ABSTRACT

BRENNAN, MATTHEW PHILIP. Geology and Depositional Environment of Strata in the Vicinity of Jacob's Creek Quarry, Denton, NC: Implications for the Stratigraphy and Age of the Albemarle Group. (Under the direction of Dr. James P. Hibbard).

The Albemarle Group is one of the major defining stratigraphic units of the Carolina terrane, the best-known division of the southern Appalachian peri-Gondwanan block of Carolinia. As such, the group has been recognized as important for correlating Carolinia with other peri-Gondwanan Appalachian blocks. Until recently, it had been considered a conformable sequence of mainly Late Neoproterozoic age; however, this age assignment has been in question due to reports of Paleozoic (Late Cambrian and younger) fossils from two quarries in the group. To accommodate the reported fossil finds, significant revisions to the stratigraphy and structure of the group were proposed.

This study focused on resolving the stratigraphy and structure of the group in the vicinity of Jacob's Creek Quarry near Denton, North Carolina, one of the reported Paleozoic fossil locations. Measurement of a 20-meter stratigraphic section across the Cid mudstone and Flat Swamp member contact, recently proposed as a regionally significant thrust, identified an intercalation of mudstone, greywacke, epiclastics and tuffaceous siltstone indicative of a conformable and gradational contact. No significant tectonic structures, other than a weak regional cleavage that is observed throughout the study area, were observed.

Facies associations also suggest that the Cid and Floyd Church Formations form part of a conformable, coarsening upward sequence. In addition, field and facies evidence did not reveal evidence of Paleozoic outliers. Therefore, the rocks in the vicinity of Jacob's Creek Quarry are considered Neoproterozoic and changes to our understanding of the stratigraphy and structure of the Albemarle Group are unwarranted.

A secondary objective of this investigation was to compile in digital geospatial format, geological field maps produced by previous graduate students from North Carolina State University that are contiguous to the area studied herein. This was done by direct digitization of paper maps produced as part of unpublished theses. The product is a geological map of contiguous portions of the Morrow Mountain, Badin and Handy quadrangles.

Geology and Depositional Environment of Strata in the Vicinity of Jacob's Creek Quarry, Denton, NC: Implications for the Stratigraphy and Age of the Albemarle Group

by
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DEDICATION

Sheila and Emma,

I love you.

Mom and Dad,

For your love and understanding

BIOGRAPHY

Matt Brennan was born in Marquette, Michigan on March 1, 1973 and grew up in Rome, New York. He graduated from Rome Catholic High School and then enrolled at Boise State University. Upon graduation he travelled the Pacific Northwest and southern United States before working as an environmental consultant in North Carolina and the Republic of Ireland. In 2006 he was accepted into the graduate program at North Carolina State University under the direction of Dr. Jim Hibbard. He graduated with a Master of Science degree in 2009.

ACKNOWLEDGEMENTS

I would especially like to thank Dr. Jim Hibbard for giving me the opportunity to work with him on this project. I leave with a better understanding and passion for geology than when I started. Also, my committee, Dr. Ron Fodor, Dr. John Diemer and Dr. Helena Mitasova for taking the time to review my work and furthering my knowledge of geology and GIS.

I am extremely grateful to Jeff McKinney, his family and everyone at the Jacob's Creek Quarry for access. I would also like to thank Jeff Pollock for his field assistance, company and introduction to the Trailer Park Boys. Also, Gordon Box for accompanying me in the field and carrying back the heavy rocks. Last but not least, thanks to my sister, Meg, for offering her couch when needed and much more.

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Introduction

Focus of Study

The Albemarle Group is one of the major defining stratigraphic units of the Carolina terrane, the best-known division of the southern Appalachian peri-Gondwanan block of Carolinia (Hibbard *et. al.*, 2007). The group extends from central North Carolina to the South Carolina state line (Figure 1), is estimated at greater than 15 km thick (Butler and Secor, 1991) and has long been considered a conformable sequence of mainly late Neoproterozoic age (Stromquist and Sundelius, 1969; Gibson and Teeter, 1984; Milton, 1984, Stromquist and Henderson, 1985; Harris and Glover, 1988). However, this age assignment has been in question for more than a decade because of conflicting reports indicating both Paleozoic (Late Cambrian and younger) (Koeppen *et. Al.*, 1995) and Neoproterozoic fossils in the vicinity of Jacob's Creek Quarry near Denton, North Carolina (Koeppen, *et. al.,* 1995; Ingle *et. al.*, 2003; Hibbard *et. al.*, 2006). Paleozoic fossils were also reported from the Albemarle Group at the Martin Marietta Quarry near Asheboro, North Carolina (Koeppen, *et. al.*, 1995).

To accommodate the purported fossil finds, Offield (2000) revised the stratigraphic order of the group and introduced regional scale thrusts at the base of the Tillery Formation and at the base and top of the Cid Formation (Figure 2). If true, these revisions would demand major changes to our conception of the tectonic evolution of the Carolina terrance

At present, there are three possible hypotheses to account for the stratigraphy of the Albemarle Group (Hibbard *et. al.*, 2009). The first alternative is that the entire mapped extent of Tillery and Cid formations is Paleozoic, on the basis of the reported fossils (Koeppen et al., 1995) and that major stratigraphic and structural reinterpretation of the

Albemarle Group (Offield, 2000) is valid. A second alternative possibility is that the Paleozoic fossils occur in limited erosional remnants of once larger basins, unconformable atop the mainly Neoproterozoic Albemarle Group. This interpretation constitutes a 'compromise' between the reported Paleozoic fossil data and the traditional stratigraphic/structural view of the Albemarle Group. The final hypothesis is that the reports of Paleozoic fossils in the group are erroneous and that the generally accepted stratigraphic and structural interpretation of Milton (1984) is correct.

The results of this study have broad implications for our understanding of the Appalachian Orogen. The nature and age of the Albemarle Group has recently been recognized as an important factor in interpreting late Neoproterozoic-early Proterozoic tectonic models (Hibbard *et. al.,* 2007). Therefore, changes to our understanding of the geological history of the Albemarle Group necessitate change to our understanding of these late Neoproterozoic-early Proterozoic tectonic models.

The goal of this study is to reconcile the structure, stratigraphy and sedimentology of the Albemarle Group in the vicinity of Jacob's Creek Quarry, where both Neoproterozoic and Paleozoic fossils have been reported (Koeppen *et. al.*, 1995; Hibbard *et. al.*, 2006, Weaver *et. al.*, 2008). Detailed 1:24,000 scale field mapping in the vicinity of the quarry was completed in order to determine the relationship between rocks underlying the area. This included detailed outcrop scale analysis to establish the depositional environment of rocks in the field area. This investigation is part of a larger study, which includes recent mapping by Jill Kurek near the second reported fossil find in Asheboro, North Carolina.

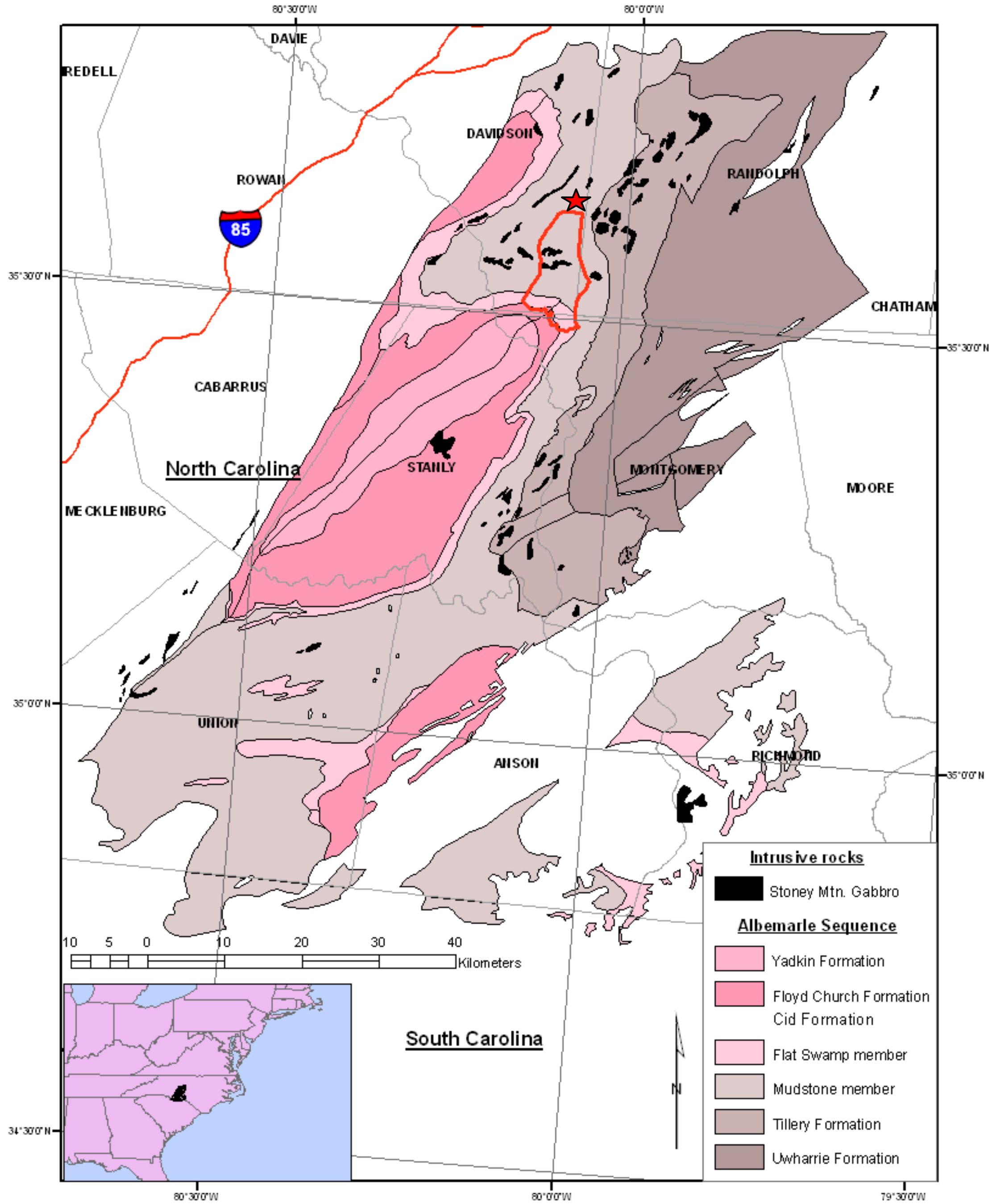

Figure 1: Geographic extent of the Albemarle sequence in central North Carolina and South Carolina. Study area outlined by red polygon. Red star to the north of the field area boundary indicates approximate location of Denton, NC.

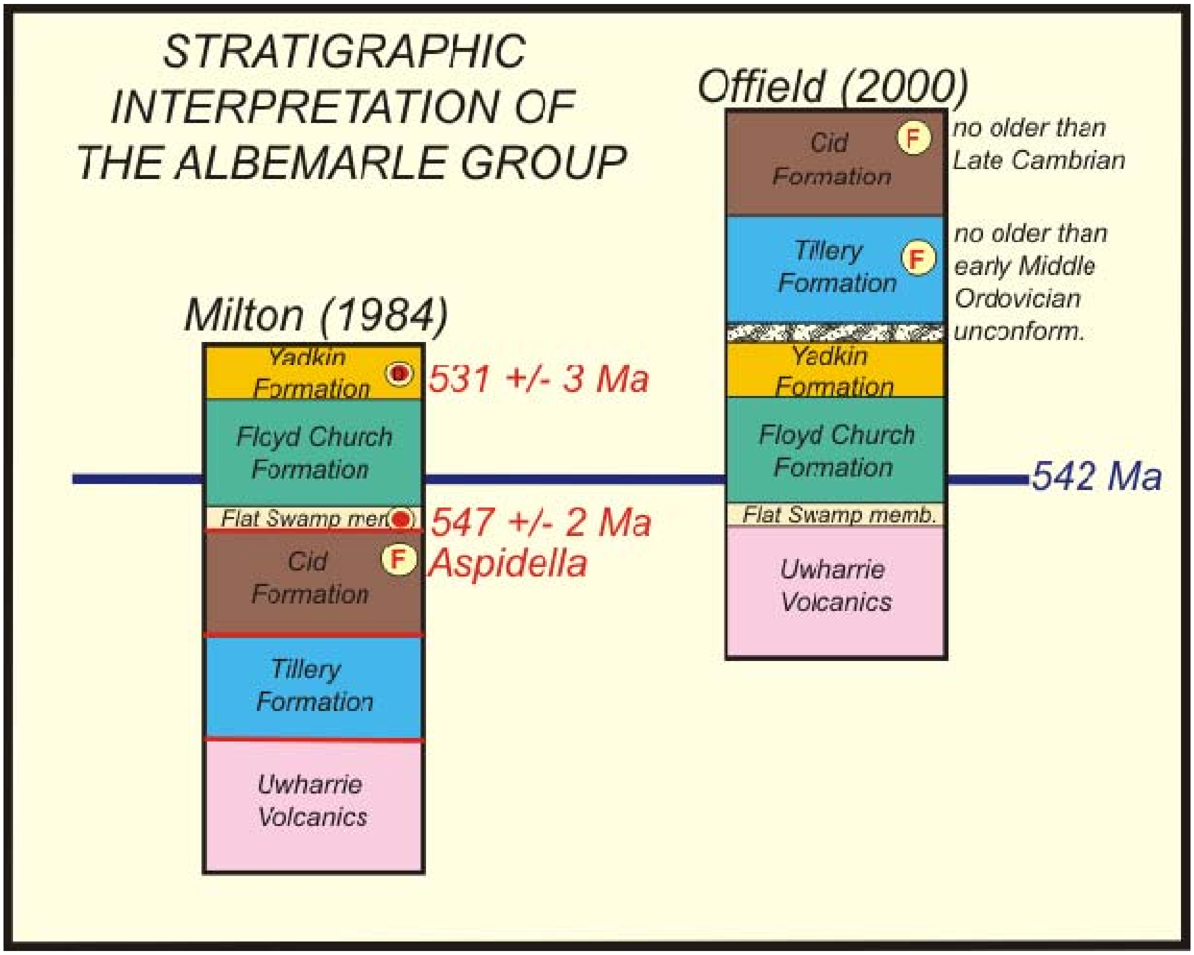

Figure 2: Comparison of Albemarle sequence stratigraphy of Milton (1984) and Offield (2000). Red lines on Milton column indicate thrusts required to reconcile observed field stacking order with interpreted geologic age as shown in column on the right (from Hibbard *et. al, 2006*). Solid blue line represents the Precambrian-Cambrian boundary. F = fossil constraint.

Regional Geology

The Appalachian Orogen extends for more than 3,000 kilometers from Alabama to Newfoundland and from west to east it can be separated into three lithotectonic realms; the Laurentian, Iapetus, and peri-Gondwanan realms (Figure 3). Each realm has unique first order geological characteristics that allow for determination of their paleogeographic origin. Laurentian realm rocks comprise Mesoproterozoic basement and Paleozoic rocks deposited on or adjacent to the Laurentian margin following the breakup of Rodinia. Gondwanan rocks formed proximal to Gondwana and are therefore considered exotic to North America (Hibbard, 2004). The Iapetan Realm comprises mainly oceanic and volcanic arc elements that formed within the Iapetus Ocean between Laurentia and Gondwana in the time between the breakup of the Neoproterozoic supercontinent Rodinia and the formation of the late Paleozoic supercontinent of Pangea.

Peri-Gondwanan crustal blocks within the orogen include Ganderia, Avalonia and Meguma in the northern Appalachians and Carolinia and Suwanee in the south; although, the Suwanee block lies entirely in the subsurface immediately to the south of the exposed orogen (Hibbard, *et. al.*, 2007). Each crustal block has a unique stratigraphic, structural, metamorphic, plutonic and isotopic history that helps distinguish relationships between blocks, important for understanding the accretionary history of the orogen and the evolution of the Iapetus and Rheic Oceans (Hibbard *et. al.*, 2007).

The southern-most exposed peri-Gondwanan crustal block of the orogen is Carolinia, a collection of heterogeneously deformed and metamorphosed Neoproterozoic to Cambrian magmatic arc terranes. Each terrane is distinguished on the basis of second-order differences in age, stratigraphy, isotopic evolution, deformation and metamorphism.

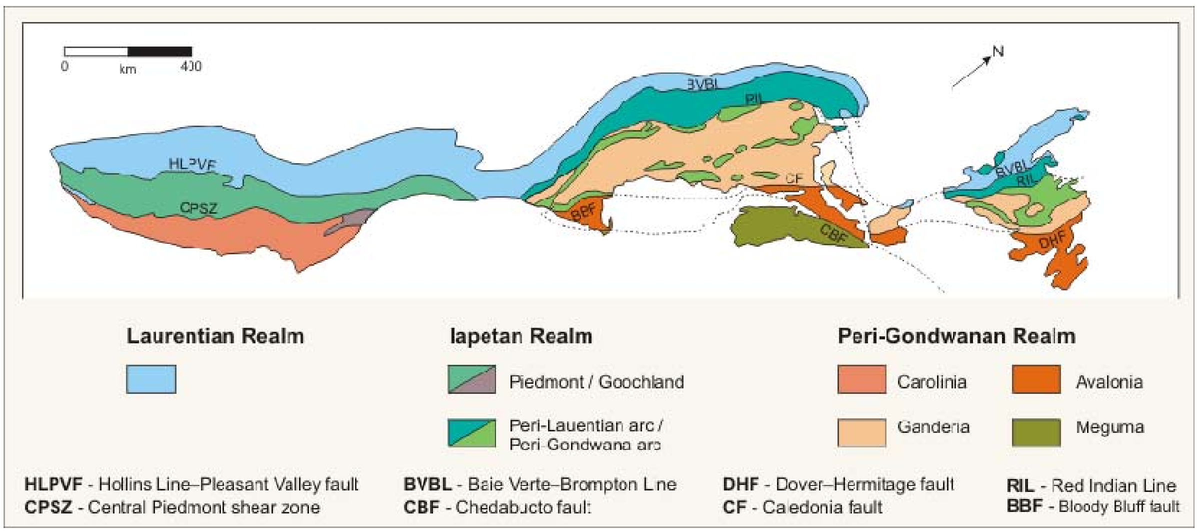

Figure 3: Realm distribution within the Appalachian orogen illustrating Laurentian, Iapetan and peri-Gondwanan realms (from Hibbard *et. al.*, 2006).

They are considered exotic to Laurentia based on their stratigraphic and tectonic evolution, paleontology and overall position in the orogen relative to that of exotic terranes in the northern Appalachians (Hibbard *et. al.*, 2002).

Component terranes of Carolinia can be separated into two divisions, suprastructural and infrastructural (Figure 4). Surpastructural terranes remained higher in the crust throughout their history, resulting in less deformation and metamorphism; as such, their stratification and primary structures are well preserved. Conversely, infrastructural terranes were subjected to mid/lower crustal conditions, resulting in higher metamorphism/deformation. Due to these more dynamic conditions, fossil remains, stratification and primary structures have typically been obliterated.

Our current knowledge and understanding of the geological history of Carolinia is best deduced from component suprastructural terranes and particularly germane to this investigation is the Carolina terrane. The Carolina terrane is a Neoproterozoic to Cambrian volcanic island arc terrane exposed in the Piedmont from Georgia to Virginia (Secor *et. al*. 1991; Hibbard *et. al.*, 2002). It is comprised of metavolcanic rocks that are of mainly pyroclastic and epiclastic origin with less than 10-percent consisting of lava flows (Butler and Secor, 1991).

