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Tectonic Studies Of Southeastern North America: The Suwannee Basin, Brunswick Suture Zone, Osceola Arc, And Pangean Transcurrent Fault System

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TECTONIC STUDIES OF SOUTHEASTERN NORTH AMERICA: THE SUWANNEE BASIN, BRUNSWICK SUTURE ZONE, OSCEOLA ARC, AND PANGEAN TRANSCURRENT FAULT SYSTEM

by

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ABSTRACT

A series of exotic terranes with complex tectonostratigraphic relationships construct the North American margin and record information critical to understanding the evolution of the Appalachian orogen. The Coastal Plain cover remains a challenge in this region; however, synthesis of seismic reflection, seismic refraction, well, and aeromagnetic data allows for a substantially revised interpretation of the basement rocks and structures that comprise the pre-Mesozoic crust of southeastern North America. These data reveal: (1) a Neoproterozoic subduction zone and paired continental-margin arc are preserved in Gondwanan crust in southeastern North America, (2) the Gondwanan Suwannee Basin of Early to Mid-Paleozoic age is much more extensive than previously thought, and (3) one of the largest faults in eastern North America, termed the Pangean Transcurrent Fault System (PTFS), transects the Alleghanian suture and crosscuts tectonic boundaries internal to Laurentian and Gondwanan crust. The revised extent of the Suwannee Basin strata provides critical new age constraints on the long-debated age and tectonic origin of the dipping reflectivity associated with the Brunswick Magnetic Anomaly (BMA). Previously thought to be the Alleghanian suture, this tectonic boundary is now documented to represent a Neoproterozoic suture zone, termed the Brunswick Suture Zone (BSZ). The geometry and location of the BSZ can be correlated with Neoproterozoic volcanic and intrusive rocks identified as the Osceola Arc. Lithological, geochemical, and geochronologic evidence suggest these igneous rocks formed in a continental margin arc along the former Gondwanan margin, and are now preserved along with their inferred subduction zone (BSZ) in the subsurface of southeastern North America. Integration of known geological constraints with aeromagnetic and seismic reflection data suggest that the BSZ, the Alleghanian suture, and other tectonic boundaries internal to the Appalachian orogen are all truncated by a regionally extensive, dextral, transcurrent fault system identified as the PTFS. This crust-scale boundary likely transects the former plate boundary between Gondwana and Laurentia and therefore, cannot represent the Alleghanian suture as previously interpreted.

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LIST OF ABBREVIATIONS

BA or BMA	Brunswick Anomaly or Brunswick Magnetic Anomaly
BSZ	Brunswick Suture Zone
BZ	Brevard Zone
COCORP	Consortium for Continental Profiling
CPS	Central Piedmont Suture
FL	Florida
GA	Georgia
MAD	Master Appalachian Decollement
PTFS	Pangean Transcurrent Fault System
SSZ	Suwannee Suture Zone

CHAPTER 1

INTRODUCTION

The southeastern North American margin has been one of the type locations for investigating how continents collide and break apart since the development of Wilson cycles by J. Tuzo Wilson (1966). However, the Coastal Plain cover and Mesozoic rift-related deformation and magmatism, create a challenging environment to identify crustal boundaries and their respective tectonic origins. To address these challenges, the three studies presented in subsequent chapters integrate a variety of datasets including seismic reflection, seismic refraction, well, and aeromagnetic data to provide spatial and temporal constraints on key tectonic boundaries preserved in southeastern North America.

This dissertation is organized into five chapters, including an introductory chapter, three core chapters, and a concluding chapter. Each of the core chapters were written as a manuscript for a peer reviewed journal. Chapter 2 was submitted to and published by *Gondwana Research*, Chapter 3 has been submitted to *Tectonics* and is currently in the review process, and Chapter 4 is intended to be submitted to *Geology*.

The first core chapter, Chapter 2, focuses on the identification and mapping of the Gondwanan early- to mid- Paleozoic Suwannee Basin sequence offshore, using seismic reflection, seismic refraction, and well data. Recognition of the Gondwanan Paleozoic

Suwannee Basin sequence in Florida, southern Georgia, and southeastern Alabama (Campbell, 1939; Applin, 1951; Wilson, 1966; Barnett, 1975; Pojeta et al., 1976; Chowns and Williams, 1983; Duncan, 1998) prompted the search in the 1980s for the Alleghanian suture and the investigation into the extent of Gondwanan continental crust preserved in southeastern North America. To our knowledge, the Suwannee Basin strata have never been mapped offshore, probably as a result of limited seismic reflection data available to the public. The relatively recent release of the once proprietary legacy industry dataset allowed for a denser coverage of the continental shelf and the mapping of the Suwannee Basin strata across the continental shelf from well control. The revised extent of the Suwannee Basin dictates a much greater extent of preserved Gondwanan continental crust in the southeastern United States and provides new constraints on the location of the Alleghanian suture.

Using the Suwannee Basin sequence as a critical age constraint, Chapter 3 investigates the tectonic origin of the dipping reflectivity observed in deep seismic reflection data and spatially associated with the Brunswick Magnetic Anomaly (BMA) (Nelson et al., 1985a, b; McBride and Nelson, 1988). Once thought to represent the Alleghanian suture, Chapter 3 redefines the dipping reflectivity associated with the BMA as the Neoproterozoic Brunswick Suture Zone (BSZ). Constraints on the age and tectonic origin of the BSZ are provided by the overlapping early- to mid- Paleozoic Suwannee Basin sequence as well as, an extensive suite of Neoproterozoic volcanic and intrusive rocks of the newly identified Osceola Arc. Integration of lithological, geochemical, and geochronologic data support the inference that the BSZ represents the subduction zone that generated the Osceola Arc magmatism along the Gondwanan continental margin in the Neoproterozoic.

Chapter 4 documents the onshore investigation and analysis of known geological and geophysical data which reveal a post-collisional, crustal-scale boundary, the Pangean Transcurrent Fault System (PTFS), that crosscuts previously identified tectonic boundaries in southeastern North America. The PTFS represents a post-collisional series of dextral-slip faults, largely including the previously recognized Eastern Piedmont Fault System (EPFS). Re-establishing the age of the PTFS as post-collisional through known geologic constraints and observations of crosscutting relationships in aeromagnetic and seismic reflection data, is in direct conflict with recently proposed tectonic models (Hatcher, 2010; Hopper et al., 2017) that suggest transcurrent faulting pre-dated head-on collision. The PTFS appears to transect the former plate boundary between Laurentia and Gondwana, and therefore does not represent the long-sought-after Alleghanian suture as previously interpreted in Alabama and Georgia.

CHAPTER 2

OFFSHORE EXTENT OF GONDWANAN PALEOZOIC STRATA IN THE SOUTHEASTERN UNITED STATES: THE SUWANNEE SUTURE ZONE REVISITED [1]

The recognition of the Suwannee terrane in southeastern North America was a critical step in advancing our current understanding of the tectonic evolution of ocean basins. Unfortunately, further clarification of the boundaries of the Suwannee terrane has proven difficult due to the thick coastal plain cover, limited well log analyses, and a paucity of seismic reflection data onshore. We present the results from a new compilation and analysis of legacy marine seismic reflection, refraction and well data from offshore the southeastern United States, which reveals in the subsurface a previously unmapped lower Paleozoic sedimentary section spanning the continental shelf from Florida to North Carolina. Previously only identified in two deep offshore wells (COST GE-1 and Transco 1005-1), this Paleozoic platform sequence is identified in seismic reflection profiles as a package of low-frequency, sub-horizontal, laterally-continuous reflectors which are clearly discordant with and distinct from the overlying Mesozoic and Cenozoic stratigraphy above the post-rift unconformity (PRU). The inferred base of the Paleozoic sequence is marked by the downward diminution of

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[1] Boote, S. K., Knapp, J. H., 2016. Offshore extent of Gondwanan Paleozoic strata in the southeastern United States: The Suwannee suture zone revisited. Gondwana Research, v. 40, p. 199-210.
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parallel seismic reflectors, as well as an increase in seismic velocities to > 6 km/s observed on numerous offshore seismic refraction surveys. While clearly deformed in some areas, these Paleozoic strata are generally sub-horizontal, range in thickness from 4 to 6 km, and can be mapped continuously over an area in excess of 130,000 km^2. Similar sedimentary rocks have been recognized from onshore exploration wells in Florida since the 1930's, and were subsequently identified to be part of the Suwannee basin within the larger exotic Suwannee terrane of Gondwanan affinity. Recognition of the presence and extent of these Gondwanan strata offshore implies: (1) the inferred position of the Suwannee suture zone offshore lies > 200 km further north, approximately along the boundary between the Carolina terrane and the Charleston terrane; (2) previously identified terranes (Brunswick, Charleston, Suwannee, Northern Florida) are likely distinct crustal blocks, but their amalgamation predates deposition of the overlying Paleozoic section of the Suwannee basin; (3) collectively, this crust represents the Gondwanan continent based on the size and presence of a stable platform stratigraphy, nominally doubling the size of the last sutured terrane, the Suwannee terrane.

2.1 INTRODUCTION

Recognition of Paleozoic strata of Gondwanan (non-Laurentian) affinity in the subsurface of southeastern North America was a critical observation leading to Wilson's (1966) seminal work on the opening and closing of ocean basins. Termed the Suwannee basin by King (1961), this sequence of early- to mid-Paleozoic strata was originally identified through extensive onshore petroleum exploration drilling during the first half of the 20th century in northern Florida, and southern Georgia and Alabama (Applin, 1951; Barnett, 1975; Fig. 2.1a). Subsequent clarification of the regional extent of the Suwannee basin and identification of the boundaries of the associated Suwannee terrane has proven difficult due to the thick coastal plain cover, limited analyses of deep well penetrations, and lack of extensive seismic reflection data onshore (Williams and Hatcher, 1983; Tauvers and Muehlberger, 1987; Horton et al, 1989; Mueller et al, 2014).

Offshore data collection initiated in the 1950s with a series of refraction profiles aiming to characterize the crustal structure of the southeastern United States Atlantic margin (Hersey et al, 1959; Sheridan et al, 1966). Following the initial refraction surveys, the United States Geological Survey (USGS) and various research cruises, completed seismic reflection and refraction surveys between the 1960s and 1980s. In the 1970s, offshore petroleum exploration accelerated data collection leading to the acquisition of the “legacy industry Atlantic margin” dataset, which included extensive 2D seismic reflection surveys, and the completion of seven exploration wells offshore the southeastern United States. Two of these seven wells reside just offshore northern Florida and drilled a similar sequence of Paleozoic strata correlated to the onshore Suwannee basin rocks (Poppe and Dillon, 1989; Poppe et al, 1995; Fig. 2.1a). After the mandatory 25 years of confidentiality, the Bureau of Ocean and Energy Management (BOEM) has recently released the Atlantic legacy industry dataset.

Integration of four decades of refraction profiles, 2-D seismic reflection surveys, including the much denser legacy dataset, in addition to well penetrations, demonstrate the presence of Paleozoic strata of inferred Suwannee basin origin across the continental shelf. The mappable extent of the Suwannee basin is limited to the continental shelf, bounded to the east by the Basement Hinge Zone (BHZ), and stretches from onshore Florida to offshore Cape Lookout, North Carolina (Fig. 2.1a).

