavolcanic sequence appears to be the oldest rocks present in this area of the Charlotte terrane, consistent with the Primitive Arc sequence, although

Davidson (**1981**) interprets it as oceanic crust. To the northeast and south, these mafic flows interfinger with heterogeneous biotite gneiss, biotite schists, hornblende gneiss, and amphibolite interpret as immature epiclastic sediments interbedded with mafic volcanic and volcaniclastic units.

The Primitive Arc mafic volcanic sequence of the Eastern Oglethorpe County complex is metamorphosed to the amphibolite facies and isoclinally folded into a northeast-trending antiform (minimum 6 kilometers wavelength) overturned slightly to the NW with the axial plane dipping 87° SE (**Davidson, 1981**). Bedding (S_0) generally strikes 030°E and dips 87°SE to 79°NW on the fold limbs. An axial planar S_1 foliation is generally subparallel to the isoclinally folded bedding. Small scale isoclinal folds plunge 1°-2° northeast, with smaller and more numerous folds (30-120 centimeters wavelength) in fine-grained lithologies.

Primitive Arc metavolcanic-metasedimentary sequence in Taliaferro and Wilkes County, Georgia

Around 40-50% of the Charlotte terrane in southern Wilkes County and adjacent Taliaferro County consists of a thick sequence of Primitive Arc immature epiclastic metasediments and mafic metavolcanic and metavolcaniclastic rocks. These units dominate the area southwest of the town of Washington in the Washington West 7.5" Quadrangle, with mafic metavolcanic sequences more abundant to the west and northwest (**Fig. 6**, **Fig. 8**) in the limbs of a first-order synclinorium.



Simplified geologic map of the Stoney Ridge area in the Charlotte Terrane in parts of Wilkes and Taliaferro counties NE Georgia
(modified from Allard and Whitney, 1994; Moye, 1987)

Fig. 8: Geology of the Stoney Ridge area of the Charlotte terrane (see explanation Fig. 5).

The Primitive Arc stratigraphic sequence in the Washington West 7.5' Quadrangle is dominated by compositionally and texturally variable biotite gneiss heterogeneously interbedded with subordinate biotite schist, biotite-hornblende gneiss, hornblende gneiss, amphibolite, and leucocratic granitic gneiss. Thin units (1-5 centimeters) of calc-silicate and quartz-epidote granofels of metamorphic origin are common throughout the sequence and generally conformable with the dominant structural fabric.

The biotite gneiss is highly variable in grain-size, texture, and composition. The rock is commonly medium to fine grained (0.1-1.2 millimeters) with a lepidoblastic to granoblastic texture (**Dunnagan, 1986**). The dominant component by volume (42-60%) is oligoclase (An_{24-30}) with 25-30% quartz and 1-20% brown biotite (**Dunnagan, 1986**). Common but minor accessory minerals include sericite, hematite, pyrite, and epidote. A variably-developed compositional banding averaging 1-4 centimeters thick parallel to the dominant foliation is common in the biotite gneiss, with alternating layers dominated by quartz + feldspar and biotite ± hornblende. This banding may represent original bedding or tectono-thermal segregation of felsic and mafic mineral components. A weak to strong S_1 foliation defined by aligned biotite grains is common parallel to compositional banding and a weak subparallel S_2 foliation has also been noted. This heterolithic lithology is interpreted as probable volcaniclastic greywacke and arkosic wacke.

There is a continuous compositional variation from biotite gneiss to hornblende gneiss to amphibolite throughout the sequence, with interbedding on a scale of centimeters to tens of meters. Hornblende gneiss and amphibolite may also form distinct units and sequences tens to hundreds of meters thick, especially to the west. Both lithologies commonly show weak to strong compositional layering with variable segregation of felsic and mafic minerals.

Hornblende gneiss is commonly composed of 40-60% andesine plagioclase (An_{37-42}), 5-25% quartz, and 10-35% hornblende as prismatic crystals variably aligned with the dominant foliation (**Dunnagan, 1986**). Epidote is commonly present as a minor accessory, but locally forms up to 30% in some intervals where quartz is a minor component (**Dunnagan, 1986**). Amphibolite is composed largely of prismatic hornblende crystals with subordinate plagioclase and variable minor quartz, biotite and epidote. These units are interpreted as probable mafic volcanic and volcaniclastic sequences (**Dunnagan, 1986**).

Biotite-rich schist is fine-grained, strongly foliated, and dominantly composed or biotite with up to 40% granular quartz and minor oligoclase (**Dunnagan, 1986**). Leucocratic granitic gneiss is usually fine to medium grained and composed largely of oligoclase (50-70%) and quartz (30-40%) with minor biotite (2-5%), but is distinctly different from metaintrusive units (**Dunnagan, 1986**). The protolith for the biotite schist may be siltstone, and the leucocratic granitic gneiss may be metamorphosed arkosic wacke or possibly felsic volcaniclastic units.

The same metasedimentary sequence was similarly described and interpreted by **Conway** (**1986**) in the northern Philomath 7.5' Quadrangle to the west of the Washington West 7.5' Quadrangle and by **Hall** (**1991**) in the southern portion of the Celeste 7.5' Quadrangle to the north. **Davis** (**1980**) also described thick sequences of quartzofeldspathic biotite gneiss interbedded with biotite-rich units, hornblende gneiss, and amphibolites near the western boundary of the Charlotte terrane in Greene County, Georgia.

This Primitive Arc sequence is everywhere extensively intruded by numerous small conformable to cross-cutting amphibolite and metagabbro bodies that may represent mafic plugs, dikes and sills that were feeders for higher-level mafic volcanism. The heterogeneous but broadly uniform composition, mineralogy, and interrelationships among these lithologies are consistent with a widespread sequence of immature greywacke, arkosic wacke, siltstone, and mafic volcanic and volcaniclastic units. The entire sequence was strongly deformed and metamorphosed to the amphibolite facies during the D_1 event.

The Rifted Arc Sequence of the Charlotte South domain

Plutonic complexes and associated volcanic and sedimentary units of the Rifted Arc Sequence in Georgia dominate the northwestern portion of the Charlotte terrane, and include the Heardmont-Latimer complex and part of the Eastern Oglethorpe County magmatic complex (**Fig. 6**, **Fig. 7**). The Rifted Arc plutonic complexes intrude mafic magmatic complexes and metasedimentary sequences of the Primitive Arc complex and are locally intruded in turn by gabbro of the Concord Plutonic Suite and Carboniferous granites.

Rifted Arc magmas show strong differentiation trends and range from ultramafic to granitic in composition, but plutonic phases are dominantly hornblende-bearing diorite, quartz diorite, and tonalite. Formation of the Rifted Arc Sequence is synchronous with D_1 deformation and metamorphism of the Charlotte terrane and the intrusion of orogenic plutons unrelated to Rifted Arc magmas. The older, more voluminous Rifted Arc plutonic phases are metamorphosed to the amphibolite facies; however, the youngest, typically more felsic and lower volume intrusive units and associated volcanic and sedimentary sequences are only metamorphosed to the middle greenschist facies.

The Heardmont-Latimer magmatic complex

The Heardmont-Latimer complex (**Allard and Whitney, 1994**) is a large compound Rifted Arc plutonic igneous center that dominates most of southeast Elbert County, Georgia (**Fig. 6**, **Fig. 7**). It extends northeast to include the Latimer complex in southern Abbeville and northern Lincoln counties, South Carolina (**Griffin, 1978**; **Griffin, 1979**; **Weisenfluh and Snoke, 1978**), and may continue southwest to include similar units in eastern Oglethorpe County, Georgia (**Davidson, 1981**). The entire complex extends for at least 50 kilometers along the northwest flank of the Charlotte terrane and is up to 16 kilometers wide. The northwest portion of this complex is truncated and deformed against the Middleton-Lowndesville segment of the Central Piedmont Shear Zone.

The Heardmont-Latimer complex is dominated by an extensive area of metamorphosed hornblende meladiorite to quartz diorite and hornblende tonalite, gradational northwards into hornblende-biotite granodiorite and granite and southward into gabbro (**Allard and Whitney, 1994**). Numerous small bodies of metamorphosed peridotite, pyroxenite, and gabbro are scattered throughout the complex. Although interpreted by **Allard and Whitney** (**1994**, **1995**) as relict klippen from an eroded thrust sheet, these occurrences may be analogous to small ultramafic bodies that intrude the Mean Crossroads and Wildcat Branch zoned intrusive complexes in northern South Carolina (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**).

The Latimer portion of the complex in Abbeville and McCormick counties, South Carolina is characterized by **Griffin** (**1978**) as a genetically related assemblage of mafic metaplutonic and metavolcanic rocks, with composite plutons of Rifted Arc metagabbro and metadiorite intruding a thick Primitive Arc sequence of dominantly mafic metavolcanics. **Weisenfluh and Snoke** (**1978**) restricted the term "Latimer complex" to the Rifted Arc metagabbro-metadiorite-trondhjemite-tonalite plutonic suite within the area identified by **Griffin** (**1978**).

The trondhjemite and tonalite, extensions of the Heardmont complex to the west, intrude the older metagabbro-metadiorite plutonic sequence to the north and may be comagmatic with intermediate and felsic metavolcanic and undivided pelitic metasedimentary sequences (**Fig. 6**, **Fig. 7**) to the northeast, south, and southwest (**Weisenfluh and Snoke, 1978**). This Rifted Arc metavolcanic-metasedimentary sequence appears to stratigraphically overlie the older Primitive Arc mafic-dominated metavolcanic sequence, which interfingers with thick sequences of quartzofeldspathic biotite paragneiss, interpreted as metagreywacke by **Griffin** (**1978**) with interbedded mafic metavolcanic and metavolcaniclastic units.

Small, more evolved, younger, but possibly comagmatic epizonal felsic plutonic-volcanic centers are present at the southwest, southern, and northeast margins of the Heardmont-Latimer complex (**Fig. 6**). The southern margin of the complex is intruded by quartz-phyric dacite porphyry plugs and dikes in northern Wilkes County, Georgia (**Allard and Whitney, 1994**), locally associated with areas of phyllic to silicic hydrothermal alteration metamorphosed to the upper greenschist facies.

The Latimer complex of **Weisenfluh and Snoke** (**1978**) and the older mafic metavolcanic-metasedimentary sequence of **Griffin** (**1978**) are intruded by the Calhoun Falls and Mount Carmel gabbro-diorite-syenite plutons if the Concord suite (**Fig. 6**). Both are dominantly gabbro with minor pyroxenite, hornblendite, diorite, and syenite differentiates. These bodies truncate or deform the older metaplutonic, metavolcanic, and metasedimentary units and are commonly surrounded by subtle to distinct contact metamorphic aureoles that are variably enriched in amphibole, pyroxene, epidote, cordierite, and sillimanite-muscovite-chloritoid.

The Mount Carmel pluton appears to dome the stratigraphic sequence to the east of the Heardmont-Latimer complex, exposing the Primitive Arc stratigraphic sequence, metamorphosed to the amphibolite facies, below the overlying Rifted Arc stratigraphic sequence, metamorphosed to the greenschist facies (**Fig. 6**, **Fig. 7**).

Latimer magmatic complex late felsic differentiates

A Rifted Arc felsic metavolcanic unit along the southern margin of the Latimer complex in South Carolina (**Fig. 9**) is intruded by a lenticular body of biotite metatrondhjemite that grades locally into biotite tonalite (**Weisenfluh and Snoke, 1978**) or metadacite (**Griffin, 1978**). Hornblende metatonalite occurs as numerous small stocks and cupolas that intrude metagabbro-diorite and metatrondhjemite units along the southern margin of the Latimer complex (**Weisenfluh and Snoke, 1978**).

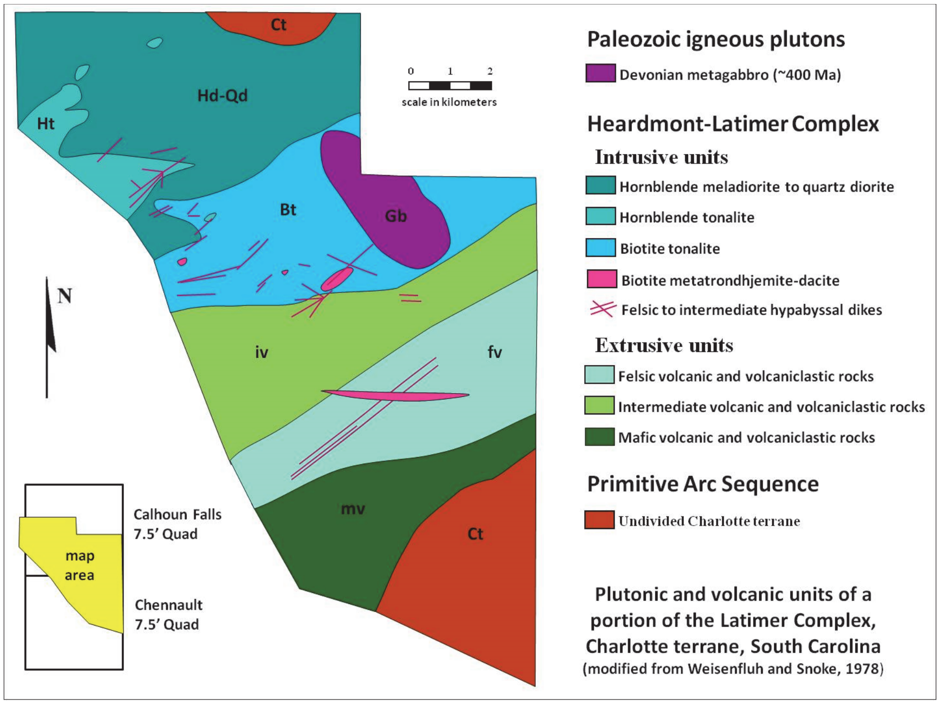


Fig. 9: Low-volume differentiates along the southern margin of the Latimer complex

The metagabbro-metadiorite, metatrondhjemite, and metatonalite of the complex are intruded by numerous hypabyssal dikes, sills, and plugs of intermediate to felsic composition (**Weisenfluh and Snoke, 1978**). Many of the dikes occur as swarms and radial clusters (**Fig. 9**). Most dikes are 1-2 meters wide, but some attain widths of 6 meters. They are typically subvertical and most trend 050°-055°, with a subsidiary set oriented east-west (**Weisenfluh and Snoke, 1978**).

Hornblende tonalite is intruded by andesite porphyry and the biotite metatrondhjemite is intruded by small circular to elliptical plugs and dikes of porphyritic quartz keratophyre (**Weisenfluh and Snoke, 1978**). The porphyry is characterized by blue quartz phenocrysts 0.5-2.0 centimeters in diameter that are commonly bipyramidal to rounded with embayed margins and subordinate plagioclase phenocrysts in a groundmass of microcrystalline quartz + albite + sericite (**Weisenfluh and Snoke, 1978**). Granophyric intergrowths of quartz and feldspar suggest shallow emplacement with rapid crystallization and volatile loss. Rhyolite porphyry dikes, the only intrusive phases with significant potassium feldspar content, intrude the biotite trondhjemite and hornblende gabbro in the southwest part of the Latimer complex.

The generally small, apparently younger epizonal intermediate to felsic intrusive bodies and possible comagmatic volcanic units along the southern margin of the Latimer igneous complex are typically metamorphosed to the middle to upper greenschist facies. This strongly contrasts with the older Primitive Arc mafic metavolcanic-metasedimentary sequence and the older plutons of the Rifted Arc sequence, which are everywhere strongly deformed by D_1 and metamorphosed to the middle to upper amphibolite facies.

The Rifted Arc sequence of the Eastern Oglethorpe magmatic complex

In eastern Oglethorpe County GA in the South domain (**Fig. 6**), the older mafic Primitive Arc sequence of the Charlotte terrane is intruded by plutons of metamorphosed hornblende meladiorite to quartz diorite and hornblende tonalite similar to those of the Heardmont-Latimer complex to the northeast (**Davidson, 1981**; **Allard and Whitney, 1994**). The thick Primitive Arc sequence of dominantly mafic flows forming the base of the complex is overlain by an apparently younger sequence of intermediate and felsic volcanic rocks up to 460 meters wide that extends for around 7.3 kilometers along strike (**Davidson, 1981**). Intrusive activity, including trondhjemite bodies and a small dacite plug, was synchronous with both intermediate and felsic volcanism.

The Rifted Arc volcanic sequence consists largely of massive to porphyritic dacite flows and tuffs interbedded with minor mafic flows and tuffs. Individual units are 0.3-2.4 meters thick, fine-grained, and commonly white to buff-colored. Porphyritic dacite flow units are massive, homogenous, non-foliated and plagioclase- and quartz-phyric **Davidson** (**1981**). Plagioclase phenocrysts are 0.5-1.0 millimeter long and quartz phenocrysts average 0.3 millimeters in diameter, are subrounded to angular, and partly resorbed. Pyroclastic units interbedded with the flows are very fine grained and well foliated, although **Davidson** (**1981**) reports that delicate graded bedding is well preserved.

Rhyolite to rhyodacite flows are a more localized, minor component of the Rifted Arc sequence as 0.6-4.6 meters thick units interbedded with crystal-lithic felsic volcaniclastic units and pyritic chert (**Davidson, 1981**). Quartz and plagioclase phenocrysts average 0.5-1 millimeter in diameter and form 6-30% of the rock, with an unfoliated groundmass of quartz + plagioclase + magnetite + epidote + sericite with local minor chlorite and biotite. Interbedded crystal-lithic volcaniclastic units are identical in composition with 1-6% subrounded masses of quartz + plagioclase interpreted as lithic fragments.

Chert units are 0.3-4.6 meters thick and discontinuous, gray to green-black, and very fine grained. They are composed of equigranular 0.05 millimeter diameter quartz grains with variable accessory sericite, chlorite and epidote and 2-3% pyrite + magnetite + chalcopyrite (**Davidson, 1981**). Rather than true chert, these units appear to be zones of intense silicic alteration.

Davidson (**1981**) concludes that the Primitive Arc mafic volcanic sequence of the Eastern Oglethorpe County complex is at amphibolite metamorphic facies, but the younger intermediate to felsic sequence of the Rifted Arc is at greenschist facies. The change in grade is marked by the albite/oligoclase isograd and generally coincides with the lithologic change. Peak metamorphic conditions are estimated at 530-600°C at 4-7 kilobars for the amphibolite facies rocks and 450-500°C at 4-6 kilobars for the greenschist facies rocks (**Davidson, 1981**). Deformation and metamorphism of the sequence during D_1 was accompanied by synkinematic intrusion of the

Hutchings quartz monzonite and Georgia Farm metagabbro, both possibly formed though partial melting of the lower crust and mantle (**Davidson, 1981**).

The volcanic sequence in eastern Oglethorpe County is intruded by the Chafin and State Farm gabbro plutons of the Concord suite. The Chafin Gabbro covers and area of around 6 km^2 and is strongly differentiated with orthopyroxenite and hornblende gabbro dominant to the west and anorthositic gabbro and granophyre present along the east side (**Davidson, 1981**). The Georgia Farm Gabbro pluton is rimmed by a contact metamorphic aureole that ranges from dark green to black pyritic pyroxene-hornblende hornfels to magnetite-bearing muscovite-chlorite-corundum hornfels (**Davidson, 1981**).