Four sequences make up the bulk of the Carolina terrane (Hibbard *et. al*, 2002), namely: the Virgilina sequence in Virginia and North Carolina, the Albemarle sequence in North Carolina, the South Carolina sequence in South Carolina and northeast Georgia, and the Cary sequence in eastern North Carolina (Figure 4). These sequences define the geological history of the terrane separated into three stages: (1) Pre ca. 580 Ma. rocks of the Virgilinia sequence with an oceanic arc geochemistry;

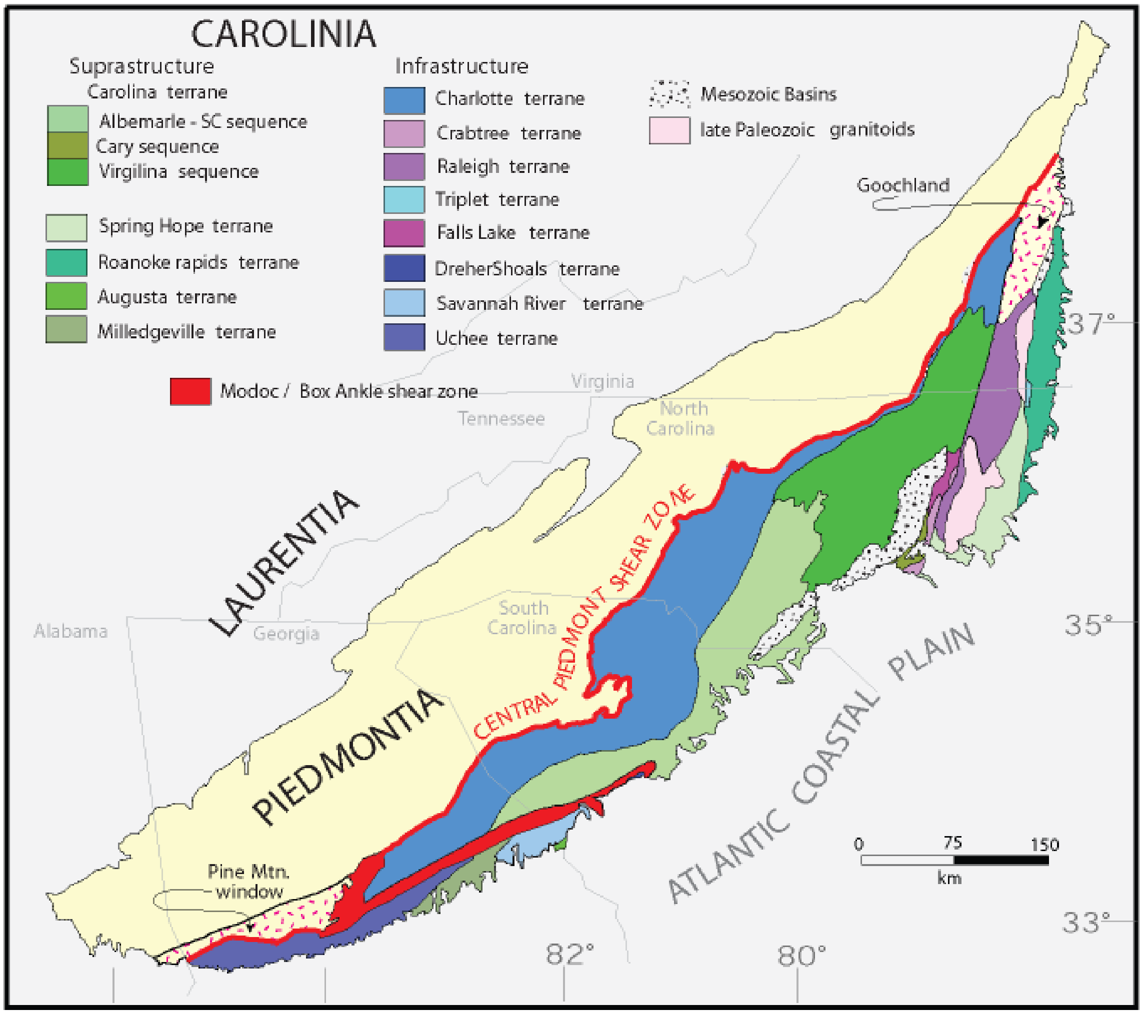

Figure 4: Terrane distribution within Carolinia (Hibbard et. al. 2002).

(2) ca. 580 – 555 Ma. magmatic – siliciclastic rocks of the Cary sequence; and (3). Post 555 Ma. rocks of the Albemarle and South Carolina sequences. The Albemarle sequence is directly related to this study and will form the focus of the regional discussion that follows.

The base of the Albemarle sequence is the Uwharrie Formation, which is dominated by felsic metavolcanic rocks, with subordinate amounts of mafic tuffs and layered beds of reworked volcanic debris (Butler and Secor, 1991). The Uwharrie Formation is overlain by the Albemarle Group, which from oldest to youngest includes the Tillery, Cid, Floyd Church and Yadkin formations. The Tillery Formation is dominated by alternately laminated silt and claystone. The Cid Formation is separated into the lower mudstone member and an upper volcanic unit named the Flat Swamp member (Stromquist and Sundelius, 1969). The Floyd Church Formation comprises mainly silty mudstone with up to 50 percent interbeds and interlaminations of siltstone and fine-grained sandstone (Gibson and Teeter, 1984). The youngest unit, the Yadkin Formation, is mainly poorly sorted silt and sand of volcanic origin with interbedded sequences of well-sorted quartz sandstone (Gibson and Teeter, 1984). As noted above, the age of the Albemarle Group has recently come into question.

In 1995, workers from the USGS reported euconodont and bryozoan fragments in a sample collected from a calcareous bed in the Tillery Formation at the Martin-Marietta quarry in Asheboro, North Carolina (Koeppen *et. al.*, 1995). The euconodonts and bryozoan fragments indicated an age no older than early Middle Ordovician. A similar calcareous bed from mudstone of the Cid formation collected in the Jacobs Creek quarry south of Denton, North Carolina yielded euconodonts suggesting an age no older than Late Cambrian; but, judging from the euconodont forms present, are most likely Ordovician (Offield, 2000).

To accommodate the purported fossil finds, Offield (2000) revised the stratigraphic order of the group and introduced regional-scale thrusts at the base of the Tillery Formation and at the base of the Flat Swamp member of the Cid Formation (Figure 2). If true, these revisions would demand major changes to our conception of the tectonic evolution of the Carolina terrane (Hibbard *et. al.*, 2006). In 2006, the Neoproterozoic fossil *Aspidella* (Figure 5) was reported from rocks within the Jacobs Creek quarry (Hibbard *et. al.* 2006; Weaver et. al. 2006), the same quarry that purportedly hosts one of the Paleozoic fossil finds. *Aspidella* is not considered an index fossil; however, the Edicaran fauna is mainly confined to the time span 600-542 Ma, although some elements are documented as extending into the Early Cambrian (Waggoner, 2003).

Recent studies suggest a lithostratigraphic correlation between the Albemarle and South Carolina sequences (Ingram, 1999; Offield, 2000; Hibbard, 2002) which comprises three formations: the Persimmon Fork, Richtex and Asbill Pond formations. The Persimmon Fork Formation is an andesitic volcanic unit with subordinate hypabyssal intrusions that underlie turbiditic wackes and intercalated greenstones of the Richtex Formation. The sequence is capped by the Asbill Pond Formation, which includes an upper mudstone member separated by coarser-grained siliciclastic shelf rocks (Dennis and Shervais, 1996). Dennis *et. al.* (1993) interpreted the contact between the upper mudstone and lower siliciclastic member as being unconformable. The age of the Asbill Pond Formation is constrained by Middle Cambrian trilobites identified from the upper mudstone member (Samson *et. al.*, 1990).

The relationship between the Albemarle and South Carolina sequences has important implications for this investigation. For example, considering that the South Carolina sequence is capped by Middle Cambrian rocks and the South Carolina and North Carolina

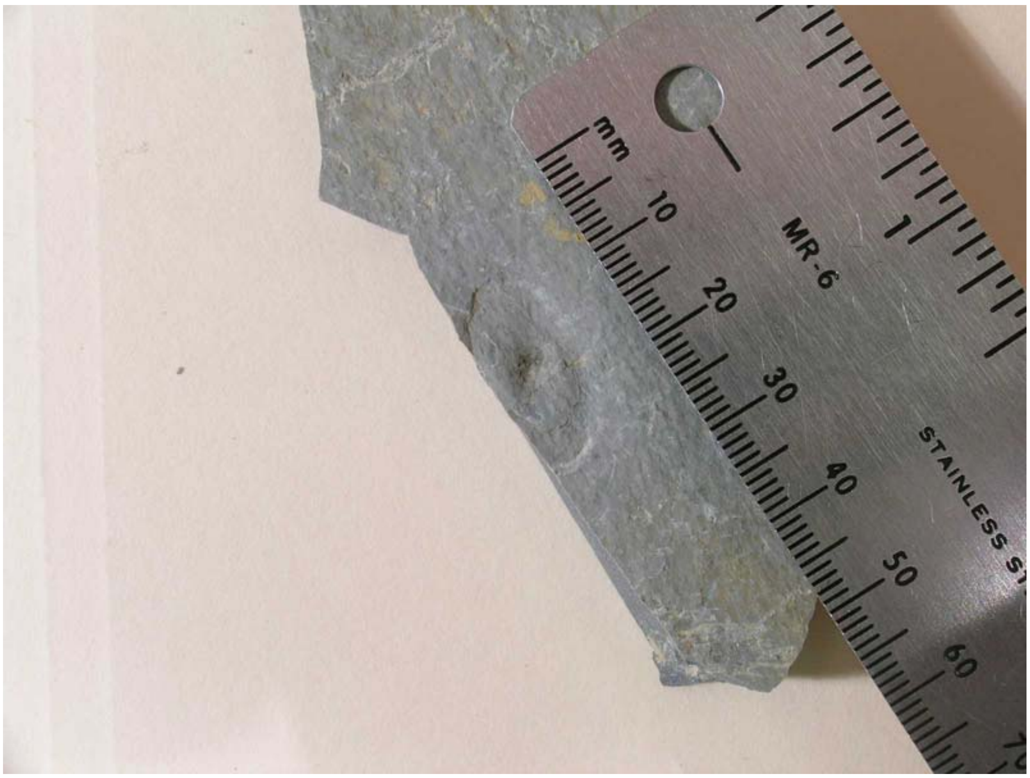

Figure 5: *Aspidella* specimen on Cid mudstone from Jacob's Creek Quarry near Denton, North Carolina. Photograph courtesy of Chris Tacker from North Carolina Museum of Natural Sciences.

sequences are correlative, it is entirely possible that the Albemarle Group is also capped by Cambrian.

Three deformation/metamorphic events have affected Carolinia, namely: (1) Late Neoproterozoic to Early Cambrian Virgilina deformation and concomitant arc-magmatism, (2) A regional Late Ordovician-Silurian deformation event resulting in greenschist facies metamorphism, and (3) Late Paleozoic Alleghanian events (Hibbard, 2002). The Late Neoproterozoic to Early Cambrian event, the "Virgilina deformation" (Glover and Sinha, 1973) is interpreted as representing the arc-arc collision of the Charlotte and Carolina terranes (Hibbard and Samson, 1995; Dennis and Wright, 1997, Barker *et. al.,* 1998).

The Late Ordovician-Silurian event has been attributed to subduction and collision of Carolinia beneath Laurentia; resulting in the upright, subhorizontal southeast verging regional folds, steep northwest dipping cleavage and greenschist facies metamorphism. (Noel *et. al.,* 1988; Offield *et. al.* 1995; Hibbard *et. al.*, 2003). $^{40}Ar/^{39}Ar$ ages on biotite and muscovite have been interpreted as indicating peak metamorphism between c. 455 – 443 Ma (Noel *et. al.*, 1988, Offield *et. al.*, 1995). The third event is associated with the Alleghanian orogeny and the collision between Laurentia and Gondwana.

Previous Work

Geologic mapping has been conducted in the central portion of North Carolina since the early 19th century and this study is evidence that there is still debate over the stratigraphy. An understanding of the evolution in the stratigraphic interpretations of the Albemarle sequence is essential to this investigation; this section summarizes investigations relevant to this study.

Early Work

The first significant geological investigation of central North Carolina rocks was by Denison Olmsted, founder of the North Carolina Geological Survey, who depicted the "Great Slate Formation" on his Geological Map of North Carolina (Olmsted, 1825). Ebenezer Emmons expanded on Olmsted's work in "Geology of the Midland Counties" (Emmons, 1856), suggesting the rocks of the Great Slate Formation were Precambrian in age and part of the Taconic System. Emmons proposed the rocks were sedimentary and possibly the oldest in the country. G.H. Williams was the first to recognize volcanic rocks in the vicinity of the Albemarle sequence, and Nitze and Hanna (1896) were the first to assign the name "Carolina Slate Belt" (Conley and Bain, 1965).

By 1959, the rocks in central North Carolina were being referred to as the "Carolina Volcanic-Sedimentary Group" (Stromquist and Conley, 1959). No definitive age was yet agreed upon; although, most workers suggested a Paleozoic age because of similarities to the Arvonia and Quantico shales in north-central Virginia that had produced Ordovician fossils (Stromquist and Conley, 1959). Stomquist and Conley (1959) proposed a stratigraphic sequence for the group that, from lowest to highest, included: the Lower Volcanic, Varved Argillite, Tuffaceous Argillite, Graywacke and Upper Volcanic Units. The Upper Volcanic Unit was proposed to unconformably overlie the Graywacke Unit and the contact between the two was designated as the Flat Swamp Unconformity.

Modern Work

Conley (1962) completed the first modern geologic investigation of the Albemarle sequence while mapping the Albemarle 15'quadrangle for the State of North Carolina, which formed the basis for all subsequent interpretations. Conley and Bain (1965) set down the initial formation names for the Albemarle sequence. Their interpretation of the stratigraphy included two groups, the Albemarle Group unconformable beneath the Tater Top Group. From lowest to highest, the Albemarle Group was defined by the Uwharrie, Tillery, McManus Formations and the Yadkin Greywacke. These units were unconformable beneath the Badin Greenstone and Morrow Mt. Rhyolite which comprised the Tater Top Group (Figure 6). In their interpretation, the Tillery Formation was conformable above the basal Uwharrie Formation.

Stromquist and Sundelius (1969) refined the stratigraphy of the area by refining the Albemarle Group (Figure 6). They abandoned the Tater Top group altogether, introduced the Cid and Millingport Formations and proposed a conformable relationship between formations. The Cid Formation was separated into the lower mudstone member and an upper volcanic unit designated the Flat Swamp member. The Millingport was separated into the Floyd Church and Yadkin members. An Ordovician age was assigned to the sequence based on zircon ages from the Uwharrie Formation of 470 ± 60 and 440 ±60 Ma (White *et. al.*, 1963) and a fossil misidentified as a Middle-Ordovician trilobite and later identified as the Neoproterozoic fossil *Pteridinium* (Gibson *et. al*, 1984).

Stromquist and Sundelius (1969) interpreted the contact between the Cid mudstone and Flat Swamp members as conformable.

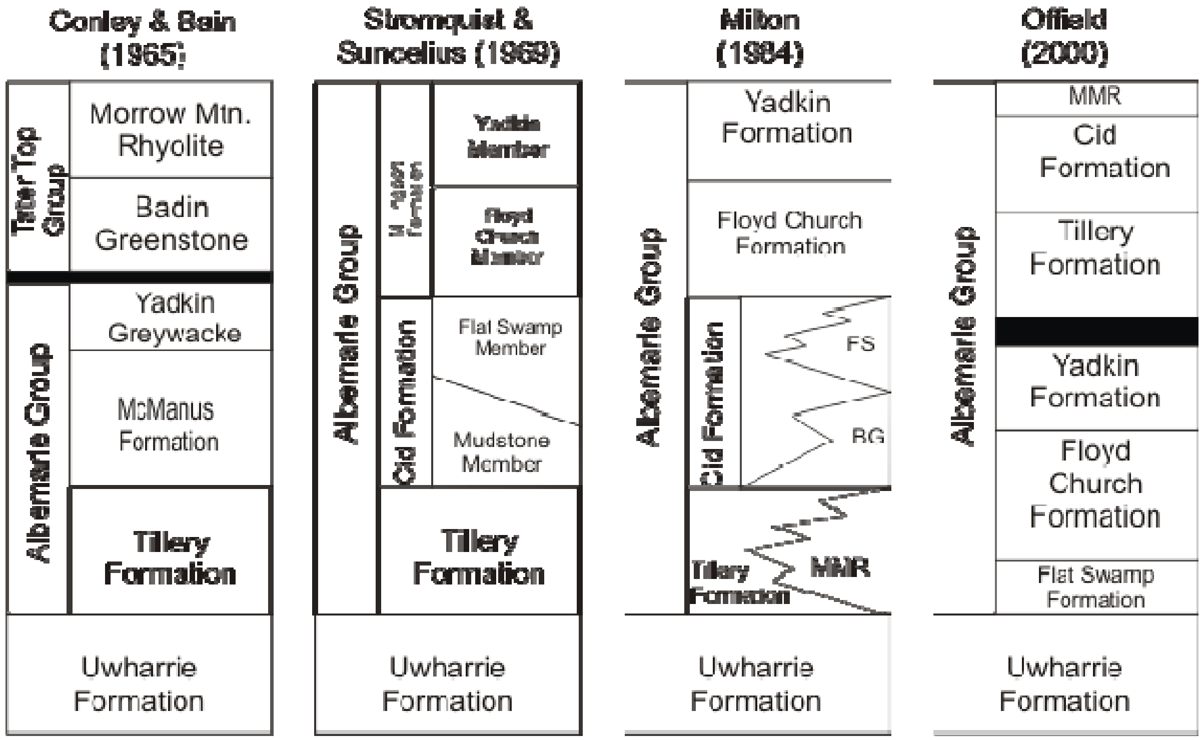

Figure 6: Evolution of the stratigraphic interpretation of the Albemarle sequence of the Carolina terrane (revised from Hibbard et. al, 2002). FS – Flat Swamp, BG – Badin Greenstone, MMR – Morrow Mountain Rhyolite. Black bars represent unconformities.

They suggested that the rocks near the base of the Flat Swamp member indicated a change from subaqueous deposition of the underlying Cid mudstone to largely subaerial conditions. These rocks were interpreted as tuffaceous siltstone and transitional claystone; of shallow water deposition based on the presence of planoconvex laminae.

Butler and Ragland (1969) completed an extensive geochemical investigation of the volcaniclastic rocks in the Albemarle Group. They reported that the felsic and intermediate rocks intercalated throughout the group had mutually similar geochemical and crystalline compositions and that Albemarle Group was metamorphosed to greenschist facies.

Additional work by Stromquist, Choquette and Sundelius (1971 and 1975) and Sundelius and Stromquist (1978) during the 1970's retained the stratigraphic nomenclature and age assignments of Stromquist and Sundelius (1969). Seiders (1978) noted that the Carolina terrane was dominated by felsic volcanics interbedded throughout. Feiss (1982) loosely suggested the rocks of the Albemarle group were part of a subduction-related orogenic environment based on major element analysis of 296 volcanic rocks and associated dikes. He suggested a predominant subaqueous depositional environment based on interbeds of well-laminated, continuous siltstones and mudstone without evidence for channel fill deposits.

Gibson and Teeter (1984) reintroduced the Uwharrie, Tillery, McManus and Yadkin formation nomenclature of Conley and Bain (1965); however, they separated the McManus Formation into two members, a lower mudstone member and the upper Floyd Church member (Gibson and Teeter, 1984). The Flat Swamp volcanics were not present in the field area worked by Gibson and Teeter and were left out of their conformable stratigraphic column.

Based on the recognition of the Ediacarian fossil *Pteridinium* in the Floyd Church Formation, Gibson and Teeter proposed a late Precambrian age for the Albemarle sequence. In terms of depositional environment, it was proposed that the Albemarle sequence was deposited on a shallow marine platform, not from turbidity currents, adjacent to an active island arc and that the sequence represented a transition into deeper basin environments accompanied by explosive, episodic volcanism (Gibson and Teeter, 1984).

Milton (1984) supported the interpretation of a conformable Albemarle Group (Stromquist and Sundelius, 1969) (Figure 6) and he abandoned the Millingport Formation, giving the Floyd Church and Yadkin formational status. Milton suggested the Albemarle Group was deposited by turbidity currents and represents a general shallowing upward sequence.

Through assessment of 25 outcrops over an area of 1,050 square kilometers, Dockal and Huntsman (1989) proposed three northwest dipping thrusts in the Tillery and Cid Formations east of Albemarle, North Carolina. One thrust was proposed between the Tillery and Cid and another between the Cid mudstone and Flat Swamp members. The thrusts were interpreted on the basis of spatial variation in depositional features. For example, classical turbidites (Bouma, 1964) are assumed to have a statistically predictable sequence of bed thicknesses and by comparing these differences (Crittenden, 1961) throughout a stratigraphic section, fault offset can be determined. These interpretations were dismissed by Butler and Secor (1991) on the following grounds: (1) lack of offset within the Flat Swamp Member of the Cid Formation; (2) the calculations do not apply to turbidite deposits in a volcanic arc environment which lack a stationary source area and relatively constant initial size of successive turbidity flows; (3) the variations in grain size and bed thickness observed could be the result of large-scale slump deposits rather than thrusting; (4) Gibson and Teeter (1984) interpreted the rocks as shallow water deposits rather than turbidite deposits.

In 1995, workers from the USGS reported two new fossil finds from the group (Koeppen et al., 1995). Euconodonts and byrozoan fragments were found from the Tillery Formation near Asheboro indicating an age no older than early Middle Ordovician. Additionally, euconodonts were identified in a calcareous bed from the Cid Formation at Jacobs Creek quarry near Denton, North Carolina indicating an age no older than Late Cambrian to Ordovician (Offield, 1999). If true, these data require the Tillery Formation to be unconformable or faulted over the Uwharrie Formation and the Flat Swamp to be faulted over the Cid (Offield, 2000).

Ingram (1999) carried out detailed 1:24,000 scale mapping of an area containing contacts between the Uwharrie, Tillery and Cid Formations near Morrow Mountain, North Carolina. Field mapping identified Tillery Formation conglomerates interlayered with mafic and felsic tuffs of the Uwharrrie Formation indicating a conformable contact. Field observations and geochemical analyses indicated the Morrow Mountain rhyolite forms a coherent geochemical suite that is intrusive and extrusive into the Uwharrie, Tillery and Cid Formations; thereby, magmatically linking the units and implying a similar age (Ingram, 1999).