Implications of the revised Gondwanan affinity Suwannee basin rocks offshore include (1) the inferred position of the Suwannee Suture zone is now constrained in the east to lie much further north, along the boundary between the Carolina and Charleston terranes (Figs. 2.1a and 2.1b), (2) previously identified terranes (Charleston, Brunswick, Suwannee, Northern Florida) and their inferred boundaries (e.g. Brunswick Magnetic Anomaly) may yet be distinct crustal blocks, but their amalgamation predates deposition of the overlying Paleozoic section of the Suwannee basin (Fig. 2.1b); (3) the size and presence of the Suwannee basin offshore suggests that the underlying crust represents a continuous piece of Gondwanan continental lithosphere, nominally doubling the size of the previously interpreted Suwannee terrane.

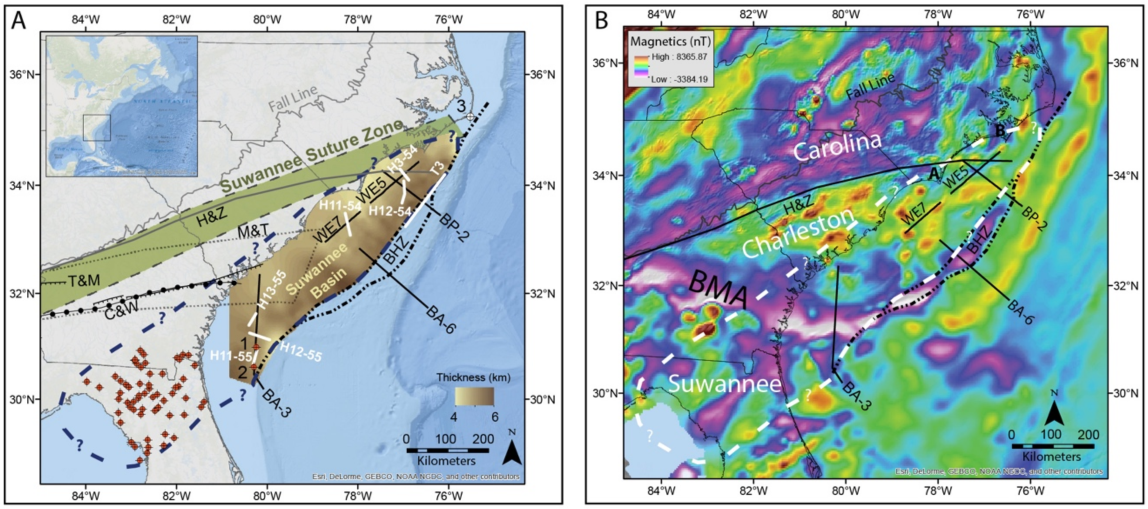

Figure 2.1: (A) Map of southeastern North America illustrating revised extent of Suwannee basin (navy dashed line), re-defined location of Suwannee suture zone, previously interpreted positions of suture, and location of data referred to in text. Isochore (brown) indicates mappable extent and thickness (4-6 km) of Suwannee basin rocks. Seismic reflection profile locations (BA-3, BA-6, WE-007-7 (WE7), WE-007-5(WE5), and BP-2) shown as black lines; refraction surveys (Hersey et al, 1959 (H) and Trehu et al, 1989 (T)) shown as white lines. Abbreviations for previous suture interpretations: C&W (Chowns and Williams, 1983); T&M (Tauvers and Muehlberger, 1987); M&T (Mueller et al, 2014; Thomas, 2010); H&Z (Higgins and Zietz, 1983). Onshore wells penetrating Suwannee basin strata in northern Florida and southern

Georgia shown by red well symbols. Offshore wells 1 (Transco 1005-1) and 2 (COST GE-1) tie to profile BA-3. Well 3 (Hatteras Light No.1) encountered granitic basement, marking the northeastern extent of identifiable Suwannee basin strata. Fall line marks western boundary of coastal plain sediments. BHZ (dot-dashed line) offshore identifies "Basement Hinge Zone" (modified after Hutchinson et al, 1995.) (B) Magnetic anomaly map (EMAG2, 2009) of southeastern North America and previously interpreted exotic terranes (Carolina, Charleston, and Suwannee). Locations of seismic reflection profiles (black) illustrated offshore as well as the revised extent of the Suwannee basin highlighted in white dashed line. Abbreviations: A - Cape Fear; B - Cape Lookout. BMA - Brunswick Magnetic Anomaly. H&Z - Carolina-Mississippi fault (Higgins and Zietz, 1983) is a dextral strike slip fault separating the Carolina Terrane and Charleston terrane previously interpreted to be the location of the Alleghanian suture.

2.1.1 Suwannee Basin

Extensive petroleum exploration in the early 1900s led to the identification of Paleozoic sedimentary rocks in the subsurface of the southeastern United States. The basin containing these Paleozoic sedimentary rocks in Florida, Georgia and Alabama was first termed the "Suwannee River Basin" by Braunstein (1957), and was later contracted to the "Suwannee basin" by King (1961). Chowns and Williams (1983) proposed to abandon the term "Suwannee basin" due to confusion with the younger and unrelated feature, the Suwannee Strait. However, other authors have continued use of the term "Suwannee basin" to identify the region that contains Paleozoic sedimentary rocks (Nelson et al, 1985; Poppe et al, 1995; Pollock et al, 2012). Therefore, this study continues use of the term "Suwannee basin" in reference to the area containing Gondwanan Paleozoic sedimentary strata, highlighted by the onshore well penetrations in Figure. 1.

The Suwannee basin Paleozoic strata are lithologically and faunally distinct from equivalent-age sequences in the Appalachian foreland and correlated to similar age sedimentary rocks and faunal assemblages in the conjugate West African basins (Wilson, 1966; Arden, 1974; Dillon and Sougy, 1974; Barnett, 1975; Pojeta et al, 1976; Poppe et al, 1995). Subsequent dating of detrital zircons from the Suwannee basin sedimentary rocks revealed ages of typical Gondwanan orogenic events, generally not observed in southeastern Laurentian zircon records (Mueller et al, 1994; Mueller et al, 2014).

The Paleozoic strata consist of Lower Ordovician quartzites and Middle Ordovician to Middle Devonian fossiliferous shales and sandstones overlying a complex terrain of pre-Cambrian felsic volcanic and intrusive rocks (Applin, 1951; Barnett, 1975; Chowns and Williams, 1983). Using seismic refraction, reflection, and gravity data, the thickness of the Paleozoic strata onshore is estimated to be 2.5-3 km, however onshore wells have only penetrated the upper ~600 m of the sedimentary sequence (Arden, 1974; Chowns and Williams, 1983; Thomas et al, 1989; Pollock et al, 2012). The Paleozoic sedimentary rocks represent a typical continental platform sequence with a mixed source of continental derived sands and marine muds, suggesting that the Suwannee basin was deposited on Gondwanan continental crust (Duncan, 1998; Arden, 1974).

Scientists have previously used the mappable extent of Suwannee basin Paleozoic rocks and associated Gondwanan affinity basement onshore to help delineate the boundaries of the associated Suwannee terrane. Similar methods using well and seismic reflection data offshore could provide additional constraints on the boundaries of the Suwannee terrane. Paleozoic strata penetrated by two offshore wells, Transco 1005-1 and Continental Offshore Stratigraphic Test (COST) Georgia (GE)-1, have previously been correlated to the onshore Suwannee basin rocks but never rigorously integrated with seismic reflection and refraction data offshore to better constrain the boundaries of the Suwannee terrane and eastern location of the Alleghanian suture. Pre-rift, layered reflections were recognized below the PRU and suggested to be Paleozoic sedimentary and meta-sedimentary rocks and/or layered Paleozoic volcanic rocks along reflections lines acquired in the 1970s-1980s by the United States Geological Survey (USGS) and the University of Texas Institute of Geophysics (UTIG) (Dillon and Popenoe, 1988; Austin et al, 1990; Lizarralde et al, 1994). This layered sequence was commonly lumped into the generalized description of basement or layered basement without characterizing the extent or the implications of the proposed Paleozoic layered sequence. The overlooked significance of this pre-rift section was at least partially a result of the sparse public domain dataset.

Introduction of the legacy Atlantic margin industry dataset provides denser seismic reflection coverage of the continental shelf with surveys that tie directly to the well penetrations. However, analysis of the seismic reflection data is limited to the shelf west of the basement hinge zone (BHZ). The BHZ is a previously recognized structural boundary that stretches from offshore Florida northward along the entire eastern coast of the United States (Sheridan, 1974; Hutchinson et al, 1995). Thought to be associated with significant extensional structures, the BHZ and associated structural complexity limits the current mappable extent of Suwannee basin rocks seaward. Nevertheless, the integration of the legacy marine seismic data set, well data, and previously acquired seismic reflection and refraction data, provides more coverage of the continental shelf than ever before, allowing the Suwannee basin rocks to be mapped offshore.

2.1.2 Terrane Boundaries

Numerous studies used various geophysical and geological data to characterize and define the boundaries of the exotic terranes that make up the eastern North American Atlantic margin. A succession of collisional events culminating in the final Alleghanian orogeny in the Late Paleozoic time involved the accretion of several arc and Peri-Gondwanan terranes (e.g. Carolina terrane; Fig. 2.1b) as well the Gondwanan continent.

Using a combination of stratigraphic and geophysical analyses, Williams and Hatcher (1982) first identified a series of “suspect” terranes sutured to the Laurentian margin. In the southeast, two key terranes were defined by their potential field signature as the Tallahassee/Suwannee and Brunswick terranes (Williams and Hatcher, 1982). Subsequently, Higgins and Zietz (1983) identified, the “Northern Florida terrane” and the “Charleston terrane”, based primarily on their magnetic anomaly signature. Due to using similar datasets to define terrane boundaries, the Northern Florida terrane (Higgins and Zietz, 1983) and Tallahassee/Suwannee terrane (Williams and Hatcher, 1982) have nearly identical boundaries. This is also the case for the differentiated Brunswick and Charleston terranes; therefore, we recognize the need to clarify the terminology used in this paper.

Herein referred to as the Suwannee and Charleston terranes, each terrane can be recognized by their magnetic signature and the two are separated by a strong magnetic low (Fig. 2.1b). The magnetic low was originally termed the Altamaha Magnetic Low (Higgins and Zietz, 1983), but is now referred to as the Brunswick Magnetic Anomaly (BMA). The BMA trends relatively north-south offshore North Carolina and South Carolina and then swings nearly due west onshore in southern Georgia (Fig. 2.1b). The Charleston terrane has a low frequency and high amplitude magnetic signature that is distinctly different from its southern and eastern boundary, the BMA, and distinctly more positive than its northern and western boundary, the Carolina terrane (Williams and Hatcher, 1982; Higgins and Zietz, 1983; Fig. 2.1b). The high frequency, high amplitude pattern associated with the Suwannee terrane also contrasts with the strong negative anomaly of the BMA (Williams and Hatcher, 1982; Higgins and Zietz, 1983; Fig. 2.1b).

Thomas and others (1989) further defined the Suwannee terrane as the terrane south of the "Suwannee-Wiggins" suture that separates Gondwanan affinity basement rocks from Piedmont-type basement rocks (Chowns and Williams, 1983; Thomas et al, 1989; Lizarralde et al, 1994). Based on the definition provided by previous authors, we use the term "Suwannee terrane" to define the last terrane sutured onto Laurentia during the Alleghanian that hosts the Suwannee basin rocks overlying Gondwanan affinity basement.

While identifiable on a magnetic anomaly map, the boundaries of the Charleston terrane are more obscure when looking at lithologic data. We prefer the term "Charleston terrane" that is defined solely on magnetic signature for the following reasons: (1) Suwannee basin rocks have been identified north of the BMA, (2) U/Pb dating of zircons within Neoproterozoic granites of the Charleston terrane are consistent with being derived from Suwannee terrane basement (although not deterministic) (Mueller et al, 2014) and, (3) while distinct in magnetic signature, Higgins and Zietz (1983) suggests that the Charleston and Suwannee terranes are virtually identical in lithology and age, further complicating the definition of terrane boundaries. The boundaries between the collage of exotic terranes and the Laurentian margin has proven difficult; however, by determining the extent of the Suwannee basin rocks offshore we provide additional constraints on the relationship between the Suwannee and Charleston terranes and ultimately the boundaries of the last sutured geologic terrane.