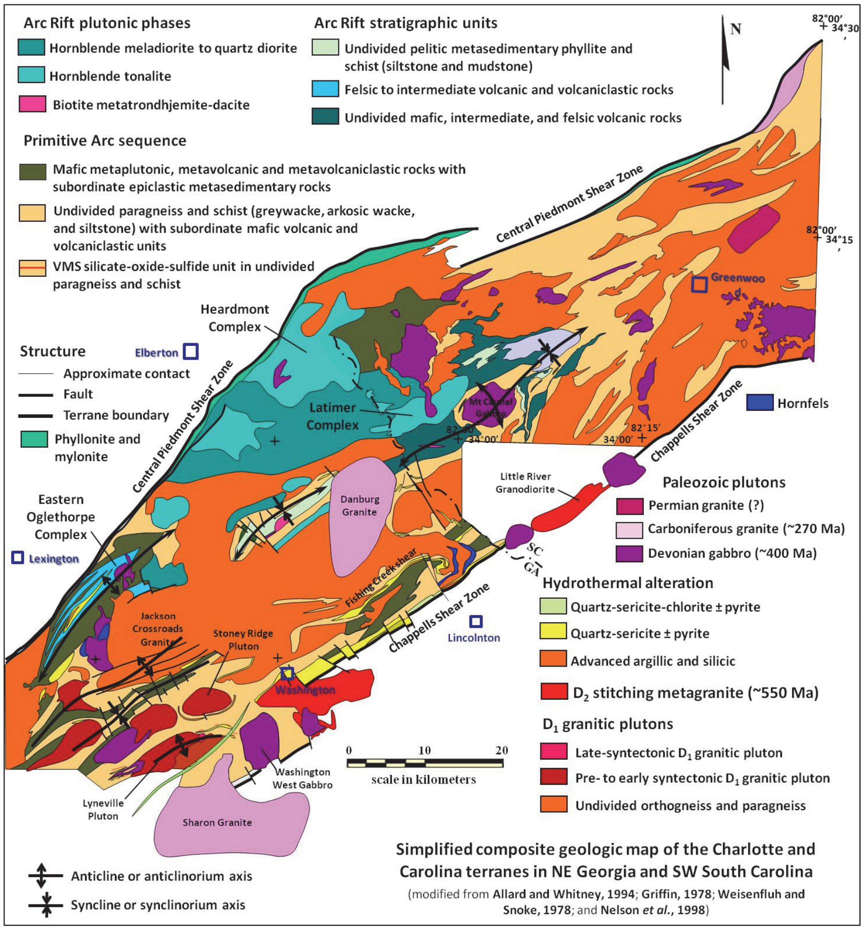
D_1 deformation and metamorphism in the Charlotte terrane

Documenting and interpreting the deformation history in the Charlotte terrane is made difficult by poor outcrop, deep weathering, and the presence of numerous large syn- to post-tectonic igneous intrusions. Regional marker units are not typically present to aid in structural interpretations and bedding (S_0) is seldom preserved. There are exceptions in both the North and South domains in the form of distinctive stratigraphic units of the Primitive Arc sequence that can sometimes be traced for tens of kilometers. These marker units are relatively thin and distinct lithologies that contrast strongly with enclosing rocks; they include some felsic and mafic metavolcanic units and stratabound and strataform VMS deposits and their associated footwall zones of hydrothermal mineralization.

The relatively thin felsic volcanic sequence and associated silicic to phyllic alteration that host the Nanny Mountain VMS deposit in the North domain (**Fig. 4**) can be traced for around 15 kilometers around a large F_1 antiform with a wavelength of 3 kilometers that trends NNE and plunges gently north (**Butler, 1966**; **Brazell, 1984**). However, there is a general absence of metavolcanic and metasedimentary sequences with well-defined marker units throughout the North domain. Compositional layering and schistosity in metavolcanic and metasedimentary rocks of the North domain typically strike northeast with dips either steep or vertical, consistent with large-scale isoclinal folding (**Butler and Fullagar, 1978**).

Stratigraphic marker units of the Primitive Arc sequence in the South domain in Georgia include an extensive and well-defined mafic sequence in Oglethorpe, Taliaferro, and Wilkes counties, the TM and Tyrone VMS-type exhalative horizons in parts of Taliaferro and Wilkes Counties, and several laterally extensive metamorphosed phyllic to advanced argillic and silicic hydrothermal alteration zones (**Fig. 6**, **Fig. 8**, **Fig. 10**). The presence of multiple generations of hydrothermal alteration and mineralization in the Taliaferro-Wilkes counties area, each associated with specific events in the geologic evolution of the Charlotte terrane, is useful in constraining the timing and character of deformation and metamorphism.

Some workers have proposed an initial deformational event (D_i) characterized by large-scale recumbent F_i folding (**Conway, 1986**; **Dunnagan, 1986**; **Turner, 1987**; **Allard and Whitney, 1994**) that produced a subhorizontal planar fabric (S_i) only preserved in the noses of subsequent F_1 folds in basement gneiss. However, these “basement gneiss” units are strongly deformed pre-D_1 plutons with foliation locally developed parallel to the contacts. No F_i fold axes at any scale have been identified in the Charlotte terrane, and there is no compelling evidence for these earlier structures and fabrics.



Simplified composite geologic map of the Charlotte and Carolina terranes in NE Georgia and SW South Carolina

(modified from **Allard and Whitney, 1994**; **Griffin, 1978**; **Weisenfluh and Snoke, 1978**; and **Nelson *et al.*, 1998**)

Fig. 10: Recognized first order F_1 folds in the Charlotte terrane in the South domain

The character of regional-scale deformation and metamorphism in the Charlotte terrane in northeast Georgia (**Thurmond, 1979**; **Davis, 1980**; **Davidson, 1981**; **Conway, 1986**; **Dunnagan, 1986**) and adjacent areas of South Carolina (**Secor and *et al.*, 1982**; **Halik, 1983**; **Hauck, 1984**; **Offield, 1995**) is consistent with that documented in the Charlotte terrane of north-central South Carolina (**Butler, 1971**; **Brazell, 1984**; **Dennis and Wright, 1997**). Regional structure and rock fabrics are dominated by large-scale F_1 folds and foliations, although only a few first order folds are recognized or well constrained (**Fig. 10**). Structures and fabrics related to subsequent deformation events are regionally subordinate and largely localized along the terrane margins.

The dominant D_1 event and synchronous amphibolite facies regional metamorphism (M_1) produced the dominant subvertical foliation (S_1) present throughout the South domain of the

Charlotte terrane. This fabric appears to be axial planar to large upright, tight to isoclinal F_1 folds with axes trending around 065°E (**Thurmond, 1979**; **Davis, 1980**; **Davidson, 1981**; **Conway, 1986**; **Dunnagan, 1986**; **Hall, 1991**; **Allard and Whitney, 1994**). Metamorphogenic compositional banding and original bedding (S_0) are generally parallel to this foliation. The fold pattern is repeated at scales ranging from centimeters to kilometers, with the largest forming poorly defined, possibly doubly plunging anticlinoria and synclinoria with wavelengths of around 5-10 kilometers and lengths of 20-50 kilometers (**Fig. 10**).

Identified second order anticlines and synclines appear to have wavelengths of 1-5 kilometers and lengths of 5 to over 20 kilometers. These two largest orders of fold structures are primarily responsible for the large-scale map pattern of stratigraphic lithologies of the Charlotte terrane in the South domain. Smaller orders of folds are seldom observed at map scales but may be present in individual outcrops at scales of tens of meters to millimeters.

The greatest intensity of D_1 deformation and regional M_1 amphibolite facies metamorphism is expressed in the Primitive Arc Sequence throughout the South domain of the Charlotte terrane. This observation extends to pre-D_1 and early syn-D_1 plutons. This same intensity of deformation and metamorphism is not expressed in late D_1 plutons or in the intrusive bodies, volcanic units, and sedimentary sequences associated with the late-D_1 Rifted Arc sequence (**Griffin, 1978**; **Griffin, 1979**; **Weisenfluh and Snoke, 1978**; **Davidson, 1981**).

Carolina terrane constraints on deformation in the Charlotte terrane

The timing of D_1 tectonism and the onset of arc-rifting in the Charlotte terrane in north-central South Carolina are broadly constrained to between ca. 571 Ma and 540 Ma, with both deformation and arc-rifting ended by ca. 535 Ma (**Dennis and Wright, 1997**). There are few geochronological constraints on the timing of D_1 in the South domain. The tectonic history of the adjacent Carolina terrane suggests additional possible constraints on the tectonic evolution of the Charlotte terrane.

Regional D_1 deformation and greenschist facies metamorphism of the South Carolina Sequence of the adjacent Carolina terrane (Delmar event of **Secor *et al.,* 1986**) is characterized by mega-scale F_1 tight to isoclinal, gently doubly plunging, southeast-verging folds that strike northeast. The scale, character, and orientation of these folds are similar to F_1 folds in the Charlotte terrane in northeast Georgia, although the latter are often truncated or obscured by younger plutons.

The D_1 deformation and regional greenschist facies metamorphism of the Carolina terrane from northeast Georgia to central South Carolina preceded collision and suturing of the Charlotte and Carolina terranes. Dextral transpression along the Chappells shear zone, overprinting the suture zone, is dated to ca. 550 Ma by the synkinematic Longtown Metagranite (**Barker *et al.*, 1998**) and Little Mountain Metatonalite (**Dallmeyer *et al.*, 1986**) stitching plutons in central South Carolina. Regional D_1 structures and fabrics in both the Charlotte and Carolina terranes in Georgia are overprinted by D_2 deformation within and along the margins of the Chappells shear zone. In central South Carolina, both D_1 and D_2 appear synchronous with M_1 regional metamorphism of the Carolina terrane and may represent different phases of arc-arc collision.

In central South Carolina, U-Pb zircon age dates for the Persimmon Fork Formation of the Carolina terrane, deformed by both D_1 and D_2 events, range from 557 ± 15 Ma to 550.5 ± 5.9 Ma (**Barker *et al.*, 1998**; **Ayuso *et al.*, 2005**). These data suggest that arc volcanism in the Carolina terrane in central South Carolina continued until collision with the Charlotte terrane. It appears likely that D_1 deformation and regional metamorphism of both the Charlotte terrane and adjacent South Carolina Sequence from Georgia to central South Carolina were broadly synchronous with the initial collision of the these two volcanic arcs, suggesting that the D_1 event in the Charlotte terrane in Georgia begins prior to this event and probably ends no later than ca. 550 Ma.

VMS deposits of the Primitive Arc Sequence

The most characteristic style of mineralization associated with the Primitive Arc Sequence of the Charlotte terrane in the North and South domains is VMS-type sulfide deposits and associated hydrothermal alteration. Four deposits of this type are recognized; one in the North domain and three in the South domain. The Nanny Mountain deposit is located in York County SC in the North domain. The South Domain hosts the TM Prospect in Taliaferro County, the Tyrone occurrence in southern Wilkes County GA, and an unnamed occurrence in north-central McCormick County SC.

All are characterized by extensive associated phyllic to silicic hydrothermal alteration and local stringer-type mineralization, typically located in the stratigraphic footwall of the VMS mineralized horizon. All three occurrences in the South domain are characterized by stratabound units of manganiferous garnet ± barite ± silica ± base metal sulfides ± gold and silver. The Nanny Mountain VMS deposit in the North domain is a body of massive pyrrhotite ± pyrite enclosed by footwall and hangingwall zones of intense phyllic alteration. There is potential for the discovery of additional VMS deposits in the Primitive Arc sequence in the North and South domains of the Charlotte terrane.

The Nanny Mountain VMS deposit

In the type area for the Charlotte terrane in northern York County South Carolina, VMS-style hydrothermal alteration and mineralization is present at Nanny Mountain (**Fig. 4**). Nanny Mountain is a prominent ridge with a local relief of 100 meters, formed by a resistant sequence of muscovite schist and phyllite that enclose units of siliceous granofels. **Butler** (**1971**) reports a continuous gradation from schist and phyllite composed of 90% muscovite/sericite to nearly pure granular quartz with minor white mica and pyrite. Disseminated pyrite is most abundant where the granofels is thickest (**Butler, 1971**) and this unit is locally "heavily impregnated" with pyrite (**Graton, 1906**).

This extensive alteration zone occurs within a localized Primitive Arc sequence of dominantly dacitic metavolcanic units with subordinate rhyolite and basalt members (**Brazell, 1984**). Although **Butler** (**1971**) interprets the granofels as quartzite, possibly a single unit repeated by folding, **Brazell** (**1984**) interprets the occurrence as metamorphosed hydrothermal alteration assemblages. The central granofels unit is intensely silicified quartz porphyry with up to 80% rounded and partially resorbed, bluish-gray opaline quartz phenocrysts in a matrix of fine-grained quartz.

This alteration zone is up to 2 kilometers wide at Nanny Mountain, where a central siliceous granofels unit up to 10 meters thick is traced continuous along strike for almost 8 kilometers. Additional granofels units up to 1.2 kilometers long parallel the main unit to the east and west within the enclosing mica schist/phyllite zone (**Brazell, 1984**). The alteration zone thins to the north and south and the quartz granofels units are discontinuous, but the alteration zone is traced continuously for about 15 kilometers around the nose of a somewhat irregular or refolded F_1 antiform **Brazell** (**1984**). Nanny Mountain is located on the western limb (**Fig. 4**).

There is a direct association between the granofels and schist/phyllite sequence and the massive sulfide mineralization. A gossan deposit 1-2 meters wide extends intermittently for over 1200 meters northeast along the crest of Nanny Mountain. The gossan was mined and smelted locally for iron from 1760-1820 (**Sloan, 1908**). Drilling confirmed that the gossan was the surface expression of a massive pyrrhotite body (**Sloan, 1908**). The Nanny Mountain VMS is associated with a localized stream sediment arsenic anomaly (**Goldsmith *et al.*, 1989**).

Brazell (**1984**) reports that the Nanny Mountain massive sulfide deposit has been drilled three times; it consists of a zone of massive pyrrhotite up to 10 meters thick, hosted by the central granofels alteration unit, and is surrounded by a halo of disseminated pyrite. The mica schists and phyllite enclosing the siliceous granofels appear to be part of an extensive zone of variable phyllic alteration. Zones of green micas (Cr or Ba muscovite) are present in the phyllitic schists west of the central granofels (**Brazell, 1984**). **Brazell** (**1984**) interprets the Nanny Mountain occurrences as a stratabound VMS deposit and associated footwall and hangingwall hydrothermal alteration zones. This is the largest VMS-style deposit identified in the Charlotte terrane but with the lowest base metal sulfide content.

Possible VMS system near Cramerton, Gaston County NC

An ENE-trending zone of silicic to phyllic alteration around 3000 meters long and up to 300-500 meters wide is located about 3.5 kilometers southeast of the center of Cramerton in eastern Gaston County NC (**Goldsmith *et al.*, 1989**). This alteration zone is developed in a sequence of felsic volcanic rocks of the Primitive Arc sequence that is over 26 kilometers long and up to 4 kilometers wide (**Fig. 11**). Additionally, there are four known occurrences of gold mineralization in the area and, like the Nanny Mountain VMS system to the south, a possible association with two areas of stream sediments anomalous in arsenic (**Fig. 11**).

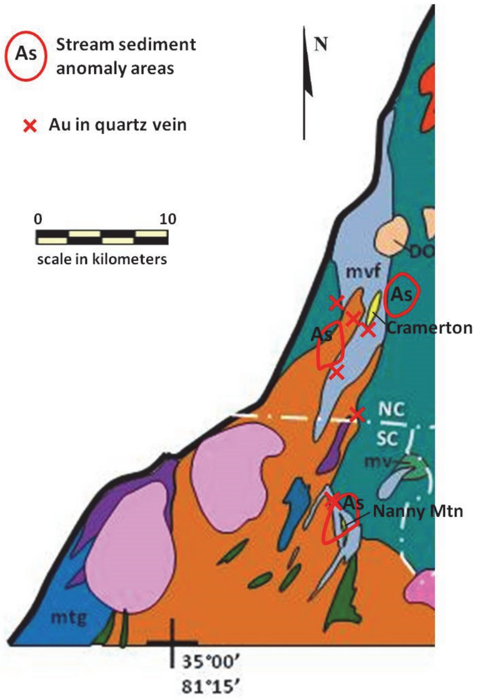


Fig. 11: Cramerton hydrothermal alteration zone, Gaston County NC

Although there is no report of VMS style mineralization in this area, the hydrothermal alteration could be related to a VMS system. However, this alteration zone is located in an urbanized area and has limited economic potential.

VMS deposits in Taliaferro and Wilkes County, Georgia

Of special significance in the Primitive Arc sequence in Georgia is the presence of VMS-style exhalative mineralization and associated footwall zones of phyllic alteration at the TM Prospect in Taliaferro County and the Tyrone occurrence in southern Wilkes County (**Fig. 8**). These deposits provide a stratigraphic marker horizon and facing criteria for evaluating mega- and meso-scale structure in this area of the Charlotte terrane.

The TM Prospect is located about 24 kilometers southwest of Washington in northwest Taliaferro County (**Fig. 8**). The VMS mineralized zone varies from < 2 to 20 meters thick and consists of one to two massive, locally discontinuous 1-3 meters thick manganiferous granofels units in a sequence of manganiferous quartz + muscovite and muscovite schists with narrow interbedded intervals of quartzofeldspathic gneiss and schist (**Moye, 1988**). The granofels are composed of aggregated medium to coarse-grained yellow-brown to red-brown manganiferous garnet intimately mixed with less than 5% to locally over 50% magnetite/martite and <5%-25% quartz (**Moye, 1988**).

Barite is a common component of the granofels, ranging from around 1% to locally 80% over narrow intervals. Strongly baritic intervals characteristically contain minor sulfides, including pyrite, sphalerite, galena, and rare chalcopyrite (**Moye, 1988**). There is a strong association between higher barite content and increased base metal and precious metal values in the granofels. Base metal mineralization seldom exceeds 0.5 wt% combined, and varies from Pb-rich to Zn-rich with up to 1 oz/t Ag associated with intervals of more abundant galena.

The mineralization is repeated on the nearly vertical limbs of a northeast-trending 2nd order F_1 anticline, forming two parallel horizons separated by about 820 meters (**Fig. 8**). These horizons are flanked towards the axis of the anticline by zones of quartz + muscovite + pyrite ± sillimanite schist up to 120 meters wide that are interpreted as metamorphosed phyllic alteration footwall to the VMS horizons (**Moye, 1988**). Localized sub-seafloor thermal convection may have been driven by the intrusion of irregular, discontinuous gabbroic sills that form 30-50% of the deeper footwall sequence in the core of the anticline. The northern VMS horizon is traced continuously along strike as outcrop and float for over 1500 meters, with discontinuous occurrences of similar mineralization traced for another 2000 meters to the southwest (**Moye, 1988**).

The similar Tyrone VMS occurrence is located 10 kilometers southwest of Washington and 2.5 kilometers south of the Stoney Ridge Gold Mine on the south side of Georgia highway 44 in Wilkes County (**Fig. 8**). Discontinuous thin (0.5-2.0 meters) units of locally massive manganiferous garnet + quartz ± barite granofels extend along strike for at least 3 kilometers. Footwall to the VMS horizon on the south side is a continuous zone of quartz + muscovite ± sillimanite ± pyrite schist that extends almost east-west for at least 5 kilometers and varies from 10 to 100 meters thick (**Fig. 8**). This alteration zone is interpreted as a sub-seafloor zone of localized hydrothermal circulation that vented onto the seafloor to form the overlying exhalative mineralization. The eastern end of both the alteration zone and VMS granofels is offset about 800 meters to the south across the northeast-trending Stephens Creek shear zone (**Fig. 8**).

The Tyrone occurrence may be stratigraphically correlative with that at the TM Prospect, located 10 kilometers to the west-southwest. Although discontinuous, this style of VMS mineralization is traced for a total of at least 20 kilometers along strike, suggesting deposition of probably low temperature, locally barite-rich manganiferous to ferruginous, silicic to calcic, locally base metal sulfide-bearing VMS-style exhalative chemical sediments across an area of possibly up to 400 km^2.

The presence of thick, extensive areas of apparently stratabound phyllic hydrothermal alteration footwall to these exhalative units suggests broad areas of subsurface thermal convection venting mineral-rich fluids to the seafloor. The driver for this thermal activity may be the numerous small mafic plugs, dikes, and sills that intrude the Primitive Arc Sequence in this area of the Charlotte terrane, some possibly feeders for mafic volcanism at multiple stratigraphic levels. An especially thick set of mafic sills is present in the deep footwall of the TM Prospect VMS-style deposit, which has the higher base metal sulfide and silver content.