Offield (2000) proposed a reorganization of the Albemarle Group based on the fossil evidence of Koeppen (1995) and his own regional field mapping. Offield suggested thrust contacts between the Uwharrie and Tillery, Tillery and Cid mudstone and Cid mudstone and Flat Swamp member; purportedly based on disjunctive relations of small-scale structures and cleavage disarray (Offield, 2000). A thrust was also introduced between the Morrow

Mountain rhyolite and the Tillery, which Conley and Bain (1965) had interpreted as an unconformity and Ingram (1999) mapped as conformable. The Cid mudstone and Flat Swamp were also elevated to formational status (Offield, 2000).

Ingle *et. al.* (2003) presented U-Pb ages of zircons for volcanic and plutonic rocks from the Carolina terrane. Results indicated that volcanism was subduction-related and culminated with the eruption of the Morrow Mountain Rhyolite at ca. 540 Ma. Samples collected from volcanic exposure in the Tillery and Cid formations provided U – Pb zircon ages of 553 ± 20 Ma and 542 ± 14 Ma, respectively.

Hibbard *et. al.* (2006) and Weaver *et. al.* (2006) reported the Ediacaran fossil *Aspidella* from Jacob's Creek Quarry, the same quarry that Paleozoic fossils were purportedly identified (Koeppen *et. al.,* 1995). Pollock (2007) analyzed detrital zircons from the Tillery, Cid and Yadkin formations to suggest that sedimentation of the entire Uwharrie – Albemarle sequence was between ca. 555-528 Ma. One sample collected from the Jacob's Creek Quarry comprised a thin laminated to thin bedded, blue-grey greywacke. Results from the Jacobs Creek sample defined a restricted Neoproterozic-early Paleozoic range of zircons between 539 ± 12 Ma and 568 ± 15 Ma. These ages are compatible with the presence of *Aspidella* in the Cid Formation (Hibbard *et. al.*, 2006; Weaver *et. al,* 2006).

Location and Methods

The Jacobs Creek quarry opened over sixty years ago and was originally operated by the Jacob's Creek Company of Charlotte, North Carolina. The McKinney family purchased the quarry more than thirty-five years ago and continues to operate under the original trade name. There is no geographical feature named Jacobs Creek in the vicinity of the quarry. The active pit of the quarry is within rocks mapped as the upper part of the mudstone member of the Cid formation, an approximately three kilometer thick sequence of mainly muddy metaclastic rocks with subordinate mafic and felsic volcanic and hypabyssal rocks (Milton, 1984). The top of the formation, the Flat Swamp Member, is an approximately 0.75 kilometer thick felsic to intermediate volcanic unit (Butler and Secor, 1991) that has precise U-Pb zircon ages of 547±2 Ma (Hibbard *et. al.* 2006) and 540 ± 1.2 Ma (Ingle *et. al.,* 2003) from localities nearby. Rocks of the Flat Swamp member outcrop approximately 70-meters stratigraphically above and to the south of the quarry pit.

The primary objectives of this investigation are to resolve the nature of the contact between the mudstone and Flat Swamp members of the Cid Formation and determine if Paleozoic outliers are present. To this end, detailed 1:24,000 scale mapping was carried out during the summer of 2006 and spring of 2007 in the area near Jacob's Creek Quarry, where Paleozoic fossils were reported (*Koeppen et. al.* 1995) and near the mudstone and Flat Swamp member contact. The study area extends north from the quarry beyond North Carolina State Route 47 south of Denton, North Carolina and south into Montgomery County, to Badin Lake.

The majority of field mapping was completed within stream beds and hill tops, which provided the best exposure. Where outcrops were located, the rock type, structure and attitude of outcrops were noted in order to help establish the local stratigraphy. Petrographic study of 10 thin sections was also completed. This investigation is part of a collaborative study, which includes mapping near the second reported Paleozoic fossil find near Asheboro, North Carolina.

General Geology in the Vicinity of Jacob's Creek Quarry

Introduction

As the main objectives of this investigation are to understand the nature of the contact between the Cid mudstone and Flat Swamp members of the Cid Formation and determine if Paleozoic outliers are present, it is important to describe and understand the rock types in each unit. This section presents general field-based descriptions for lithostratigraphic units within the study area in addition to a discussion of structural data collected during field mapping. Two of the four formations that comprise the Albemarle Group were identified in the field area and include the Cid and Floyd Church formations. These formations were separated based on composition, depositional environment and/or stratigraphic position. Two types of intrusive rocks occur in the study area: sills of Stony Mountain gabbro and diabase dikes. The following section presents lithostratigraphic descriptions, contact and age relationships of rocks identified in the field area.

The term volcaniclastic is used here as a non-genetic term for rocks with fragmental aggregates of volcanic parentage but with an undetermined mode of deposition (e.g. mode of deposition could be pyroclastic or epiclastic). Epiclastic is used to describe rocks with an obvious volcanic parentage and strong evidence of secondary transport and redeposition.

Cid Formation

The Cid Formation is divided into the unnamed mudstone and Flat Swamp members (Milton, 1984) and underlies approximately 90 percent of the study area (Figure 7). It underlies the field area from its northern boundary south of Denton, North Carolina to Badin Lake at the southern end extent.

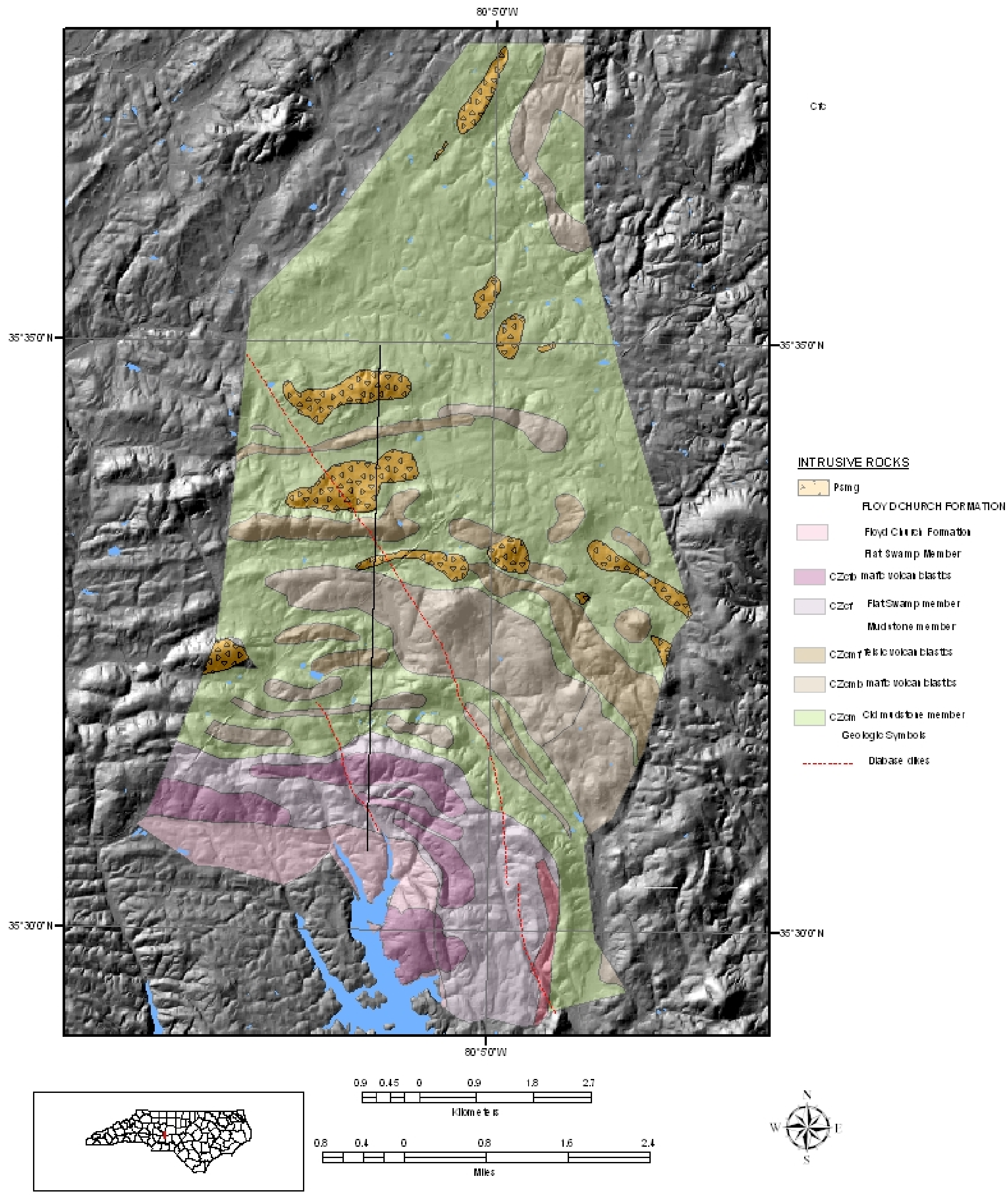

Figure 7: Geologic map of the study area. Psmg = Stony Mountain gabbro.

Mudstone Member

Distribution

The Cid mudstone member underlies the northern two-thirds of the study area, extending from just south of Denton, North Carolina to the Jacob's Creek Quarry. The mafic and felsic rocks form ridges and hilltops, while the mudstone typically underlies low-lying areas. Extensive exposures are rare to absent, with the best outcrops observed in streams, quarries and road cuts.

Previous workers (Conley and Bain, 1965, Stromquist and Henderson, 1969, Stromquist and Henderson, 1985, Offield, 2000) have mapped sections of the Albemarle Group outside of the study area and described mafic units as tuffs; thereby, implying a pyroclastic origin. However, direct evidence for a pyroclastic origin was not observed in the mafic rocks underlying the study area. As such, the term *volcaniclastic* is applied herein for these rocks.

Rock Types

Mudstone

The mudstone member is dominated by thinly laminated to thickly bedded, bluish gray tuffaceous argillite (Figure 8), mudstone, with minor fine-grained sandstone and local layers of greenish-gray coarse volcanogenic sandstone up to 30 cm thick. Gray, ellipsoidal and tabular shaped carbonate concretions are commonly found distributed along bedding planes within the mudstone layers. Mineralogically, the mudstone consists of approximately 75 percent quartz and feldspar, 15-20 percent sericite, small amounts of chlorite, traces of epidote and sphene-leucoxene, pyrite, and local sulfide and biotite (Stromquist and Sundelius, 1969).

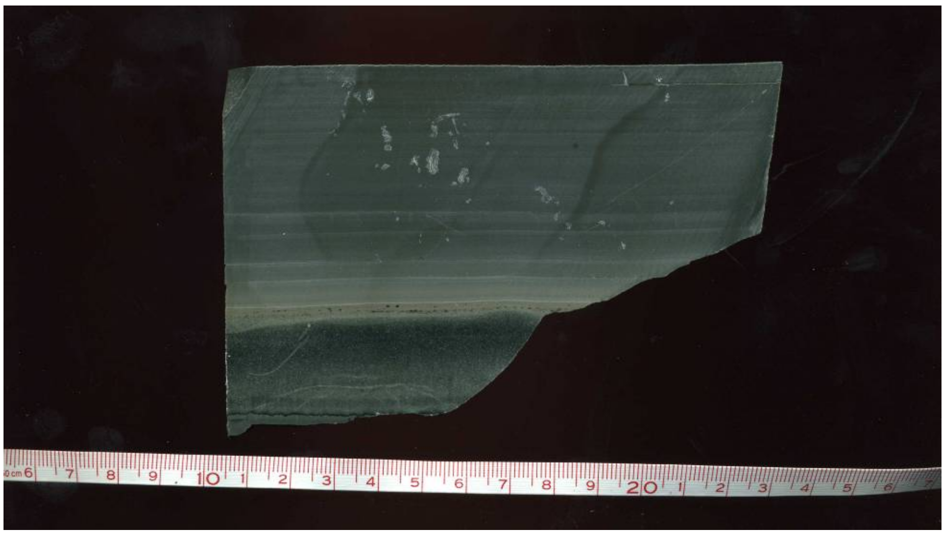

Figure 8: Polished slab illustrating typical laminated Cid mudstone and volcanogenic sandstone. Dark green sandstone makes up bottom 2 cm of slab. Note rhythmic laminations defined by normal grading overlying sandstone. Scale in centimeters. Sample from Jacob's Creek Quarry.

Volcanogenic sandstone within the mudstone consists of bluish-gray to greenish-gray, normally graded, fine to medium-grained sandstone up to 30 cm thick. Sandstone beds have sharp basal contacts, with both sharp and graded upper contacts to the mudstone and argillite.

The mineralogical composition of the sandstone consists of volcanic quartz and sodic plagioclase (up to 80 percent), fine-grained mica (15 – 20 percent) with trace amounts of chlorite, epidote, titanite and zircon (Stromquist and Henderson, 1985). In some sandstone units, calcite comprises the dominant cement (Figure 9).

Mafic volcaniclastics rocks

Mafic rocks in the unnamed mudstone are greenish-gray, thinly to massively bedded, poorly to well sorted rocks with a composition of andesitic-basalt (Stromquist *et. al.* 1971; Stromquist and Henderson, 1985). Where present, bedding is determined by differences in grain size, with normal, reverse and multiple normal grading (Fisher and Schmincke, 1984) present (Figure 10). Mineralogically these rocks are comprised of albite + chlorite + actinolite + potassium feldspar + epidote + quartz ± biotite ± muscovite (Butler and Ragland, 1969).

Felsic volcaniclastics

Felsic volcaniclastic rocks within the mudstone member comprise poorly to massively bedded, light gray rocks that weather tan to chalky-white. The rocks have variable amounts of angular to subrounded quartz and feldspar crystals (<10% to 50%) less than 3mm in diameter and lithic fragments (<10% to 60%) up to 20mm in diameter.

Figure 9: Photomicrograph under plane polarized light of volcanogenic sandstone overlying mudstone of unnamed Cid Mudstone member. Intergranular calcite is stained with Alizarin *red-S*. Sample obtained from active pit at Jacob's Creek Quarry. Width of view is 5 millimeters.

Figure 10: Typical mafic volcaniclastic in the mudstone member of the Cid Formation. Photograph taken near Jacob's Creek Quarry. Shading contrast on the outcrop is due to tree canopy and lichen. Hammer for scale.

In hand specimen some felsic rocks appear to have a vitric texture with an aphanitic dark purplish-gray to dark gray groundmass surrounding crystals of quartz, feldspar and lithic fragments up to 20mm in diameter. Geochemical analysis indicates a composition intermediate between rhyolite and rhyodacite (Butler and Ragland, 1969; Stromquist and Henderson, 1985; Stromquist *et. al.* 1971).

<u>Contacts between rock types</u>

Contacts between lithostratigraphic units in the mudstone member are conformable yet abrupt, with mafic and felsic rocks appearing as either lenses or intertonguing, within the mudstone member. A contact between mudstone and mafic rocks was observed in Beaverdam Creek approximately 150-meters southwest of the Jacob's Creek Quarry office. Here, saprolitic mafic rocks are in abrupt contact with underlying mudstone. Although not directly observed in most outcrops, the location of contacts can be approximated through stream traverses where separate lithostratigraphic units were observed within several meters perpendicular to strike. At these locations, bedding attitudes indicated parallel deposition, with no physical evidence of non-deposition or hiatus; and no significant tectonic structures, other than a weak regional cleavage. The abrupt nature of the contacts is due to variable local sedimentary depositional conditions typical to volcanic arc environments where volcanic aprons receive sediment from multiple sources (Carey and Sigurdson, 1984).

Flat Swamp Member

<u>Distribution</u>

The Flat Swamp member of the Cid Formation is named for Flat Swamp Mountain in the west-central part of the Denton quadrangle (Stromquist and Sundelius, 1969) and has a thickness of approximately 770 meters. The resistant rocks of the Flat Swamp form ridges and hilltops throughout the study area that define the New London Syncline. The Flat Swamp comprises felsic volcanic and epiclastic rocks with subordinate andesitic-basalt volcaniclastics. It underlies the central portion of the field area between the mudstone and Floyd Church Formations.

Rock Types

Felsic volcaniclastics

Felsic volcaniclastic rocks dominate the Flat Swamp member of the Cid Formation accounting for over 80% of the entire member. These rocks are fine-grained, light gray and weather to tan and chalky white with variable amounts of quartz, feldspar and lithic fragments (<10% to 50%) less than 3mm in diameter (Figure 11). Geochemical analysis indicates a composition intermediate between rhyolite and rhyodacite (Butler and Ragland, 1969; Stromquist and Henderson, 1985; Stromquist *et. al.* 1971).

Felsic epiclastic

Coarse-grained felsic epiclastic rocks were observed near the base of the Flat Swamp member above the contact with the unnamed mudstone. These rocks displayed normal grading and comprised of rounded to angular crystals of quartz and feldspar with lithic fragments in a fine grained groundmass. At the contact with the Cid mudstone member, a thin bed of felsic epiclastic rocks was observed with lithic fragments identical to the Cid mudstone. The mudstone fragments are angular and range in size from 2 to 20 mm across (Figure 12).

Figure 11: Felsic volcaniclastic from the Flat Swamp member of the Cid Formation. Scale in centimeters. Sample collected from Beaverdam Creek north of Badin Lake.

Figure 12: Felsic epiclastic from the Flat Swamp member of the Cid Formation. Light gray clasts near the center of the slab are identical to the underlying Cid mudstone. Sample collected from Beaverdam Creek at Jacob's Creek Quarry. Slab dimensions are 40mm x 20mm.

Laminated siltstone

Laminated siltstone is characterized by thinly laminated to thickly bedded, cream to light-gray, normally-graded, siltstone (Figure 13) observed in the Flat Swamp member of the Cid Formation. Layering is emphasized by normal grading of lighter colored silts to darker colored muds with sharp to erosional contacts. Beds were observed as tabular and laterally extensive at outcrop scale but poor exposure prevented correlation of individual beds or successions beyond individual outcrops.

Mafic Volcaniclastic Rocks

Mafic volcaniclastic units are greenish-gray, thinly to massively bedded, poorly to well sorted with a composition of andesitic-basalt (Butler and Ragland, 1969; Stromquist and Henderson, 1985;Stromquist *et. al.* 1971). They are otherwise similar to mafic units present in the underlying mudstone except they have a higher percentage of rhyo-dacitic clasts.

<u>Contacts between rock types</u>

Like the underlying mudstone member, contacts between lithostratigraphic units in the Flat Swamp member are conformable yet abrupt, with mafic and felsic epiclastic rocks appearing as lenses or intertonguing, within the dominant felsic tuffs. Laminated tuffaceous siltstone, similar in appearance to the underlying laminated mudstone but cream in color, was observed at the base and middle of the Flat Swamp member.

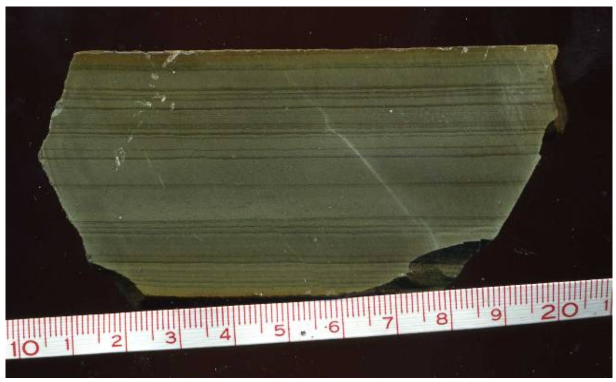

Figure 13: Laminated siltstone from Flat Swamp member of the Cid Formation. Scale in centimeters. Sample collected from Beaverdam Creek near Jacob's Creek Quarry.

Contact between Cid mudstone and Flat Swamp member

The nature of the contact between the unnamed mudstone member and the Flat Swamp member is of critical importance in the interpretation of the stratigraphy of the Albemarle Group. In Offield's (2000) interpretation of the stratigraphy, this contact must be a fault, whereas in the interpretation of Milton (1984), the contact is conformable.

The thickest and best exposed contact between the mudstone member and the overlying Flat Swamp member is submerged in Beaverdam Creek on the quarry property, approximately 250-meters west of the confluence with Grassy Fork (Figure 14). A stratigraphic section was measured across the contact, but precise measurements were difficult to record due to water depth and turbidity. The measured section (Figure 15) is approximately 20-meters thick with the mudstone member, exposed at the bottom, to the northeast and Flat Swamp volcaniclastic rocks exposed at the top of the section, to the southwest. In between is an intercalation of mudstone, greywacke, epiclastics and tuffaceous siltstone. Near the bottom of the section, overlying the mudstone and visible in the creek bank, is a thin bed of coarse-grained felsic epiclastics containing lithic fragments identical to the Cid mudstone. The mudstone fragments are angular and range in size from 2 to 20 mm across (Figure 13). At the top of the section, a thin bed of greywacke lies between two thin beds of felsic epiclastics. There are no significant tectonic structures, other than a weak regional cleavage, observed throughout the study area. Based on these observations, the contact is considered to be conformable and gradational.