2.1.3 Previous Alleghanian Suture Interpretations

The Alleghanian suture in southeastern North America separates rocks of Laurentian and Carolina terrane affinity from rocks of Gondwanan affinity involved in late Paleozoic continental collision during the formation of the supercontinent Pangea. Many of the same studies that sought to define the exotic terrane boundaries also proposed locations for the Alleghanian suture using a variety of geophysical and geological data. Current interpretations for the suture are relatively well constrained in western Georgia and Alabama, however, interpretations of the eastward continuation of the suture range from offshore Georgia to North Carolina (Figs. 2.1a and 2.1b).

Previous interpretations of the position of the suture were primarily, if not solely, based on onshore data. Using aeromagnetic data, Higgins and Zietz (1983) first proposed that the Alleghanian suture resides along the northern boundary of the Charleston terrane as a NE-SW dextral strike-slip fault, which they termed the Carolina-Mississippi fault (Figs. 2.1a and 2.1b). Simultaneously, Chowns and Williams (1983) mapped the subsurface extent of Gondwanan sedimentary rocks from drill holes and suggested a more southerly location for the suture in Georgia, between Savannah and Charleston (Fig. 2.1; C&W). Using deep seismic reflection data from the Consortium for Continental Reflection Profiling (COCORP) program, Nelson and others (1985) correlated the Alleghanian suture with a series of southward-dipping, crustal-scale reflections and diffractions, pinning one location of the probable suture in western Georgia that also happens to coincide with the Brunswick Magnetic Anomaly.

Multiple authors have suggested that the BMA most closely defines the Alleghanian suture even though Suwannee basin rocks are found north of the anomaly onshore

(McBride et al, 2005; Horton et al, 1989; Tauvers and Muehlberger, 1987; Fig. 2.1b). The origin of the BMA has remained elusive and in 1988 the University of Texas Institute of Geophysics (UTIG) collected the BA (Brunswick Anomaly) multichannel seismic reflection profiles and refraction data offshore to characterize the boundary as either a terrane boundary or the result of Mesozoic extension. Subsequent studies using the BA survey ultimately determined the BMA was an unlikely candidate for the Alleghanian suture (Austin et al, 1990; Oh et al, 1991; Holbrook et al, 1994; Lizarralde et al, 1994).

More recent workers propose the Alleghanian suture is not a vertical boundary but is probably a zone. More specifically, Thomas (2010) suggested that the suture is a wide zone of crustal-scale lithons and mylonites similarly described by the "Suwannee-Wiggins" suture of Thomas and others (1989). The latest Alleghanian suture interpretation is referred to as the "Suwannee suture zone" (Tauvers and Muehlberger, 1987; Thomas, 2010; Mueller et al, 2014; Fig. 2.1; M&T), which this study uses interchangeably with the "Alleghanian suture". The Suwannee suture zone defined by Mueller and others (2014) and modified from Thomas (2010) overlies the crustal scale dipping reflections identified in the COCORP profiles by Nelson et al, (1985) and suits the proposed Paleozoic dextral strike-slip stress regime of Hatcher (2010). The suture zone is largely coincident with the BMA, but can reconcile the fact that Paleozoic Suwannee basin rocks are found north of the prominent magnetic low onshore. Mueller et al, (2014) were able to show that Suwannee basin rocks in southeastern Georgia have detrital zircon ages consistent with typical Gondwanan ages that strongly support an exclusive Gondwanan provenance, constraining the suture zone north of those well locations. Further analyses on zircons from crystalline rocks in Alabama and central

Georgia, interpreted to be a part of the Suwannee suture zone, further pinned the probable western location of the Alleghanian suture. However, the eastern location of the Alleghanian suture is limited to the Suwannee basin rocks in southeastern Georgia and there is little to no geologic evidence constraining the suture between Georgia and North Carolina.

The mappable extent of the Suwannee basin has been an important constraint onshore for determining the position of the Suwannee suture zone. This study provides further insight into the location of the Alleghanian suture by rigorously integrating a denser array of previously unpublished offshore seismic reflection (legacy Atlantic margin dataset), refraction, and well data. By determining the extent of the Suwannee basin rocks offshore, we provide constraints on the boundaries of the last sutured terrane, the Suwannee terrane, and the location of the Alleghanian suture.

2.2 DATA

The Atlantic continental margin of the United States has been the focus of marine geophysical surveys for decades. Starting in the 1950s, extensive datasets were collected offshore the southeastern United States Atlantic margin including well data, 2D seismic reflection, and refraction data. Some of the earliest marine geophysical surveys collected offshore the southeastern United States were a series of seismic refraction surveys designed to evaluate the crustal structure of the Atlantic margin and continental shelf (Hersey et al, 1959; Sheridan et al, 1966).

Beginning in the early 1970s, the USGS and other various research efforts collected crustal scale seismic reflection surveys and refraction data, including the 1988 BA (Brunswick Anomaly) survey collected by University of Texas Geophysical Institute

(UTIG) that sought to define the source of the BMA. However, the densest reflection surveys collected on the margin resulted from the single period of U.S. Atlantic offshore petroleum exploration in the late 1960’s and 1980’s. A total of 51 wells (46 industry wells and 5 Continental Offshore Stratigraphic Tests) were drilled and about 240,000 miles of 2D seismic reflection profiles were acquired. The BOEM recently released this once proprietary data to the public domain, completing the mandatory 25 years of confidentiality after acquisition for the relevant surveys. We have obtained the never before published digital reflection data and well logs from the BOEM and created a database to provide a denser coverage of data along the United States Atlantic margin.

2.2.1 Seismic Refraction Data

Seismic refraction data collected along the continental shelf between Florida and North Carolina provide independent velocity constraints and important insight into the geology of the margin. The first series of marine geophysical refraction surveys conducted in the 1950’s (Hersey et al, 1959; Sheridan et al, 1966) explored the geologic structure of the submerged continental margin. Hersey et al, (1959) used two sets of data; the first included a series of 15 profiles collected by Dietz and Hersey in 1954 and the second set of data totaled 24 refraction profiles collected by Wyrick and Nafe of the Lamont Geological Observatory in 1955. The 1955 profiles are reversed and both sets of profiles have apertures at least 25 km wide. While the 1954 profiles are unreversed, they do have a wide enough aperture to image the high-velocity boundary at the base of the Coastal Plain sequence.

The study of Hersey and others (1959) provides layer thicknesses and velocities for individual Mesozoic and Cenozoic post-rift sequences as well as the depth and velocity at the inferred basement contact which they interpreted to be granite. Six of these profiles (H11-54, H12-54, H3-54, H11-55, H12-55; H13-55; Fig. 2.1a) provide independent velocity and depth constraints on the seismic reflection interpretations in this study. Using the measurements and calculations from Hersey et al, 1959, we converted layer thickness using measured velocity back to depth in two-way travel time (TWTT) in order to quality check the reflection data interpretations.

A large offset refraction profile, Line 3 (T3; Fig. 2.1a), from the Trehu et al, (1989) study constrains the depth to the crystalline basement contact offshore North Carolina. Based on onshore observations in Florida, crystalline basement includes felsic volcanic rocks, volcanic clastic sedimentary rocks, and granite. This line was originally collected to target the transition from continental to oceanic crust and therefore has an aperture of ~115 km, sufficient to image depths of greater than 25km. T3 provides information on velocity changes in the deeper crust, not imaged by the Hersey et al, (1959) study (Trehu et al, 1989). T3 intersects one of the reflection profiles presented in this study (BP-2) and provides independent velocity and depth control. It is important to note that while acquiring T3 they were only able to shoot from either end due to permitting issues.

Refraction data collected during the 1988 UTIG BA survey and published in the early 1990s provides additional velocity and thickness constraints (Lizarralde et al, 1995; Holbrook et al, 1994). The survey used 32 ocean-bottom seismometer/ocean bottom hydrophone (OBS/OBH) instruments, with the majority deployed along BA-3 and BA-6. Holbrook et al, (1994) and Lizarralde et al, (1994) created two velocity models using the OBS/OBH data for BA-6 and BA-3 respectively, that demonstrate the major velocity boundaries and thicknesses of associated layers. The two velocity models, in combination with interpretations from the seismic reflection data, as well as independent velocity measurements (Hersey et al, 1959), provide a robust analysis of the thickness of interpreted Suwannee Basin rocks along the BA profiles.

2.2.2 Seismic Reflection Data

Extensive marine seismic reflection surveys for both research and commercial purposes were collected on the southeast Atlantic margin beginning in the late 1960's. Many of the commercial surveys were acquired in support of oil and gas exploration efforts during the 1970's and early 1980's, but were held as proprietary data until the requisite 25-year moratorium expired. Subsurface mapping of the post-rift unconformity (PRU) and the underlying stratigraphy used a series of overlapping 2-D seismic reflection surveys from offshore Florida to North Carolina. This study used eight independently acquired seismic reflection surveys totaling over 150,000 km of 2-D reflection profiles along the southeastern continental margin. Seven of the reflection surveys are from the previously unpublished Atlantic margin legacy dataset. The two crustal scale profiles are from the BA survey. The two legacy dataset surveys presented in this paper include the WE profiles and BP profiles collected during exploration in 1975. While the conclusions derive from interpretation of the entire dataset, representative seismic reflection profiles are presented to illustrate the primary conclusions (Figure.1).

Three reflection profiles presented in this study, WE-007-7 (WE7), WE-007-5 (WE5), and BP-2, provide constraints on the lateral extent and width of the Suwannee basin. Limited information is available about the acquisition and processing of these surveys. The WE survey was recorded to 5 s TWTT, sufficient to image the upper ~10 km of the crust on the shelf. Profiles WE7 and WE5 constitute a SW-NE transect, sub-parallel to the coast between Charleston and Cape Lookout (Fig. 2.1a). The combination of these two profiles provides constraints on the northern extent of the mappable inferred Suwannee basin rocks. Refraction profiles H11-54 and H3-54 intersect the WE7 and WE5 respectively, providing independent depth and velocity control.

To provide constraints on the mappable width of the Suwannee basin strata, we used profile BP-2 from a separate legacy industry survey that ties directly to WE5 (Fig. 2.1a). The BP survey has record lengths of around 7 s TWTT and can sufficiently image mid crustal depths. BP-2 intersects two independent refraction profiles H12-54 and T3, providing important velocity and depth information constraining the reflection profile interpretations.

In addition to the industry surveys, two crustal scale profiles from the BA (Brunswick Anomaly) survey provide important constraints on the presence, thickness, and width of Suwannee basin rocks. The BA survey collected by UTIG in 1988 includes a series of six crustal-scale (16 s TWTT) integrated reflection and refraction profiles collected in an effort to characterize the origin of the BMA. Profiles BA-3 and BA-6 both have record lengths of 16 s TWTT and are presented as 240 fold and 60 fold stacks respectively that have previously been described by Austin et al, (1990), Oh et al, (1991), Holbrook et al, (1994), and Lizarralde et al, (1994).

Profile BA-3 is ~250 km long and reaches from offshore Charleston harbor to offshore northern Florida. BA-3 is the only profile where we have well penetrations, two separate refraction surveys (BA survey and H11-55, H12-55, H13-55), and a crustal scale reflection profile that can be integrated to characterize the Paleozoic strata.