Both occurrences lie along the northern flank of a possible doubly plunging F_1 antiform, informally designated the Lyneville Anticlinorium, cored by granitic orthogneiss and granodiorite (**Fig. 8**). The Tyrone and TM Prospect VMS-type mineralization and associated footwall alteration zones provide invaluable stratigraphic marker horizons and facing criteria that are consistent with the interpreted structure of the Lyneville Anticlinorium.

Volcanogenic massive sulfide (VMS) mineralization and associated hydrothermal systems are typically associated with volcanic rift environments, including mid-ocean ridges, back-arc basins, intra-oceanic arc rifts, and continental arc rifts (e.g., **Swinden, 1991**; **Hannington *et al.*, 1995**; **Scott, 1997**; **Syme *et al.*, 1999**; **Barrett *et al.*, 2001**; **Piercey *et al.*, 2001**; **Dusel-Bacon *et al.*, 2004**). Specific environments and associations include extensional and transtensional grabens, calderas, and synvolcanic and synsedimentary faults (e.g., **Gibson, 1989**; **Allen, 1992**; **McPhie and Allen, 1992**; **Setterfield *et al.*, 1995**; **Allen *et al.*, 1996**; **Gibson *et al.*, 1999**; **Stix *et al.*, 2003**; **Gibson, 2005**).

The occurrence of the TM Prospect and Tyrone VMS-type occurrences suggest the possibility of localized rifting within the Primitive Arc Sequence of the Charlotte terrane that pre-dates the regional D_1 deformation and terrane-scale arc-rifting recognized in northeast South Carolina (**Dennis and Shervais 1996**; **Dennis and Wright, 1997**; **Fullagar *et al.*, 1997**; **Shervais *et al.*, 2003**).

In terms of host lithologic succession, the TM and Tyrone occurrences of VMS-type mineralization may be most similar to the class of VMS deposits characterized by mafic-siliclastic sequences with subequal proportions of mafic ± ultramafic volcanic and siliclastic sedimentary rocks ± minor felsic volcanic rocks, such as the Besshi (Shikoku, Japan), Outokumpu (Finland), and Windy Craggy (British Columbia, Canada) deposits (**Barrie and Hannington, 1999**; **Franklin *et al.*, 2005**; **Piercey, 2010**). These environments are dominated by mafic material in juvenile magmatic environments with minimal input from continental crustal rocks.

Unnamed Prospect in McCormick County SC

Another occurrence of VMS-type mineralization is located about 7 kilometers south-southwest of Parson's Mountain in northern McCormick County, South Carolina, where a narrow horizon of manganiferous mineralization was traced discontinuously for up to 3 kilometers. This occurrence is hosted by interbedded mafic metavolcanic rocks, immature clastic metasediments, and possibly minor felsic metavolcanic rocks of the Primitive Arc Sequence. Evaluation by Amselco Minerals Incorporated in 1983-84 indicated a discontinuous, narrow zone of Ag-bearing manganiferous oxide and garnet with accessory pyrite and traces of chalcopyrite, galena, and sphalerite. Two core drill-holes intersected a possible footwall zone of disseminated and stringer pyrite with trace of chalcopyrite in silicified rocks.

Hydrothermal alteration zones of the Rifted Arc Sequence

The most common style of hydrothermal alteration in the North and South domains of the Charlotte terrane is distinctly zoned elongate tabular to elliptical units of silicic ± advanced argillic + phyllic alteration that parallel the local tectonic fabric. These units are especially abundant in the North domain, with the largest clustered in Mecklenburg County NC (**Fig. 2**). The largest zones are up to 10 kilometers long and up to 3 kilometers wide, mapped as phyllite and schist or quartzite in the Charlotte 1° x 2° Quadrangle (**Goldsmith *et al.*, 1989**). All observed alteration zones in the North domain are metamorphosed to the amphibolite facies. These alteration zones typically contain disseminated rutile and minor heterogeneously disseminated pyrite or hematite ± magnetite. Reconnaissance rock sampling suggests that many of these zones in the North Domain contain strongly anomalous concentrations of gold.

The character and geologic associations of most of the hydrothermal alteration systems in the North domain are unknown. Although mapped as quartzite and muscovite phyllite and schist (**Goldsmith *et al.*, 1989**), most of the alteration zones in northern Lancaster County SC are heterogeneously altered felsic volcanic and volcaniclastic units of the Primitive Arc sequence, including that at Nanny Mountain (**Fig. 2**). The large alteration zone located southwest of the Concord syenite ring dike (**Fig. 2**) contains aluminum silicate minerals indicative of advanced argillic alteration. An irregular arcuate body in northwest Mecklenburg County about 3 kilometers south of the southeast end of Lake Norman (**Fig. 2**) includes zones of quartzite with sillimanite and magnetite and quartzite with sillimanite, chloritoid, muscovite, pyrite, and rutile (**Milton, 1986**).

A large body of "quartzite" located about 15 kilometers farther to the south includes the assemblage andalusite + quartz + muscovite (**Milton, 1986**). These alteration zones are not well constrained in their character or potential for mineralization. Many contain accessory rutile (**Milton, 1986**) and sometimes pyrite, gahnite, and aluminum phosphate minerals (azulite, rarely trolleite and augelite). Some of the smaller alteration zones east of Charlotte are known to carry anomalous gold in association with disseminated pyrite.

Many of the hydrothermal alteration zones of the North domain are hosted within an extensive sequence (mgd) mapped as metagranodiorite and related metagranitoids (**Goldsmith *et al.*, 1989**). These rocks are light gray to yellowish-gray in color, fine- to coarse-grained, with a heterogeneous range of grain-sizes, and massive to distinctly foliated. They are interpreted as metamorphosed plutonic rocks ranging from monzogranite to leucodiorite and composed mostly of plagioclase, quartz, potassium feldspar, and biotite with accessory epidote, sericite, and various opaque minerals (**Goldsmith *et al.*, 1989**). However, this is a highly heterogeneous sequence that may include both older and younger rocks that include paragneiss and orthogneiss. Similar rocks in the South domain of the Charlotte terrane are largely paragneiss and interpreted as immature epiclastic metasedimentary units of the Primitive Arc sequence.

Most of the larger hydrothermal alteration systems in the North domain shown of the geologic map of the Charlotte 1° x 2° Quadrangle (**Goldsmith *et al.*, 1989**) are hosted within the widespread unit (mqd) interpreted as metamorphosed quartz diorite and tonalite (**Fig. 2**). These rocks are gray, usually medium- to coarse-grained, generally foliated rocks composed dominantly of plagioclase, quartz, biotite, hornblende, and epidote (**Goldsmith *et al.*, 1989**). Similar rocks in the South domain of the Charlotte terrane are plutonic units of the Rifted Arc sequence. Large silicic ± advanced argillic + phyllic hydrothermal systems of the South domain are characteristically associated with Rifted Arc magmatic centers and associated volcanic and sedimentary sequences (**Fig. 6**).

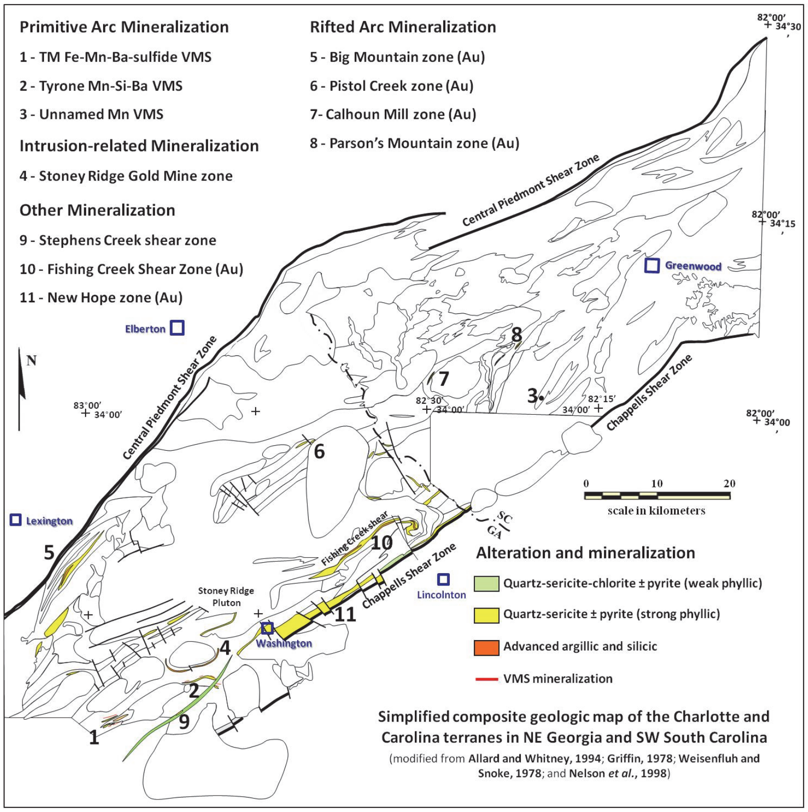
In the North domain, the association of auriferous metamorphosed hydrothermal alteration formed along shear zones concurrent with Rifted Arc magmatism is best constrained in the Mean Crossroads plutonic complex (**Fig. 5**). Phyllic to advanced argillic alteration units along these shear zones are 10-150 meters wide, up to several kilometers long, and were locally the focus of small-scale historic gold mining. These shear zones cut across mafic to intermediate metavolcanic units and are crosscut by metamorphosed mafic and ultramafic dikes, possible feeders for higher-level volcanism, suggesting that they formed synchronous with deformation and contemporaneous with rift-related mafic and ultramafic magmatism (**Dennis and Shervais, 1991**; **Dennis and Shervais, 1996**).

Hydrothermal alteration zones associated with the Heardmont-Latimer complex

Major zones of intense hydrothermal alteration with precious and base metal sulfide mineralization spatially associated with the Heardmont-Latimer complex include Parson’s Mountain, Calhoun Mill, Pistol Creek, and an unnamed alteration zone (**Fig. 12**). Parson’s Mountain (8) is part of an extensive zone of metamorphosed hydrothermal alteration in southern Abbeville County, South Carolina that is hosted by Rifted Arc felsic to mafic volcanic and volcaniclastic units and epiclastic sedimentary rocks of the Latimer complex.

This complex alteration zone has a strike length of at least 7 kilometers, is up to 800 meters wide, and is largely characterized by extensive zones of phyllic alteration metamorphosed to quartz + sericite ± sillimanite + pyrite and/or magnetite schist. This phyllic alteration encloses several zones of silicic and advanced argillic alteration, the largest forming the summit of Parson’s Mountain. The presence of sillimanite may be a metastable result of the highly aluminous composition of the schist, rather than a reliable indicator of amphibolite facies metamorphic conditions.

The main body of hydrothermal alteration is centered at Parson’s Mountain and strongly zoned. It consists of a central core of massive silicic granofels 15-30 meters thick, which is enclosed by and gradational into a zone of advanced argillic alteration about 1500 meters long and up to 200 meters wide. The silicic and advanced argillic core is enclosed by an intense phyllic alteration zone 3000 meters long and up to 500 meters wide. Pyrophyllite in the advanced argillic zone is retrograded from andalusite, suggesting an epithermal alteration system metamorphosed to the greenschist facies. The silicic granofels and phyllic schists contain 2-10% disseminated pyrite.



Simplified composite geologic map of the Charlotte and Carolina terranes in NE Georgia and SW South Carolina

(modified from Allard and Whitney, 1994; Griffin, 1978; Weisenfluh and Snoke, 1978; and Nelson *et al.*, 1998)

Fig. 12: Mineralization in the Charlotte terrane, South domain

A total of 34 small gold mines and prospects are located in the vicinity of Parson's Mountain. Most are opened along small quartz ± pyrite veins that often assay in excess of 1 oz/t Au. The veins are generally conformable with the local tectonic fabric and often occur in unaltered or propylitically altered rock. Lower grade but larger tonnage Au mineralization is associated with disseminated pyrite in quartz + sericite schists, often near redox transitions into magnetite-bearing schist.

Exploration work in the Parson's Mountain system by Asarco and Texasgulf in the mid-1980s identified a zone of Au mineralization almost 400 meters long and 12 meters thick that averaged 0.16 oz/t Au. Within this zone is a higher-grade interval averaging 2 meters in width with 5.5 oz/t Au. The mineralization is hosted by quartz + sericite + sillimanite ± pyrite ± magnetite schist and saccaroidal quartz granofels interpreted as hydrothermally altered andesitic tuffs. The highest Au grades are hosted by intense granoblastic silicic alteration.

The characteristics of the Parson's Mountain alteration system are consistent with epizonal high-sulfidation hydrothermal systems, and may be associated with hypabyssal felsic intrusions or volcanism on the periphery of the Heardmont-Latimer complex concurrent with active faulting.

Thirteen kilometers southwest of Parson's Mountain, the Calhoun Mill (7) alteration zone (**Fig. 12**) of massive to banded granular quartz granofels is up to 30 meters wide extends for 1500 meters near the contact of a diorite phase of the Mount Carmel Pluton. The granofels is locally ferruginous, containing less than 10% to more than 50% magnetite + hematite. The oxides occur as disseminated grains and concentrated in oxide-rich bands that alternate with oxide-poor bands on a scale of one millimeter to one centimeter. The granofels is enclosed by a symmetric envelope of phyllic alteration, metamorphosed to quartz-sericite schist with 2-5% disseminated pyrite, which is up to 200 meters wide and two kilometers long. Minor andalusite and pyrophyllite are locally present in the schist adjacent to the quartz granofels. There is no known associated precious or base metal sulfide mineralization.

The Pistol Creek (6) zone of silicic and phyllic alteration, located in an F_1 synclinorium on the northwest margin of the Danburg Pluton (**Fig. 6, Fig. 12**), is associated with small felsic intrusions and associated volcanic and sedimentary units along the southern periphery of the Heardmont-Latimer complex. Abundant green muscovite is locally present within this alteration zone. Although investigated as a potentially auriferous deposit, it appears to be very low-grade or barren.

Hydrothermal alteration zone associated with the Eastern Oglethorpe County complex

Thick, hydrothermally altered, graphite-, magnetite-, and chloritoid-bearing dacitic volcaniclastic units of the Rifted Arc volcanic sequence in the Eastern Oglethorpe County complex host a zone of silicic alteration and associated mineralization centered at Big Mountain (**Fig. 12**). This northeast-trending ridge has a local relief of over 150 meters. **Davidson** (**1981**) mapped a zone of intense silicic alteration ranging from 1-213 meters thick, averaging 12-13 meters thick, that was traced along strike for 5.3 kilometers and forms the crest of Big Mountain. This unit is composed of 90-95% fine-grained (0.1 millimeter), equigranular, slightly strained and elongated quartz grains with minor sericite and chlorite and accessory pyrite, hematite, and magnetite (**Davidson, 1981**). Chlorite and sericite (0-10%) are aligned to locally form a weak foliation and are least abundant along the crest of Big Mountain, increasing to the northeast and southwest.

Numerous small gold mines and prospects are present in the area. Most are anomalous in gold ± silver and were extensively prospected during the 19th and 20th centuries. Discontinuous 0.3-2.1 meters thick quartz veins conformable with foliation are common throughout the felsic volcanic sequence at Big Mountain and contain accessory pyrite, magnetite, and hematite. Pyrite is locally present up to 10% in 0.6-5 centimeter parallel bands. Although anomalous Au and locally anomalous Cu are present, there was no significant production from the historic mines and no economically significant mineralization was encountered during extensive evaluation of these occurrences from the 1970s through the 1990s.

The large silicic alteration zone that forms Big Mountain, along with numerous zones of quartz veins in the Eastern Oglethorpe complex, are zones of possibly epizonal hydrothermal alteration, similar to the Parson's Mountain occurrence associated with the Heardmont-Latimer complex.

Other hydrothermal alteration zones in the South domain

Additional zones of hydrothermal alteration present in the South Domain (**Fig. 12**) include numerous unnamed alteration zones that are not known to be mineralized, including several clusters of occurrences east and southeast of the Danburg granite pluton. Others located south and southeast of Big Mountain (**Fig. 12**) appear to be associated with splays of the late Paleozoic Central Piedmont Shear Zone.

Extensive zones of intense and locally auriferous hydrothermal alteration along the Fishing Creek shear zone (10) and Chappells shear zone (11) are associated with ca. 550 Ma D_2 dextral transpression along the Charlotte-Carolina terrane tectonic boundary. Weak phyllic to intense silicic alteration along the Stephens Creek shear zone (9) may also be associated with this event.

Intrusion-centered alteration and mineralization the Charlotte south domain

Intrusion-centered hydrothermal alteration and mineralization are generally atypical of the Charlotte terrane, especially in the South domain. The Stoney Ridge deposit in Wilkes County GA appears to be an entirely unique occurrence within the Charlotte terrane. If formed along a ring dike centered on a pre- to early D_1 granodiorite pluton that is unrelated to Primitive Arc or Rifted Arc magmatism.

A single occurrence of porphyry Mo-Cu mineralization is associated with an evolved monzonite-quartz diorite-granite plutonic center of the Salisbury Plutonic Suite in Cabarrus County NC in the North domain of the Charlotte terrane. However, localized Mo mineralization is associated with other plutons of this suite and there is potential for additional occurrences of mineralized evolved plutonic centers. Additionally, an REE-rich calcsilicate skarn with Mo-W-Ba and base metal sulfides is associated with an arcuate aeroradioactivity anomaly at the contact one Salisbury suite pluton. Similar aeroradioactivity are present around additional plutons of this unique magmatic suite.

The Stoney Ridge mineralized ring dike, Wilkes County GA

The historic Stoney Ridge Gold Mine, located southwest of the town of Washington in Wilkes County, Georgia (**Fig. 8, Fig. 12**) was opened along a narrow, arcuate zone of asymmetric silicic, advanced argillic, and phyllic alteration up to 90 meters wide that locally hosts subeconomic Au-Ag-Cu-Ba mineralization. This alteration zone extends for almost 10 kilometers (**Fig. 8, Fig. 13**) and partially encircles an oval metagranodiorite pluton that intrudes a thick sequence of immature epiclastic sedimentary rocks and mafic volcanic and volcaniclastic units of the Primitive Arc Sequence of the Charlotte terrane. The sediments, pluton, and alteration are all deformed and metamorphosed to the amphibolite facies.

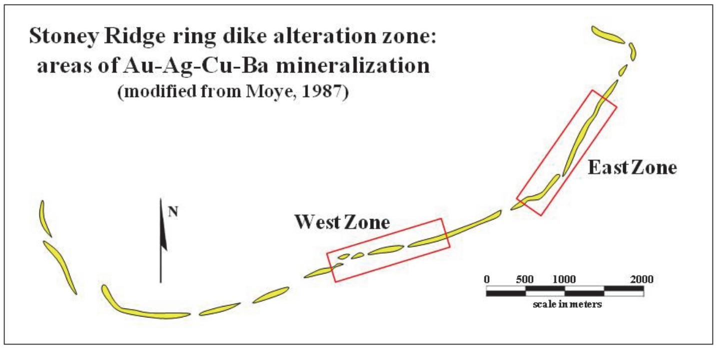


Fig. 13: Mineralized portions of the Stoney Ridge ring dike alteration zone

The Stoney Ridge deposit was evaluated in the mid-1980s by Amselco Exploration Incorporated, through detailed geologic mapping and soil and rock chip sampling, trenching, and two core drill holes. Although not of economic grade and tonnage, the deposit is of significant geologic interest. Stoney Ridge alteration and mineralization are developed within and peripheral to a discontinuous 15-75 meter wide arcuate granitic dike. The dike is fine to medium-grained with a granoblastic texture and weak S_1 and S_2 fabrics poorly defined by aligned biotite grains. The dike is similar in composition to the central Stoney Ridge Pluton, which measures 6.4 by 3.5 kilometers and appears to be a pre- to early-D_1 intrusion that is genetically unrelated to either Primitive Arc or Rifted Arc magmatism. This occurrence is interpreted as a deep exposure through a ring fracture dike that is comagmatic with the central granodiorite body.