Additional field observations from the surrounding area that support a conformable, gradational contact between the Cid unnamed mudstone member and the Flat Swamp member include:

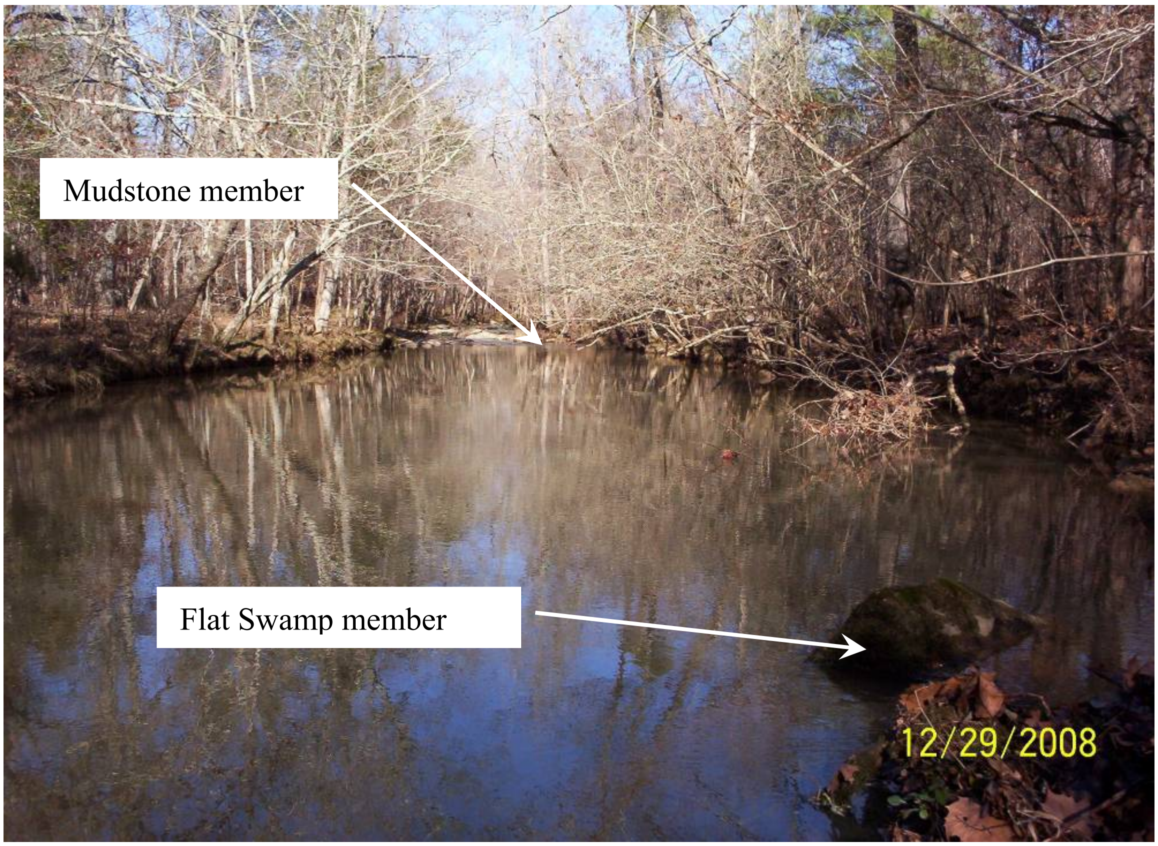

Figure 14: Beaverdam Creek illustrating submerged contact between mudstone and Flat Swamp members of the Cid Formation. Rocks of the mudstone member outcrop in the background and rocks in the foreground are Flat Swamp member felsic volcaniclastics. View to the northeast. Distance between mudstone and felsic volcaniclastics approximately 20-meters.

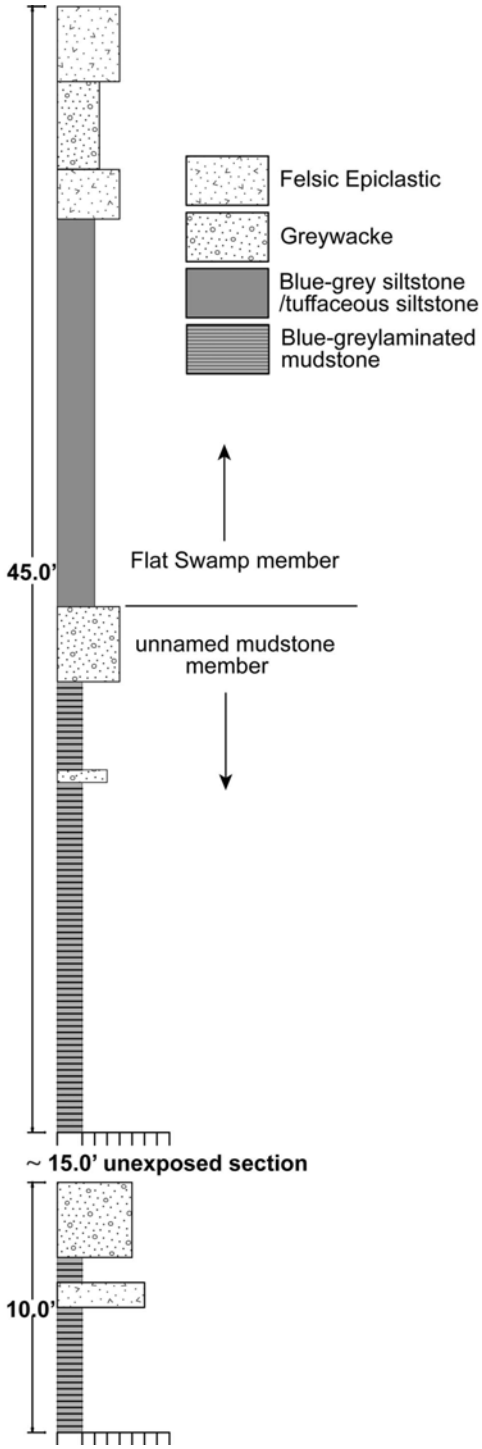

Figure 15: Stratigraphic column of the contact between the unnamed mudstone and Flat Swamp members of the Cid Formation. The contact is considered to be conformable and gradational.

1) greenish-grey, mafic volcaniclastics with a composition of andesitic basalt (Stromquist *et. al.* 1971; Stromquist and Henderson, 1985) are interbedded throughout the mudstone and Flat Swamp members of the Cid Formation. On the quarry property, separate but identical mafic volcaniclastic deposits are found on either side of the mudstone-Flat Swamp contact, stratigraphically within 100 meters of one another; 2) felsic volcaniclastics, typical of the Flat Swamp member, were mapped within the Cid mudstone member approximately two kilometers east along strike of the quarry; 3) In addition, paleontological and geochronological evidence supports a conformable mudstone – Flat Swamp member contact. The Neoproterozoic fossil *Aspidella* was identified from the Jacob's Creek Quarry (Hibbard *et. al.*, 2006; Weaver et al., 2008). The presence of *Aspidella* is consistent with the Cid unnamed mudstone being Neoproterozoic in age, not Late Cambrian or younger as suggested by the Paleozoic fossil report (Koeppen et al., 1995); and 4) Dates obtained for the youngest zircons in a sample of volcanogenic sandstone collected from Jacob's Creek Quarry (Pollock, 2007) overlap with uncertainity with a younger 540 ± 1.2 Ma age for the Flat Swamp member (Ingle *et. al.*, 2003). Detrital zircon ages for the entire Uwharrie-Albemarle sequence suggest deposition between ca. 555-528 Ma (Pollock, 2007).

Floyd Church Formation

Distribution

The Floyd Church Formation is the youngest formation in the field area and underlies the area south of State Route 2550 near Badin Lake (Figure 7) which forms approximately 10% of the field area.

Rock Types

The Floyd Church Formation comprises light brown to bluish gray, thinly laminated to very thinly bedded siltstone and mudstone. Sedimentary features include flaser, wavy and lenticular bedding. Mafic and felsic rocks typical of the underlying mudstone and Flat Swamp members were not present in the field area; however, similar units have been mapped in the Floyd Church Formation outside of the field area (Stomquist and Henderson, 1985; Standard, 2003). Although not identified during this investigation, the age of the Floyd Church is constrained by the Neoproterozic fossil *Pteridinium* (Gibson *et. al.*, 1984).

Contact between Floyd Church and Cid Formations

The Floyd Church Formation conformably overlies the Flat Swamp member of the Cid Formation. The contact is inferred by traversing Alls Fork and Beaverdam Creek north of Badin Lake near State Route 2550 where bluish-grey siltstone typical of the Floyd Church was observed intercalating with felsic tuffs of the Flat Swamp member. Outside the field area, previous workers interpret the Floyd Church to be in conformable stratigraphic contact with the underlying Flat Swamp member (Stromquist and Sundeleius, 1985; Offield, 2000).

Intrusive Rocks

Two intrusive rock types were observed within the field area, gabbro and diabase dikes.

Gabbro

Distribution

Gabbro bodies were identified within the mudstone and Flat Swamp members at the northern and central part of the field area (Figure 7). They are typically elongated parallel to bedding suggesting they originated as sills or laccoliths. Gabbro bodies throughout the Albemarle Group have been interpreted as representing early Paleozoic back-arc rifting of Carolina from western Gondwana (Pollock, 2007).

Rock Type

The gabbros are dark green on fresh surfaces and in hand specimen is fine to coarse crystalline. Gabbro has a mineral assemblage of clinopyroxene, orthopyroxene, actinolite, epidote, plagioclase, quartz and chlorite.

Contacts with Country Rock

Contacts of gabbro with surrounding country rock are poorly exposed in the field area but the relationship is best observed along Route 49, just west of Surratt Road where the gabbro outcrops in the roadcut. On the south side of the road approximately ½-kilometer southwest of Surratt Road, the gabbro is observed within two meters of Cid mudstone. Here, the gabbro is more finely crystalline than at other outcrops in the field area and no evidence of contact metamorphism was observed. A tightly spaced, axial planar cleavage that trends to the northeast was observed in the Cid mudstone at this location.

Stratigraphic relationships in the Albemarle Group indicate that intrusion of gabbro units occurred after deposition of the early Paleozoic Yadkin Formation (Pollock, 2007) but before a Late Ordovician tectonothermal event responsible for upright folding and greenschist facies metamorphism (Offield, 2000).

Diabase

Distrubution

Triassic diabase dikes trend towards the northwest and were observed in stream beds of the Alls Fork, Mountain Branch and an unnamed tributary of Beaverdam Creek to the east of Jacob's Creek Quarry (Figure 7). In outcrop they ranged in width between one and five meters.

Rock Type

Diabase outcrops have a mineral composition of pyroxene, plagioclase and accessory magnetite. Where fresh they are dark black with an interlocking igneous texture. Diabase weathers to orange-brown.

Contacts with Country Rocks

Diabase dikes trend northwest and were observed to cross-cut bedding and cleavage indicating intrusion following deformation. These dikes are identical to diabase dikes from throughout the southern Appalachians. They were observed in both members of the Cid Formation. Diabase dikes in the Carolinas are related to the rifting stage of Pangean breakup in the Early Mesozoic (Ragland, 1991). Due to limited exposure in outcrop, no chill margins were observed.

Structure

The USGS interpretation of a Paleozoic age for the Cid Formation mudstone (Koeppen *et. al.*, 1995) requires that the contact between the Cid mudstone and Flat Swamp members is a fault (Offield, 2000). However, stratigraphical data from this investigation contradicts this interpretation. Within the field area there is evidence for one deformational event, which resulted in the development of the folds and cogenetic cleavage. This section presents structural data obtained during field mapping.

New London syncline

The main structural feature in the field area is the southeast vergent New London syncline (F_m) (Figure 7). Parasitic folds were not observed on this structure with the field area. Strike and dip of bedding (S_0) on the northeast limb were towards east and dip to the south, while on the southeastern limb they strike to south and dip to the west. Strike attitudes ranged from 080° to 200° (right hand rule) with an average dip of 25°.

The π-method was used to determine the plunge of the New London Syncline in the study area. 144 bedding attitudes measured from the Cid and Floyd Church Formations were loaded into StereoWin (Allmendinger, 2003) and a best fit great circle, measuring 330°/76° (right hand rule), was selected for the profile plane of the syncline (Figure 16). The pole of the profile plane, indicating trend and plunge of the axis of the New London syncline, was determined to be 240°/14°. This information was used to retrodeform the strata as part of paleocurrent analysis (Chapter 3).

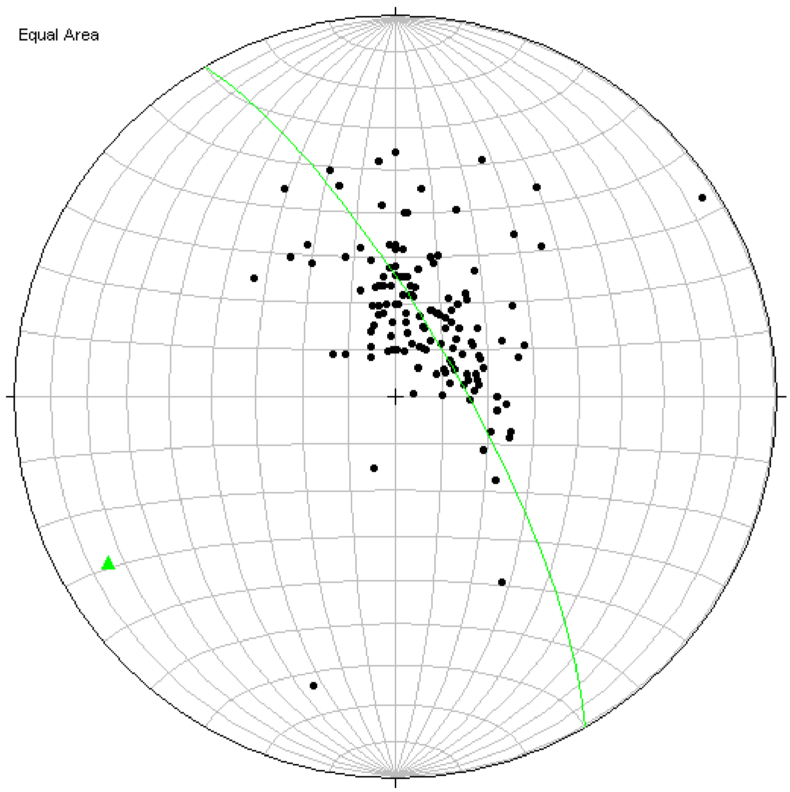

Figure 16: Southern hemisphere equal area projection of poles to bedding attitudes measured in the study area for determination of fold plunge. Green line indicates best-fit great circle for the profile plane of the New London syncline (330/76 right hand rule). Green triangle indicates the trend and plunge of the profile plane or the trend and plunge of the New London syncline (240/14).

Cleavage

A steeply dipping, cleavage (S_m) striking northeast (average strike 68° - axial plane trends 240°) is observed throughout the study area (Figure 17). It is axial planar to the New London syncline. S_m is weakly developed in the mudstone and felsic rocks and moderately to well developed in the mafic units (Figure 18) of the mudstone and Flat Swamp members. S_m density in the area is between 4 and 15 domains per centimeter (Dockal and Huntsman, 1989). S_m in the study area is defined by biotite and muscovite. Biotite cooling has been dated at 455±2 Ma and muscovite cooling has been dated at 444±1.4 by Ar^{40}/Ar^{39} (Offield, *et. al.*, 1995), indicating cleavage formed during the Late Ordovician or earlier. S_m was not observed in Mesozoic diabase dikes confirming their cross-cutting relationship and younger age.

Elongate lithic clasts resulting from regional strain were observed in mafic volcaniclastic rocks of the mudstone and Flat Swamp members of the Cid Formation, as the trace of cleavage on bedding is near parallel to the long axis of clasts and perpendicular to the extension plane (Figure 19).

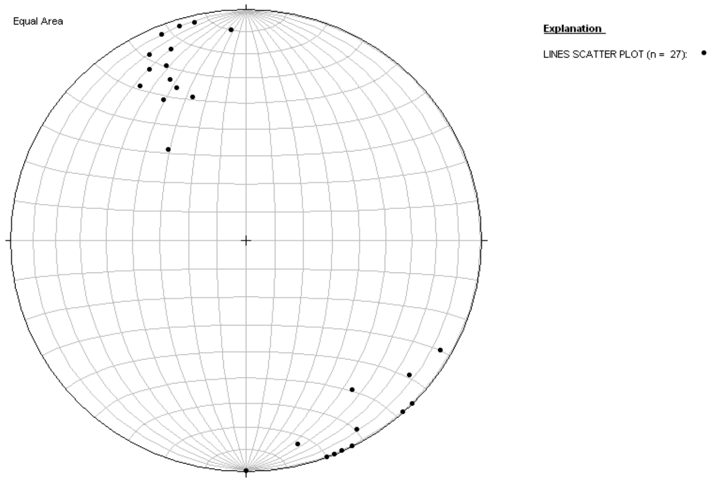

Figure 17: Lower hemisphere plot of poles to cleavage for the mudstone and Flat Swamp members of the Cid Formation.

Figure 18: Mafic unit of the Cid mudstone near Jacob's Creek Quarry illustrating well developed penetrative cleavage. The regional penetrative axial planar cleavage is responsible for the 'fin' shape of many mafic units in the field area.

Figure 19: Elongate clast in mafic volcaniclastic unit in Flat Swamp member of Cid Formation. Clasts are observed in mafic units throughout the study area with long axis oriented parallel to axial planar cleavage. Black arrow indicates approximate trend of cleavage.

Facies, Paleoslope and Paleocurrent Analysis

Introduction

The contact between the Cid mudstone and Flat Swamp members was observed submerged in Beaverdam Creek. Although an approximately 20-meter section was measured across the contact, the entire section could not be measured due to water depth and turbidity. Facies analysis was therefore used to reinforce the interpretation of a conformable relationship between members of the Cid Formation. Individual facies and their associations are important in defining the stratigraphic framework of the Cid Formation. Offield (2000) proposed the contact between the unnamed mudstone member and the Flat Swamp Member is tectonic and one might expect an abrupt facies change at such a contact. Alternatively, Milton (1984) interpreted the contact between the two members as stratigraphic and one might expect any facies changes at this contact to be gradational.

This chapter presents detailed facies descriptions for rocks observed within the study area and is presented as three sections. The first section provides lithofacies descriptions, interpretations and facies associations; the second section presents a discussion of paleocurrent and paleoslope analysis; and, the final section presents a discussion of depositional model for the Albemarle Group based on data presented in the preceding sections.

Facies Descriptions and Interpretations

The following section outlines the eight facies identified in the field area, namely: laminated mudstone (facies 1), mudstone with carbonate concretions (facies 2), volcanogenic sandstone (facies 3), silt/sand with hummocky-cross bedding (facies 4), silt/sand with flaser and lenticular bedding (facies 5), mafic volcaniclastics (facies 6), felsic epiclastics (facies 7) and felsic volcaniclastics (facies 8). Each is defined in terms of lithologic features and sedimentary structures recognizable in the field. The depositional environment of some facies cannot be determined from their internal structures and textures alone. However, most facies are interbedded with other facies and the mode of deposition can be inferred. Consideration of these facies associations enabled the environment and mode of transport of facies which lack environmental criteria, to be established.

Facies 1: Laminated mudstone

Sedimentological characteristics:

Facies 1 is the most abundant in the study area and was observed in the mudstone and Flat Swamp members of the Cid Formation. Where fresh (Figure 20), this facies is characterized by thinly laminated to thinly bedded, normally-graded, bluish gray tuffaceous argillite, and mudstone. In the Flat Swamp member, this facies is beige (Figure 21) to grayish-purple. In the mudstone member, facies 1 consists of approximately 75 percent quartz and feldspar, 15-20 percent white mica, small amounts of chlorite, traces of epidote and sphene-leucoxene, pyrite, and local sulfide and biotite (Stromquist and Sundelius, 1969). Thin section analysis of a sample collected from the Flat Swamp member identified up to 80% quartz and feldspar, 15% white mica and traces of biotite, pyrite and sulfide.

Figure 20: 60-centimeter section of laminated mudstone of Facies 1 at Jacob's Creek Quarry.

Note concretion bearing layer at base of section.

Layering is accentuated by normal grading, from light gray silt underlying darker colored mud (Figure 20) with sharp lower contacts. Individual laminations range in thickness from one-millimeter up to one-centimeter and were observed as tabular and laterally extensive at outcrop scale. Poor exposure prevented correlation of individual beds or successions beyond individual outcrops. Lamination defining normal grading also provides a sense of stratigraphic facing direction.

Folds (Figure 21) were observed on the quarry wall of Jacob's Creek Quarry, bounded by undisturbed sediment, suggesting a synsedimentary slump rather than tectonic origin (Collinson *et. al.*, 2006). Slump unit thickness ranged from 300 to 500 millimeters. The overturning direction of intrastratal folds within slumped units provides a general sense of paleoslope facing direction (see below). Slumped units were not assigned a separate facies designation because deformation does not obscure the primary sedimentation features (cf. Wood *et. al.,* 2003).

Loose blocks containing stromatolite-like mounds up to twenty centimeters in diameter and up to two centimeters thick (Figure 22) were identified to the south of the active quarry. Unfortunately, the carbonate forming these features is coarsely recrystallized and thus they cannot be confidently identified as stromatolites (J. Hibbard, pers. comm., 2008). The Ediacaran trace fossil *Aspidella sp. cf. A. terranovica* (Hibbard *et. al.,* 2006; Weaver *et. al.*, 2006) was found on bedding planes of this facies in the active quarry. There was no evidence of bioturbation.