Profile BA-6 lies ~150 km offshore southeast of the South Carolina-North Carolina border and stretches perpendicularly from the continental shelf to the abyssal plain. BA-6 is approximately 190 km long however, this study focuses updip in the first 50-100km. The BA reflection profiles and associated velocity models discussed previously provide important lateral and thickness constraints on the interpreted Paleozoic strata.

2.2.3 Offshore Well Data

Two deep offshore wells provide stratigraphic constraints for the rocks below the PRU. The COST GE-1 and Transco 1005-1 wells are two of seven wells drilled in the late 1970's as part of a phase of oil and gas exploration on the southeast United States Atlantic margin; both penetrated the PRU into Paleozoic sedimentary rocks (Dillon and Popenoe, 1988; Poppe and Dillon, 1989; Poppe et al, 1995). A combination of published literature, and proprietary well logs and reports obtained from the BOEM and National Center for Environmental Information (NCEI) respectively, provide important lithologic and age constraints for the COST GE-1 and Transco 1005-1 wells.

The COST GE-1 well was drilled in 1977 as part of the Continental Offshore Stratigraphic Test (COST) program of the USGS, and was summarized by Scholle (1979). This well penetrated the PRU at ~11,050 ft (~3,368 m), encountered ~ 2,204 ft (~672 m) of presumed Paleozoic sedimentary strata, and bottomed at a total depth (TD) of 13,254 ft (~4,039 m) (Scholle, 1979; Poppe et al, 1995; Fig. 2.2). The top of the

Paleozoic section consists of partly fossiliferous quartzite, shale, and slate, underlain by metasedimentary and metavolcanic rocks (Scholle, 1979). This well exhibits some low-grade metamorphism in the Paleozoic section compared to the un-metamorphosed onshore Suwannee basin penetrations; however, there is also evidence for significant Mesozoic intrusive activity post-dating the deposition of this sequence and resulting in some of the metamorphic signature observed. The average interval velocity for the lower 2,000 ft (~610 m) of Paleozoic rocks is calculated to be ~5.7 km/s (Scholle, 1979). The entire Paleozoic section below the unconformity lacks paleontological evidence to constrain its age. Seven whole rock samples collected from 3,429 m to TD yielded a Rb-Sr isochron age of 363 ± 7 Ma and K-Ar ages ranging between 346-374 Ma (Scholle, 1979; Poppe et al., 1995). Given the inherent problems with whole-rock K-Ar and Rb-Sr ages, we argue that these likely represent minima. Thus, the COST GE-1 well appears to penetrate ~672 m (~2,204 ft) of Devonian (or potentially older) strata beneath the PRU.

The Transco 1005-1 well, drilled in 1979, resides ~50 km north of the COST GE-1 well. The Transco 1005-1 well encountered the PRU at a depth of ~8,750 ft (2,667 m), continued through 2,885 ft (879 m) of Paleozoic sedimentary rocks, and bottomed at a TD of 11,635 ft (3,546 m) (Dillon and Popenoe, 1988; Poppe and Dillon, 1989; Poppe et al, 1995; Fig. 2.2). The Paleozoic section in the Transco well is predominately quartzite with some interbedded sections of shale and argillite. Palynological analysis in the Transco well report identified the section from ~8,750 - 9,900 ft (2,667 – 3,018 m) to be Silurian in age, and the lowermost section from ~9,900 - 11,635 ft (3,018 – 3,546 m) to be early

Ordovician in age (Poppe and Dillon, 1989), constituting a total thickness of lower Paleozoic strata in the Transco 1005-1 well of 879 m (~ 2,885 ft.)

Although the Paleozoic rocks in the COST GE-1 and Transco 1005-1 wells have previously been correlated with the Suwannee basin strata onshore (Poppe and Dillon, 1989; Poppe, et al, 1995), they have not been tied directly by seismic reflection data. The two wells are located ~120 km offshore, near the Florida-Hatteras Escarpment, and are ~145-160 km from the nearest onshore penetration of Paleozoic strata (Fig. 2.1a). Marine seismic reflection data come no closer than 30 km to the shoreline, due in part to the shallow water depths on the shelf. Despite the lack of a direct seismic tie to the Suwannee basin strata, the offshore Paleozoic strata (1) are lithologically similar, (2) occupy a similar stratigraphic and structural position beneath the PRU, and (3) lie along the northeastward projection of the Suwannee basin strata onshore.

2.3 RESULTS

Integration of the legacy Atlantic margin seismic reflection dataset with crustal scale seismic reflection, refraction and well data introduces a denser coverage of data along the southeastern Atlantic margin. Analysis of the data reveals a 4-6 km (1.5-2.0 s TWTT) thick sequence of Paleozoic strata below the PRU that can be mapped throughout the continental shelf, east of the BHZ, from Florida to North Carolina, and is interpreted as the continuation of the Suwannee basin from onshore Florida.

The Transco 1005-1 and COST GE-1 wells penetrate a 672 - 879 m sequence of Paleozoic sedimentary rocks correlated to the onshore Suwannee basin rocks based on similar age and lithology (Poppe and Dillon, 1989; Poppe et al, 1995). The two wells provide lithologic and age constraints for the offshore Suwannee basin strata and tie directly to seismic reflection profile BA-3, constraining the reflection picks of the PRU and depth to Suwannee basin rocks (Fig. 2.4). Crustal scale profiles BA-3 and BA-6 (Figs. 2.3 and 2.4) with accompanying velocity models demonstrate a 1.5-2.0 s TWTT package of reflectivity and 4-6 km thick package of high velocity material below the PRU. This section is interpreted as the Paleozoic sedimentary and metasedimentary sequence, in agreement with interpretations from Lizarralde et al, (1994) and Holbrook et al, (1994).

Overlapping surveys of seismic reflection data provide a direct tie from the well penetrations along BA-3 across the continental shelf and allow for continuous mapping of the Suwannee basin sequence. Seismic refraction data supplies independent velocity control at the PRU and for the top of crystalline basement contact (generally accepted to have a velocity of > 6 km/s) away from the well penetrations. While the Paleozoic strata have previously been recognized offshore (Scholle, 1979; Holbrook et al, 1994; Lizarralde et al, 1994; Poppe et al, 1995), the denser coverage area provided by the legacy industry data allows us to map the Paleozoic Suwannee basin rocks across the continental shelf to offshore Cape Lookout, North Carolina.

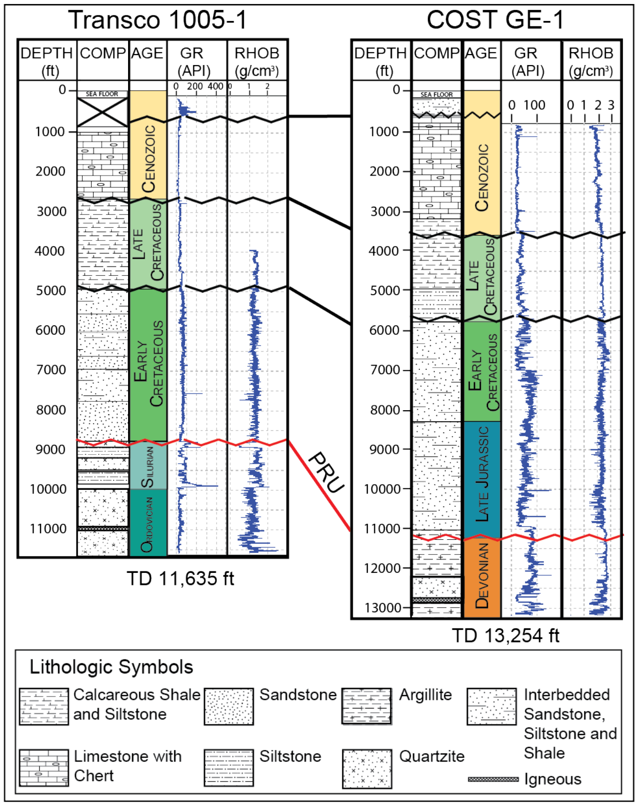

Figure 2.2: Well correlation illustrating lithology, major unconformities, and associated well logs of gamma ray (GR) and density (RHOB) for Transco 1005-1 and COST GE-1 (modified from Poppe et al, 1995). Inset of lithologic key below well sections. The PRU is highlighted near base of wells illustrating change from overlying Mesozoic sequence to underlying Paleozoic sedimentary and meta-sedimentary rocks. Note the Devonian age in the COST GE-1 well is a minimum age constraint.

2.3.1 Thickness of Suwannee Basin Rocks on Continental Shelf

The preserved thickness of the Suwannee basin strata is best constrained where there are coincident seismic reflection, seismic refraction and well data. BA-3 directly ties to the Paleozoic sedimentary rocks identified in the Transco 1005-1 and COST GE-1 wells. Integration of well data, independent refraction surveys from Hersey et al, (1959), and the Lizarralde et al, (1994) velocity model associated with profile BA-3 allow us to identify the geophysical signature of the Suwannee basin rocks to be traced across the continental shelf. The combined velocity model and reflection profile along BA-6 demonstrates the consistency in both velocity and thickness of Suwannee basin rocks away from well control. Interpretation of profiles BA-3 and BA-6 reveal a ~1.5-2.0 s TWTT thick package of reflectivity or 4-6 km thick package of Suwannee Basin rocks below the PRU (Fig. 2.3, 2.4).

The Transco 1005-1 and COST GE-1 wells tie directly to the BA-3 profile where the PRU was picked using lithology reports and noticeable excursions in gamma ray, density, spontaneous potential, and resistivity logs and is consistent with Poppe and others (1995) well log correlations (Fig. 2.2, 2.3b). Illustrated in Fig. 2.3b, the PRU updip (north) resides at about 1 s TWTT and dips towards the south as a strong, continuous reflector to ~3 s TWTT, which is in agreement with Lizarralde and others (1994) interpretation. Across profile BA-3 there is a ~1.1 s TWTT thick section of relatively high amplitude, low frequency, continuous, sub-horizontal reflectors updip of the BHZ and below the PRU, with few localized areas of disturbance. The appearance of an additional 0.3-0.5 s TWTT thick section of lower amplitude layered reflectivity suggests that the full thickness of layered Paleozoic strata is around 1.4 - 1.6 s TWTT. The base of this section, which is also the inferred top of crystalline basement, is picked at about 2.5 s TWTT on the north end of the profile and dips gently towards the offshore. This section of sub-horizontal reflectivity directly ties to the unmetamorphosed to greenschist facies Paleozoic sedimentary rocks in the two wells and agrees with the interpretation by Lizarralde and others (1994) that the upper section of "basement" along BA-3 is layered

Paleozoic sedimentary and meta-sedimentary rocks.