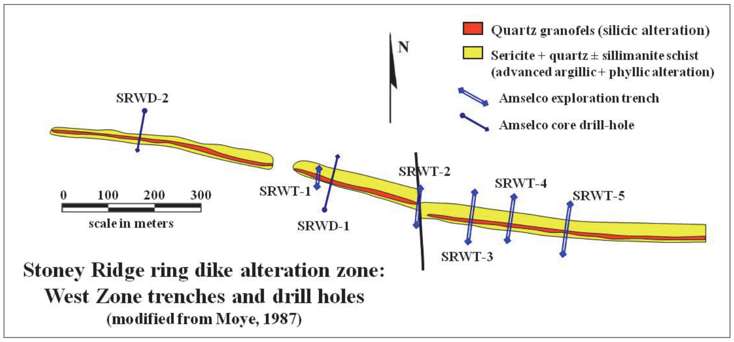


Fig. 14: West mineralized zone of the Stoney Ridge ring dike alteration

The Stoney Ridge alteration zone is generally 30-90 meters wide and remarkably continuous over a strike length of almost 10 kilometers. It encircles about 60% of the Stoney Ridge Pluton on the south, east, and west (**Fig. 8**, **Fig. 13**). The alteration often forms a low, rounded ridge with a relief of 3-6 meters and bold outcrops with a relief of 0.3-1.5 meters. The attitude is vertical to subvertical but the strike changes continually as the zone parallels the contact of the central pluton at a distance of around 100 meters (east end) to 800 meters (west end). The alteration is locally segmented and offset, possibly by post-alteration faulting of uncertain age. Two 1500-meter long zones of anomalous Au-Ag-Cu-Ba mineralization were defined by surface rock and soil sampling and tested through a series of 1x1 meter backhoe trenches and two angled diamond core drill holes (**Fig. 13**, **Fig. 14**).

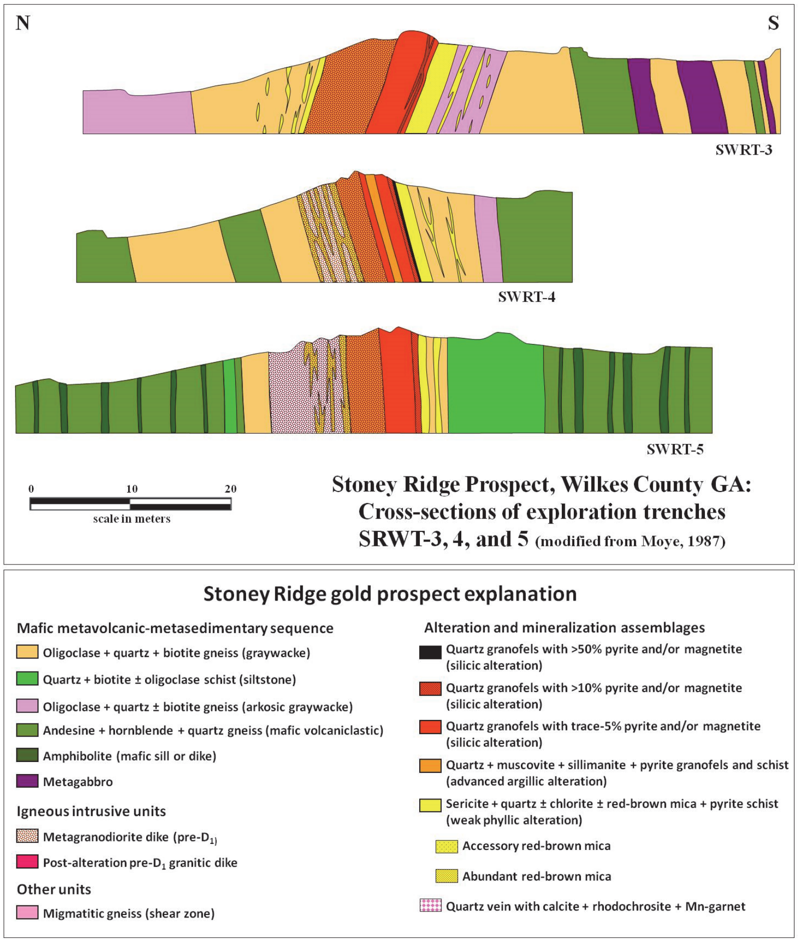
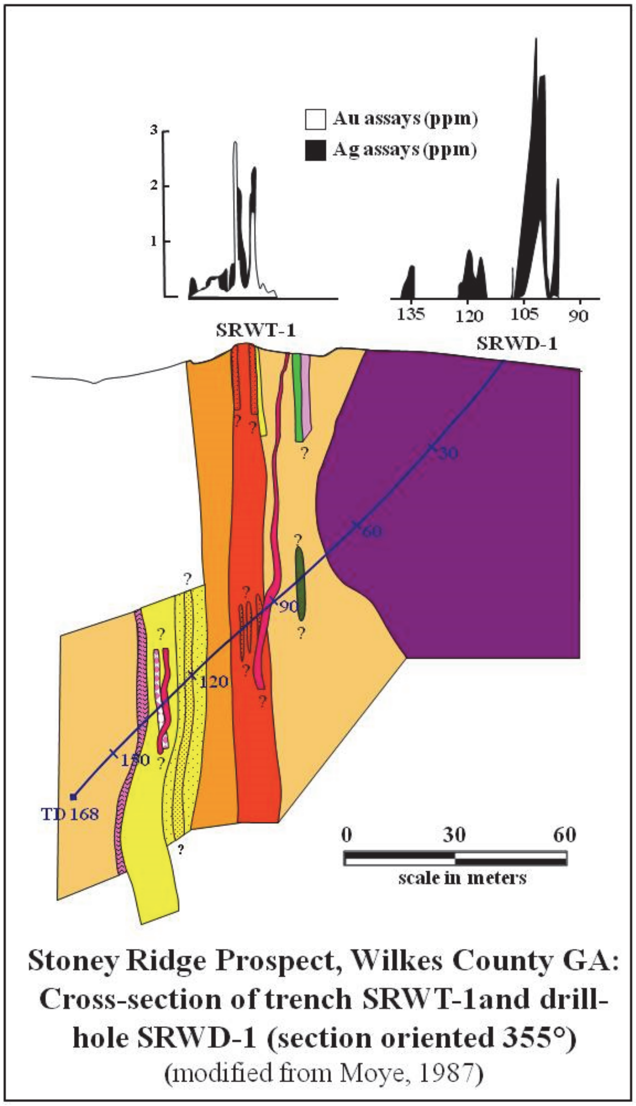


Fig. 15: Cross-sections of trenches SRWT-3, 4, and 5 at Stoney Ridge

The zonation of hydrothermal alteration mineral assemblages is highly asymmetric (**Fig. 14**, **Fig. 15**, **Fig. 16**). A zone of intense silicic alteration up to 7.6 meters thick with 1-5% disseminated pyrite or hematite largely replaces the outer portion of the dike, with decreasing alteration intensity towards the central pluton.

The silicic granofels is gradational into a zone of advanced argillic alteration 6-15 meters thick, which grades through a thick zone of strong to weak phyllic alteration that extends into the host metasediments between the dike and pluton. Weak argillic alteration at the periphery of the system appears to grade into propylitic alteration, but this change is largely obscured by subsequent metamorphism.

The character and distribution of alteration assemblages is generally correlative with distance from the outer dike contact and the composition of the host rocks. The Stoney Ridge ring dike was particularly susceptible to alteration, and is the host for the intense silicic alteration, the advanced argillic zone, and much of the more widely developed phyllic alteration halo (**Fig. 15**, **Fig. 16**).



Stoney Ridge Prospect, Wilkes County GA: Cross-section of trench SRWT-1and drill-hole SRWD-1 (section oriented 355°)
(modified from Moye, 1987)

Fig. 16: Cross-sections of trench SRWT-1 and drill hole SRWD-1 (see Fig. 14 explanation).

The granofels is rheologically rigid and the margins are commonly sheared or strongly foliated parallel to the contacts. These intervals are 30-90 centimeters wide and locally contain up to 20-25% disseminated pyrite. The sulfide-rich intervals were the target of earlier gold mining and yielded the highest assayed gold values, locally exceeding 0.1 oz/t Au. South of the Stoney Ridge Mine, narrow zones 1-2 meters wide within the granofels near the outer (convex) dike contact locally contain up to 20% disseminated magnetite-hematite instead of pyrite.

Mineralization associated with the alteration at Stoney Ridge is characterized by strongly anomalous but subeconomic Au + Ag + Cu + Ba. Although anomalous values above background are present across the entire width of the alteration zone, the most significant values are invariably associated with the silicic granofels. Grade is directly correlative with pyrite content, especially along the margins of the granofels where shearing is common and sulfide content may reach 30% over intervals 0.5 to 2.0 meters wide (**Fig. 15**, **Fig. 16**).

Maximum Au values commonly range between 2-4 ppm with a high value of 4.12 ppm from the underground mine workings. Silver values range as high as 23 ppm over the same intervals, and copper values locally ranged from a few hundred to 1000 ppm. Anomalous barium is ubiquitous, ranging from less than 1000 ppm to almost 8% by weight.

A late phase of mineralization is recognized only in drill hole SRWD-1, and consists of a single quartz vein about a meter wide containing calcite, rhodochrosite, and manganiferous garnet (**Fig. 16**). The vein clearly post-dates the argillic alteration and is in turn cut by a late granitic dike about a meter wide.

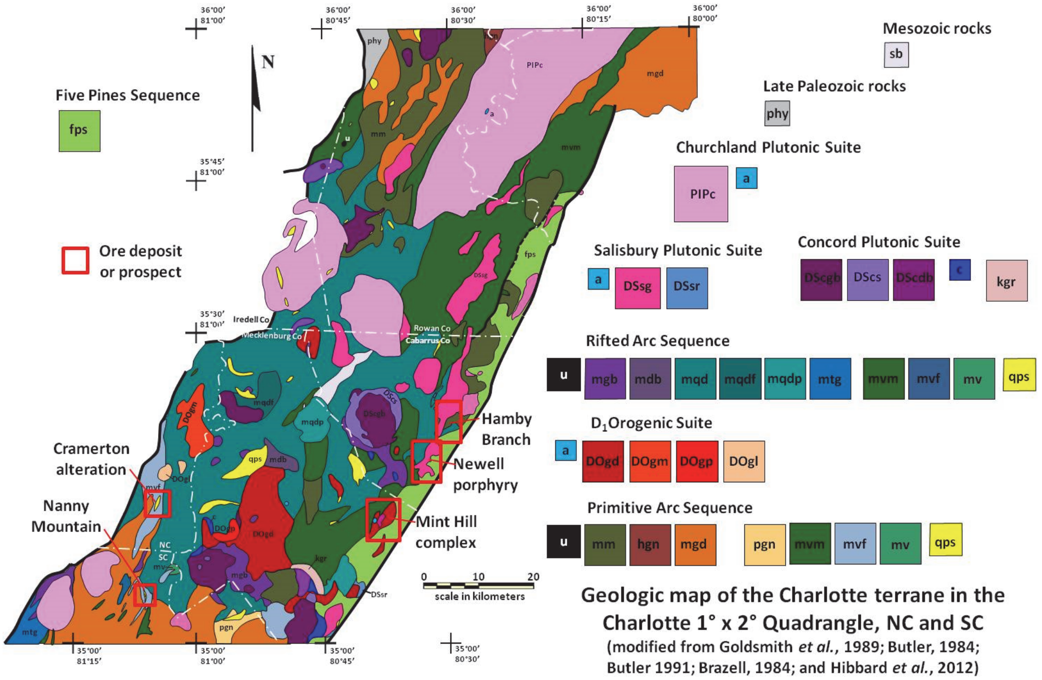


Fig. 17: Metallic mineral deposits of the North domain

Intrusion-related mineralization in the Charlotte North domain

There is a series of intrusion centered metallic mineral occurrences associated with the Devonian age Salisbury Plutonic Suite along the southeast margin of the North domain of the Charlotte terrane (**Fig. 17**). These include the Newell Cu-Mo porphyry deposit and the adjacent Salisbury plutons to the northeast and southwest. These aligned intrusions show evidence of significant magmatic differentiation to form increasing smaller volume melts that are progressively enriched in silica and potassium and may have generated hydrothermal fluids that formed mineralization in one or more of the intrusive phases or in the adjacent country rocks.

The Newell Cu-Mo porphyry prospect, Cabarrus County NC

The Newell intrusive complex (**Fig. 17**) is located on the southern margin of the Bogers Chapel granite pluton of the Salisbury suite. It intrudes Rifted Arc Sequence metadiorite that contains numerous large inclusions of Five Pines Formation metavolcanic and metasedimentary rocks in the hangingwall of the Gold Hill Fault. The distribution of these inclusions suggests that the Salisbury granite pluton is emplaced near the contact between the Five Pines Formation and the Charlotte terrane.

The historic Newell (Copper Queen) Mine is located in southeastern Cabarrus County, 4.6 miles northwest of Midland and l.4 miles south of Flows Store in a large metasedimentary inclusion within the Newell complex. The mine was opened between 1895 and 1900 and was primarily a copper mine. The property was again worked in 1923. Two shafts were opened on a 2 foot wide quartz vein containing pyrite, chalcopyrite, bornite, chalcocite, malachite, and euhedral grains of magnetite.

The Pioneer Mills Mine, located 3.2 kilometers southwest of the Newell Mine, was opened about 1844 but very little work has been done since 1857. The mine was opened in a quartz vein enclosed by locally sheared hornblende-quartz diorite containing abundant magnetite. Mafic volcanic rocks just east of the mine suggest that it is near the contact with the Five Pines Formation. The vein is 60 centimeters thick and strikes 080° with a dip of 80° northwest. The vein is vuggy iron-stained cellular quartz with siderite, chalcopyrite, calcite and minor chrysocolla and malachite (**Emmons, 1856**). Additionally, molybdenite is reported from the East Shaft of the Pioneer Mills Mine, possibly associated with a granite dike (**Genth, 1891**; **Nitze and Hanna, 1896**).

Examination of the mineralization at both the Newell and Pioneer Mills mines suggested the presence of two separate and distinct phases of mineralization **(Worthington and Lutz, 1975)**. Much of the gold and some of the base-metal sulfide mineralization present at the Newell are associated with zones of silicic alteration in the strongly sheared metasedimentary host rocks. A second type of mineralization, represented by the Dixie Queen quartz vein, has a higher sulfide and base-metal content and thin peripheral zones of sericitic alteration, interpreted to be related to the mineralized Newell pluton **(Worthington and Lutz, 1975).**

The dominant rock type in the Newell area (**Fig. 18**) is equigranular, medium-grained diorite composed of plagioclase, hornblende, biotite, and quartz with minor disseminated pyrite **(Worthington and Lutz, 1975)**. Locally there are more mafic phases with abundant hornblende and also coarse-grained gabbroic varieties. The diorite commonly contains elongate inclusions of fine-grained amphibolite that may be mafic metavolcanic rocks of the Five Pines sequence (**Fig. 18**). These inclusions range from a few centimeters to over a kilometer in length and the larger ones are oriented in an easterly to northeasterly direction. To the north is a large body of quartz diorite. These metaintrusive rocks are plutonic phases of the Rifted Arc sequence.

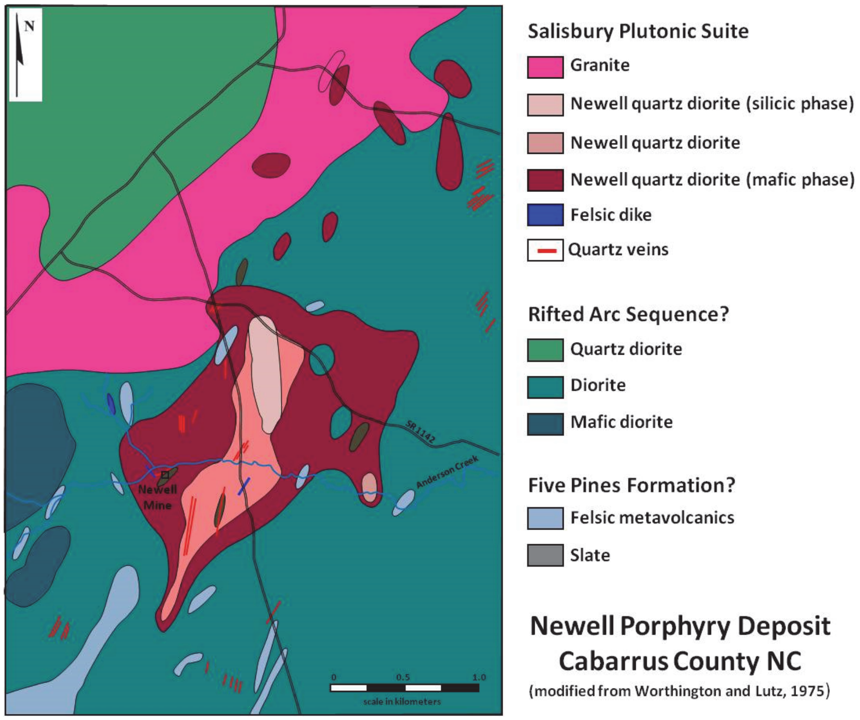


Fig. 18: Geologic map of the Newell porphyry deposit

The contact between the diorite and quartz diorite is intruded by the small irregularly shaped Bogers Chapel pluton of Salisbury granite (**Fig. 18**) composed of uniform, equigranular quartz, microcline, plagioclase, and minor biotite **(Worthington and Lutz, 1975)**. This body is generally elongated NE-SW with maximum dimensions of about 3 x 6.5 kilometers. Injection and contact breccias are locally present along the margins with occasional dikes extending into the diorite. This intrusive phase is barren of mineralization.

The mineralized "Newell" intrusion is an irregularly oval-shaped, compositionally zoned pluton measuring around 1220 x 2440 meters that is emplaced along the southeast margin of the Bogers Chapel granite pluton (**Fig. 18**). The Newell pluton **(Worthington and Lutz, 1975)** is largely composed of quartz diorite that is intruded by a strongly NNE elongated irregular quartz monzonite body measuring about 500 x 2000 meters (**Fig. 18**). The core of the Newell pluton is a roughly N-S oriented oval intrusion of quartz monzonite rich in K-feldspar and quartz with only minor mafic minerals (**Fig. 18**). Biotite from a drill-hole sample of the Bogers Chapel granite pluton returned a K-Ar age date of 388 ± 12 Ma and a similar sample of the mineralized Newell pluton gave a K-Ar age of 417 ± 15 Ma **(Worthington and Lutz, 1975)**.

Also present in the Newell pluton are rare quartz-rich, fine-grained aplite dikes, some with prominent quartz phenocrysts, and a few feldspar porphyry dikes were intersected in drill hole DH-2 **(Worthington and Lutz, 1975)**. The porphyry dikes contained prominent plagioclase phenocrysts in an often strongly sericitic fine-grained quartz, feldspar, biotite ground mass.

Mineralization and alteration associated with the Newell pluton appear to be pervasive deposit-scale vein-hosted and disseminated type, similar to classic Cu and Cu-Mo porphyry deposits. Two zones of hydrothermal alteration centered on the Newell pluton are recognized **(Fig. 19)**; a 1220 x 2440 meters zone of moderate to strong phyllic (sericite) alteration that encompasses much of the Newell pluton and locally extends into the host diorite, and a peripheral zone of epidote alteration of diorite located to the south and southeast of the pluton over a 2500 x 500-1000 meter area **(Worthington and Lutz, 1975)**.

Both sericite and epidote are strongly concentrated as residual weathering products at the surface in the Newell area. Rather than pervasive phyllic alteration, sericite largely occurs as alteration haloes up to 7 centimeters thick around quartz veins within the mineralized pluton. Other alteration minerals present include biotite, epidote, actinolite, sulfides, and topaz **(Worthington and Lutz, 1975)**. Propylitic alteration peripheral to the zone of phyllic alteration is characterized by secondary epidote, actinolite and chlorite with minor sericite and quartz and trace disseminated pyrite.