Figure 21: Slump fold in Facies 1 cored by deformed concretion. Folding of concretions within slump folds suggests concretions formed prior to lithificaiton.

Figure 23: Plan view of mudstone bedding plane in Jacob's Creek quarry showing stromatolite-like forms.

Facies interpretation:

In either fine grained or low concentration turbidity currents, depositional sorting by increased shear in the boundary layer separates clay flocs from silts grains and results in a regular silt/mud lamination at low velocities (10 – 20 cm s^{-1}). Slump structures typically occur in rapidly deposited units where the rapid sedimentation and oversteepened slopes lead to instability (Boggs, 2006). The presence of slump units within Facies 1 suggests that deposition occurred rapidly on slopes steep enough to fail. Absence of wave-generated sedimentary structures, such as symmetrical ripples or bi-directional palaeocurrent indicators, indicates deposition below storm-wave base (White and Busby-Spera, 1987). The presence of sharp or erosional basal contacts, slumps, and rare cross lamination suggests rapid deposition more common to turbidity currents than contour currents or by fluctuating sediment supply (Boggs, 2001; Tucker, 2003).

The most important characteristic for distinguishing turbidites from contourites is both the repetitive internal structure and a tendency to form thick and repetitively bedded stratigraphic successions (Stow and Piper, 1984). In addition, the rocks of this facies show no relation to the contourite facies model of Stow and Piper (1984). As such, Facies 1 is interpreted as mud-dominated $T_{D\text{-}E}$ (Bouma, 1962) or T_3 (Stow and Shanmugam, 1980) turbidites.

Late Neoproterozoic seafloors were typically characterized by well-developed microbial mats (e.g., Gehling, 1986, 1999; Schieber, 1986; Hagadorn and Bottjer, 1997, 1999) and poor development of sediment mixing by vertically oriented burrowing (e.g., Droser et al., 1999; McIlroy and Logan, 1999). Recent work (e.g., Awramik, 1991; Hagadorn and Bottjer, 1997, 1999) has shown that in the Cambrian marine environments characterized by seafloors covered with microbial mats became increasingly scarce, largely due to increasing vertically oriented bioturbation. The absence of vertical bioturbation throughout the study area further supports a Late Neoproterozoic period of deposition.

Facies 2: mudstone with carbonate concretions

Sedimentological characteristics: Carbonate concretions (Figure 23) occur morphologically as single concretions and as tabular sheets of similar thickness (<30 mm) within the mudstone member. On fresh surfaces concretions are bluish-gray in color with a black rim and weather to creamy-white. They are found preferentially distributed within select bedding planes; although, the reason why they concentrate within particular bedding planes is unknown. Ellipsoidal concretions are typically 3-5 cm thick and up to 20 cm in length, while tabular concretions are of similar thickness, but extend several meters up to several tens of meters in length. In cross section, concretions preserve bedding lamination of the host internally and deflect laminations externally around their perimeter (Figure 24).

Facies Interpretation: Use of stable carbon isotopes has shown that most concretionary carbonate is derived from microbiological oxidation of organic matter by processes such as sulphate reduction or methanogenesis (Raiswell and Fisher, 2000). Carbonate concretion development in marine environments occurs in suboxic environments from bacterial sulphate reduction or microbial methanogenesis (Morad, 1998). During sulfate reduction, sulfate is reduced by methane or organic matter generating sulfides and bicarbonate. Below the sulfate reduction zone, methanogenesis becomes the dominant form of anaerobic respiration and generation of methane. The methane diffuses upward to the sulfate reduction zone and is used by sulfate-reduction bacteria to produce bicarbonate, leading to carbonate precipitation in pores (Figure 25) (Dong Jin *et. al*, 2008).

Figure 23: Carbonate concretion in mudstone slab at Jacob's Creek Quarry.

Figure 24: Sawn and polished slab through carbonate concretion of Facies 1. Note deflection of host laminae around concretion suggesting an early diagenetic origin. Sample collected form Jacob's Creek Quarry. Width of slab approximately 20cm.

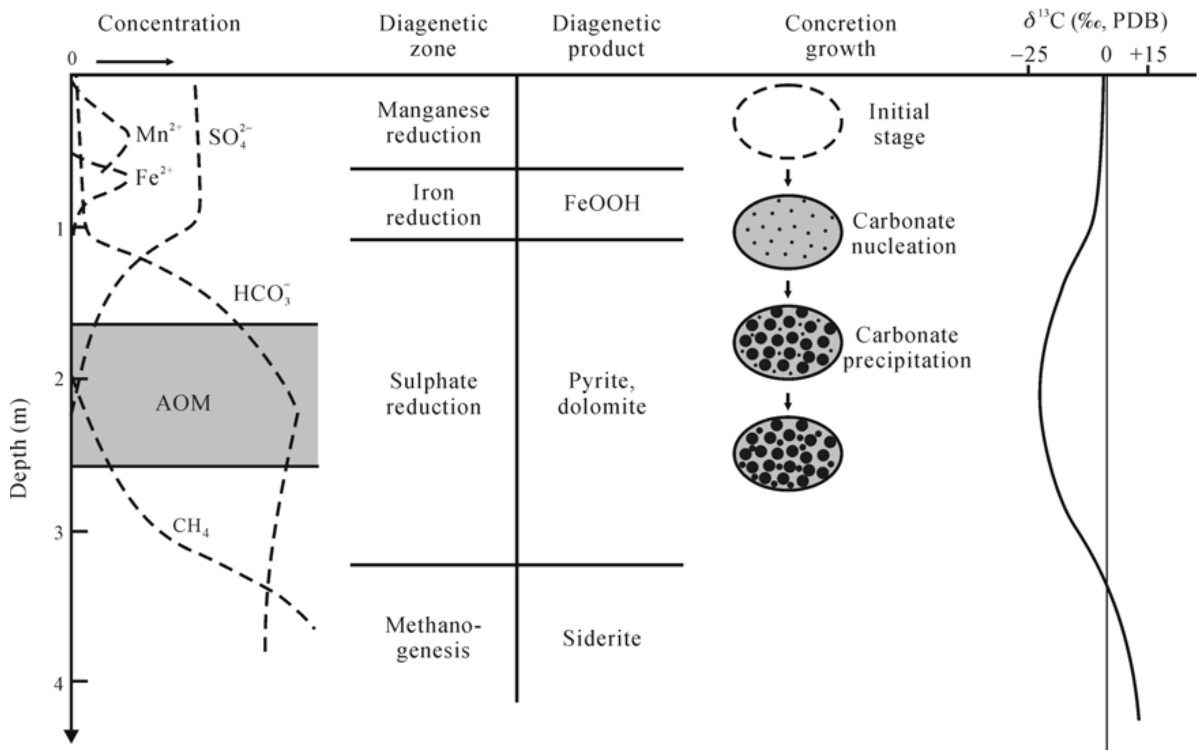

Figure 25: Geochemical classification scheme of marine sedimentary environment below sediment-water interface and possible growth model for concretions (from Dong *et. al*, 2008).

Anaerobic methane oxidation (AOM) occurring in the sulfate reduction zone, is generally considered the major stage of concretionary development (Dong *et. al*, 2008).

The preservation of parallel laminations within concretionary bodies observed in outcrop and polished slabs indicates cementation was sufficient to provide resistance to the effects of compaction (Raiswell and Fisher, 2000) and the presence of deflected laminae in the host rock (Figure 24) near concretions reflects early concretionary growth before compaction (Dong Jin *et.* al, 2008). Further evidence for early concretionary development includes deformed concretions within synsedimentary folds (Figure 23) and compaction of host-sediment laminae around undeformed concretions (Figure 24). This observation also suggests concretions were initially poorly-lithified and plastic (Raiswell, 1988; Raiswell and Fisher, 2000).

The areal extent of concretion-bearing layers also makes them useful tools for correlation and when conditions for concretionary growth are met, they occur at a regional scale (Sellés-Martínez, 1996). Outside of the field area, Conley and Bain (1965) reported the following:

1. Lenticular shaped concretions ranging from 5 to 20 cm in length at their type locality from the McManus Quarry (Cid Mudstone as mapped by Stromquist and Henderson, [1985]) in Stanley County on County Road 1963 0.3 miles north of its intersection with County Road 1964. Now SR1963 and SR1964.
2. Limestone beds up to 3 cm thick interbedded with massive, waterlaid, argillaceous tuff beds near Albemarle on the south side of N.C.27 Bypass, 100 yards east of its intersection with N.C. 52 (Cid Mudstone as mapped by Stromquist and Henderson, 1985).

Because the physico-chemical conditions that result in concretionary growth are reached synchronously in broad areas of a basin, the areal extent of concretion-bearing layers makes them useful tools for correlation and stresses that when conditions for concretionary growth are met, they occur at a regional scale (Sellés-Martínez, 1996). The presence of concretionary bodies in the Cid mudstone approximatley 30-kilometers to the south of Jacob's Creek Quarry suggests the unit is Neoproterozoic, regionally extensive and not confined to the quarry area.

Facies 3: Volcanogenic sandstone

Sedimentological characteristics: Graded volcanogenic sandstone and calcareous sandstone (metacarbonate) (Figure 26) interbedded with laminated mudstone were observed at the Jacob's Creek Quarry on either side of the contact of the mudstone member with the Flat Swamp member. Where fresh, facies 3 consists of bluish-green, fine to medium-grained sandstone and calcareous sandstone up to 30 cm thick with an average thickness of 10cm. It weathers to shades of rusty-red. Sandstone beds have sharp basal contacts, with both sharp and graded upper contacts with the mudstone and argillite. No evidence of bioturbation was observed.

Sedimentary structures include laminations, rip-up clasts (Figure 27), flame structures (Figure 27), convolute laminations, load casts and ripple-drift cross-lamination (Figure 28). The mineralogical composition comprises angular to subrounded quartz and sodic plagioclase, mica and traces of chlorite, epidote, titanite and zircon (Stromquist and Henderson, 1985).

Figure 26: Metacarbonate sandstone bed of facies 3. Acid digestion of two samples of metacarbonate sandstone beds did not reveal the presence of microfossils.

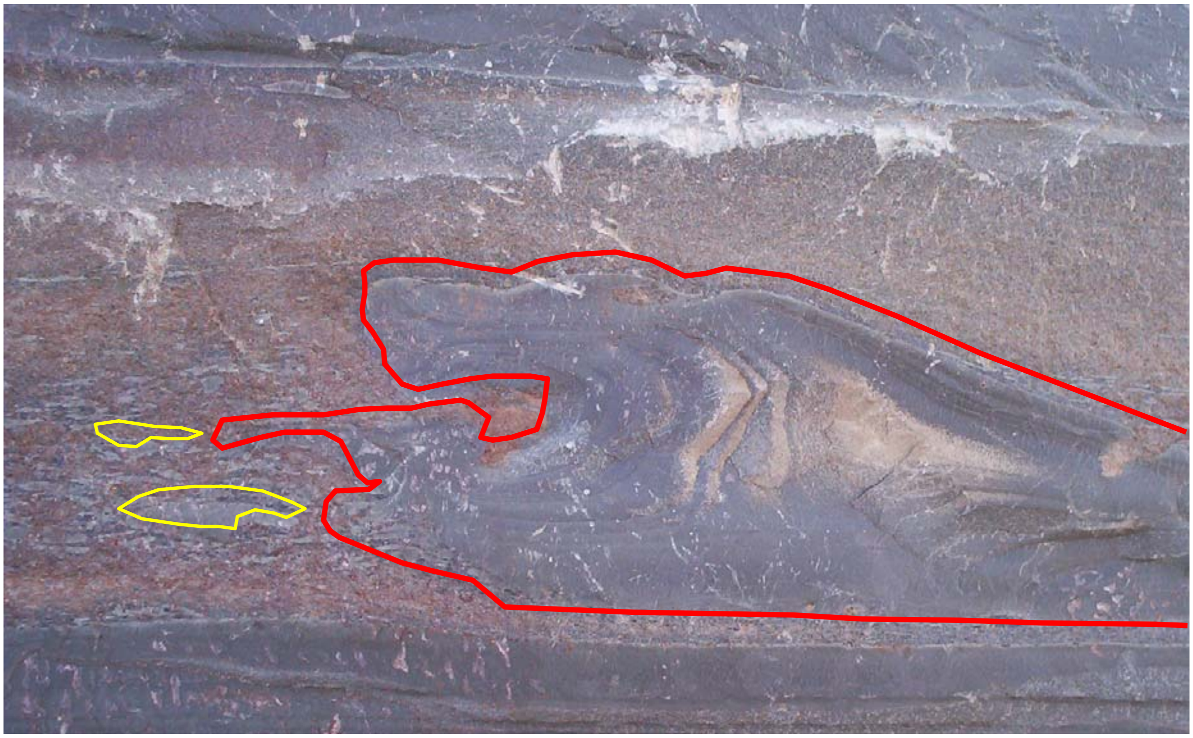

Figure 27: Flame structure and rip up clasts in Bouma $T_{a,b}$ turbidite deposit of facies 3. Flame structure outlined in red, rip up clasts outlined in yellow.

Figure 28: Ripple drift cross laminations overlain by laminated silt and fine sand of facies 3 at Jacob's Creek Quarry. Interpreted as $T_{c,d}$ divisions.

Koeppen et al. (1995) described fossils from metacarbonate beds reported to be in a large loose block of mudstone along the road leading to the quarry (T. Offield, pers. comm., 1998). Metacarbonate beds were recognized in the operating quarry pit during the present study and numerous metacarbonate beds were observed up to ten centimeters thick, in large (multiple meter scale) loose blocks to the southwest of the pit. Two samples from one of these blocks was analyzed by acid digestion for microfossils by personnel from the North Carolina Museum of Natural Sciences. Acid residues indicated grey silica rich particles, grey-green quartz, chlorite and sulphide. No microfossils were identified (P. Weaver, personnel communication, 2009).

Facies interpretation: In internal structure and geometry the sandstone beds resemble turbidity deposits (Bouma, 1962). The presence of sharp or erosional basal contacts, load-casts, flame structures and rip-up clasts and cross lamination suggests rapid deposition more common to turbidity currents than deposition by contour currents or fluctuating sediment supply (Middleton and Hampton, 1973; Lowe, 1975; Boggs, 1995; Tucker, 2003). Bouma $T_{a,b}$ beds dominate but Bouma $T_{c,d}$ divisions are present as well. Turbidite sedimentation in proximity to volcanic arcs typically results from mass-flow events that originate on the flanks of individual arc volcanoes and therefore includes abundant immature sediment from the associated debris (Cas and Wright, 1997; Underwood *et. al.*, 1995). The immature texture suggests a volcanic source and the absence of pumiceous or scoriaceous material suggests that the detritus is epiclastic or autoclastic rather than pyroclastic in origin. The presence of subrounded quartz and plagioclase indicate derivation from shallow water (Mitchell, 1970).

Facies 4: Silt to fine sand with hummocky-cross bedding

Sedimentological characteristics: Near the top of the eastern quarry wall is a medium to thickly bedded, siltstone to fine-grained metacarbonate sandstone layer with hummocky cross stratification (Figure 29). The hummock wavelength measured 1.5 meters with a height of 25 centimeters. Hummocky cross bedding is bounded with a planar laminated base and top.

Facies Interpretation: Dumas and Arnott (2006) suggest hummocky cross-stratification optimally forms above (but near) storm wave base, which is rarely greater than 200 meters (Johnson and Baldwin, 1997); thus the strata with hummocky cross bedding are interpreted as representing deposits in water less than approximately 200 meters deep.

Facies 5: Siltstone and fine grained sandstone with flaser and lenticular bedding

Sedimentological characteristics: The Floyd Church Formation is characterized by thinly laminated to thinly bedded blue-gray siltstone. Sedimentary structures present in the Floyd Church Formation in the field area include flaser, wavy and discontinuous lenticular bedding. Bedding is also defined by dark gray mats of microbial mud (Figure 30).

Facies interpretation: The Floyd Church Formation defines a transition to a higher energy depositional environment the that of the underlying Cid Formation. Lenticular bedding is common to tidal and subtidal areas (Reineck and Wunderlich, 1968). As such, this facies is interpreted as being deposited in shallower water than the underlying Mudstone in an environment with bimodal current directions.

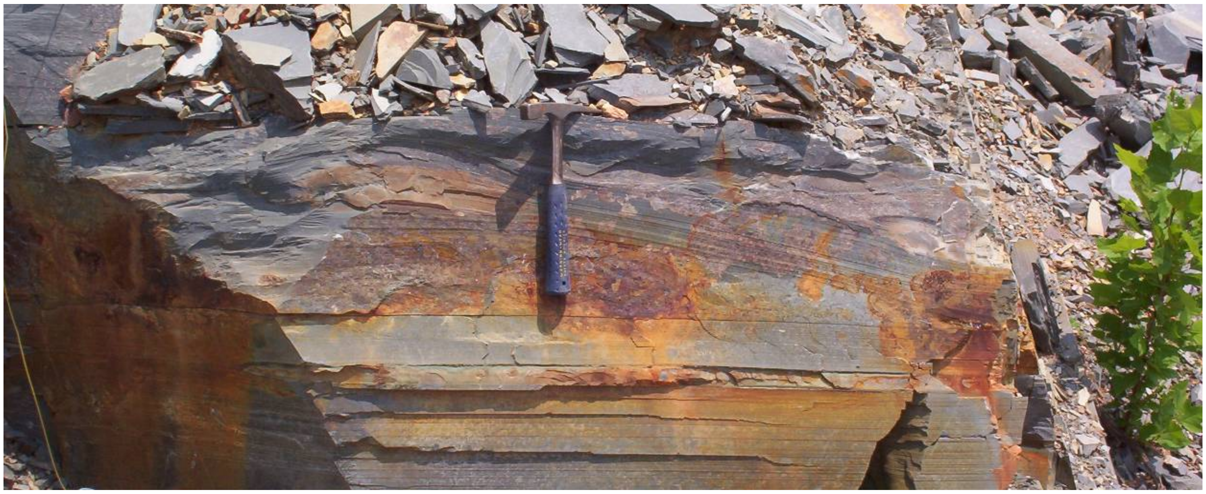

Figure 29: Hummocky cross bedding of facies 4 at Jacob's Creek Quarry. Hammer length is 25 centimeters.

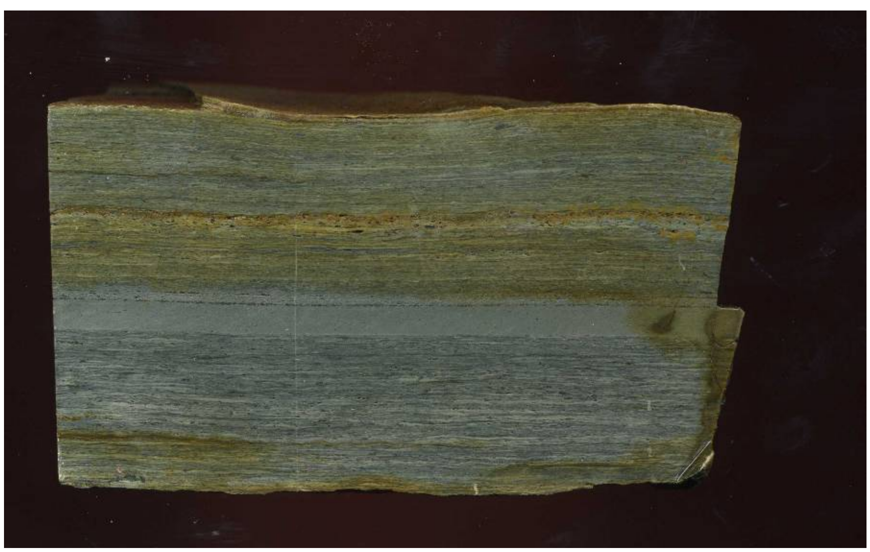

Figure 30: Polished slab of light gray siltstone and fine sandstone with mats of dark gray to black microbial mud (facies 5). Sample collected from unnamed tributary of Badin Lake near State Route 2550.

Facies 6: Mafic volcaniclastic

Sedimentological characteristics: Facies 6 consists of greenish-gray, thinly laminated to massively bedded, poorly to well sorted rocks with a composition of andesitic-basalt (Stromquist and Henderson, 1985; Stromquist *et. al.* 1971). Facies 6 was observed in the mudstone and Flat Swamp members of the Cid Formation. Although, this facies was not observed within the Floyd Church Formation in the study area, other workers have mapped mafic volcaniclastic rocks in the Floyd Church Formation outside the study area (Stromquist and Sundelius, 1969; Stromquist and Henderson, 1985).

Where present, bedding is laminated (Figure 31) to thickly bedded (Figure 32), and defined by grain size. Grain size ranges from fine silt to boulder with normal, reverse (Figure 33) and multiple normal grading (Fisher and Schmincke, 1984) present (Figure 32). No evidence of bioturbation, fossils or post depositional reworking by wave or fluvial action was observed.