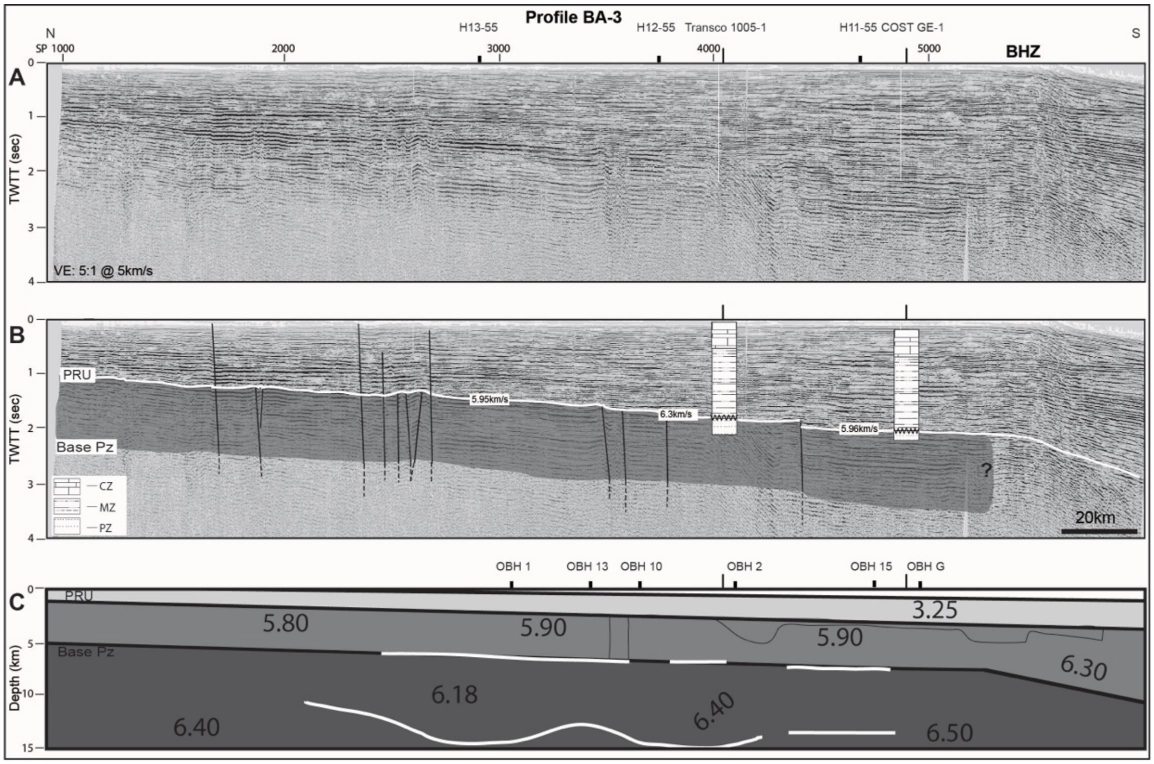

Figure 2.3: Uninterpreted (A) and interpreted (B) multi-channel seismic (MCS) reflection profile BA-3 from BA survey (UTIG, 1988). Profile is ~255 km long and shows upper ~4 seconds TWTT at a 5:1 vertical exaggeration. Shot points, well locations, and refraction survey locations annotated above. (B) Post-rift unconformity (PRU), interpreted base of Paleozoic strata (Base PZ), and simplified wells are illustrated. Velocities from refraction surveys (H13-55, H12-55, and H11-55; Hersey et al, 1959) are indicated. Basement hinge zone (BHZ) at SP 5500 limits interpretation of Paleozoic strata towards the southeast. (C) Upper 15 km of velocity model and locations of ocean-bottom hydrophone (OBH) instruments modified after Lizarralde et al, (1994.) The 4 km thick high velocity layer below PRU is interpreted to be the Paleozoic sedimentary and meta-sedimentary rocks with a change to > 6 km/s indicating inferred crystalline basement contact at the base of the Paleozoic section.

The velocity model created for profile BA-3 by Lizarralde et al, (1994) reveals a ~4km thick, high velocity section below the PRU (Fig. 2.3c). Velocities in this section range from 5.8-5.9 km/s with a basal velocity change to > 6 km/ s, interpreted to be the contact between layered Paleozoic sedimentary rocks and crystalline basement respectively. The velocities of the inferred Paleozoic sedimentary sequence in the velocity model are consistent with both the calculated interval velocity of 5.7 km/s for the basal section of Paleozoic sedimentary rocks from the COST GE-1 well (Scholle, 1979) as well as the velocities from independent refraction profiles from the Hersey et al, (1959) study.

Refraction profiles H11-55, H12-55, and H13-55 demonstrate a significant increase in velocity at the PRU, consistent with the BA-3 velocity model. Although Hersey et al, (1959) previously interpreted the high velocity layer at the PRU as the basement contact of inferred granite; we suggest that this is actually the contact between high velocity Suwannee basin sedimentary and metasedimentary rocks and overlying Mesozoic sequence.

Using layer thickness and velocity, the depth in TWTT was calculated for the high velocity refractor for all three refraction profiles (H11-55, H12-55, and H13-55). In all three cases, the high velocity refractor was calculated to reside along the PRU, providing an independent quality check on our reflection data interpretations. For example, calculations for the southernmost profile H11-55 suggest the refractor with a velocity of 5.96 km/s is located around 1.7 s TWTT on BA-3 and the PRU is picked using the reflection data at the same location around 2 s TWTT (Fig. 2.3b).

The northern-most profile H13-55 has a calculated velocity of 5.95 km/s at the interpreted PRU, which is also consistent with the BA-3 velocity model. The central profile H12-55 implies a much higher velocity just north of the Transco 1005-1 of 6.3 km/s at the PRU. However, H12-55 is sandwiched between H11-55 and H13-55, which both demonstrate velocities of < 6 km/s at the PRU. Additionally, the two well penetrations into Paleozoic sedimentary rocks tied to continuous packages of layered reflectivity below the PRU suggest that there is a continuous package of Paleozoic sedimentary rocks across profile BA-3. These observations imply that the H12-55 higher velocity measurement (6.3 km/s) may be associated with localized deformation or an anomalous measurement.

The Paleozoic sedimentary section is relatively uniform in velocity, thickness, and reflection character across profile BA-3; however, Crutcher (1983) and Poppe and others (1995) previously have documented deformation below the PRU where the Transco 1005-1 penetrates the Paleozoic strata. At this location, there is a series of more steeply dipping reflections that were interpreted to be a Mesozoic extensional basin (Crutcher, 1983; Poppe et al, 1995). While there could be alternative interpretations for this structure, it is important to highlight that there are localized areas of deformation within the Paleozoic strata (confirmed by the well penetration) bordered by undeformed, sub-horizontal Gondwanan strata, providing evidence that the package of reflectivity below the PRU represents true stratified material and not a series of multiples.

The interpreted Suwannee basin rocks across BA-3 are limited to the east by the BHZ around shotpoint (SP) 5500. The BHZ is interpreted to be a fundamental boundary altered by significant extensional structures that can be mapped from offshore Florida to offshore Cape Hatteras, NC (Sheridan, 1974; Hutchinson, 1995). The nature of the BHZ results in significant diffractions in the seismic data associated with the structures as well as substantial modification of the basement and pre-rift strata. While it may be possible to identify pre-rift Paleozoic strata down dip of the BHZ, the lack of deep well penetrations below the unconformity make the tie to the continental shelf more difficult.

Due to the structural complexity associated with the BHZ, we focus updip of this boundary where we can identify thick packages of sub-horizontal reflectivity that is tied to well penetrations of established Paleozoic sedimentary rocks.

Interpretation of BA-6 presented in Figure. 4, demonstrates that the Paleozoic strata remain relatively constant thickness across the margin with the identification of a similar ~2 s TWTT thick sequence of reflectivity below the PRU, limited to the east by the BHZ. Along profile BA-6 the PRU dips towards the southeast starting at about 1.5 s TWTT (Fig. 2.4b), consistent with previous interpretations (Austin et al, 1990; Oh et al, 1991; Holbrook et al, 1992, 1994). Although we only have published images of the original BA-6 profile, a 2 s TWTT thick section of layered reflectivity can be observed below the PRU which correlates to the 4-6 km thick section of high velocity material below the PRU in the velocity model created by Holbrook and others (1994). The package below the PRU updip of the BHZ has a range in velocity from 5.5 – 5.9 km/s and a density of 2420 kg/m^3 that was previously interpreted to be pre-rift, metasedimentary rocks (Holbrook et al, 1994). This 4 – 6 km thick high velocity section correlates to the layered reflectivity observed along BA-6 and is the inferred Suwannee basin sequence, consistent with profile BA-3.

2.3.2 Mappable Extent of the Suwannee Basin

The mappable extent of Suwannee basin rocks constrains the boundaries of the associated Suwannee terrane, consequently providing insight into the eastern location of the Alleghanian suture. The definition of the Alleghanian suture is the boundary between the Suwannee terrane and the previously accreted terranes and/or the Laurentian margin rocks; therefore, the lateral extent of the Suwannee basin towards the northeast defines the southernmost possible location for the Suwannee suture zone offshore the continental shelf of North Carolina.

Analysis of the denser marine geophysical and well dataset demonstrates the Suwannee basin is on average 200 km wide and stretches for 900 km from onshore Florida to offshore Cape Lookout, NC. The eastern extent of the basin is constrained by the BHZ, while the western boundary remains elusive onshore due to limited seismic reflection data and deep well penetrations. The Suwannee basin on the continental shelf has an approximate areal extent of 130,000 km2, creating a total estimated area of ~250,000 km2 for the entire Suwannee basin, including the Paleozoic sedimentary rocks onshore Florida and Georgia.

2.3.2.1 Northeastern extent

The northeastern extent of the Suwannee basin can be mapped as far north as Cape Lookout, NC, implying the suture must be located north of that boundary (Fig. 2.1a). Two profiles, WE7 and WE5, illustrate the continuity of the Suwannee basin rocks for over 300 km laterally to offshore North Carolina (Fig. 2.5a). The PRU can be continuously mapped starting at the southwestern edge of profile WE7 at 0.7 s TWTT to about 1 s TWTT at the Cape Fear arch and then dips gently back down to 1.4 s TWTT at the northeastern edge of WE5. The rise in PRU towards Cape Fear arch agrees with the interpretation that the Cape Fear arch is a southeastward plunging, basement high (Maher, 1971).