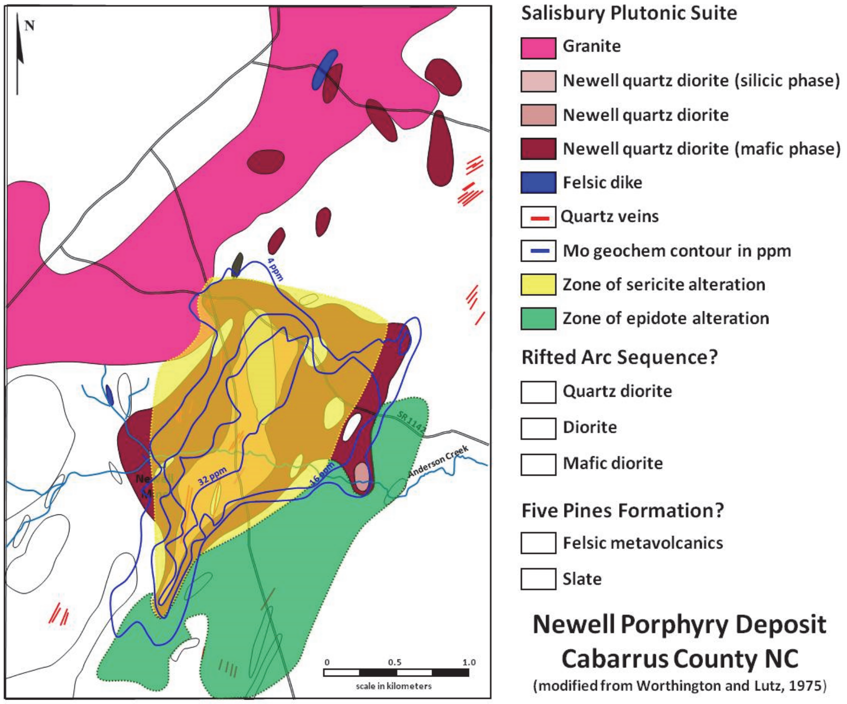


Fig. 19: Alteration and mineralization at the Newell porphyry deposit

Over 1000 soil samples were collected over the project area and analyzed for Cu and Mo. The Cu soil geochemistry anomaly was around 200-400 ppm over a background of around 20 ppm. The soil Mo anomaly ranged to over 100 ppm with an average value of around 30 ppm above a background value of 1 ppm **(Worthington and Lutz, 1975)**. The Cu and Mo soil anomalies closely correspond to the zone of phyllic alteration (**Fig. 19**), which is coincident with a ground and aeromagnetic low due to the sulfidation of magnetite to pyrite.

Sulfide mineralization is most intense in the phyllic alteration zone, averaging around 1-4%. Sulfides are dominantly pyrite, present in quartz veins and disseminated in the wall rocks, with chalcopyrite and molybdenite present in quartz veins, especially in the quartz-rich core of the Newell pluton **(Worthington and Lutz, 1975)**. Additional vein minerals include magnetite, usually with pyrite and chalcopyrite, and gypsum as fracture coatings. Like sericite and epidote, both barren and mineralized vein quartz is strongly concentrated by weathering and erosion at the surface over the deposit.

The highest grade mineralization was up to around 0.1% Cu and 0.03% Mo. The average grade of the best mineralization ranged from 0.03-0.04% Cu and 0.01-0.02% Mo in an area around 600 meters in diameter (**Fig. 19**). The low tenor of the Newell porphyry mineralization may be the result of a weaker hydrothermal system compared to economic Cu and Cu-Mo porphyry deposits, possibly to the small volume of the intrusive complex, or to a deeper level of exposure in the hydrothermal system **(Worthington and Lutz, 1975)**.

The occurrence of porphyry-type mineralization in association with a strong magmatic differentiation trend in the Newell pluton, part of a larger body of Salisbury granite, suggests the possibility of similar compositional diversity through differentiation in other bodies of the Salisbury Plutonic Suite and the possibility of additional associated intrusion-centered hydrothermal alteration and mineralization.

The Mint Hill intrusive complex, Mecklenburg County NC

Although not recognized as a mineralized intrusion, the Mint Hill complex in the eastern corner of Mecklenburg County (**Fig. 17**, **Fig. 20**) consists of a northeast-elongated 8 x 4 kilometer D_1 granodiorite pluton that intrudes Five Pines Formation metavolcanic rocks in the hangingwall of the Gold Hill Fault to the east and mafic metavolcanic rocks of the Primitive Arc sequence to the west. The granodiorite is intruded by a small (2.5 x 1 km) plug of Salisbury granite and an adjacent 1 km^2 body of aplite. The granite is cut by a zone of silicic to phyllic hydrothermal alteration measuring about 750 x 150 meters (**Fig. 20**).

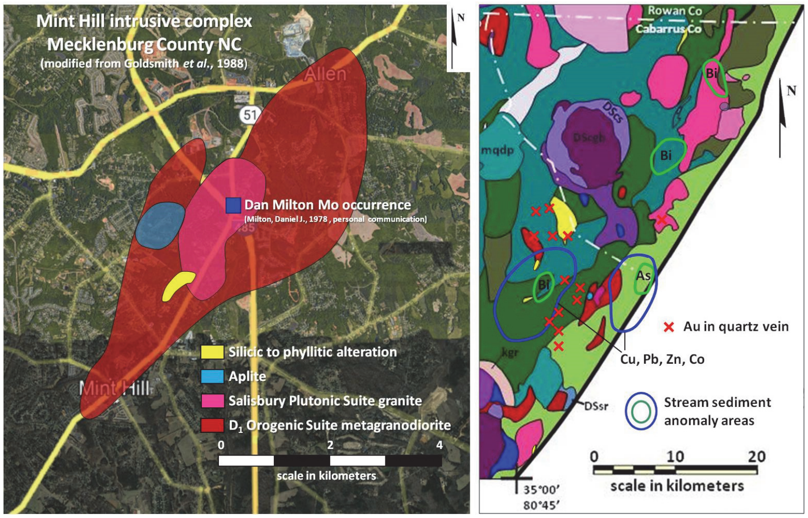


Fig. 20: Mint Hill intrusive complex

Although no mines or prospects are reported in this association, an occurrence of molybdenite is reported in the Salisbury-type granite pluton (**Milton, 1978**; MRDS ID-10079187). The outcrop is in the bank of a northern tributary to Clear Creek under the route NC51 bridge at the intersection of I485 with NC51 (**Fig. 20**). The mineralization is described as disseminated flakes of molybdenite with numerous grains of pyrite in granite.

The presence of the aplite body suggests the end product of a strong felsic magmatic differentiation trend, possibly generating a mineralizing hydrothermal fluid. Additionally, the Mint Hill intrusive complex is flanked to the east by an area of stream sediment samples (**Goldsmith et al., 1988**) anomalous in Cu, Pb, Zn, Co, and As; and to the west by a series of Au-bearing quartz veins and an area of stream sediments anomalous in Cu, Pb, Zn, Co, and Bi (**Fig. 20**).

Given that subeconomic Cu-Mo porphyry mineralization at the Newell Cu-Mo porphyry deposit, located about 12 kilometers to the northeast, is associated with a Salisbury suite granite plutonic complex with small bodies of aplite, it seems possible that the Mint Hill intrusive complex may locally host similar alteration and mineralization.

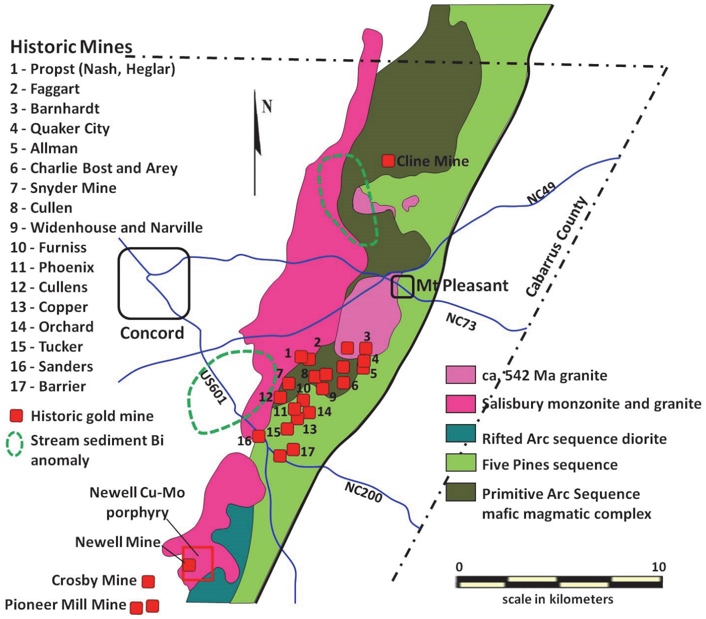


Fig. 21: Hamby Branch mineralized area (modified from Goldsmith *et al.*, 1989)

Mineralization associated with the Hamby Branch granite, Cabarrus County NC

Like the Bogers Chapel-Newell pluton to the south, intrusion-related vein mineralization may be associated with the elongated pluton of the Salisbury Plutonic Suite (**Fig. 17**) located between Concord and Mount Pleasant in eastern Cabarrus County NC. A cluster of around 20 small historic Au ± Cu ± W mines and numerous small prospects form an arcuate zone measuring 2.5 x 7.5 kilometers along the Hamby Branch watershed on the eastern periphery of the southern end of this pluton (**Fig. 21**), informally named the Hamby Branch granite.

These occurrences are almost exclusively mineralized quartz veins up to 1.5 meters thick that strike NE to NW and dip moderately to steeply. Most veins were prospected throughout their strikes and exploited for free-gold in the oxidized upper portions of the lode; many were only worked as deep as the water table (typically 15-20 meters). The veins are commonly anastomosing and typically pinch and swell, with ore minerals often concentrated in shoots that were the focus of underground mining. Several subparallel quartz veins are present in many areas, with the most notable production only from the major vein.

Most of the veins carry gold and copper mineralization (chalcopyrite ± bornite) and most are characterized by oxidized assemblages with accessory barite and magnetite or hematite typically present. The Furniss (10) and Phoenix (11) mines contain significant scheelite, which is also reported at Cullen's (7) Mine (**Genth, 1891**), on the dumps of the Tucker (15) Mine (**Jones and Peyton, 1950**), and possibly at the Copper Mine (13).

There are a variety of host rocks for the Hamby Branch deposits, including the Devonian Hamby Branch granite pluton, mafic metavolcanic rocks of the Primitive Arc or Rifted Arc sequence, the ca. 542 Ma Mount Pleasant pluton (**Hibbard *et al.*, 2012**), and metavolcanic and metasedimentary rocks of the Hyco-equivalent Five Pines sequence of the Carolina terrane in the hangingwall of the Gold Hill Fault. The host rocks are typically sheared around the quartz veins and often altered to sericitic, biotite-chlorite or chlorite-epidote schist and may be silicified.

The Propst (Nash, Heglar) prospect (1) is unique within the Hamby Branch cluster and hosted by the Hamby Branch granite pluton (**Fig. 21**). The site features a shallow 1.5 x 1.5 meters shaft and numerous exploration trenches that were opened in the mid-1950s near the south end of a NNE-trending radiometric anomaly of 2000 to over 3000 counts/second (**Sundelius and Bell, 1964**). They expose a bleached and silicified cataclastic zone cutting the pink granite of the pluton. The radiometric anomaly parallels the contact of the granite with the adjacent mafic metavolcanic sequence for around 5 kilometers.

Mineralization is a fine-grained, dark-gray to brown siliceous zone with andradite, allanite, magnetite, pyrite, chalcopyrite, sphalerite, galena, molybdenite, and barite. The mineralization is dominantly fine-grained pyrite and andradite, locally in 1-10 millimeter thick bands alternating with fine-grained silica (**Sundelius and Bell, 1964**). The siliceous groundmass shows colliform banding and a botryoidal texture with vugs partly filled with chalcedony and opal. Sulfides are observed to replace and occur interstitial to andradite (**Sundelius and Bell, 1964**). The andradite contains numerous inclusions of apatite and the garnet is altered to chlorite and epidote along fractures (**Sundelius and Bell, 1964**). Apatite is also present in the siliceous matrix. Semiquantitative spectrographic analyses of grab samples of the mineralization have a combined content 0.14% to 0.42% cerium, lanthanum, praseodymium, and neodymium (**Sundelius and Bell, 1964**).

This occurrence has a distinctly skarn-like character and was examined by the author for Phelps Dodge Exploration East in the early 1980s as a possible REE deposit. An initial calc-silicate assemblage dominated by andradite, allanite, epidote, and magnetite is overprinted by lower temperature silicic alteration and sulfides. The presence of abundant allanite and REE content were confirmed, but the refractory nature of the ore discouraged further exploration.

The Furniss (10) and Phoenix (11) mines to the east appear to be 300 meters apart on the same vein system, striking 060° and dipping 80° NW. They appear to represent two areas of rich ore shoots in veins 75-90 centimeters thick, with shoots up to 90 meters long that extend over vertical distances of over 100 meters (**Nitze and Hanna, 1896**). Ore minerals include pyrite, chalcopyrite, bornite, chalcocite, gold, and galena with accessory barite, scheelite, and magnetite. The Phoenix ore shoot carried from 3-60% ore minerals, averaging around 5-10% (**Nitze and Hanna, 1896**).

The Middle Vein is subparallel to the Phoenix vein about 60 meters to the southeast and worked by open pits with masses of sulfides yielding up to 1.74 oz/ton gold (**Nitze and Hanna, 1896**). The Copper Mine (11) vein also parallels the Phoenix-Furniss vein system 305 meters to the southeast of the Middle Vein. Assays from the surface were as high as 22% copper and 2 oz/ton gold. The Copper Mine shaft extends to a depth of 46 meters with 71 meters of drifts. Vein minerals include pyrite, chalcopyrite, barite, and siderite. Abundant fluorescent material is present on the mine dumps, including some of the barite and possibly scheelite.

In 1946 and 1948 to 1950, the U.S. Bureau of Mines drilled the Furniss Mine and the Cline Mine to the north (**Fig. 21**) to evaluate the resource potential (**Stuckey and Conrad, 1961**). In 1954 new interest was developed in the area and in 1955 and 1956, DMEA aided Carolina Tungsten Mining Company in further exploration. The Phoenix mine was dewatered and examined, and further examinations were made at the Cline and Furniss mines (**Stuckey and Conrad, 1961**). Commercial deposits of tungsten minerals were not encountered and mining attempts were discontinued.

The character and mineralogy of many of the quartz veins in the Hamby Branch group (**Fig. 21**) are similar to that of the Newell (Copper Queen) Mine vein that occurs within the Newell Cu-Mo porphyry prospect in the differentiated plutonic complex to the southeast (**Fig. 21**). Although the Hamby Branch group of Au-Cu mineralized veins to the north cannot be directly linked to fluids associated with the adjacent intrusive body, the presence of highly anomalous tungsten in the Phoenix-Furniss veins system, the Cullen's and Tucker mines, and possibly the Copper vein suggests the possibility. Additionally, the Hamby Branch pluton is bordered to the northeast and southwest by areas of anomalous bismuth (**Fig. 21**) in stream sediment samples (**Goldsmith *et al.*, 1989**) but Bi analyses for area mineralization are not available.

Genetic linkage between the Hamby Branch quartz vein deposits and the adjacent Salisbury suite granite is difficult to establish. Like the quartz vein deposits, the Probst Prospect (1) skarn is oxidized with accessory barite and magnetite and carries accessory molybdenite. Mineralization in the Newell Cu-Mo porphyry deposit to the south includes quartz veins with pyrite, chalcopyrite, and molybdenite but also with accessory magnetite **(Worthington and Lutz, 1975)**. The presence of similar ore metals and oxidized accessory minerals in porphyry, skarn, and quartz vein mineralization suggest a possible relationship.

However, the Probst prospect mineralization is the product of two separate hydrothermal events; **1**) higher temperature skarn formation (with Mo) genetically related to the granite pluton, and **2**) overprinting lower temperature sulfide mineralization with chalcopyrite, sphalerite, galena, barite, and magnetite. The second event could be unrelated to the pluton but associated with the Hamby Branch vein deposits. This question cannot be resolved at this time.

The age of the Hamby Branch quartz vein mineralization is constrained by that of the host rocks, which include the 542 ± 18 Ma Mount Pleasant pluton (**Hibbard *et al.*, 2012**), the Newell (Copper Queen) vein in the 417 ± 15 Ma Newell pluton (**Worthington and Lutz, 1975**), and the probably similarly age Hamby Branch granite that hosts the Probst Prospect (**Fig. 21**). The Hamby Branch vein deposits appear to be no older than ca. 415-417 Ma.

The Newell Cu-Mo porphyry and the Probst Prospect skarn deposit appear to be directly associated with Salisbury suite granite plutons. However, the fault and shear structures hosting the Au-Cu ± W mineralized quartz veins in the same area appear to post-date emplacement of the granitic plutons of the Salisbury Plutonic Suite, although the exact timing is uncertain. Vein-associated alteration and mineralogy is consistent with post-emplacement greenschist facies metamorphism and mild, heterogeneous deformation and of the Salisbury suite plutons. Metamorphism and variable weak foliation in these plutons is defined by the parallel orientation of micas, undulatory extinction and deformation bands in quartz grains, and by elongate aggregates of recrystallized quartz grains (**Butler and Fullagar, 1978**; **Goldsmith *et al.*, 1989**).

Interestingly, the other known scheelite-bearing veins in this area are the Cline Mine, located about 6 kilometers north of Mount Pleasant, and the Crosby (Poplan) Mine, located southwest of the Newell Cu-Mo porphyry deposit (**Fig. 21**). The Cline Mine is opened on a series of quartz lenses 30-90 centimeters thick, often linked by quartz stringers. The deposit strikes 330° and dips 75°NE over a distance of around 300-365 meters through a series of shafts, pits, and trenches (**Beck, 1946**). The vein contains pyrite, chalcopyrite, siderite, hematite, and scheelite. The deposit is located along a shear zone in mafic metavolcanic rocks of the Primitive Arc sequence about 5 kilometers east of the northern end of the Hamby Branch granite pluton. Little information is available on the Crosby Mine, but **Genth** (**1891**) reports a quartz vein that contains pyrite, gold, siderite, barite, cupro-tungstite, cuprian scheelite, and scheelite.

This occurrence of tungsten-bearing quartz veins is anomalous in the Charlotte terrane and appears to be broadly aligned over a distance of 25 kilometers. This series of veins is also generally aligned with the two Salisbury granite plutons shown in **Fig. 21**, both host to molybdenite ± base metal sulfide mineralization. Local molybdenite + pyrite mineralization is also present in the Salisbury suite granite at Mint Hill farther southwest, indicating a NNE-alignment of three Mo-bearing granites over a distance of around 30 kilometers. Molybdenite is also reported in a granite dike that cuts the Pioneer Mills Au-Cu quartz vein in the East Shaft (**Genth, 1891**).

The intrusion-hosted Mo mineralization in the three Salisbury suite plutons does not appear to include tungsten and molybdenite is not reported in the Hamby Branch and Cline mines or other tungsten-bearing quartz veins. The coincidence of the two alignments suggests a separate, possibly basement control for both styles of mineralization.

The Salisbury Plutonic Suite and associated mineralization

Granites of the Salisbury suite are abnormally rich in K-feldspar, albite, and quartz with MgO usually < 0.1%. They represent extreme differentiation or limited partial melting in the lower crust or mantle (**Butler and Fullagar, 1978**). Many show local enrichment trends in Mo, F, Nb, Y, Th, U, and Zr.