Clasts present in decreasing order of abundance consist of rhyodacite lithics, flow-banded rhyolite, volcaniclastic sandstone, mafic pumice and laminated mudstone (Figure 34). Clast populations in the Flat Swamp are more dominantly rhyodacitic than in the mudstone; although, these were not distinguished as a separate facies because clasts of this composition are present throughout both members of the Cid. Their increased abundance in the Flat Swamp is likely due to increased felsic volcanism that dominates that member. Clasts are predominantly matrix supported and are rounded to angular, at places being brecciated.

Figure 31: Polished slab of mafic volcaniclastic (facies 6) from the Flat Swamp member of the Cid Formation illustrating laminated texture. Width of sample is 10cm. Sample collected from Cid Flat Swamp member west of National Forest Road 6507.

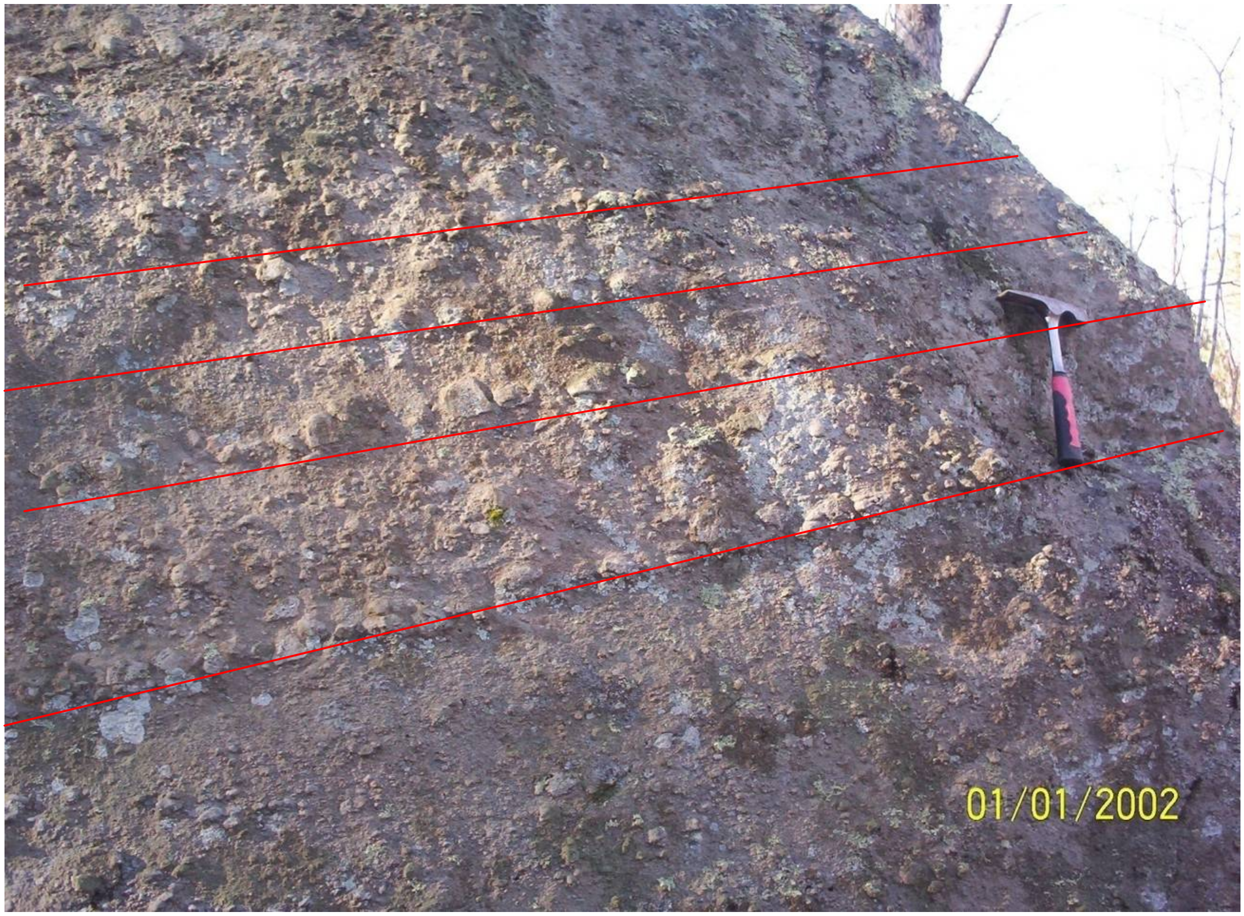

Figure 32: Volcaniclastic debris flow deposit (facies 6) exhibiting multiple normal graded bedding (red lines). Flat Swamp member near Jacob's Creek Quarry, approximately 100-meters upsection from the contact with the Cid mudstone member.

Figure 33: Reverse grading in mafic volcaniclastic (facies 6) located approximately 500m north of State Route 1550, near Badin Lake.

Figure 34: Volcaniclastic mafic volcaniclastic facies with clast of laminated mudstone identical to Facies 1. Note inclusions of volcaniclastics within mudstone indicating contemporaneous deposition prior to lithification. Scale in centimeters. Sample collected at Jacob's Creek Quarry.

Cobble to boulder sized ‘rip-up’ clasts of flow-banded volcanic rock were observed at the base of the volcaniclastic deposit located to the east of South Chapel Hill Church Road. Clasts were observed to be matrix supported throughout the study area.

Mineralogically this the matrix of this facies is comprised of albite + chlorite + actinolite + potassium feldspar + epidote + quartz ± biotite ± muscovite (Butler and Ragland, 1969). A penetrative axial planar cleavage, striking to the northeast (070°), is responsible for the ‘fin’ shaped outcrop pattern for this facies observed throughout the study area. Larger, elliptical shaped clasts in debris flows throughout both the mudstone and Flat Swamp members were observed with extension cracks; likely the result of regional strain, as the trace of cleavage on bedding is parallel to the long axis of the clasts and perpendicular to the plane of extension.

Facies interpretation: Field observations failed to identify evidence for subaerial pyroclastic origins such as fiamme or welding structures, degassing structures, or columnar jointing that would suggest a definitive subaerial pyroclastic origin (Cas and Wright, 1988; Fisher, J.V., 1984; Fisher and Schmincke, 1984). In addition, the facies characteristics of the host sediments suggest deposition in deeper marine waters. As such, a subaerial origin for this facies is unlikely.

Definitively distinguishing these deposits as either subaqueous pyroclastic or reworked volcanigenic material is difficult given the similarity in textures ascribed to deposits of these types (Cas and Wright, 1996; Fisher and Schmincke, 1984). The presence of rounded lithic clasts implies some post-eruptive reworking by surface processes (Cas and Wright, 1996; Allen, 2004). The presence of volcaniclastic sandstone as cognate lithics also suggests migration from or through a shallow or subaerial source zone.

Some beds are ungraded, while rare beds display inverse-to-normal grading, suggesting a debris flow origin (Balance *et. al.*, 2004; Allen, 2006). The presence of multiple normal grading (Figure 32) suggests deposition from more than one distinct depositional event or from closely spaced "pulses" within a single event (Sparks, 1976).

Mixed mafic and felsic clasts within the same deposits suggests that the material was sourced from separate eruptions on the same volcano and were likely mixed before or during initiation of debris flow events (Balance, 2004). The presence of contorted clasts of Cid mudstone suggests the mudstone was not lithified at the time the time of entrainment.

Facies 7: Felsic epiclastics

Sedimentological characteristics: This facies comprises thinly bedded, cream to dark gray, silt to coarse-grained sandstone. It was identified above and below the contact between the mudstone and Flat Swamp members of the Cid Formation. Bedding is defined by normal grading (Figure 35) and other than slumping (Figure 36) no other sedimentary structures were observed.

The composition includes rounded to angular crystals of quartz and feldspar with lithic fragments in a fine grained tuffaceous groundmass. At the contact with the Cid mudstone, a thin bed of felsic epiclastic rocks was observed with lithic fragments identical to Cid mudstone. The mudstone fragments were angular and range in size from 2 to 20 mm across (Figure 13).

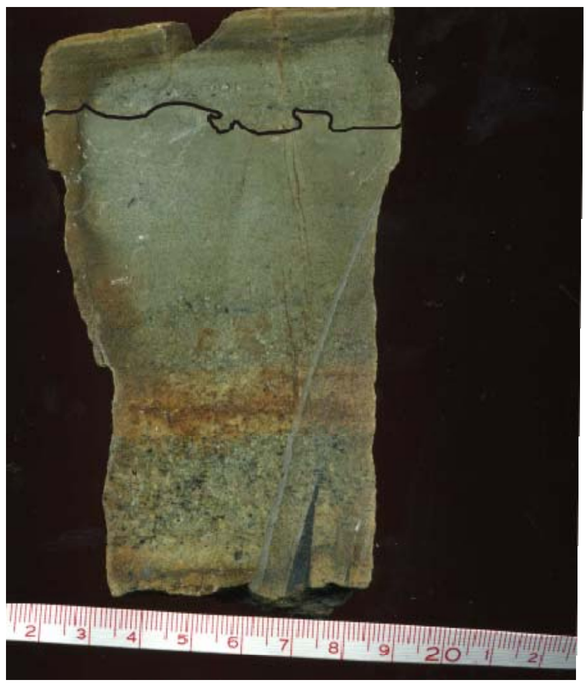

Figure 35: Normally graded felsic epiclastic (facies 7) collected from Flat Swamp member of the Cid Formation at Jacob's Creek Quarry approximately 15-meters upsection of the contact with the unnamed mudstone member. This facies was also observed with slump folding.

Figure 36: Slump fold from Cid Flat Swamp member. Note horizontal laminations at base of slab. Slump is five centimeters in height. Sample collected near Beaverdam Creek at Jacob's Creek Quarry.

Facies interpretation: Facies 7 is most likely the result of subaqueous gravity flows. The lack of sedimentary structures may be the result of rapid deposition (Wood *et. al.*, 2003) and is consistent with the interpreted depositional mode of other facies in the study area. The felsic nature of this facies and its association with facies 8 suggests deposition from the remobilization, mixing and down-slope movement of newly deposited felsic volcanic material (*cf.* Wood *et. al.*, 2003). Slump structures typically occur in rapidly deposited units where the rapid sedimentation and oversteepened slopes lead to instability (Boggs, 2006). The presence of slump units within facies 7 suggests that deposition occurred rapidly on slopes steep enough to fail.

Facies 8: Felsic volcaniclastics

Sedimentological characteristics: Felsic volcaniclastics dominate the Flat Swamp member, accounting for over 80% of the entire member. Felsic volcaniclastics are also present in the mudstone member but are thinner and less abundant. These rocks are poorly to massively bedded, light gray and weather tan to chalky-white with variable amounts of quartz, feldspar and lithic fragments (<10% to 50%) with diameters between three and 20-centimeters in a fine grained groundmass (Figure 37 and 38). No sedimentary structures were observed.

Facies interpretation: Crystal-rich deposits are not uncommon in volcanic terrains or in the surrounding basins that derive their sediment from volcanic terrains (Cas and Wright, 1997). In these areas, aggregates of pyroclastic debris that have not been significantly reworked, but have been redeposited by epiclastic processes shortly after eruption, may superficially resemble primary pyroclastic deposits (Fisher, 1984; Cas and Wright, 1997).

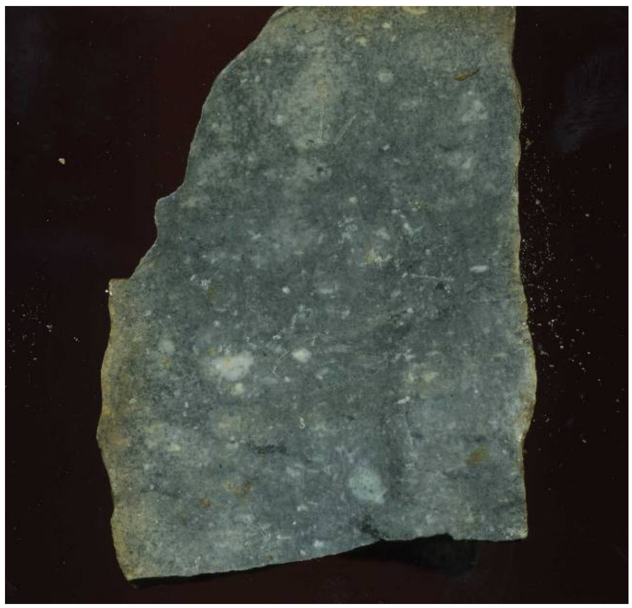

Figure 37: Felsic volcaniclastic from the unnamed mudstone member of the Cid Formation. Width of sample is 15 cm. Sample collected from west side of Chapel Hill Church Road approximately 400 meters northeast of the intersection with State Route 109.

Figure 38: Felsic volcaniclastic from the Flat Swamp member of the Cid Formation. Scale in centimeters. Sample collected from Beaverdam Creek approximately 400 meters north of Blain Road.

It is therefore important to determine the possible modes of fragmentation, transportation and deposition independently, before a final interpretation of genesis is made. Field observations failed to identify evidence for direct pyroclastic origins such as fiamme or welding structures, degassing structures, or columnar jointing that would suggest a definitive pyroclastic origin (Cas and Wright, 1988; Fisher, J.V., 1984; Fisher and Schmincke, 1984). Based on an absence these features and the facies characteristics of the host sediments suggesting deposition in deeper marine waters dominated by mass flow deposits, it is difficult to confidently designate these rocks as primary pyroclastic deposits. As such, these rocks are interpreted as either primary or partially reworked material from volcanic eruptions.

Facies Associations

Facies associations are groups of facies occurring together (Boggs, 2002). Paleoenvironmental interpretations can be improved by understanding facies associations and successions rather than using individual facies alone. Field observations indicate that the eight facies observed in the field area vary in abundance throughout the field area and three facies associations were noted. These are described below and suggest that the Cid and Floyd Church Formations form part of a conformable, coarsening upward sequence.

Facies Association 1

Facies association 1 (FA1) is dominated by Facies 1 with inter-bedded mafic volcaniclastics (facies 6), felsic epiclastics (facies 7) and felsic volcaniclastics (facies 8). In descending order of abundance, concretion layers (facies 2), sandstone (facies 3) and hummocky cross bedding (facies 4) are also present. Facies 1 is dominated by turbidity and mafic debris flow deposits. The presence of felsic rocks in FA1 suggests nearby concomitant felsic volcanism. FA1 includes the entire Cid mudstone member present in the area and the bottom 20-meters of the Flat Swamp member of the Cid Formation.

Facies Association 2

Facies association 2 (FA2) is dominated by felsic volcaniclastics and in descending order of abundance felsic epiclastics, mafic volcaniclastics and laminated mudstone. Laminated mudstone is present at a minimum of two intervals within FA2 suggesting that the depositional conditions changed little with the onset of felsic volcanism and further suggesting the felsic facies are submarine. This association is approximately 700-meters thick and the abundance of felsic rocks indicates a transition to increased felsic volcanism. FA2 includes the all but the bottom 20-meters of the Flat Swamp member, which is assigned to FA1.

Facies Association 3

Facies Association 3 (FA3) is dominated by the silt and fine grained sandstone with lenticular and wavy cross-bedding; it is confined to the Floyd Church Formation. Mafic and felsic volcaniclastics/epiclastic rocks were not observed within FA3 in the field area, but other workers have indicated their presence within the Albemarle Group (Stromquist and Sundelius, 1969; Stromquist and Henderson, 1985). FA3 is interpreted as being deposited following abundant felsic volcanism of FA2 in a shallow marine environment affected by tidal currents.

Paleoslope and Paleocurrent Analysis

Introduction

Planar sedimentary structures such as cross-beds provide directional information for a particular place and time and many observations collected over a large area are required to discern regional patterns (Pettijohn *et. al.*, 1987). Slump structures, formed by deformation of unconsolidated sediments during downslope translation, can be excellent paleoslope indicators as they form folds with hinge lines sub-parallel to the paleoslope strike (Woodcock, 1979) and axial planes that dip upslope (Tucker, 2003). In tilted and folded strata the paleo sense cannot be accurately determined without first restoring field data (present day reference frame) to their orientation prior to deformation (stratigraphic reference frame).

The object of this section is to present the paleocurrent and paleoslope data obtained, summarize the retrodeformation techniques used, and compare the results with those found in the published literature. Unfortunately, there is only a modest number of published paleocurrent data for the Albemarle Group for comparison. For example, over an area of approximately 1,050 km, Dockal and Huntsman (1989) reported five paleocurrent attitudes. Several authors (Stromquist and Sundelius, 1969; Gibson and Teeter, 1984; Dockal and Huntsman, 1989; Offield, 2000) have made mention of slump folds from outcrops within the group; although, no studies have reported attitudes or tried to interpret this data for determination of regional paleoslope.

Methodology

The field area lies at the hinge of the New London Syncline and the first step in determining the paleo-sense was to restore the field data to its orientation prior to deformation. This was done using a two step process: (1) remove the effects of tilting/folding, and (2) remove the effects of the regional plunge of the New London syncline. To remove the effects of tilting, paleocurrent/slope data was rotated about a horizontal axis parallel to strike using StereoWin (Allmendinger, 2003). The π-method (Lisle and Leyshon, 2002) was used to determine the degree of plunge of the New London syncline from bedding attitudes collected in the study area.

Paleoslope was determined using the slump vergence method. This method determines the upslope direction using the axial surface of slump folds and is similar to imbrication planes that provide up-stream current directions. Axial surfaces were measured and recorded for four slumps; three from the Cid mudstone member in the working Jacob's Creek Quarry (Figure 39) and one from the Flat Swamp member (Figure 36) approximately 100-meters up-section of the working quarry. Strike and dip of slip-planes on cross-beds (Figure 40) and long axis orientation of clasts (Figure 41) in a mafic debris flow bed were used to provide a sense of paleocurrent direction.

Potential Sources of Error

Bradley and Hanson (2002) identified several potential sources of error encountered in paleoslope/paleocurrent analysis, including: (1) discrimination between sedimentary and tectonic structures; (2) retrodeformation procedures; and (3) measurement errors. The following paragraphs detail some of these potential errors and the methods used to avoid them.

Discrimination between sedimentary and tectonic structures

The primary concern in slump fold analysis is incorrectly identifying a tectonic fold as a slump feature. The regional structure of the study area is straight forward; a gently plunging regional syncline cut by a regional cleavage that strikes to the northeast.

Each identified slump horizon was bounded above and below by non-folded rocks of similar texture and composition, eliminating the possibility of tectonic origin. The rocks near the quarry are metamorphosed to greenschist facies and there were no discernable tectonic structures that could be misidentified as a paleocurrent indicator.

Retrodeformation Procedures

Reversing the effects of deformation is simple for dipping strata in structurally simple geologic settings by the single-tilt method. Where fold plunge is more than a few tens of degrees, a double-tilt restoration is required, and the results can be ambiguous (Bradley and Hanson, 2002). However, the regional fold plunge in the study area was determined to be 14-degrees (see below) and the difference in paleocurrent directions between restored data when ignoring plunge versus restorations including plunge was less than 5°. For the study area, the effect of the gentle plunge of the New London syncline appears negligible.

Measurement Error

A 2° error in measuring cross-bedding with a 30° foreset dip, could yield a paleocurrent error of up to ± 4° (Bradley and Hanson, 2002). Although, some potential for error is always present, to reduce the possibility, attitudes for each potential paleocurrent/slope indicator was measured at least three times.

Figure 39: Slumped bed in Cid mudstone member at active pit of Jacob's Creek Quarry.

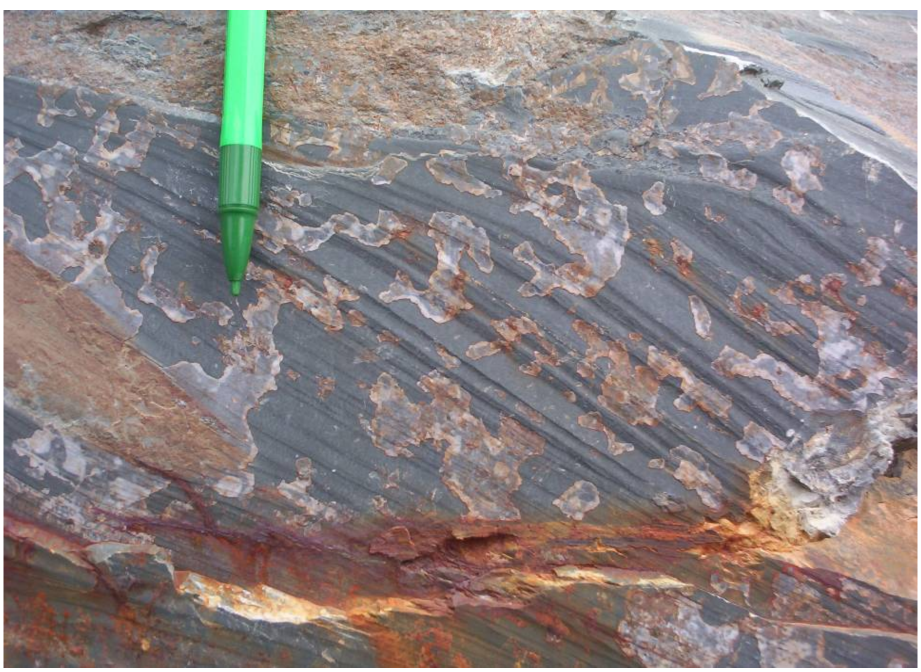

Figure 40: Slip faces on cross-beds in Cid mudstone member at active pit of Jacob's Creek Quarry used in paleocurrent analysis. Attitude of the slip face is 138°/40°.