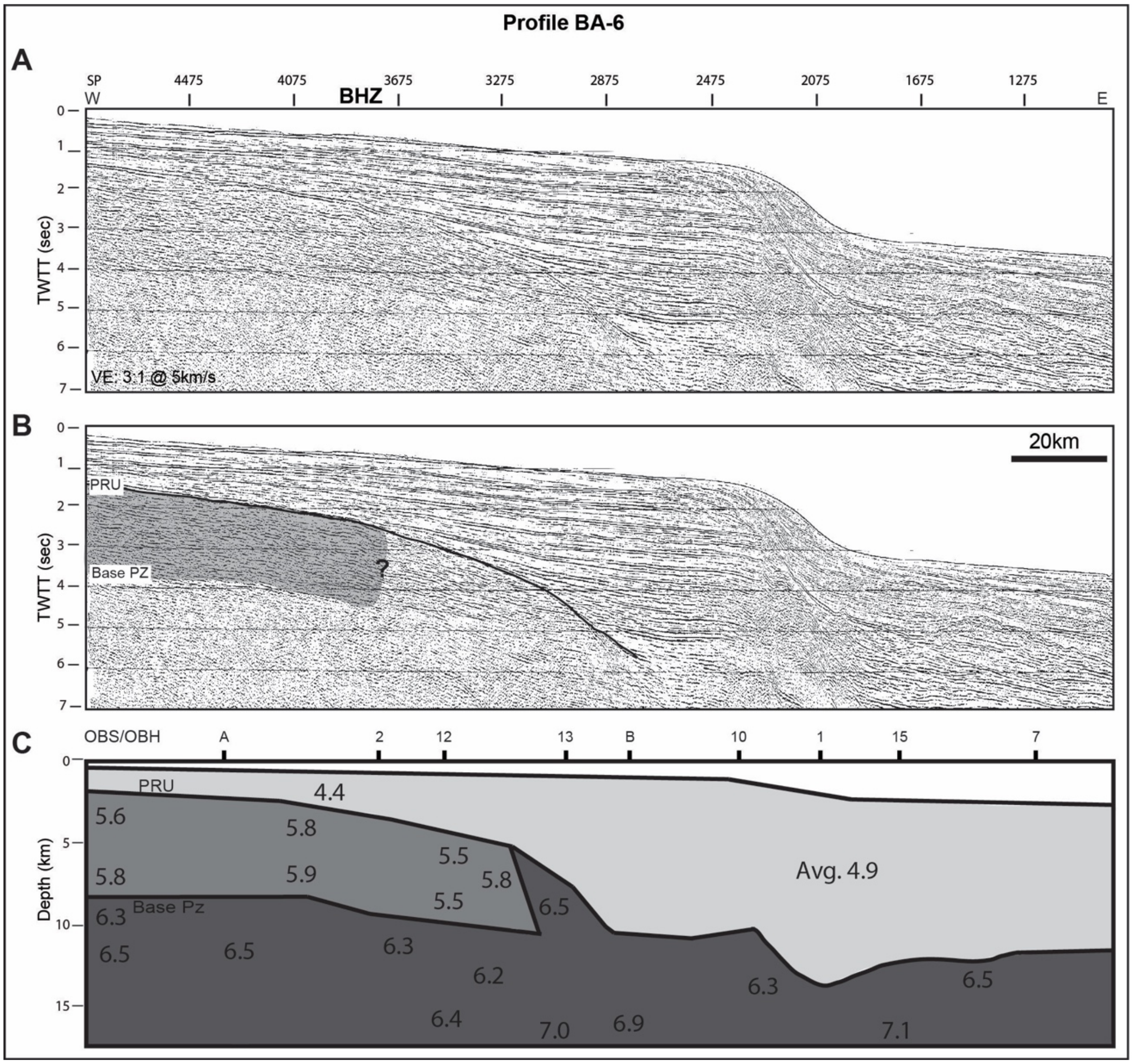

Figure 2.4: Uninterpreted (A) and interpreted (B) multi-channel seismic (MCS) reflection profile BA-6, reproduced from Austin et al, 1990. Profile is ~190 km long and shows upper ~7 seconds TWTT at a 3:1 vertical exaggeration. Shot points annotated above. (B) Post-rift unconformity (PRU), interpreted base of Paleozoic strata (Base PZ) are illustrated with the eastward extent of the interpreted Paleozoic strata limited by the basement hinge zone (BHZ) around SP 3875. (C) Upper 18 km of velocity model and locations of ocean bottom seismometer/ocean-bottom hydrophone (OBS/OBH) instruments (modified after Holbrook et al, 1994). The 4-6 km-thick high-velocity (5.5-5.9 km/s) layer below PRU is interpreted to be the Paleozoic sedimentary and meta-sedimentary rocks with a change to > 6 km/s indicating inferred crystalline basement contact at the base of the Paleozoic section.

Beneath the PRU there is a 1.5-2 s TWTT thick section of horizontal reflectivity that terminates at the interpreted crystalline basement where the profiles become riddled with diffractions and layered reflectivity is no longer apparent. Although the true thickness of the Paleozoic sedimentary section is not well constrained in the reflection data, the layered reflectivity below the unconformity, above the crystalline basement across both profiles is a comparable thickness to the section found along profile BA-3. We suggest that at least the entire 1.5 s TWTT of layered reflectivity below the PRU along the WE profiles represent layered stratigraphy. The relatively low frequency and continuity of the reflectors as well as a consistent thickness suggest that this is the same sequence of Paleozoic strata observed along the BA profiles. Additionally, between SPs 6200 and 6000 along profile WE7 (Fig. 2.5b) there is an area of disturbance below the unconformity dictating unique geometries of the reflectors in the inferred Paleozoic section not reflected above in the overlying stratigraphy. The identification of structures that predate the overlying sequence supports the inference that the reflectivity below the unconformity is the geophysical signature of layered sedimentary rocks.

In addition to the consistent thickness of Suwannee basin rocks towards the northeast, we observe relatively consistent velocities from independent refraction profiles along each reflection profile. Refraction profiles H11-54 and H3-54 tie to WE7 and WE5 respectively. H11-54 images a refractor with velocity of 5.89 km/s and H3-54 images a refractor with a velocity of 5.49 km/s (Hersey et al, 1959). The location of the two high velocity refractors for H11-54 and H3-54 correlated well with the associated PRU pick within 0.006 s TWTT and 0.18 s TWTT respectively. The measured velocities are consistent with the range in velocities observed along the BA profiles (5.5 - 5.9 km/s) where the high velocity layer of reflectivity directly ties to the Paleozoic sedimentary rocks. Based on independent velocity control along WE7 and WE5, we interpret the

PRU to be the contact between high velocity Paleozoic sedimentary rocks and the overlying Mesozoic sequence.

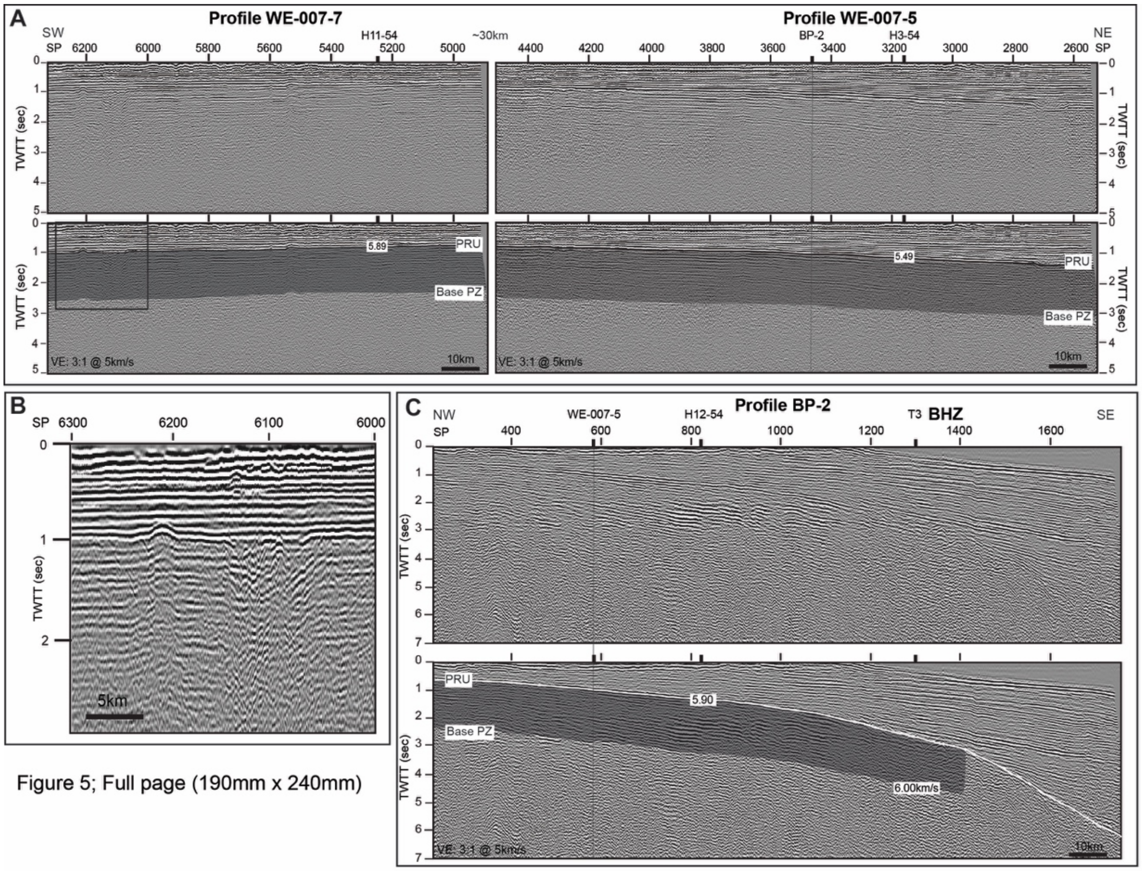

Figure 2.5: (A) Uninterpreted and interpreted profiles WE7 (WE-007-7) and WE5 (WE-007-5) demonstrating lateral continuity of interpreted Paleozoic sedimentary rocks from offshore South Carolina (SW) to south of Cape Lookout (NE). Tie of profile WE7 to reflection profile BP-2 denoted by thin grey line. Refraction profiles, H11-54 and H3-54, intersect WE-007-7 and WE-007-5 respectively and provide velocity control at the interpreted PRU. Box at southwestern end of profile WE-007-7 illustrates region of deformation below the unconformity zoomed in for Figure 5b. (B) Enlarged portion of profile WE7 = illustrated by black box on southwestern end of profile in 5a. Below 1 sec TWT (interpreted PRU) there are clear changes in the geometry of reflections below the unconformity that are discordant with the overlying reflectors. (C) Uninterpreted and interpreted sections of profile BP-2, showing tie to reflection profile WE-007-5 (thin grey line), locations of refraction profiles (H12-55; Hersey et al, 1959 and T3; Trehu et al, 1989), and the basement hinge zone (BHZ). Velocity control is provided for the interpreted PRU (5.90 km/s from H12-54) and the base of Paleozoic strata (Base PZ) (6.00 km/s from T3).

The northern edge of profile WE5 constrains the northeastern extent of the Suwannee basin to at least offshore Cape Lookout, NC. The Hatteras Light No.1 Well (Fig. 2.1a) penetrated Coastal Plain sediments directly into crystalline basement (Spangler, 1950), implying that the Suwannee basin strata must either have been eroded away at that location or the Alleghanian suture lies offshore somewhere between Cape Lookout and the Hatteras Light No.1 well. We favor the latter interpretation based on the aeromagnetic signatures in that region, however analysis of onshore well penetrations in North Carolina could provide additional constraints on the suture zone.

2.3.2.2 Eastern extent

The Suwannee basin rocks can be continuously mapped throughout the continental shelf, however the eastern mappable extent of Suwannee basin is currently limited by the BHZ. In addition to the two BA profiles previously presented, profile BP-2 (Fig. 2.5c) illustrates the continuity of Suwannee basin rocks eastward across the shelf to the BHZ. Additionally, profile BP-2 directly ties to profile WE5 demonstrating consistency in the interpretation between independent seismic reflection surveys.

Along profile BP-2, the PRU dips seaward from 0.6 s TWTT to 3.1 s TWTT between SPs 225 and 1300 where it then steepens significantly at the BHZ and plunges oceanward to over 6 s TWTT. There is a package of wavy layered reflectivity below the PRU between SPs 700 and 1100 where the reflectors are significantly higher amplitude and lower frequency than the overlying sedimentary section, arguing against the suggestion that the package below the PRU is a series of multiples (artifacts created during acquisition resulting from erroneous travel paths of the acoustic waves). The top of crystalline basement is located around 2.1 s TWTT at SP 225 and dips towards the offshore to about 4.8 s TWTT at SP 1400. The average thickness of the package of reflectivity below the PRU is around 1.5 s TWTT up to SP 1400 where we limit our interpretations due to the structural complications associated with the BHZ.

Analysis of two independent refraction surveys tied to BP-2 illustrates the consistency in both thickness and velocity of the Suwannee basin rocks seaward. H12-54 and T3 provide velocity and depth constraints at the PRU and the top of crystalline basement respectively. H12-54 is located around SP 830 where the PRU is mapped at 1.36 s TWTT. The calculated depth of the 5.90 km/s refractor is 1.3 s TWTT, which correlates well with our PRU pick using the reflection data. The velocity of this basal refractor is also consistent with the observed velocities for the Suwannee basin strata in the BA-3 and BA-6 velocity models.