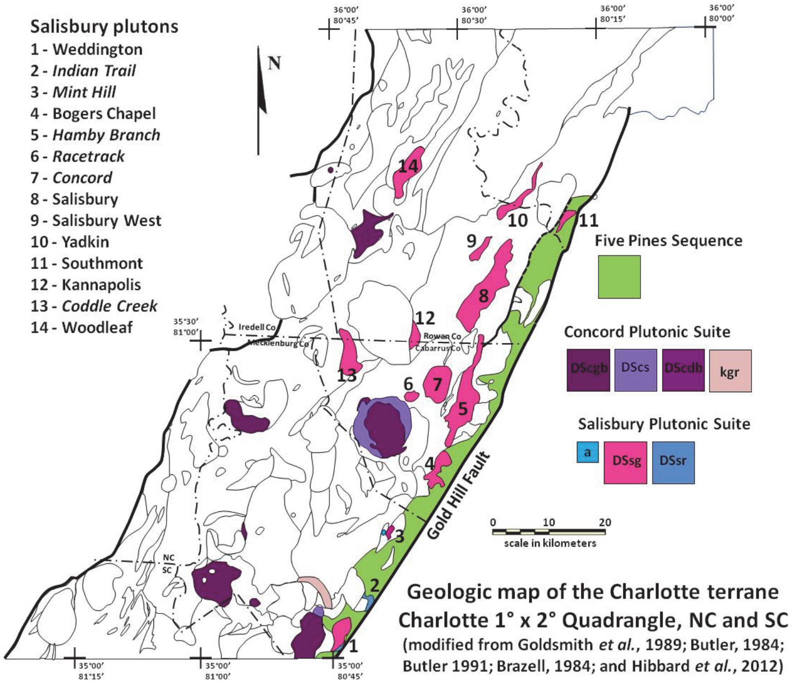


Fig. 22: Plutons of the Concord and Salisbury plutonic suites (informal names in italics)

Of the 14 known granitic plutons of the Salisbury Plutonic Suite (**Fig. 22**), the southernmost five (1-5) are strongly aligned at a bearing of 029° over a distance of 60 kilometers subparallel to the Gold Hill Fault at a distance of up to 5 kilometers to the northwest. A fault at a similar orientation extends from the pluton at the northern end of this alignment for another 30 kilometers. *En echelon* about 5 kilometers to the west, a second general alignment of granite five bodies (6-10) extends for a distance of approximately 50 kilometers, and includes the Salisbury and Yadkin plutons. The Southmont pluton (11) intrudes the Five Pines Sequence of the Carolina Terrane in the immediate hangingwall of the Gold Hill Fault, and may be a continuation of the plutons 1-5 alignment. The other Salisbury granite plutons are scattered across the central part of the northern Charlotte terrane in North Carolina (**Fig. 22**).

The alignment of Salisbury granite plutons (1 to 5) adjacent to the Gold Hill Fault (**Fig. 22**) strongly suggests a structural control in their emplacement. Additionally, their position generally corresponds with the indefinite contact between rocks of the Charlotte terrane and the Five Pines sequence of the Carolina terrane in the hangingwall of the Gold Hill Fault (**Fig. 22**). Plutons 1-4 of this alignment appear to include more evolved plutonic components, including porphyritic and aplite phases, and at least three (3-5) appear to host heterogeneous hydrothermal mineralization. Potentially intrusion-related mineralization appears to be absent in the other intrusions of this suite, with the exception of the Salisbury and Woodleaf plutons (**Fig. 22**).

The Mint Hill pluton (3) is a small plug that intrudes an older granodiorite pluton, with an associated body of aplite and a zone of hydrothermal alteration. An occurrence of molybdenite is reported in the granite pluton (**Fig. 20**), suggesting possible localized porphyry-style mineralization. The Newell Cu-Mo porphyry deposit is directly associated with the Bogers Chapel pluton (4) and the Probst skarn prospect occurs on the margin of the Hamby Branch pluton (5). These occurrences strongly suggest localized mineralizing events genetically associated with the emplacement of these Salisbury suite granite plutons.

The linear character of the easternmost Salisbury suite plutons (1-5), the apparent magmatic differentiation of four of these bodies (1-4) and hydrothermal mineralization directly associated with three (3-5) suggest an additional metallogenic factor that is missing from most other occurrences of the Salisbury suite. This missing factor may be associated with the presence of a strong basement structural control in their emplacement. This may have resulted in higher volatile content that facilitated magma differentiation and concentration of incompatible elements in a late hydrothermal phase.

The Salisbury pluton

Just to the west of plutons 1-5 of the Salisbury suite, the *en echelon* alignment (**Fig. 22**) that includes the Salisbury pluton (8) is less linear and generally shows less evidence of fractionation and associated mineralization. However, molybdenite occurs at several locations in the northern part of the Salisbury pluton with several generations of molybdenite-bearing mineralization observed (**English, 1984**). Molybdenite occurs as flakes up to 2 millimeters across associated with pitted and embayed 0.8 millimeter disseminated pyrite grains in the primary igneous assemblage, and as a second generation of 0.2 millimeters flakes disseminated with 0.3 millimeter euhedral pyrite and 0.4 millimeter subhedral arsenopyrite in fine-grained quartz (**English, 1984**), possibly the result of late autometasomatism. There is no significant observed hydrothermal alteration with either occurrence (**English, 1984**).

Molybdenite also occurs in this area as fine-grained aggregates disseminated with 0.5 millimeter pyrite in a 3-4 centimeter wide shear zone with quartz-albite-epidote-muscovite-hematite alteration of the granite (**English, 1984**). According to quarry workers, aggregates of fine-grained molybdenite up to several centimeters in diameter occur in shear zones in the Central Pink Quarry (**English, 1984**). Reconnaissance of the northern part of the pluton found no molybdenite-bearing quartz vein stockworks, no sulfide veinlets, and no large-scale hydrothermal alteration that would suggest porphyry-style mineralization (**English, 1984**).

The Salisbury granite pluton varies from white to pink with the Fe content of plagioclase feldspars, with the molybdenite occurrences in the pink phase at the north end of the pluton (**Lemmon, 1969**). **Phillips** (**1967**) reports the occurrence of two generations of accessory minerals. Primary igneous accessories include apatite, magnetite, monazite, rutile, sphene, and zircon. Minerals formed during deformation and metamorphic recrystallization include epidote, fluorite, and garnet. It appears that fractional crystallization in the northern and south-central portions of the Salisbury pluton increased the concentration of incompatible elements including Nb, Th, U, Y, and Zr (**Lemmon, 1969**; **Fullagar *et al.*, 1971**), as well as Mo, As, and F. Many of these incompatible elements may have been remobilized and locally concentrated during a late stage of autometasomatism (**Fullagar *et al.*, 1971**), which may have been concurrent with heterogeneous deformation and greenschist facies metamorphism. However, there was no large-scale hydrothermal event to generate porphyry-type mineralizing fluids in the Salisbury pluton.

Several post-intrusion Au-Cu mineralized quartz veins are present in the Salisbury pluton (8), including the Reimer and Bullion mines on the same NW-striking vein, and the three veins at the Dunn's Mountain Mine, which strike NW, NE, and almost N-S. However, all are generally weakly mineralized, there is no clustering of numerous mineralized veins, and they show no obvious igneous association. They are generally similar in character to the Hamby Branch quartz vein deposits to the east but are more weakly mineralized and lack tungsten mineralization and accessory barite and magnetite or hematite.

Formation of these Au-Cu bearing quartz veins was synkinematic with heterogeneous oblique strain and greenschist facies metamorphism that may be only slightly younger than the emplacement of the Salisbury pluton and associated Mo mineralization.

The Woodleaf pluton

At the Woodleaf Quarry in the Woodleaf pluton (**Fig. 22**) in northwest Rowan County, molybdenite in flakes up to 50 millimeters across occur with pyrite, chalcopyrite, fluorite, epidote, and calcite in late stage vuggy quartz + microcline veins (**D'agostino, 1982**; **Privett, 2014**). The Woodleaf granite pluton intrudes diorite with numerous dikes and sill and contains xenoliths and pendants of the diorite, with flow lines in the granite around the larger xenoliths (**Privett, 2014**). The mineralized quartz + microcline veins cut both the granite and the host diorite (**Privett, 2014**). This occurrence may suggest late-stage Mo-Cu-F enriched igneous fluids forming veins in the upper part of the Woodleaf pluton.

Au ± Cu mineralized quartz veins in the North domain

The most widespread and historically significant form of metallic element mineralization present in the North domain of the Charlotte terrane is orogenic quartz vein hosted Au ± Cu deposits **(Fig. 23)**. The greatest concentration of gold-bearing quartz veins in the North domain occurs in a 1550 km^2 area of Mecklenburg County (**Fig. 23**) with historic gold production from around 100 mines, many within 15 kilometers of the city center of Charlotte (**Gair, 1989**). The term "mines" could refer to several small operations along a single vein or to works on adjacent veins in a set or parallel or intersecting veins. This concentration of gold deposits in and around the city of Charlotte, some with Au production of up to 50,000 ounces, was a major factor in the local economy in the 19th century and led to the opening of the Charlotte Mint in 1837. Major mines of this district include the Rudisil (the largest producer), Isenhour, Saint Catherine, and the Capps Hill-McGinn group of mines (**Gair, 1989**).

Fig. 23: Gold ± Cu quartz veins deposits of the North domain

Most historically mined veins are 10-100 meters long and 0.6-5 meters thick, although some veins systems had lengths of up to 4000 meters and widths of up to 7 meters (**Gair, 1989**). Multiple veins at various orientations cluster in some areas, such as the Capps Hill-McGinn Group. Many veins were only mined over the better mineralized portions of their extent and often only exploited for free gold in the oxidized ores above the local water table (up to 40 meters deep). However, particularly rich shoots were mined to depths of up to 115 meters at grades averaging around 0.3 oz/ton Au (**Gair, 1989**).

Ore minerals are typically gold, pyrite, and chalcopyrite (minor bornite and galena are also reported) with a gangue of quartz, muscovite, and carbonate (often siderite). Associated alteration is typically sericite + pyrite + carbonate, especially in granitic rocks, and chlorite + epidote + pyrite in mafic rocks.

Many of the historic gold mines of the Charlotte District are hosted within or peripheral to the 10 x 20 kilometer D_1 orogenic metagranodiorite pluton (**Fig. 23**) that underlies the city and contains numerous aplite dikes, including the famous leopardite quarry in a 7.6 meters thick dike near the corner of Belmont and Sigel avenues (**Watson, 1904a**). The rheology of the intrusion may have been a significant factor in vein formation. Other mineralized veins are hosted by metaintrusive and metavolcanic units of the Primitive Arc and Rifted Arc sequences to the east (**Fig. 23**).

The gold-bearing quartz veins are commonly developed along tabular phyllic-altered shear zones up to 30 meters wide striking NE to NW and dipping at steep to moderate angles (**Pardee and Park, 1948**). These are ductile-brittle structures formed under mesothermal conditions with vein and alteration mineralogy consistent with greenschist facies metamorphic conditions. This contrasts with the amphibolite facies metamorphic assemblages of the host rocks.

Although some mineralized quartz veins parallel the dominant NE-trending, the steeply-dipping S_1 tectonic foliation, the majority of veins cross-cut this foliation. There are few constraints on the age of this mineralization, but it must post-date F_1 large-scale isoclinal folding, S_1 axial foliation development, and amphibolite facies metamorphism. Some vein could have formed in the waning stages of D_1, but most are probably younger than ca. 540 Ma.

The second most significant cluster of historically mined gold-bearing quartz veins in the North domain is the previously discussed Hamby Creek group in eastern Cabarrus County (**Fig. 21, Fig. 23**), unique for the occurrence of scheelite in some veins. They are further distinguished from the gold-bearing veins of the Charlotte District by the presence of oxidized vein gangue minerals including barite, magnetite, and hematite. The same is true for most of the known auriferous quartz vein deposits in the eastern part of the North domain, which are typically hosted by mafic metavolcanic and metaplutonic rocks.

The relevance of host rocks

Pratt (1907) noted the differences between the quartz vein deposits within the Gold Hill Fault Zone and those of the hangingwall, which include Greenstone- type (hosted by the Five Pines Sequence), the Dutch Creek-type (hosted by Ediacaran granite), and Cline-type veins (hosted by Primitive Arc mafic metaplutonic and metavolcanic units). Veins of the Greenstone-type have a similar northeast trend to those at Gold Hill within the fault zone, but the ores are dominated by bornite and chalcocite in a quartz and epidote gangue (**Pratt, 1907**). The veins may consist of narrow stringers in epidote-altered host rocks of the Five Pines Sequence of the Carolina terrane and possibly the Primitive Arc sequence of the Charlotte terrane within 1-2 kilometers of the Gold Hill Fault. The veins are typically well defined and easily traced on the surface by residual quartz and epidote, but have low Au-grades and have not been extensively prospected (**Pratt, 1907**).

The Dutch Creek-type quartz veins (**Pratt, 1907**) contain auriferous pyrite and minor chalcopyrite with a gangue of quartz and minor siderite. Examples include the Dutch Creek Mines and Gold Knob Mines (**Fig. 23**) and the diggings in the vicinity of Garfield. These mines are hosted by the ca. 541 Ma Gold Hill granite pluton. The southeastern contact of the pluton is sheared in the immediate hangingwall of the Gold Hill Fault (**Hibbard *et al.*, 2012**). There are at least 20 known mineralized veins at the Dutch Creek Mine over a distance of 150 meters within a NW-trending zone at the north end of the pluton. The veins mostly strike 030°-048° NE and a few intersect. The vein footwall is typically silicic altered and the hangingwall phyllic altered (**Kerr and Hanna, 1888**).

Most of the veins are 30 to 60 meters long, dip at steep to moderate angles SE, and the most productive are 0.3 to 5.5 meters thick at vein intersections. The most productive veins are the Katie, Hill, Tip-top, and Spring. All were worked by open cuts and shafts to the water table, and contain pyrite, chalcopyrite, and specular hematite. There are another 11 veins within about a kilometer the south that strike 035°-040° with vertical dips and include the Atlas and Bame mines (**Kerr and Hanna, 1888**).

The Gold Knob Mine, located about 3 kilometers southwest of the Dutch Creek Mine, features at least 11 quartz veins that strike NE and dip 70°-75° southeast. The Haynes, the Gold Knob, and the Holtshauser veins carry pyrite and chalcopyrite and form a low ridge in the biotite granite host rock. The Gold Knob Vein was up to 6 meters thick and strikes 048° with a dip of 45° southeast (**Kerr and Hanna, 1888**; **Carpenter, 1976**). Largely worked in the 1880s, the last production was in 1895 from the Holtshauser Vein. The veins were of generally low gold grade and produced gold and silver.

The Cline-type occurrences (**Pratt, 1907**) are characterized by auriferous pyrite and chalcopyrite in a gangue of quartz, calcite and siderite, with varying amounts of specular hematite. These veins are hosted in both greenstone and diorite of the Primitive Arc sequence. Two examples are the Cline Mine and the Dan Hopkins diggings near Cross Roads in eastern Cabarrus County. The Cline Mine (**Fig. 21**, **Fig. 23**) has been previously discussed. The Dan Hopkins Diggings (Hopkins No. 2), worked in the 1890s, is located about 2 kilometers just west of north from the Cline Mine near Watts Crossroads. Gold occurs with pyrite, chalcopyrite, calcite, siderite, and specular hematite in a quartz vein hosted by metadiorite rocks near the contact with greenstone in the Primitive Arc sequence. Another example is the Hopkins No.1 Mine, located 1.8 kilometers southeast of the Cline Mine on the east side of Buffalo Creek on the south side of Mt Olive Road (NC2416). Gold-bearing quartz-epidote veins with bornite and chalcocite and minor chalcopyrite and pyrite occur in sheared and altered mafic metavolcanic rocks.

The Greenstone- and Cline-type veins of **Pratt** (**1907**) are similar and both are broadly consistent with the mineralized quartz veins of the Hamby Branch group (**Pratt, 1907**), previously discussed. Many are hosted by mafic metaplutonic or metavolcanic rocks of the Primitive Arc Sequence and carry gold and significant copper sulfides with accessory oxidized gangue species that include barite, magnetite, and hematite. This observation also extends to many of the quartz vein lode gold ± Cu deposits in the eastern part of the North domain of the Charlotte terrane. Structural controls and the presence of greenschist facies metamorphic mineral assemblages in the sheared and altered wall rocks and the veins are consistent, copper sulfides are often significant ore minerals, and the vein assemblage is typically oxidized with accessory barite, magnetite, and/or hematite.

Significant differences among these three types of veins may be largely related to the composition, texture, and associated rheology of the host rocks. Veins formed in mafic plutonic and volcanic rocks are commonly Cu-bearing and have peripheral alteration assemblages dominated by chlorite and epidote. Veins hosted by felsic plutonic and volcanic rocks typically contain less copper sulfide and have phyllic (sericite) altered marginal assemblages. Preexisting fabrics and structures may influence the orientation of veins, while those formed in more homogenous lithologies, such as unfoliated or weakly foliated plutons, may more closely reflect the kinematics of regional or local strain.

The majority of the Au ± Cu quartz vein occurrences in the North domain are consistent with mesozonal orogenic quartz vein gold mineralization formed by regional metamorphogenic fluids with the component metallic elements largely derived from the host rocks in the area. However, the W-bearing veins of the Hamby Branch group and similar occurrences at the Cline Mine to the northeast and the Crosby Mine to the southwest (**Fig. 21**, **Fig. 23**) may have an additional hydrothermal component, possibly derived from a felsic magmatic source.

The age of Au ± Cu mineralized quartz veins in the North domain

The presence of rock units ranging in age from Precambrian to Devonian in the eastern part of the North domain of the Charlotte terrane provides some constraints on the timing of the formation of some Au ± Cu bearing orogenic quartz veins. Host rocks in eastern Rowan and Cabarrus counties include > 570 Ma mafic volcanic and plutonic rocks of the Primitive Arc sequence, ca. 570-540 Ma metaintrusive units of the Rifted Arc sequence, ca. 617 Ma metavolcanic and metasedimentary units of the Five Pines Sequence (Carolina terrane), ca. 540 Ma granitic plutons in the immediate hangingwall of the Gold Hill Fault, and ca. 415 Ma granite plutons of the Salisbury suite. All serve as hosts for Au ± Cu mineralized quartz veins. The ca. 400 Ma mafic plutons of the Concord suite appear to largely post-date mineralized quartz vein formation, as do the Carboniferous granites (ca. 290 Ma) of the Churchland suite and Mesozoic diabase dikes (< 250 Ma).

In addition to several Au ± Cu bearing quartz veins at various orientations, the northeast part of the Salisbury pluton, with a zircon U-Pb age of 415 ± 6 Ma (**Hibbard *et al.*, 2012**), is cut by multiple parallel shear zones up to 60 centimeters thick that strike 055°-070° with epidote alteration (**Watson, 1904b**;**Watson, 1910**; **Phillips, 1967**). The NE- and NW-striking shear zones hosting Au + Cu ± W mineralization in the Hamby Branch area probably formed at the same time, as did the similar mineralization at the Dixie Queen Mine within the enclosing Newell Cu-Mo porphyry deposit, with a K-Ar age of 417 ± 15 Ma **(Worthington and Lutz, 1975)**. **Butler and Fullagar** (**1978**) suggest that the NE-striking shear zones in the Salisbury pluton may have formed concurrent with early Devonian reactivation of the Gold Hill Fault. **Boland and Dallmeyer** (**1997**) suggest significant Devonian movement along the Gold Hill Shear Zone to the south.

The timing and likely kinematics of deformation and mineralization along the linear trend of the southernmost Salisbury plutons (1-5) and mineralized quartz veins in the same area can be constrained by the tectonic history of deformation along the well studied Gold Hill Fault, located only five kilometers to the east. The Gold Hill Fault is an oblique reverse fault formed during sinistral transpressional in the Late Ordovician, accompanying the accretion of Carolinia to Laurentia during the Cherokee Orogeny (**Hibbard *et al.*, 2012**). The fault has an estimated 12.1 kilometers of stratigraphic displacement between the ca. 617 Ma Hyco-equivalent Five Pines Sequence in the hangingwall and the ca. 541 Ma Flat Swamp Member of the Cid Formation in the footwall (**Hibbard *et al.*, 2012**).