Figure 41: Mafic volcaniclastic deposit in Cid mudstone member at Jacob's Creek Quarry illustrating elongate clasts used for determination of paleocurrent.

Retrodeformation Techniques

The π-method was used to determine the plunge of the New London syncline in the study area. The trend and plunge of New London syncline, was determined to be 240°/14°. Restoration of paleocurrent and paleoslope attitudes was completed using a double-tilt calculation with StereoWin. Double-tilt restorations, which removed the effect of tilting and plunge, differed by between 2° - 5° from single-tilt restoration calculations where plunge was ignored.

Results

Paleoslope indicators in the study area were limited to three slumps from the unnamed mudstone and one from the Flat Swamp member. All slumps were located on the Jacob's Creek property and stratigraphically within 100-meters of each other. Dip direction of axial surfaces was presumed to indicate up-slope facing direction; therefore, constructed rose diagrams indicate upslope direction towards the southeast (Figure 43) for the mudstone and towards the east for the Flat Swamp. These data suggest a general west facing slope for both members of the Cid Formation.

Paleocurrent indicators in the study area were sparse; however, cross-bedding and ripple-drift cross laminations were observed in two beds of Cid mudstone at Jacob's Creek Quarry. Sense of direction was also obtained by measuring the apparent long-axis alignment of elongated clasts within a mafic volcaniclastic debris flow deposit in the Cid mudstone. Sense of flow indicators were not observed in the Flat Swamp member.

Flow direction was obtained by measuring the strike and dip orientations on foresets, with the presumed flow direction being downdip of the foreset (Figure 44). Trend and plunge of elongated clasts was measured and recorded. Bedding attitudes were measured at each location to allow for tectonic reconstruction. The general paleocurrent direction from the three cross-laminations indicated a westerly flow direction. Assessment of elongated clasts yielded two equally viable choices of paleocurrent direction, i.e., upcurrent and downcurrent and both directions were plotted on a rose diagram. However, a southwesterly flow direction would seem logical given the determined westerly paleoslope and paleocurrent directions.

The results presented herein indicate a west facing paleoslope and westward directed paleocurrents (Figure 45) for the Cid mudstone and Flat Swamp members, an agreement that helps support a conformable relationship. Gibson and Teeter (1984) provided directional data obtained from a limited number of cross-beds and ripple surfaces suggesting a bimodal current direction from the north-northwest or the south-southeast for the Floyd Church Formation and Yadkin Formations the conformably overlie the Cid Formation (Milton, 1984).

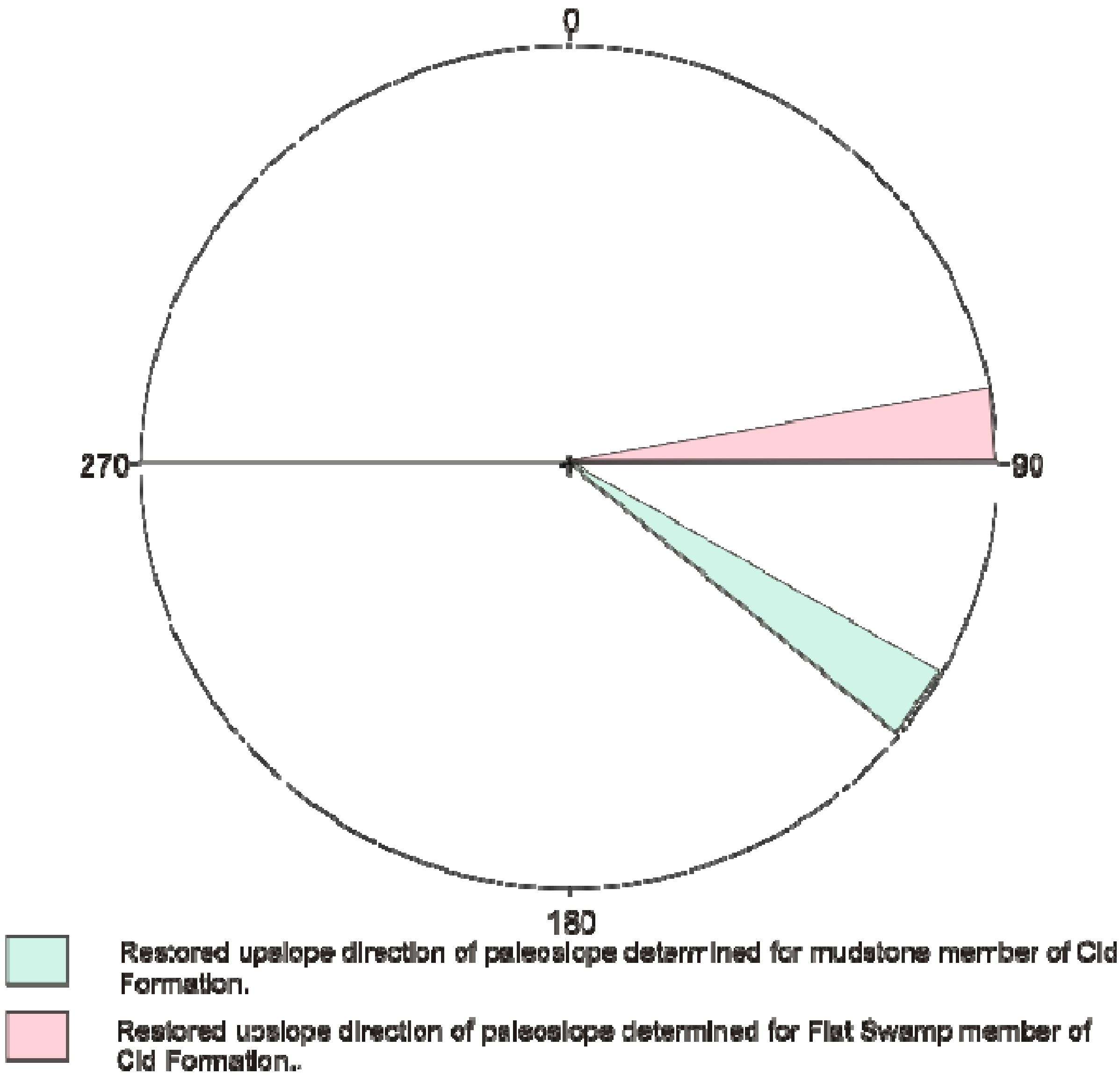

Figure 43: Rose diagram illustrating paleoslope for slump folds observed in the study area. Petals of diagram point upslope. N = 3 for mudstone member and N = 1 for Flat Swamp member.

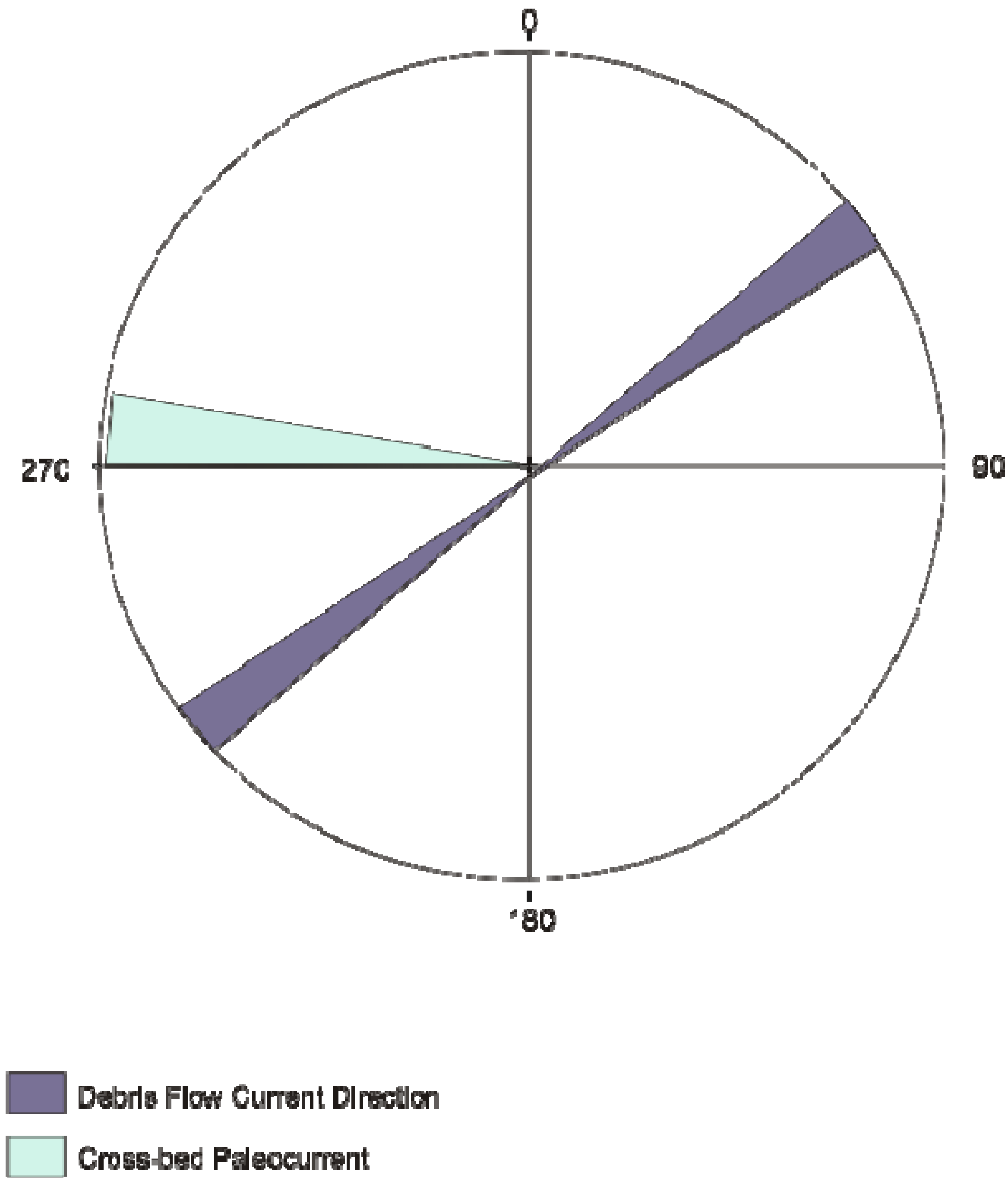

Figure 44: Rose diagram illustrating restored paleocurrent from cross-bedding and long axis orientation of clasts in debris flow deposit in Cid mudstone at Jacob's Creek Quarry near Denton, North Carolina. A southwesterly flow direction is favored for the debris flow unit based on paleoslope and paleocurrent indicators in the mudstone member.

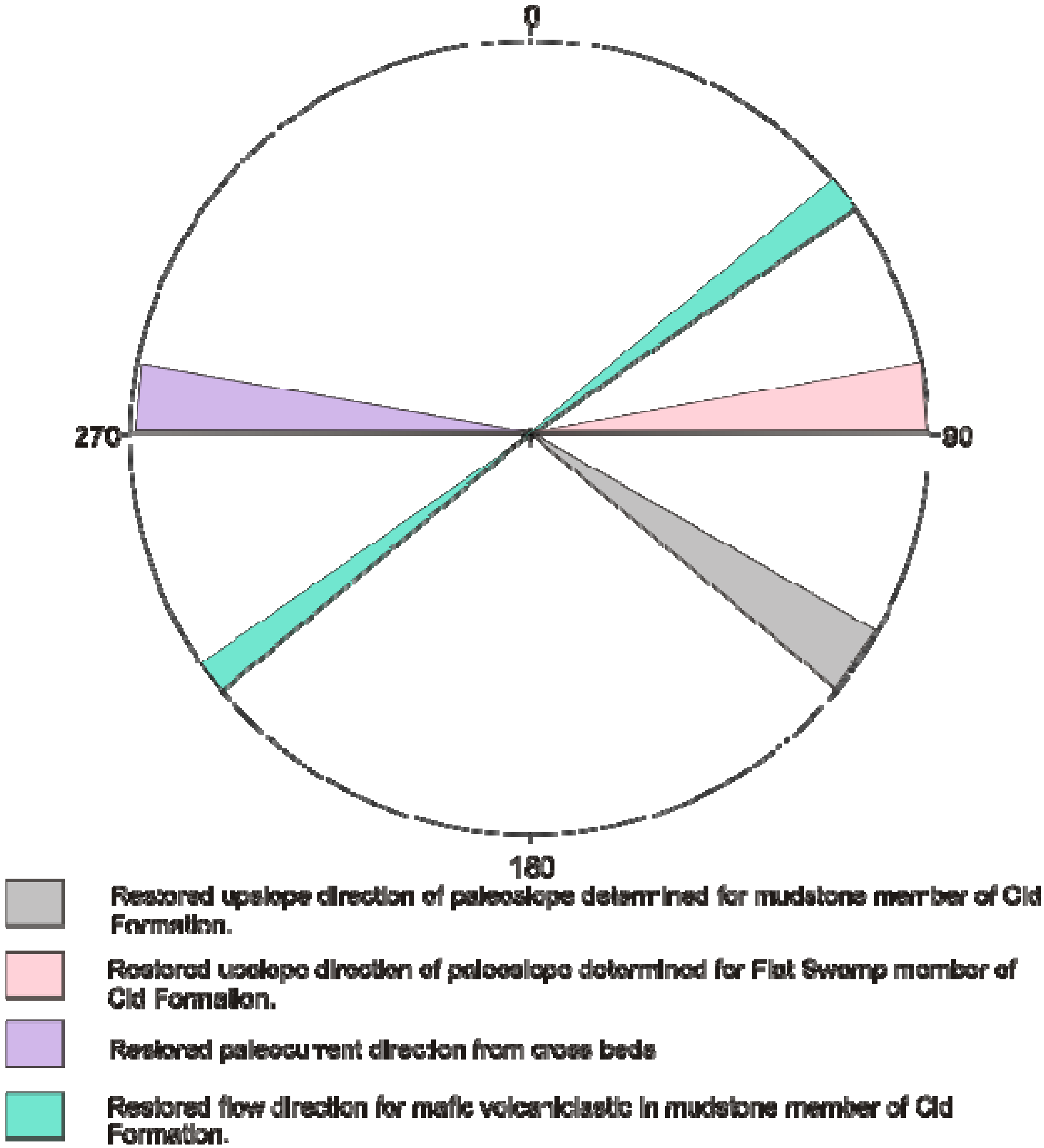

Figure 45: Rose diagram illustrating restored paleocurrent and upslope paleoslope directions determined from slump folds in the Cid Formation.

Paleoenvironmental Interpretation

Introduction

The abundance of volcanic material throughout the Albemarle Group has led most workers to agree it was deposited in an arc environment (Conley and Bain, 1965; Butler and Ragland, 1969; Stromquist and Sundelius, 1969; Gibson and Teeter, 1984; Stromquist and Henderson, 1985; Pollock, 2007). However, there has been discord concerning the depositional environment of the group, e.g. previous studies have interpreted the Albemarle Group as being deposited in a mixed subaerial and subaqueous environment (Stromquist and Sundelius, 1969), solely subaqueous (Feiss, 1982), isolated shallow marine platform (Gibson and Teeter, 1984); a general shallowing upward sequence (Milton, 1984), classic deep water turbidite deposit (Dockall and Huntsman, 1989), and back-arc rift (Pollock, 2007) to back-arc basin (Ingram, 1999; Pollock, 2007).

This section examines the facies, facies associations, paleoslope and paleocurrent data from this investigation in order to help assess the depositional environment for the Albemarle Group. Understanding the sedimentology of the field area is crucial to understanding the depositional environment of the group as a whole.

Discussion

The mudstone (facies 1) and volcanogenic sandstone (facies 3) in the Cid Fomation represent turbidite deposits with hummocky cross-bedding. Dumas and Arnott (2006) suggest that hummocky cross-stratification optimally forms above (but near) storm wave base, which is rarely greater than 200 meters (Johnson and Baldwin, 1997; Harris and Coleman, 1998); thus the strata with hummocky cross bedding are interpreted as representing a storm deposit in water less than approximately 200 meters deep. The stromatolite-like forms also found in this facies are consistent with the water depth suggested by the hummocky cross bedding, as there have been reports of stromatolites at water depths of up to 100 meters (Böhm and Brachert, 1993; Eriksson and Reczko, 1998). Paleocurrent indicators and slump folds give a general sense of paleocurrent and slope facing direction towards the west.

The depositional environment of the quarry rocks is difficult to determine from the observations made at the quarry, alone; however, considered in conjunction with data from the overlying Floyd Church Formation it is possible to tentatively deduce the depositional environment of the unnamed mudstone member. Sedimentary structures present in the Floyd Church Formation in the vicinity of the quarry include flaser, wavy and lenticular bedding which are common in intertidal areas (Reineck and Wunderlich, 1968). Collectively, these data suggest a shallow (<200 meters water depth) marine environment for the unnamed Cid mudstone member. This interpretation is consistent with the depositional model deduced by previous stratigraphers working in the Albemarle Group (Gibson and Teeter, 1984).

Transport of sediment, including mafic and felsic material, into the basin likely originated from the nearby arc due to gravity processes and volcanic eruptions. Although deposition in the basin is considered entirely subaqueous, the presence of rounded clasts and sand grains in mafic volcaniclastics and felsic epiclastic rocks of the Cid Formation suggests a nearby emergent source area. The presence of interleaved mafic-felsic sequences throughout the study area indicates the apron sediment was sourced either from separate volcanoes, from separate eruptions on the same volcano or both (Balance *et. al.*, 2004). The presence of felsic clasts within mafic volcaniclastic deposits requires a mixing process to have taken place during the gathering of sediment prior to mobilization (Balance *et. al.*, 2004). The spacing of volcanoes along an arc typically varies between 20 and 60 km so if the mafic and silicic components were derived from separate volcanoes, considerable shallow-marine transportation of at least one component is required. However, if they were derived from different eruptions on the same volcano, much less transportation is needed (Balance *et. al.*, 2004).

Basins adjacent to volcanic arcs receive volcaniclastic debris from the bordering arc, and if present the back-arc spreading center and remnant arc, with the arc being the dominant sediment source (Carey and Sigurdsson, 1984). Transport of material to the deeper parts of the adjacent basins occurs by settling through the water column or by a variety of sediment gravity flows generated by primary eruptions and secondary remobilizations (Cas and Wright, 1997); therefore, these systems are not analogous to typical deep-sea fan systems (Carey and Sigurdsson, 1984). The fundamental difference lies in the nature and delivery of sediment in each case. Deep-sea fans, usually develop from a single submarine canyon, through which sediment from a continental shelf or subaerial fluvial source is passed. In contrast, a volcanic apron receives sediment from multiple sources with sediment being delivered based on eruption location and associated ash cloud, pyroclastic flow, debris flows and lahars (Carey and Sigurdsson, 1984; Fisher, 1984).

Geochemical studies of the Stony Mountain gabbro indicate formation within an evolving early Paleozoic island arc-back arc rift basin system that developed along the ocean facing margin of west Gondwana (Pollock, 2007). The Stony Mountain gabbro was observed throughout the Cid Formation in the study area.

Backarc basin evolutionary models have been proposed by Carey and Sigurdsson

(1985) and Letouzey and Kimura (1985) and include the following stages (Figure 45):

Stage 1: Initial rifting and development of inter-arc basin;

Stage 2: Back-arc spreading and island arc volcanism;

Stage 3: Basin maturity and continued rifting; and

Stage 4: Drift stage.

Stage 1 is defined by the onset of subduction with associated volcanism and magmatism. Stage 2 includes subsidence of the basin near the spreading center and uplift at the flanks. In addition, increased volcanism leads to progradation into areas previously dominated by finer grained sediment. Stage 3 is defined by continued or increased rifting rates and migration of the basin from the spreading center. The final stage, Stage 4, includes continued rifting and isolation of the basin.

Following this model, the work by Pollock (2007), and assessment of sedimentary facies as part of this investigation, deposition in a backarc rift system is supported for the Albemarle Group. It is proposed that the group was deposited on the leading edge of west Gondwana in an isolated near arc basin.

Regarding basin development, it is proposed that deposition of the Tillery and Cid Formations occurred during rift initiation near the flanks of the spreading center (Stage 2). As rifting progressed, volcanism and magmatism increased with the intrusion of the Stony Mountain gabbro into the Tillery and Cid Formations and deposition of the Flat Swamp member of the Cid Formation. As rifting and volcanism continued, the combined effects of basin fill from volcanism and uplift elevated the Tillery and Cid Formations closer to sea level.