Refraction profile T3 resides around SP 1300 along profile BP-2 with a refractor of 6 km/s at a depth of 2.50 km. After converting the measurements from Trehu and others (1989) to two-way travel time, the basal 6 km /s refractor is estimated to be at about 4.23 s TWTT which is similar to our pick of the crystalline basement at 4.324 s TWTT. Interestingly, T3 did not receive a refracted arrival from the PRU. We can observe in the reflection data that the PRU at this location has a more chaotic signature which may be a result of the reflection profile approaching the BHZ. Nonetheless, we do have the independent refraction survey H12-54 updip, constraining the velocity of the layered reflectivity at the PRU. Thus, we are confident in the mappable extent of the 4 - 6 km thick Suwannee basin rocks seaward to the BHZ offshore North Carolina.

2.3.2.3 Isochore of Suwannee basin rocks across continental shelf

After constraining the seismic reflection data picks using an integration of well data, independent refraction profiles, and the BA-3 and BA-6 velocity models we generated an isochore for the Suwannee basin strata (Fig. 2.1a). The isochore ultimately derives from the picked horizons of the PRU and top of crystalline basement across the dense array of legacy seismic reflection data. Using an average interval velocity of 5.7 km/s (assumed from velocity models), the thickness of Suwannee basin rocks was converted from time into depth, resulting in the isochore presented in Figure 2.1a. In summary, a consistent 4-6 km thick package of inferred Suwannee basin rocks with velocities of 5.5 – 5.9 km/s can be mapped across the continental shelf, limited in the East by the BHZ, and extending as far north as Cape Lookout, NC.

2.4 DISCUSSION

2.4.1 Revised Position of Suwannee Suture Zone

The Suwannee suture zone, representing the boundary between Gondwanan crust to the southeast and crust of Laurentia and accreted terranes to the northwest, has been the subject of prolonged debate. Suwannee basin rocks represent a shallow- to deep-marine platform sedimentary sequence deposited on Gondwanan continental crust and preserved throughout continental collision during the Alleghanian orogeny and subsequent continental rifting in the Triassic. The mappable extent of the Suwannee basin across the present-day continental shelf requires that the Suwannee suture zone reside north of these sedimentary rocks of Gondwanan affinity. The majority of prior Alleghanian suture interpretations (Fig. 2.1a) project through the middle of the revised Suwannee basin offshore. The presence, consistent thickness, and generally sub-horizontal nature of the Suwannee basin strata requires the modification of previous sutures offshore to reside inboard (north – northwest) of the mappable extent of the Suwanee basin.

The western extent of the Suwannee suture zone is relatively well constrained in western Georgia and Alabama based on observations from seismic reflection and well data (including more recent isotopic data) (Chowns and Williams, 1983; Nelson et al, 1985; Tauvers and Muehlberger, 1987; Thomas, 2010; Mueller et al, 2014); however, previous studies had little data to constrain the eastern continuation between Georgia and North Carolina. The most recent suture interpretations (Thomas, 2010; Mueller et al, 2014) provide strong evidence for the orientation and implied motion along the Suwannee suture zone, but the presence and extent of the Suwannee basin rocks offshore suggests that the suture zone resides further north, arguably along the boundary between the Charleston and Carolina terranes.

Higgins and Zietz (1983) also argued that the boundary between the Charleston and Carolina terranes is the most likely candidate for the Alleghanian suture and termed this major lineament the Carolina-Mississippi fault. Their interpreted Carolina-Mississippi fault fits the inferred dextral strike-slip strain regime of the region (Hatcher, 2010; Mueller et al, 2014), as well as overlaps with the previous suture interpretations in southwestern Georgia where there are better constraints from seismic reflection and well data. Horton and others (1989) initially took issue with the abruptness and linearity of the Carolina-Mississippi fault suggesting that most steep faults follow short wavelength trends and the original drawing of the Carolina-Mississippi fault does not. However, the interpreted Carolina-Mississippi fault does approximately coincide with the abrupt change in seismic reflection character at the northern edge of the Charleston terrane that Milici and Bayer (1986) described offshore near Cape Hatteras (Horton et al, 1989). We suggest a similar region for the Suwannee suture zone based on the extent of mappable Suwannee basin rocks between Cape Lookout, NC and the Hatteras Light No. 1 well on the tip of Cape Hatteras. The new interpretation of the Suwannee basin would require the offshore projection of the Carolina-Mississippi fault to re-locate ~50 km further north; nevertheless, the Carolina-Mississippi fault appears to be a good approximation of the boundary between the Carolina and Charleston terranes.

In addition to the more northerly suture interpretation, we acknowledge that the Suwannee suture is more accurately represented as a suture zone, rather than a single linear sub-vertical boundary. The revised Suwannee suture zone in this study is projected to fit the definitions presented in Mueller et al, (2014) and Thomas (2010), based on the width and orientation of the shear zones in the west, as well as the imaged crustal boundary from the COCORP survey in western Georgia (Nelson et al, 1985). Additional investigation of onshore well penetrations of basement rocks in North Carolina could provide further insight on the dimensions of the suture zone toward the east. Nonetheless, this study shows the Suwannee suture zone is most accurately described as: (1) a complex, dextral, transpressional shear zone (similar to that of Mueller and others (2014)) located in the East between the interpreted Charleston and Carolina terranes, (2) a fundamental terrane boundary that formed during the Alleghanian orogeny as Gondwanan continental crust collided with the Laurentian margin and, (3) a major suture zone that is at a nearly 45° angle to the modern continental margin implying subsequent rifting did not capitalize on this zone of presumed weakness.

2.4.2 Re-evaluation of Terrane Boundaries

The presence of Suwannee basin rocks across the continental shelf, spanning both the Charleston terrane and Suwannee terrane, requires a re-evaluation of the inferred age of terrane boundaries. These two terranes were previously distinguished solely on magnetic signature, with a major terrane boundary approximated by the BMA (Williams and Hatcher, 1982; Higgins and Zietz, 1983). While these two terranes may be distinct in magnetic signature, the Suwannee basin rocks can be mapped continuously across both terranes. Thus, if the Charleston and Suwannee magnetic terranes were two separate crustal blocks they must have been amalgamated prior to the deposition of the early- to mid-Paleozoic Gondwanan platform sequence of the Suwannee basin.

Offshore marine geophysical surveys demonstrate the presence and general sub-horizontal nature of the inferred Suwannee basin sequence. The BA surveys, acquired to evaluate the nature of the BMA, best demonstrate the importance of the Suwannee basin strata mapped across the continental shelf. Lizarralde and others (1994) describe how the continuity of layered Paleozoic rocks below the unconformity along BA-3, as well as the lack of significant compressional structures at the BMA preclude this feature from being the Alleghanian suture. We agree with this interpretation and suggest that the source of the BMA is related to some deeper change (below the base of the Suwanee basin rocks) in crustal composition, perhaps as a result of a Precambrian suture zone.

While there is evidence for localized deformation within the Suwannee basin strata, the deformation is not spatially associated with the BMA. In general, the majority of the reflectivity observed below the PRU and tied to Suwannee basin rocks, remains sub-horizontal and relatively undeformed. In addition to the lack of significant compressional structures, there appears to be no evidence for pre-Mesozoic rifting within the Suwannee basin, suggesting that the entire Suwannee crustal block (now including the Charleston terrane) remained a part of Gondwana until subsequent rifting in the Triassic. This interpretation differs from many paleogeographic representations of the Suwannee terrane as an individual crustal block separate from Gondwana prior to collision in the Alleghanian.

2.4.3 Extent of Suwannee Terrane and Preserved Paleozoic Sedimentary Cover

The mappable extent of Suwannee basin rocks offshore allows us to infer that the entire piece of crust southeast of the revised Suwannee suture zone (including the Charleston terrane) defines the preserved extent of Gondwanan continental crust sutured to North America in the Alleghanian. The revised areal extent of the Suwannee terrane includes the entire Suwannee basin (Florida and continental shelf), as well as parts of Alabama, Georgia, South Carolina and North Carolina, amounting to over ~ 800,000 km^2, nominally doubling the previously interpreted Suwannee terrane of > 400,000 km^2 (Mueller et al, 2014). The presence of Suwannee basin Paleozoic sedimentary cover has been an important marker for defining the boundaries of the Suwannee terrane and associated Gondwanan affinity basement.

The Suwannee basin rocks represent an Ordovician to Devonian sedimentary sequence with characteristic platform margin lithologies of quartzite, shale, and argillite. A variety of data suggests that this platform sequence was deposited along the continental margin of Gondwana including: (1) faunal information that suggests the sedimentary rocks are exotic to Laurentia and can be correlated to sedimentary basins in West Africa (Arden, 1974; Dillon and Sougy, 1974; Barnett, 1975; Pojeta et al, 1976; Poppe et al, 1995), (2) paleomagnetic data from the lower Paleozoic rocks which imply the Suwanee terrane had paleolatitudes more compatible with Gondwana than Laurentia (Horton et al, 1989) and (3) detrital zircon ages from Suwanee basin rocks which are consistent with Gondwanan orogenic events (Mueller et al, 2014). Based on these observations, it would follow that the Suwannee basin overlies Gondwanan continental crust and can be used a marker for defining the Suwannee terrane boundaries.

While this study emphasizes the extent of the Suwannee basin rocks in Florida, southeastern Georgia, and across the continental shelf, it is important to recognize that sub-horizontal Suwannee basin rocks with preserved burrow features are also described in western Florida and southern Alabama (Applin et al, 1951; Nelson et al, 1985; Neathery and Thomas, 1975; Mueller et al, 2014). Drill holes in the Coastal Plain of South Carolina and North Carolina have not penetrated Paleozoic sedimentary rocks, updip of the Suwannee basin strata documented here. This study demonstrates thicknesses of 4-6 km for the Suwannee basin rocks across the continental shelf (Fig. 2.1a) and onshore Florida the Suwannee basin rocks have proposed thicknesses of 2.5 – 3 km (Arden, 1974; Chowns and Williams, 1983; Thomas et al, 1989; Pollock et al, 2012). Suwannee basin strata can be mapped to the northern end of profile BA-3 (Fig. 2.3), ~ 25 km from the South Carolina coast. Barring a major, unrecognized, structural boundary between the continental shelf and onshore, it appears that the sub-horizontal Suwannee basin rocks would continue updip, below the Coastal Plain and the Triassic rift basins onshore. Additionally, this study limits the interpretation of Suwannee basin rocks to the BHZ, but there is no evidence to suggest that the Suwannee basin would not continue down dip. Therefore, the interpreted extent of the Suwannee basin is likely a conservative estimate and additional analysis of seismic reflection data onshore may reveal layered stratigraphy in the upper “basement”.

2.5 CONCLUSIONS

The revised location for the Alleghanian suture zone is constrained by the northeastern extent of the Suwannee basin on the continental shelf and most closely defined by the boundary between the Carolina and Charleston terrane. The Suwannee suture zone presented in this paper is consistent with published observations (lithologic, Chowns and Williams (1983); isotopic, Mueller et al. (2014); seismic reflection, Nelson et al. (1985)) of the inferred suture in Alabama and western Georgia while honoring the observable extent of the Suwannee basin rocks offshore. The extent of the Gondwanan strata mapped throughout the Suwannee basin provides the control needed in the east to constrain the suture to an inferred southeastward dipping zone between Cape Lookout and the Hatteras Light No.1 well.

Constraining the suture zone to ~ 200 km further north re-defines the areal extent of the Suwannee terrane to > 800,000 km^2, nominally doubling the size of the previously interpreted Gondwanan continental crust sutured onto North America during the Alleghanian. The preserved extent of the Suwannee basin strata across previously defined terrane boundaries (e.g. BMA) suggests that the Charleston and Suwannee terrane were one continuous piece of Gondwanan continental crust prior to the deposition of the early to mid- Paleozoic sedimentary rocks. Continued efforts using both seismic reflection and seismic refraction data in South Carolina and North Carolina, may reveal as similar sequence of high velocity, layered reflectivity above crystalline basement of inferred Suwannee basin strata onshore.