Formation of the Gold Hill Fault Zone was preceded by large-scale *en echelon* folding, axial planar cleavage development, and regional greenschist facies metamorphism of the Carolina terrane to the east, with ^{40}Ar/^{39}Ar ages of ca. 450 Ma that represent cooling from this deformation event (**Noel e*t al.*, 1988**; **Offield e*t al.*, 1995**; **Ayuso *et al.*, 1997**). This deformation also extends into the Five Pines sequence in the hangingwall of the Gold Hill Fault, where it folds both bedding and phyllitic cleavage and mineral lineation, suggesting that the cleavage is older than the folding event but still associated with the fault (**Hibbard *et al.*, 2012**).

The timing of cleavage formation and folding in the hangingwall indicate that initial movement on the Gold Hill Fault predates the regional folding event, but the major offset post-dates regional folding (**Hibbard et al., 2012**). Three granitic plutons emplaced immediately adjacent to the Gold Hill Fault Zone, the Cotton Grove, Gold Hill and Waxhaw plutons, have zircon U-Pb ages of ca. 540 Ma and all are weakly and heterogeneously overprinted by Late Ordovician deformation (**Hibbard *et al.*, 2012**).

Hibbard et al. (2012) suggest that Late Ordovician sinistral transpressional deformation associated with the Gold Hill Fault extends at least two kilometers into the hangingwall. This may have resulted in the reactivation of existing structures farther west, possibly including the tectonic suture between these two terranes in the basement. The North domain of the Charlotte terrane was deformed, uplifted, and transported eastward over the adjacent Albemarle Group of the Carolina terrane during Cherokee Orogeny. Silurian ^{40}Ar/^{39}Ar cooling ages for rocks of the North domain suggest uplift prior to ca. 430-425 Ma (**Hibbard *et al.*, 2012**), consistent with this event.

Titanite U-Pb data from the Waxhaw pluton near the southern end of the Gold Hill Fault Zone indicate relatively high-temperature reheating in this area during intrusion of the Concord and Salisbury plutonic suites in the early Devonian, and U-Pb titanite analyses of the Southmont

Pluton of the Salisbury suite (**Fig. 20**) indicate cooling through 550-600°C at ca. 402 Ma (**Hibbard *et al.*, 2012**). The U-Pb titanite analyses from the Abbotts Creek diorite within the northern end of the Gold Hill Fault Zone were not reheated (**Hibbard *et al.*, 2012**), suggesting that this heating was largely localized within the Charlotte terrane.

^{40}Ar/^{39}Ar cooling ages within the Gold Hill Fault Zone and heterogeneous deformation of the Late Ordovician fabrics suggest remobilization during the Devonian and the Carboniferous (**Hibbard *et al.*, 2012**). This Devonian fault reactivation probably extended to existing structures in the eastern part of the Charlotte terrane in the North Domain. Devonian reactivation of these structures may have facilitated the emplacement of the strongly aligned easterly group of Salisbury suite plutons (1-5), followed by the formation of NW- and NE-trending shear zones that host Au ± Cu ± W quartz veins. Localized heating of this portion of the Charlotte terrane may have facilitated the formation and transport of hydrothermal fluids, as well as weak metamorphism of the granite plutons.

Carboniferous reactivation of the Gold Hill Fault does not appear to be associated with mineralized quartz vein formation or other styles of hydrothermal mineralization in the adjacent Charlotte and Carolina terranes. Although some quartz vein-hosted Au ± Cu deposits in the North domain of the Charlotte terrane could be late-D_1 (Cambrian) in age, many probably formed during the Cherokee Orogeny in the late Ordovician, during deformation and uplift, and in the early- to middle-Devonian during Salisbury suite granite plutonism and localized tectonism.

The range of ages and styles of metallic mineral deposits is greater and more diverse in the North domain of the Charlotte terrane than in the South domain. In addition to Proterozoic VMS of the Primitive Arc sequence and mineralization associated with epizonal alteration systems of the Rifted Arc suite, there is Au ± Cu quartz vein mineralization possibly associated with the Cherokee Orogeny in the late Ordovician, intrusion-centered mineralization associated with the early Devonian (ca. 415 Ma) Mint Hill, Bogers Chapel-Newell, and Hamby Branch plutons of the Salisbury suite. This event is followed by formation of the Au-Cu ± W quartz vein deposits of the Hamby Branch group and related veins in the eastern part of the North domain. These veins are hosted by units ranging from Precambrian to mid-Devonian (ca. 400 Ma) in age and probably represent the final significant mineralizing event in the North domain.

Summary and Conclusions

Geologic and metallogenic analysis of the Charlotte terrane of Carolinia is complicated by strong regional tectonic segmentation. Similarity in the character and timing of magmatic suites and their plutonic and stratigraphic members, characteristic styles of associated mineralization, and the character and timing of deformation and regional metamorphism in the North and South domains suggest that the Charlotte terrane was a relatively uniform geologic entity prior to partitioning. Tectonic segmentation largely post-dates establishment of the dominant geologic character of the terrane, largely defined by two separate and distinct plutonic-stratigraphic associations; the Primitive Arc association and the Rifted Arc association.

The character of these associations and their timing and stratigraphic relationships relative to regional deformation and metamorphism is relatively well preserved and better documented in the South domain, but in the absence of high-precision geochronologic constraints. However, geochronologic data is available for comparable plutonic-stratigraphic associations in the southern portion of the North domain (**Dennis and Wright, 1997**). This facilitates identification of Primitive Arc and Rifted Arc associations in the North domain and the probable age of these associations in the South domain, constrained by comparison and correlation of these associations in both domains.

Tectonic segmentation of the Charlotte terrane may largely the result from complex collision and suturing with the Carolina terrane in the latest Ediacaran to early Cambrian. The magmatic, tectonic, and metallogenic evolution of North and South domains appear to diverge at this time. The South domain was sutured to the Carolina terrane and perhaps largely geologically inactive by ca. 550 Ma. However, Rifted Arc magmatism and D_1 tectonism continue in the North domain until ca. 535 Ma (**Dennis and Wright, 1997**) and is followed by episodic tectonism, magmatism, and new forms of mineralization that extend into the Devonian.

The Primitive Arc sequence

The Primitive Arc Sequence is the oldest recognized stratigraphic sequence in the Charlotte terrane and may locally include oceanic crust. It is characterized by mafic-dominated plutonic-volcanic complexes that interfinger outward with extensive sequences of mafic volcanic and volcaniclastic units interbedded with heterogeneous immature epiclastic sediments, all intruded by numerous mafic dikes, sills, and small stocks. This sequence is variably preserved throughout the Charlotte terrane and interpreted as a primitive supra-subduction volcanic arc association that pre-dates 579 Ma and formed on oceanic lithosphere (**Dennis and Shervais 1996**; **Dennis and Wright, 1997**; **Fullagar *et al.*, 1997**; **Shervais *et al.*, 2003**).

The Primitive Arc sequence hosts scattered VMS-type sulfide-oxide-silicate-carbonate deposits with footwall zones of phyllic hydrothermal alteration, suggesting localized arc-rifting accompanying Primitive Arc volcanism. In the North Domain, VMS mineralization is associated with localized sequences of intermediate to felsic volcanic rocks. The Primitive Arc Sequence is everywhere strongly folded, foliated, and metamorphosed to the middle to upper amphibolite facies during the D_1 orogenic event.

Despite extensive investigation and evaluation by a dozen mineral exploration companies throughout the 1970s and 1980s, there is currently no indication of economically viable VMS mineralization associated with the Primitive Arc Sequence of the South domain of the Charlotte terrane. The only known VMS deposit of the Primitive Arc sequence in the North domain, Nanny Mountain in York County SC, is deficient in precious and base metals, but is a very large hydrothermal system associated with localized felsic volcanism. Similar environments with known areas of hydrothermal alteration are present to the north, and there is potential for additional discoveries of VMS-type mineralization.

The Stoney Mountain Au-Ag-Cu-Ba mineralized ring dike deposit

The Stoney Ridge pluton is one of a cluster of five variably deformed ~20-25 km^2 biotite-metagranodiorite plutons in the southwestern portion of the South domain of the Charlotte terrane (**Fig. 6**). They appear unrelated to Primitive Arc magmatism and appear to be emplaced prior to D_1 deformation into immature epiclastic sediments and mafic volcanic units of the Primitive Arc sequence. They are compositionally homogenous with a weak foliation defined by biotite grains and margins that are heterogeneously foliated, sheared, and cut by quartz and pegmatite veins. Similar plutons of apparently similar age are not uncommon in both the North and South domains of the Charlotte terrane.

The 6.4 by 3.5 kilometers Stoney Ridge pluton is not compositionally or texturally distinctive, but is partly encircled by an apparent ring fracture intruded by a 15-75 meters thick dike of similar composition. A zone of intense, strongly zoned hydrothermal alteration up to 90 meters wide is centered on this dike and extends continuously for almost 10 kilometers (**Fig. 8, Fig. 13**). Alteration zonation suggests that hydrothermal fluid flow was largely focused within the dike, especially along the outer contact, with silicic granofels grading into advanced argillic and phyllic alteration zones towards the pluton.

The alteration zone hosts two 1500-meter long areas of disseminated sulfide mineralization anomalous in Au-Ag-Cu-Ba, while other areas are characterized by disseminated magnetite-hematite or apparently barren. Mineralization is strongest in the silicic granofels and only reaches ore grade in 30-90 centimeters thick shear zones with up to 20-25% disseminated pyrite that formed along the inner and outer margins of the silicic granofels, suggesting remobilization and concentration of pyrite and gold during D_1 deformation. The mining grade within the oxidized ore probably exceeded 0.1 oz/ton gold, but the average grade of the bulk mineralization in the alteration zone is well below 1.0 ppm and not of economic interest.

The Stoney Ridge deposit appears to be completely unique within the Charlotte terrane, and nothing similar is reported for other pre-, syn-, or post-D_1 plutons. However, there has been no known systematic exploration for this style of mineralization in either the North or South domains of the Charlotte terrane.

The Rifted Arc sequence

Often large compositionally zoned magmatic centers of the Rifted Arc sequence everywhere intrude the Primitive Arc sequence. Their formation appears to generally accompany regional D_1 deformation and metamorphism, possibly as a result of arc-rifting (**Dennis and Wright, 1997**) but also accompanying collision of the Charlotte and Carolina terranes. Like the Primitive Arc associations, early Rifted Arc plutonic phases are strongly deformed and metamorphosed to the amphibolite facies. However, younger more evolved lower volume plutonic phases and comagmatic volcanic units are less deformed and only metamorphosed to the greenschist facies in the South domain. Formation of the final phases of the Rifted Arc association in the South domain appears to be synchronous with or even post-date the latest stages of D_1 deformation and metamorphism, which may have largely ended ca. 550 Ma (**Shervais *et al.*, 2003**).

This is not the case in the North domain, where Rifted Arc magmatism and D_1 deformation and metamorphism continued until ca. 535 Ma (**Dennis and Wright, 1997**), suggesting a more complicated tectonic history. Peak regional metamorphism in the North domain appears to continue beyond the end of active deformation (**Dennis and Wright, 1997**) and the domain appears to have experienced greater uplift than the South domain. As a result, Rifted Arc volcanic-sedimentary sequences in this domain are metamorphosed to the amphibolite facies, generally poorly preserved, and more difficult to distinguish from the older Primitive Arc sequences.

Mineralization characteristic of the Rifted Arc Sequence is associated with tabular to lenticular, variably zoned silicic-advanced argillic and phyllic alteration systems with strike lengths of kilometers and widths of up to hundreds of meters. These occurrences may be metamorphosed epizonal, possibly epithermal, high-sulfidation hydrothermal systems formed along fault or shear zones, some with associated gold ± base metal sulfide mineralization.

Despite extensive investigation and evaluation by a dozen mineral exploration companies throughout the 1970s and 1980s, there is currently no indication of economically viable precious metal mineralization associated with the Rifted Arc Sequence of the South domain of the Charlotte terrane. The most promising focus for exploration in the South domain may be often extensive areas of ca. 550 Ma D_2 hydrothermal alteration along and adjacent to the Chappells Shear Zone on the terrane boundary with the Carolina terrane.

Several large (5-8 x 1-4 kilometers) and around a dozen smaller zones of hydrothermal alteration associated with Rifted Arc magmatism are present in the North domain of the Charlotte terrane in North Carolina. Although many contain disseminated pyrite and anomalous gold, there is no known historic mining of gold associated with these alteration zones. It is possible that these zones are the deeper, hotter, and more poorly mineralized equivalents of the apparently epizonal alteration zones in the South domain.

Deformation of the Charlotte terrane

The North and South domains of the Charlotte terrane are strongly deformed and metamorphosed by the D_1 deformation event, and similar deformation is likely in the Silverstreet domain. Although suggested to result from arc-rifting (**Dennis and Wright, 1997**), the D_1 tectonic event may in significant part result from the peri-Gondwanan collision and suturing of the Charlotte and Carolina volcanic arc terranes (**Shervais *et al.*, 2003**). There are no specific geochronological constraints on the initiation of D_1 in either the North or South domains. The timing of D_1 is constrained in the southern North domain to between about 570 and 540 Ma (**Dennis and Wright, 1997**). In the South domain, geochronologic constraints in the adjacent Carolina terrane and along the suture zone with the Charlotte terrane suggest that the D_1 event may have largely ended ca. 550 Ma (**Barker *et al.*, 1998**). However, arc-rifting and D_1 tectonism continued in the North domain until ca. 540 Ma (**Dennis and Wright, 1997**).

The end of arc-rifting and Ediacaran deformation ca. 540 Ma in the North domain of the Charlotte terrane (**Dennis and Wright, 1997**) and in the adjacent Albemarle Basin of the Carolina terrane (**Pollock *et al.*, 2010**; **Hibbard *et al.*, 2013)** is coincident with dextral-reverse transpressive deformation along the Gold Hill fault zone in the Waxhaw area of Union County NC (**Allen, 2005**; **Hibbard *et al.*, 2012**) and possibly along the Gold Hill shear zone to the southwest (**Lawrence, 2008**). Deformation along this structure was accompanied by the emplacement of a series of possible stitching granite plutons and may be analogous to the ca.550 suturing of the Carolina and Charlotte terranes in central South Carolina; however it is 10 Ma younger.

This suggests that the Lincolnton sequence-South Carolina sequence of the Carolina terrane and the Hyco Arc-Virgilina Formation-Albemarle sequence to the north (North Carolina sequence) may have acted as separate and independent tectonic blocks in their interactions with the Charlotte terrane. The South and Silverstreet domains of the Charlotte terrane collided and sutured to the South Carolina sequence by 550 Ma (**Barker *et al.*, 1998**). The interaction of the North domain of the Charlotte terrane with the Carolina North sequence may have occurred later and been largely strike-slip in character, with episodic adjustments throughout much of the Paleozoic.

Major sinistral-reverse offset on the Gold Hill Fault in central North Carolina accompanied orogen-scale transpression with the docking of Carolinia with Laurentia in the Late Ordovician during the Cherokee Orogeny (**Hibbard *et al.*, 2012**). This was accompanied with large-scale *en echelon* folding, localized reverse faulting, and regional greenschist facies metamorphism of the Albemarle Sequence of the Carolina terrane (**Hibbard *et al.*, 2012**) that extends for at least 50 kilometers to the east. This was accompanied by the formation of numerous mesozonal orogenic quartz vein lode gold deposits within and adjacent to the Gold Hill fault zone and the local formation of orogenic disseminated gold deposits along reverse fault zones to the east. There is no recognized magmatism associated with this event in either the Charlotte or Carolina terranes.

It appears likely that the North domain of the Charlotte terrane may have experienced similar compressional folding, faulting, and regional metamorphism, in addition to significant uplift in the hangingwall of the Gold Hill fault during the Cherokee Orogeny. Silurian ^{40}Ar/^{39}Ar cooling ages for rocks of the North domain of the Charlotte terrane suggest uplift prior to ca. 430-425 Ma (**Hibbard *et al.*, 2012**), consistent with this event. However, associated folds and faults are poorly constrained, except in the immediate hangingwall of the Gold Hill fault (**Hibbard *et al.*, 2012**). Deformation may have largely affecting existing structures and rock fabrics. It is possible that many of the orogenic Au ± Cu quartz veins in the North domain of the

Charlotte terrane formed during this event. Their character suggests largely brittle-ductile deformation along shear zones and faults at conjugate angles to the existing D_1 foliation and largely greenschist facies metamorphic conditions accompanying hydrothermal alteration and mineralization.

Deformation, metamorphism, and mineralization associated with the Cherokee Orogeny have not been recognized and documented in the Silverstreet or South domains of the Charlotte terrane or in the South Carolina Sequence of the Carolina terrane in South Carolina and Georgia. As in the North domain of the Charlotte terrane, structures and fabrics resulting from the Cherokee Orogeny may be difficult to distinguish from those formed previously.

Devonian magmatism and mineralization

Two significant magmatic events affected the Charlotte terrane during the Devonian; generation and emplacement of the Salisbury magmatic suite in the North Domain and the emplacement of the Concord magmatic suite throughout the Charlotte terrane. The Concord magmatic event affects the entire Charlotte terrane and appears to be broadly post-tectonic at ca. 400 Ma. No significant recognized metallic mineralization is associated with these gabbroic to syenitic plutons. These plutons are heterogeneously scattered throughout the Charlotte terrane, with a number emplaced across or proximal to the suture between the Charlotte and Carolina terrane in the South domain.

It has been suggested that these Devonian gabbro plutons selectively intrude older gabbroic intrusions of the Rifted Arc sequence to form a Gabbro-Metagabbro association, possibly with a systematic spacing of 50-100 kilometers in the North domain (**McSween *et al.*, 1984; McSween and Harvey, 1997**). While this association is accurate for the Concord and Mecklenburg complexes (**McSween and Harvey, 1997**), this association is questionable for most plutons of the Concord suite.

In the Farmington-Barber complex of **McSween *et al.*** (**1984**) in the North Domain (**Fig. 2**), Devonian gabbro of the Concord suite intrudes the ~800 km^2 Mocksville Primitive Arc magmatic complex of amphibolite facies metamorphosed equivalents of gabbroic and ultramafic intrusive and hypabyssal and probably extrusive basalts with possible ophiolite associations (**Goldsmith *et al.*, 1989**). The Concord gabbroic plutons of the Mecklenburg complex intrude a wide range of plutonic and stratigraphic sequences of both the Primitive Arc and the Rifted Arc of the Charlotte terrane (**Fig. 2**). The same is true for Concord suite gabbroic intrusions in the South domain (**Fig. 6**).

It may be more accurate to state that Devonian gabbroic plutons of the Concord suite randomly intrude lithologies of both the Primitive Arc and Rifted Arc sequences of the Charlotte terrane, both of which locally include metagabbro bodies. This is especially true in the South domain, where metagabbro and gabbro plutons are seldom conjoined and Concord suite plutons are intruded along the suture between the Charlotte and Carolina terranes (**Fig. 6**).

The tectonic process or event that resulted in localized tholeiitic magmatism throughout the Charlotte terrane and emplacement of variably differentiated gabbroic plutons of the Concord suite is uncertain (**McSween *et al.*, 1984; McSween and Harvey, 1997**). However, it appears to post-date early Devonian emplacement of the granite plutons of the Salisbury magmatic suite in the North Domain and subsequent heterogeneous deformation and metamorphism.

Salisbury suite granitic magmatism and associated mineralization ca. 415 Ma is unique to the North domain, and possibly associated with local tectonic events that are reflected in reactivation of the Gold Hill Fault (**Hibbard *et al.*, 2012**) and heterogeneous syn- to post-emplacement deformation and metamorphism of the plutons. Porphyry-style Cu-Mo mineralization and skarn mineralization with high REE content is associated with some of the Salisbury suite granite plutons. Both may represent potentially under-explored significant metallic resource opportunities.

At least four Salisbury suite granite plutons appear to host minor Mo mineralization, and the Newell prospect is a subeconomic Cu-Mo porphyry system. The Probst prospect is opened on a skarn at the southern end of a strong aeroradioactivity anomaly that extends for at least 5 kilometers along the southeast flank of the Hamby Branch granite pluton (**Daniels and Zietz, 1982**). Highly anomalous REE are contained in a silica-andradite-allanite-magnetite skarn that has been overprinted by base metal sulfide + molybdenite + barite mineralization.