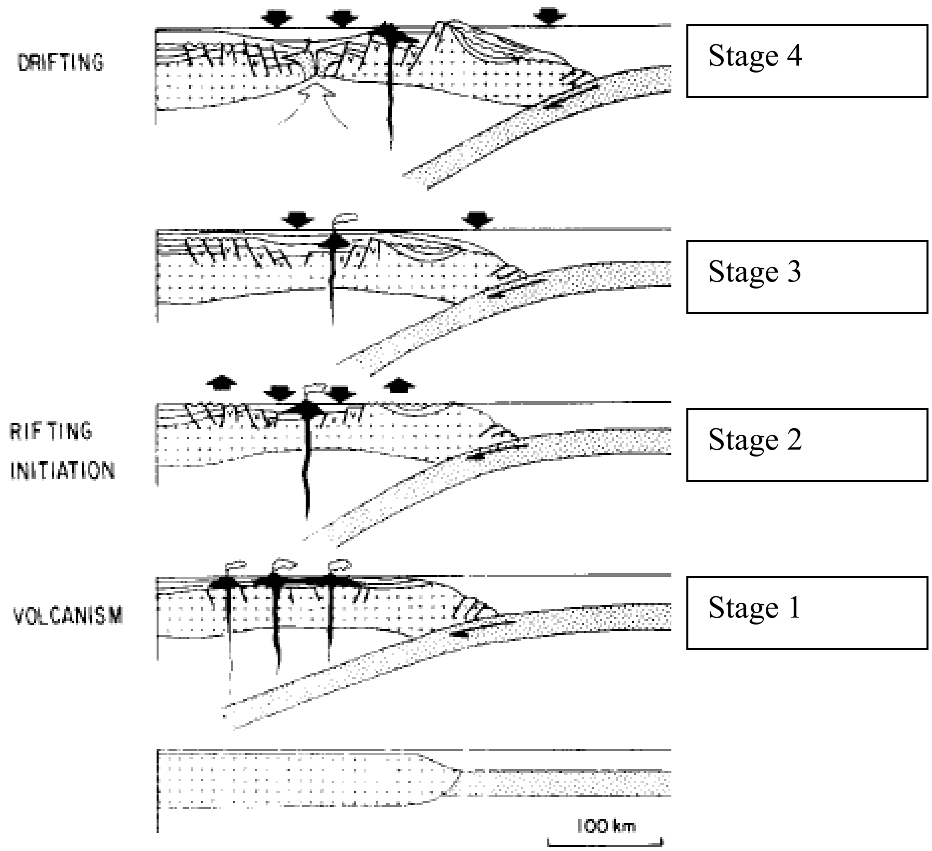

Figure 45: Evolutionary stages of development of back arc basin. Black arrows indicate uplift and subsidence. Reproduced from Letouzey and Kimura (1985).

At this time the Floyd Church and Yadkin Formations, whose sedimentary structures indicate shallow water, high energy environments were deposited.

Compared to the Cid Formation, the Floyd Church and Yadkin Formations have fewer magmatic rocks suggesting cessation or a lull in volcanic activity during deposition. This scenario implies the Floyd Church and Yadkin Formations were deposited during Stages 3 and/or 4 of backarc basin development as the leading edge of the arc migrated away from the west Gondwana and the magma source near the subduction and rift zones.

Summary and Conclusions

Significance of this Study

The age assignment of the Albemarle Group has been in question for more than a decade due to conflicting reports indicating both Paleozoic (Late Cambrian and younger) (Koeppen *et. Al.*, 1995) and Neoproterozoic rocks in the vicinity of the Jacob's Creek Quarry, Denton, North Carolina (Koeppen, *et. al.,* 1995; Ingle *et. al.*, 2003; Hibbard *et. al.*, 2006). Paleozoic fossils were also reported from the Albemarle Group at the Martin Marietta Quarry near Asheboro, North Carolina (Koeppen, *et. al.*, 1995) and are the focus of a study by North Carolina State University Master of Science Candidate Jill Kurek.

In light of this conflicting data, three possible hypothesis were provided at the outset of study: 1) the entire mapped extent of Tillery and Cid formations is Paleozoic, on the basis of the reported fossils (Koeppen et al., 1995) and that major stratigraphic and structural reinterpretation of the Albemarle Group (Offield, 2000) is valid; 2) the Paleozoic fossils occur in limited erosional remnants of once larger basins, unconformable atop the mainly Neoproterozoic Albemarle Group. This interpretation constitutes a 'compromise' between the reported Paleozoic fossil data and the traditional stratigraphic/structural view of the Albemarle Group; 3) the reports of Paleozoic fossils in the group are erroneous and that the generally accepted stratigraphic and structural interpretation of Milton (1984) is correct.

With regard to hypothesis 1, field and facies analysis indicates a conformable and gradational contact between the Cid mudstone and Flat Swamp members. Additionally, facies associations reveal that the Cid mudstone and Flat Swamp members form part of a conformable, coarsening upward sequence, consistent with field interpretations of a conformable contact. This conformity, alone, indicates that the unnamed mudstone cannot be younger than the Flat Swamp Member, as Offield (2000) contends (Hibbard *et. al.*, 2009). Additional evidence for a Neoproterozoic age for the Cid mudstone includes the presence of *Aspidella* (Hibbard *et. al.*, 2009; Weaver *et. al.*, 2008), and geochronological data of detrital zircons analyzed from a volcanogenic sandstone collected in the Cid mudstone that provided an age range between 551 - 545 Ma (Pollock, 2007) and a U-Pb zircon age of 547 ± 2 Ma from the Flat Swamp member (Hibbard *et. al.* 2009).

With regard to hypothesis 2, detailed 1:24,000 scale field mapping was completed from the quarry, beyond North Carolina State Route 47 south of Denton, North Carolina and south into Montgomery County, adjacent to Badin Lake. No evidence of small Proterozoic outliers, such as abrupt changes in depositional regime or unconformable strata, was identified in the field area. Additionally, carbonate concretions have been reported throughout the Cid mudstone (Conley and Bain, 1965). Because the physico-chemical conditions that result in concretionary growth are reached synchronously in broad areas of a basin, the areal extent of concretion-bearing layers makes them useful tools for regional correlation (Sellés-Martínez, 1996). The presence of concretionary bodies in the Cid mudstone approximatley 30-kilometers to the south of Jacob's Creek Quarry suggests the entire unit as mapped by Stromquist and Henderson (1985) is Neoproterozoic, regionally extenisve and not confined to the quarry area.

The results of this study indicate that hypothesis 3, is the most valid alternative. It is conjectured that the samples reported to contain Paleozoic fossils could have either come from an exotic block, unrelated to the bedrock on the quarry grounds, were mistakenly mixed up with Paleozoic samples before submittal for analyses, or that there was contamination in the lab during processing of the samples (Hibbard *et. al*, 2009).

Broader Implications

The results of this study have broad implications for our understanding of the Appalachian Orogen. The nature and age of the Albemarle Group has recently been recognized as an important factor in interpreting late Neoproterozoic-early Proterozoic tectonic models (Hibbard et al., 2007). Therefore, changes to our understanding of the geological history of the Albemarle Group necessitate change to our understanding of these late Neoproterozoic-early Proterozoic tectonic models.

This study focused on the Neoproterozoic to earliest Paleozoic history of one of the largest crustal blocks in the Appalachians, Carolinia. Traditionally, the peri-Gondwanan crustal blocks of Avalonia and Carolinia have been linked as a composite terrane that accreted to Laurentia in the middle to late Paleozoic (Williams and Hatcher, 1983; Keppie and Ramos, 1999; Nance *et. al.*, 2002), implying a common geological history (Hibbard, *et. al.* 2007). However, available first-order stratigraphic, structural, metamorphic, plutonic and isotopic characteristics of the peri-Gondwanan blocks suggests Carolinia is more closely related to Ganderia than to Avalonia (Hibbard *et. al.*, 2007 and references therein). The results of this study confirm the rocks in the study area are part of a conformable sequence of mainly late Neoproterozoic age. Therefore, changes to our understanding of the geological history of the Albemarle Group are unwarranted (Hibbard, *et. al.*, 2009).

Future Research

This study reveals that the contact between the Cid mudstone and Flat Swamp members is gradational and conformable and did not identify evidence of Paleozoic outliers in the vicinity of Jacob's Creek Quarry. However, there are still unresolved questions:

1. Ediacaran fossils are known from approximately 30 localities on five continents (Narbonne, 2005). The presence of the Ediacaran fossil *Aspidella* in the quarry may indicate that other Ediacaran faunal members are present.
2. Based on field mapping, Offield (2000) proposed a thrust fault between the Tillery and Cid Formations. If true, this would require revision to our understanding of the tectonic history of the Albemarle Group.

Geographic Information System and Preparation of Geological Map

Introduction

A secondary objective of this investigation was to compile in digital and geospatial format the geological maps prepared by students working under the supervision of Dr. Hibbard in the Handy, Badin and Morrow Mountain quadrangles of North Carolina. This was completed using ESRI ArcMap 9.3 software. This section describes the methodology used and data required to complete this task.

Map Preparation

A geologic shaded relief map of the eastern Handy, Badin and Morrow Mountain quadrangles was created by direct digitization of geologic data from 1:24,000 scale paper maps. Paper maps were prepared by Dr. Jim Hibbard (Badin Quadrangle), Sonja Ingram (Morrow Mountain quadrangle) Jill Oliver (Badin Quadrangle) and Matt Brennan (Handy Quadrangle). Data gaps were filled using paper maps by Stromquist and Sundelius (1969).

Geospatial data was stored in a file geodatabase designated Brennan_Geology.gdb. A new feature dataset (Albemarle) and associated topology (Geology_topology) was created within the database to maintain geologic data. Geologic polygons were created and attributed for age, name and lithologic type. Two rules were established for topology: must not overlap and must not have gaps. Topology was checked throughout the digitizing process using the topology tool in ArcGis 9.3.

Additional geospatial data, including primary roads, secondary roads, and hillshades for Stanley, Davidson, Montgomery and Randolph Counties were obtained from the North Carolina Department of Transportation (NCDOT) geospatial data distribution web site (http://www.ncdot.org/it/gis/DataDistribution/). Surface water features were obtained from the North Carolina One Map FTP site (NConemap.com). Hillshade, road and surface water spatial data was imported and maintained in the project geodatabase. This data was obtained to supplement the aesthetics of the final geological map and was not altered for use.

The map projection used is NAD 1983 State Plane North Carolina FIPS 3200 with bounding coordinates for west, east, north and south as -80.164394, -80.005650, 35.626832, and 35.311675 degrees, respectively. Geologic polygons were draped over a shaded relief image generated from Light Detection and Ranging (LiDAR) raster files compiled by the State of North Carolina in April 2007. Cell size of the LiDAR data was 20-feet with a vertical accuracy of 10-inches.

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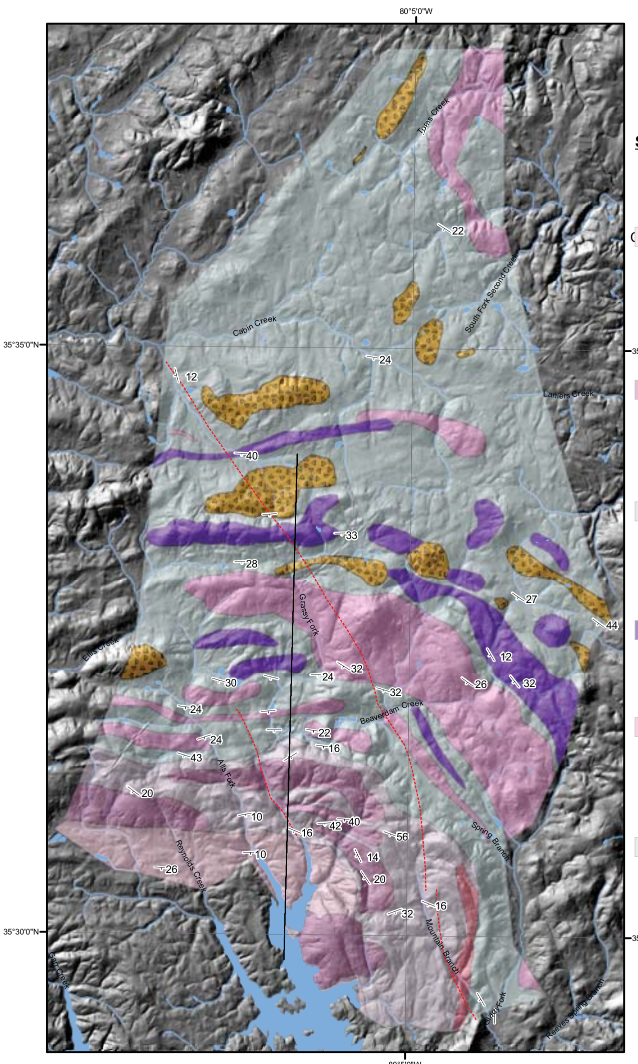
GEOLOGICAL MAPS

GEOLOGIC MAP OF JACOB'S CREEK QUARRY AND VICINITY

Matthew P. Brennan



Lithostratigraphy and Unit Descriptions

INTRUSIVE ROCKS

Psmg Stony Mountain Gabbro

SEDIMENTARY AND VOLCANICLASTIC ROCKS

FLOYD CHURCH FORMATION

mainly silty mudstone with interbeds and interlaminations of siltstone and fine-grained sandstone. The interbeds are composed mainly of quartz grains with calcite cement. Sandy-silty beds range from less than one millimeter thick to 40 - 50 centimeters thick and are internally laminated. Sedimentary structures include cross bedding, flaser, lenticular and wavy bedding indicative of bimodal current direction.

Flat Swamp Member

CZcfb Mafic volcaniclastics: Similar in appearance and composition to mafic volcaniclastic units in the underlying Cid mudstone with a higher proportion of rhyo-dacitic clasts. Otherwise rocks are greenish-gray, thinly to massively bedded, poorly to well sorted rocks with a composition of andesitic-basalt. Where present, bedding is determined by differences in grain size, with normal, reverse and multiple normal grading present. Mineralogically these rocks are comprised of albite + chlorite + actinolite + potassium feldspar + epidote + quartz ± biotite ± muscovite.

CZcf Felsic volcaniclastics: fine-grained, light gray and weather to tan and chalky white with variable amounts of quartz, feldspar and lithic fragments (<10% to 50%) less than 3mm in diameter. Geochemical analysis indicates a composition intermediate between rhyolite and rhyodacite.

Mudstone member

CZcmf Feslsic volcaniclastics: poorly to massively bedded, light gray and weather tan to chalky-white with variable amounts of quartz, feldspar and lithic fragments (<10% to 50%) with diameters between three and 20-centimeters in a fine grained groundmass. No sedimentary structures were observed.

CZcmb Mafic volcaniclastic rocks: Mafic rocks in the unnamed mudstone are greenish-gray, thinly to massively bedded, poorly to well sorted rocks with a composition of andesitic-basalt. Where present, bedding is determined by differences in grain size, with normal, reverse and multiple normal grading present. Mineralogically these rocks are comprised of albite + chlorite + actinolite + potassium feldspar + epidote + quartz ± biotite ± muscovite.

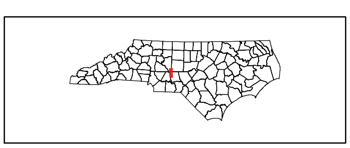
CZcm Mudstone member: The mudstone member is dominated by thinly laminated to thickly bedded, bluish gray tuffaceous argillite, mudstone, with minor fine-grained sandstone and local layers of greenish-gray coarse volcanogenic sandstone up to 30 cm thick. Gray, ellipsoidal and tabular shaped carbonate concretions are commonly found distributed along bedding planes within the mudstone layers.

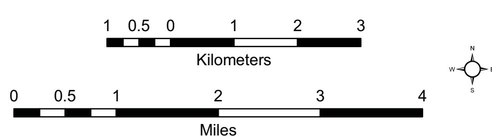
Geologic Symbols

Strike and dip of axial planar cleavage in volcaniclastics

Strike and dip of bedding

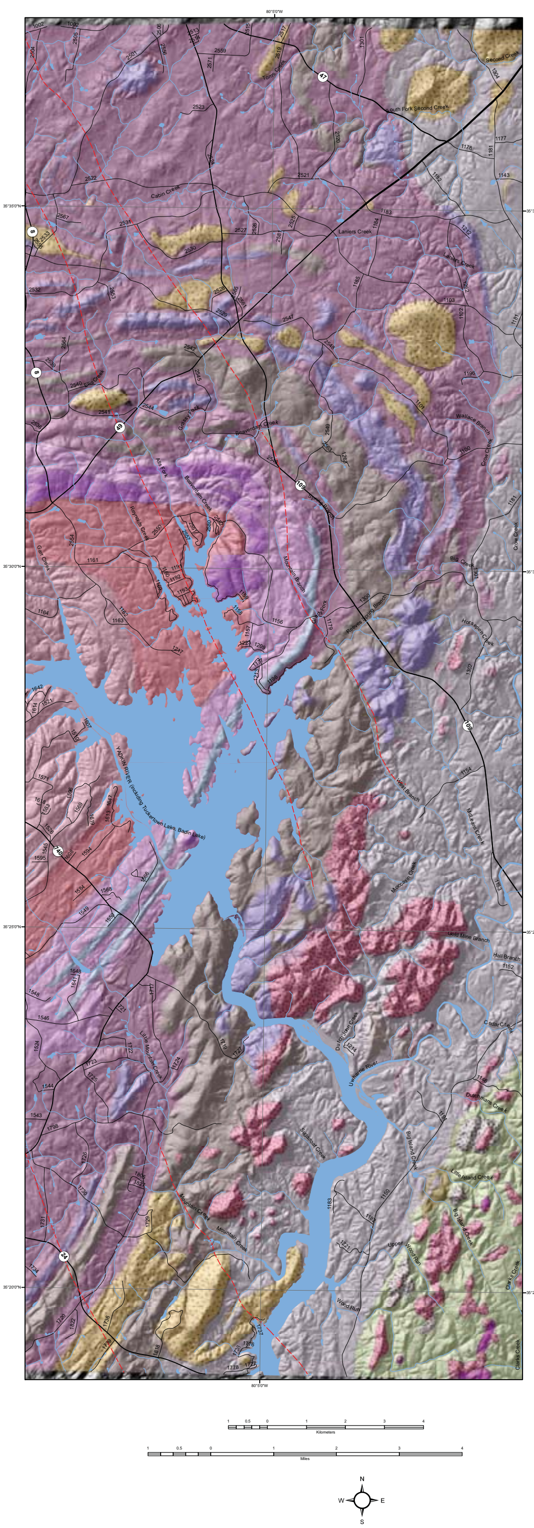
Diabase dikes





GEOLOGIC MAP OF THE BADIN LAKE REGION, CENTRAL NORTH CAROLINA

Dr. James Hibbard, Sonya Ingram, Matt Brennan, Arvid Stromquist and John Henderson.



INTRUSIVE ROCKS

Psmg — Stony Mountain gabbro

MORROW MOUNTAIN VOLCANIC COMPLEX

CZmmr — Intrusive and extrusive fine-grained black metafelsites; locally with feldspar and/or quartz phenocrysts and flow banding.

CZmmb — Felsic metabreccia: angular clasts of black aphanitic rhyolite in a groundmass of gray aphanitic rhyolite

CZmms — Lithophysae bearing metafelsites, locally with spherulitic devitrification textures.

ZUb — Extrusive dacitic breccia

SEDIMENTARY AND VOLCANICLASTIC ROCKS

YADKIN FORMATION

Cy — Poorly sorted, interbedded sequence of sands and silts.

FLOYD CHURCH FORMATION

Cfc — mainly silty mudstone with interbeds and interlaminations of siltstone and fine-grained sandstone. The interbeds are composed mainly of quartz grains with calcite cement. Sandy-silty beds range from less than one millimeter thick to 40 - 50 centimeters thick and are internally laminated. Sedimentary structures include cross bedding, flaser, lenticular and wavy bedding indicative of bimodal current direction.

Flat Swamp Member

CZcff — felsic tuffaceous breccia: contains reworked plagioclase crystals and rock fragments in a brownish matrix of shard-bearing tuff.

CZcfb — Mafic volcaniclastics: Similar in appearance and composition to mafic volcaniclastic units in the underlying Cid mudstone with a higher proportion of rhyo-dacitic clasts. Otherwise rocks are greenish-gray, thinly to massively bedded, poorly to well sorted rocks with a composition of andesitic-basalt. Where present, bedding is determined by differences in grain size, with normal, reverse and multiple normal grading present. Mineralogically these rocks are comprised of albite + chlorite + actinolite + potassium feldspar + epidote + quartz ± biotite ± muscovite.

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Mudstone member

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TILLERY FORMATION

CZtb — Tillery mafic volcaniclastic rocks.

CZtf — Felsic metavolcanics - gray felsic metavolcanic tuffs.

CZt — Gray to green, laminated to thinly-bedded, normally graded. Bedrs range from 1mm to 15cm thick. Local conglomerte units are present at the base of the Tillery Formtion and the top of the Uwharrie Formation indicating a gradational, conformable contact.

UWHARRIE FORMATION

ZUct — Volcaniclastic metaconglomerates interlayered with felsic crystal and crystal lithic tuffs.

Zu — Primarily unseparated felsic volcanic and volcaniclastic rocks. Felsic lithic tuffs, lapilli tuffs, crystal tuffs, and bedded tuffs. Local flows and mafic units associated with epiclastic rocks.