This skarn is proximal to the contact between the granite and metamorphosed mafic metaintrusive and metavolcanic units of the Primitive Arc sequence. Much of the eastern contact of the Hamby Branch pluton is in contact with this sequence. A similar but smaller aeroradioactivity anomaly is located at the northern end of the Bogers Chapel granite pluton to the south, and the Concord granite of the Salisbury suite is flanked to east and west by arcuate aeroradioactivity highs (**Daniels and Zietz, 1982**). Both porphyry and skarn mineralization appear to be far more likely along the periphery of the Salisbury suite granite plutons rather than within the interiors.

Additionally, there are several remarkable concentrations of low-tonnage but high-grade mesozonal orogenic quartz veins with Au-Cu mineralization in the North domain, some hundreds to thousands of meters long and up to 5 meters thick. A large concentration of these veins is centered on the city of Charlotte in Mecklenburg County. Many of these veins were only exploited for oxidized ore over portions of their lengths to depths of only 15-40 meters.

Multiple parallel or cross-cutting veins are present in some areas that might offer lower-grade bulk minable potential. The concentration of Au-Cu ± W mineralized quartz veins in the Hamby Creek area of Cabarrus County may offer similar potential for multiple parallel or intersecting veins. The age of these vein deposits is not well constrained, but all appear to post-date the Rifted Arc sequence. Some veins may have formed during the Cherokee Orogeny in the late Ordovician, while others are clearly of Devonian age.

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Appendix: Mines and prospect discussed in the text

Mines of the Hamby Group in Cabarrus County NC

The **Faggart Mine** is located 3 miles north of the Phoenix mine and about 100 meters east of the Probst Prospect on the same mining tract as the Snyder mine. Pyrite and specular hematite were seen in 1934 in a 46 centimeter wide auriferous quartz vein cutting pink granite, with a grade of 0.34 oz/ton gold (**Bryson, 1936**). The mine was opened by a shaft about 30 meters deep with a 15 meter drift.

The **Propst (Nash, Heglar) Mine** is located 6.8 kilometers southwest of Mount Pleasant and 8 kilometers southeast of Concord in eastern Cabarrus County. The Snyder Mine is less than 1.6 km south of the Propst Mine and the Phoenix and Furniss mines are 2.4 km to the southeast. A 1.5 x 1.5 meters shaft filled with water and numerous trenches are present, opened in the mid-1950s. The shaft was opened in a bleached silicified zone in pink granite or quartz monzonite (**Sundelius and Bell, 1964**). Metallization is in a fine-grained, dark-gray to brown siliceous zone with pyrite, molybdenite, barite, chalcopyrite and magnetite. **Sundelius and Bell** (**1964**) note the presence of abundant allanite in an andradite-chalcedony-quartz gangue.

The **Barnhardt Mine** is located 9.7 kilometers southeast of Concord and 2.4 kilometers east of the Faggart Mine. A quartz vein is 20-76 centimeters thick and enclosed by a zone of schist (shearing) 4.8-5.2 meters wide, both striking 070° through granite of the Mount Pleasant pluton (**Emmons, 1856**). **Sundelius and Bell** (**1964**) report widespread shearing and abundant pyrite in this intrusion. A 1.5 meter thick quartz vein in a dike of diorite or diabase carried galena, chalcopyrite, and pyrite with a grade of about 0.44 oz/ton gold. Coarse placer gold also has been found in a stream on the property. In 1934 a 1.2 meter thick quartz vein and two partly filled shafts were seen.

The **Quaker City Mine** has been inactive since about 1886. An alignment of three shafts, the deepest about 24 meters, and numerous pits and shafts trend 335° (**Bryson, 1936**). The largest opening is 9 meters in diameter at the surface and was collapsed to within 9 meters of the surface (**Pardee and Park, 1948**). Mining focused on a quartz vein 60 to 1.5 meters thick cutting through diorite that carried gold and copper (**Bryson, 1936**). The grade of the ore is reported as low.

The **Arey Mine** was opened on a 15 centimeter thick quartz vein carrying limonite, pyrite, and bornite (**Bryson, 1936**). It was explored by an 11 meters deep shaft in 1934. This prospect is probably near the Vanderburgh mine, said by Emmons to be on a vein composed of barite and quartz with chalcopyrite.

The **Snyder Mine** is located on the same tract as the Faggart Mine, less than 1.6 km south of the Propst Mine. The workings consist of two shafts; one is 1.5 x 3 meters and filled with water and a second collapsed shaft is located 6 meters to the west. They were opened on a milky quartz vein that contains chalcopyrite, bornite, calcite, rhodochrosite, magnetite, malachite, siderite, epidote, and pyrite (**Bryson, 1936**). The deepest shaft extends to a depth of 42 meters, where the vein pinches and swells and the gold values decreased (**Bryson, 1936**). The vein occurs in diorite sheared to form biotite-chlorite schist that contains minor pyrite, chalcopyrite, epidote, magnetite and rhodochrosite. Rhodochrosite forms large masses that are cut by veinlets of calcite that contain bornite and chalcopyrite.

Cullen's Mine in Cabarrus County is located about 500 meters WSW of the Snyder Mine in the Hamby Branch area. Mineralization includes scheelite in rounded granular patches of a grayish-yellow color with auriferous pyrite in quartz **(Genth, 1891**).

The **Narville Mine** is located 6 kilometers northwest of Georgeville. A 25-30 centimeter thick quartz vein, possibly a continuation of the Phoenix Mine vein, was worked by a 30 meters deep shaft about 1900 (**Pardee and Park, 1948**).

The **Widenhouse Mine** is located 6 kilometers northwest of Georgeville in Cabarrus County. A quartz vein carrying gold is hosted by a zone of chloritic schist (**Pardee and Park, 1948**).

The **Furniss Mine** is the probable continuation of veins in the Phoenix Mine, located 300 meters to the southeast and was worked prior to 1860, operated by Adolph Thies in the l880s, and operated by the Miami Mining Company in 1900-1906 (**Nitze and Hanna, 1896**). P.L. Furr sank an 18 meters deep shaft in 1931 said to have opened a 90 centimeter thick quartz vein containing 5% sulfides. The main quartz vein strikes 060° and dips 80° NW through Fe-oxide stained sheared diorite cut by numerous epidote stringers. Calcite, siderite, chalcopyrite and pyrite occur in both the country rock and quartz vein (**Nitze and Hanna, 1896**). Malachite stains weathered surfaces of the rocks and occasionally encloses chalcocite. Magnetite occurs with pyrite in the host rocks. Small crystals of galena occur in calcite and scheelite is disseminated through the quartz as small grains and local aggregates. As at the Phoenix Mine, ore-grade mineralization occurred in shoots. The vein was worked from the 54 meters deep Furniss shaft and several drifts, with the Furr shaft opened to the southwest to a depth of 18 meters (**Nitze and Hanna, 1896**). In 1948, the U. S. Bureau of Mines drilled eight holes and examined the underground workings of the mine to evaluate the potential for scheelite (**Stuckey and Conrad, 1961**). Four additional holes were drilled in 1949 and numerous trenches were dug but the deposit was not considered economic.

The **Phoenix Mine** was worked prior to 1856 and was developed to a depth of 43 meters and ceased operations in 1889. The mine was active again from 1900 to 1906, with the deepest shafts

extending to 183 meters and working levels over a strike length of 640 meters (**Nitze and Hanna, 1896**). Three to four ore shoots were mined from the 15 meter and 30 meter levels. The 91 meters long Phoneix shoot was mined out from the 30 meters level to the 130 meters level and pinches to the northeast. The shaft follows the dip of the vein to a depth of 150 meters, but there are no drifts. The vein averages about 76 centimeters thick but the rich pay-streak on the hangingwall is only 5-7.5 centimeters thick. The deposit is a quartz vein ranging from a few centimeters to 1.2 meters wide that strikes 057° and dips 80° NW. The vein is vuggy with tiny quartz crystals and carries bornite, pyrite, chalcopyrite, galena, calcite, barite, and scheelite with cross-cutting veinlets of siderite. Free gold was present in the barite and calcite. The mill yield was 0.40 oz/ton gold with another 0.36 oz/ton in the sulfides. The copper content of the ore is 1.5-3% (**Nitze and Hanna, 1896**). The host rock is a shear zone in fine-grained, dark greenish-gray diorite that is partly altered to epidote-chlorite schist.
The **Middle Vein**, located 61 meters southeast and subparallel to the Phoenix vein was worked by open pits, with masses of sulfides yielding up to 1.74 oz/ton gold (**Nitze and Hanna, 1896**).

The **Copper Vein** parallels the Phoenix-Furniss vein system 305 meters to the southeast of the Middle Vein. Assays from the surface were as high as 22% copper and 2 oz/ton gold (**Nitze and Hanna, 1896**). The Copper Shaft extends to a depth of 46 meters with 71 meters of drifts. Ore minerals include pyrite, chalcopyrite, barite, and siderite. Abundant fluorescent material is present on the mine dumps, including some of the barite.

The **Gibb Mine** adjoins the Phoenix mine on the west with similar host rock and quartz veins. High-grade sulfide ore was mined here in the l880s (**Nitze and Hanna, 1896**).

The **Tucker (California, Northern Shaft) Mine (10)** was worked prior to 1884. A 53 meters deep shaft was opened with 36 meters of working levels on a quartz vein that averaged only about 20 centimeters thick (**Nitze and Hanna, 1896**). A second vein on the property was worked by a line of pits and shafts 152 meters long. The quartz vein has a strike of 080° with a subvertical dip in andesitic metavolcanic rocks that strike 045°. Pyrite and minor chalcopyrite are present with barite and specular hematite at a grade of around 0.73 oz/ton gold. Scheelite is reported on the mine dumps (**Jones and Peyton, 1950**). Some variably sheared felsic crystal metavolcanic rocks are present on the mine dumps.

The **Sanders (Saunders) Mine** is located 6.4 kilometers northwest of Georgeville in Cabarrrus County. Fine gold was reported in narrow quartz stringers in diorite. A 4.5 meters deep shaft was present in 1934 (**Nitze and Hanna, 1896**).

The **Barrier Mine** is located 1.6 kilometers southwest of the Phoenix Mine on the same property. Quartz veins in greenstone schist carry pyrite, chalcopyrite, and gold. The mine was worked before 1860 by Mr. Orchard, who opened it to a depth of 49 meters on two veins; a vertical vein 36 centimeters thick and an inclined vein 30 centimeters thick. The veins are 3.7 meters apart at the surface but only separated by 60 centimeters at 49 meters depth. The gold content of the ore is reported as 2.9 oz/t (**Nitze and Hanna, 1896**). In 1893 the mine was reopened and a 5-stamp mill was built.

The **Furniss Furr Mine** is located 4.8 kilometers northwest of Georgeville, and 800 meters southwest of the Barrier mine, near the northeast bank of Rocky River. Two quartz veins carrying gold cut greenstone schist or sheared diorite (**Pardee and Park, 1948**). The hanging-wall quartz vein is around 30 centimeters thick and flinty with abundant pyrite. The footwall vein is 30 centimeters thick and partly cellular and stained by Fe-oxides, and contains barite and aggregates of pyrite. The veins strike 030° and the older mine workings extend for 457 meters feet to the north and include 2 or 3 shafts and several pits (**Pardee and Park, 1948**). In 1934 the mine produced 15 tons of ore that were treated by flotation at the White Star Mining Company plant at Smyrna, SC. The mill heads assayed about 0.44 oz/ton gold per ton.

The **Allen-Boger Mine** is located about 13 kilometers southeast of Concord where the Concord Road crosses the Mount Pleasant Road. Pits and trenches extended for up to 600 meters in a 025° direction on a vein 30-38 centimeters thick. The deepest shaft extends 12 meters on a 75° dip. The host rock is reported as granite with the vein enclosed by 76 meters of strongly foliated schist. Coarse grained diorite containing centimeter long hornblende crystals, epidote, chalcopyrite, and quartz were seen on the dumps in 1934 (**Pardee and Park, 1948**). Tetradymite and azurite were reported from the mine (**Genth, 1891**).

Mines of the Bogers Chapel Pluton area

The **Newell Mine (Dixie Queen)** is located in southeastern Cabarrus County. The mine was opened between 1895 and 1900 and was primarily work for copper. The property was again worked in 1923. Two shafts were opened on a 60 centimeter thick quartz vein containing pyrite, chalcopyrite, bornite, chalcocite, malachite, and euhedral grains of magnetite. The chalcocite is altering to malachite and much of the chalcopyrite is coated with manganese or copper oxide. The host rock is felsic metavolcanic rocks enclosed by diorite and granite; however, gabbro and granodiorite were also present on the mine dumps. The host rock is locally sheared and bleached with sericite and pyrite.

The **Pioneer Mills Mine** is located 3.2 kilometers southwest of the Newell Mine on the old Morrison Plantation. The mine includes the West Shaft and the East Shaft, separated by 500 meters. It was opened about 1844 but has been largely inactive since 1857. The East shaft was sunk to a depth of 45 meters, the lower part inclined, with drifts about 90 centimeters wide at the 30 and 40 meter levels that extend to the WSW (**Nitze and Hanna, 1896**). Shallow older workings at the surface extend for 213 meters in the same direction. A stope on the 40 meter level is 55 meters long, but increases to 213 meters at shallow levels. Numerous prospect pits and trenches are present along the small creek about 90 meters north of the mine, suggesting a parallel vein. The quartz vein is 20-76 centimeters thick in lenticular *en echelon* segments within a zone of shearing about 5 meters thick that strikes 070° (**Emmons, 1856**). The quartz vein in the East Shaft of the strikes 080° and dips 80°NW. The ore body had a length of 235 meters, was 60 centimeters wide, and worked to a depth of 45 meters from 1844 to 1857. A 24 meter long channel sample on the 40 meters level was sampled at 1.5 meters intervals and averaged 0.09 oz/ton gold, with a 6 meters long section that averaged 0.32 oz/ton gold.

The quartz vein cuts through variably sheared hornblende-quartz diorite or granodiorite with accessory magnetite. Mafic metavolcanic rocks are present to the east. The vein is stained by Fe-oxides, and is vuggy, cellular quartz with siderite, chalcopyrite, calcite and minor chrysocolla and malachite. **Nitze and Hanna** (**1896**) report the presence of outcropping decomposed granite and fine-grained granite may form a dike in gabbroic rocks. **Genth** (**1891**) reports the presence of molybdenite in granite and quartz veins in the Pioneer Mills mine area and molybdenite is reported at the East Shaft.

Emmons (**1856**) reports the presence of four gold-bearing quartz veins on the Morrison Plantation. The first vein is 1.6 kilometers southwest of the Pioneer Mine, where rich gold in vein quartz with sulfides was found on the spoil pile. The second vein is located 1.6 kilometers to the east and similar to the first. At the third vein the gold occurs with chalcopyrite. The fourth quartz vein is in the northeast part of the plantation and composed of quartz and pyrite. All of the quartz veins strike northeast.

The **Crosby (Crosby's, Poplan) Mine** is located at 35° 16' 12" North, 80° 34' 51" West in Cabarrus County, north of the Pioneer Mills Mine and possibly on the plantation of Dr. Crosby. A quartz vein is said to carry gold, siderite, barite, cuprotungstite, cuprian scheelite, and scheelite as "yellowish brown and grayish imperfect crystalline masses" (**Genth, 1891**).

The **Flowe's Mine** may be located in Cabarrus County, but the location is uncertain. Cupro-scheelite and scheelite as orange-colored tetragonal pyramids occur with barite (**Genth, 1891**).

The **Bangle Mine** in Cabarrus County (location unknown) is listed as having scheelite associated with pyrite and chalcopyrite in a gold-bearing quartz vein (**Genth, 1859**, p. 246-255).

Mines of the Salisbury Pluton

At the historic **Reimer gold mine**, located about 1.6 kilometers ESE of Granite Quarry in the Salisbury pluton (8), a variably laminated quartz vein that varies from 1.2 to 2.4 meters thick, locally to 3.7 meters, strikes 285°, dips steeply southwest (**Kerr and Hanna, 1888**). The sulfides are dominantly pyrrhotite with minor chalcopyrite. The ore shoot within the vein was 213 meters long and worked to a depth of up to 50 meters (**Nitze and Hanna, 1896**; **Nitze and Wilkens, 1897**).

The Bullion Mine, on an extension of the Reimer vein about 800 meters southeast, consists of caved and overgrown workings that strike for 150 meters on a prominent quartz vein with large masses of limonite with some relict pyrite (**Nitze and Hanna, 1896**; **Nitze and Wilkens, 1897**).

The **Dunn's Mountain Mine** is 9.7 kilometers southeast of Salisbury, a little to the left of Gold Hill Road on the west flank of Dunn's Mountain (**Kerr and Hanna, 1888**) in the Salisbury pluton. It had intermittent production and was idle by 1888. There are 3 veins; one strikes northeast, one strikes northwest, and the Office Shaft vein strikes north-south. The first of these veins is worked to a depth of 58 meters and averaged about 1.2 meters wide. It was most largely filled with strongly foliated and altered rock and quartz, and carried only a moderate amount of pyrite and trace chalcopyrite. The Office Shaft vein was worked to a nominal depth of 49 meters (about 43 meters vertically), 27 meters being in a vertical shaft and 21 meters on an incline of about 45°. The ores were largely oxidized and free milling with only a small amount of sulfides present. In the lower levels of the mine the ore body diverged into several small veins.

Mines near the Mint Hill area, Mecklenburg County

Mint Hill had an abundance of gold mines on a series of quartz veins located to the north. The Surface Hill Mine was the most productive, and named for its gold outcroppings and its large yield of nuggets (**Nitze and Hanna, 1896**). The mine was active from 1844 until 1930. By 1912, new owners from Texas and Oklahoma made a substantial investment in new equipment at Surface Hill, including a smelter.

Other mines located in the Mint Hill area were the Shaffer Mine, Dulin Mine, Ferguson Hill Mine, A. J. Wilson Mine, Poplin Mine, Bradford and Ellington Mine, Blair and Brafford Mine, Beaver Mine, Long Mine, Maxwell Mine, Hagler Mine, Zeb Teeter Mine, Black Mine, and Black Cat Mine, and Elliotte Plantation, which had six veins. The Hood Prospects, located between Mint Hill and Matthews, had two mines.

North of Mint Hill there are two series of quartz veins, one striking NE and the other NW (**Nitze and Hanna, 1896**). In the NE-set the **Beaver vein** 800 meters east of Mungo's Store is the most northern; followed by two parallel veins, the **Bradford** and **Ellington** veins; and 100 meters farther south is the **Surface Hill** vein. The middle of the **Ellington** vein is called the **Blair** and the continuation to the southwest is the **Hard Hill** vein. The NW-trending set of veins is located about 1.6 kilometers west and 800 meters SW of Mungo's Store. From the north they are the **Ferguson Hill** (35° 11' 6" N, 80° 41' 19" W), **A.J. Wilson** (35° 10' 33" N, 80° 41' 37" W), **Shafer** (35° 9' 48" N, 80° 41' 19" W), and the **Poplin** (35° 9' 4" N, 80° 41' 2" W).

The **Surface Mine** (35° 12' 24" N, 80° 38' 45" W) has two large quartz veins, the Harris, striking 045° and the Lidner or Vivian striking 350° that intersect (**Nitze and Hanna, 1896**). The veins are in granite country rock and pyrite and chalcopyrite, with a large pocket of gold nuggets found near the intersection of the two veins and where they are cut by a dike. A number of reticulated quartz veinlets have scattered their contents widely over the 66 acres comprising the mining tract.

Ellington (Brafford, Hard Hill, Blair) Gold Mine (35° 11' 45" N, 80° 39' 34" W) is located about 300 meters north of the Surface Hill Gold Mine. There are two adjacent parallel quartz veins with a mine on each; the quartz vein at the Ellington mine is the middle portion and is known as the Blair, its southwest continuation as the Hard Hill Vein. This is the same trend as the Maxwell and Hagler veins.