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CHAPTER 3

PRESERVED NEOPROTEROZOIC CONTINENTAL COLLISION IN SOUTHEASTERN NORTH AMERICA: THE BRUNSWICK SUTURE ZONE AND OSCEOLA CONTINENTAL MARGIN ARC[2]

A series of exotic terranes accreted to the eastern margin of Laurentia beginning in the Ordovician (Taconic). Many of these terranes have unclear tectonostratigraphic relationships to each other and to their parental cratons, but their accretionary history is critical to understanding the evolution of the Appalachian orogen. Two of these, the Gondwanan Suwannee and Charleston terranes, accreted during the Alleghanian orogeny and now lie beneath the Atlantic Coastal Plain in southeastern North America. Reanalysis of deep seismic reflection and well data reveals a preserved Neoproterozoic continental collision zone and associated continental margin arc, the Osceola Arc, related to their juxtaposition. The subduction zone and associated strain are recorded in the newly-termed Brunswick Suture Zone (BSZ). The BSZ is readily identified on a series of eight deep seismic reflection transects across the Brunswick Magnetic Anomaly (BMA), which we interpret as the boundary between the Charleston and Suwannee terranes. While originally interpreted to be the late-Paleozoic Alleghanian suture, new age constraints provided

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by the overlapping Gondwanan Paleozoic Suwannee Basin strata requires the BSZ to pre-date the early- to mid- Paleozoic passive margin sequence of the Suwannee Basin. These results provide new insights into the tectonostratigraphic evolution of the Charleston and Suwannee terranes, the controversy surrounding the age and origin of the dipping seismic reflectors, previously attributed to the suturing of the Suwannee terrane to Laurentia, and the relationship of this suture zone to the origin of the BMA.

3.1 INTRODUCTION

Along the eastern North American margin, “suspect” terranes were first recognized and defined by Williams and Hatcher (1982) as geologic provinces with features including, stratigraphy, magmatism, metamorphism, structure, etc., that contrast sharply with the surrounding terranes. Two of these suspect terranes, the Charleston and Suwannee terranes, reside in the southeastern United States and are separated by one of the most prominent geophysical anomalies along the margin, the Brunswick Magnetic Anomaly (BMA) (Fig. 3.1). The tectonostratigraphic histories of these two terranes have been difficult to piece together because both lie below the thick Coastal Plain cover, and they are recognized only from well-data and geophysical signatures, with no universally accepted spatial limits. Herein we use the terms Charleston and Suwannee terranes as defined by Higgins and Zietz (1983) and Horton et al. (1989).

The boundary between the Charleston and Suwannee terranes has been the subject of significant scientific inquiry for many years. Analyses of the limited deep borehole penetrations in the region revealed Gondwanan sedimentary rocks, as well as volcanic and intrusive rocks, within the Suwannee terrane that were generally not observed north of the BMA (Applin, 1951; Applin and Applin, 1965; Milton and Hurst, 1965; Milton and Grasty, 1969; Bass, 1969; Milton, 1972; Arden, 1974; Barnett; 1975; Neathery and Thomas, 1975; Pojeta et al., 1976; Chowns and Williams, 1983; Winston, 1992; Guthrie and Raymond, 1992; Duncan, 1998). Early investigations into the crustal structure of the southeastern United States as well as the nature of the boundary between the Charleston and Suwannee terranes included a series of deep seismic reflection profiles across the BMA. Onshore deep seismic reflection data collected by the Consortium for Continental Reflection Profiling (COCORP) revealed a southerly-dipping crustal-scale fabric below the BMA (Nelson 1985a,b; McBride and Nelson, 1988). The observations of the dipping intracrustal reflectivity in conjunction with the onshore extent of Gondwanan Paleozoic rocks led researchers to identify the BMA as marking the Alleghanian suture (Chowns and Williams, 1983; Nelson et al., 1985a, b; Tauvers and Muehlberger, 1987; McBride and Nelson, 1988; Thomas et al., 1989; Horton et al., 1989; Parker, 2014). Deep seismic reflection surveys across the offshore extension of the BMA (Brunswick Anomaly, BA) revealed a similar zone of S-SE dipping intracrustal reflectivity on all five transects (Austin et al., 1990; Oh et al., 1991; Oh et al., 1993; Lizarralde et al., 1994). These authors concluded that the dipping reflectivity could not be the result of the late-Paleozoic collision (Oh et al., 1991; Lizarralde et al., 1994), and if it were a suture zone, it was more likely an early-Paleozoic or Precambrian feature (Oh et al., 1991).

The debate surrounding the age and origin of the dipping reflectivity associated with the BMA was recently reignited when new studies proposed a more complex development of the Alleghanian suture, termed the Suwannee suture zone (SSZ, Fig. 3.1). Thomas (2010) and Mueller et al. (2014) suggested the dipping reflectors were formed by transpressional motion as the undeformed northern Suwannee terrane accreted and over-rode the Charleston and Uchee terranes. In this model the crust north of the reflectors was also likely Gondwanan as suggested earlier by Higgins and Zietz (1983). Boote and Knapp (2016) made stronger arguments that the reflectors associated with the BMA formed prior to the Alleghanian because they were overlain by an extensive set of sub-horizontal reflectors that likely extended the Suwannee Basin stratigraphy to off-shore North Carolina.

With new insights into the location of the Alleghanian suture zone and extent of exotic terranes accreted during the Alleghanian, the age and origin of the structures observed in the COCORP and BA seismic reflection profiles remain important, but unresolved issues critical to accurately reconstructing the evolution of the Appalachian orogeny and the growth of the North American continent. This study integrates data from deep borehole penetrations throughout the Suwannee terrane with the legacy deep seismic reflection data to establish a new interpretation for the tectonostratigraphic evolution of the Charleston and Suwannee terranes (s.l.). In this interpretation, the dipping reflectors from both on-shore and off-shore profiles demark an inter-terrane suture preserved in an amalgamated Suwannee-Charleston crustal block that accreted to Laurentia during the late Paleozoic Alleghanian orogeny.

Integration of well and seismic reflection data reveal this inter-terrane suture zone, herein named the Brunswick Suture Zone (BSZ), to be Neoproterozoic based on the sub-horizontal, early- to mid-Paleozoic Suwannee Basin sequence overlapping the BSZ in offshore profiles constrained by well penetrations. Well penetrations onshore reveal Neoproterozoic layered volcanic rocks and intrusive rocks that are inferred to originate from a single continental margin arc system (Mueller and Porch, 1983; Heatherington et al., 1996; Heatherington and Mueller, 1997), herein termed the Osceola Arc. The extent and location of Osceola Arc rocks are consistent with formation along a subduction zone associated with the BSZ and now comprise a major component of the Precambrian basement of the Suwannee terrane (Fig. 3.1A). Furthermore, the tectonostratigraphic evolution of the Suwannee terrane from a continental margin arc beginning in the Neoproterozoic to a passive margin in the Paleozoic is consistent with the age of recorded magmatism, strain, and passive margin deposition observed along potential conjugate, Gondwanan margins (Dallmeyer, 1987; Heatherington and Mueller, 1997).

3.2 CHARLESTON AND SUWANNEE TERRANES

The tectonic evolution of the Appalachian orogen has been viewed for decades in the context of the assembly of numerous tectonostratigraphic terranes. Understanding the boundaries and relationships between these terranes, and their respective spatial and temporal records of deformation, plutonism, and metamorphism, remains a challenge for geophysical and geological studies along the North American Atlantic margin. The structural and stratigraphic evolution of two

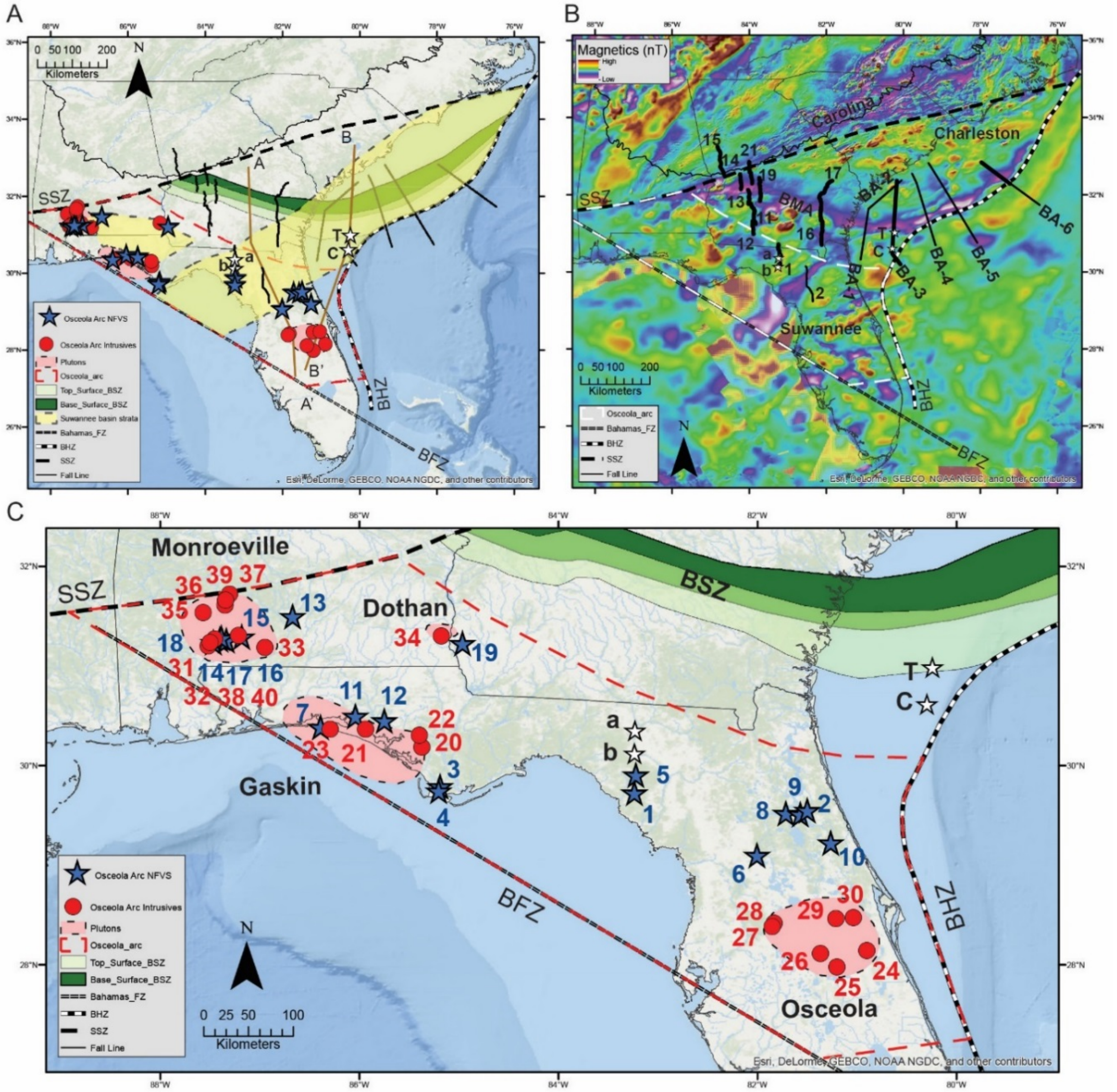

Figure 3.1. (A) Map of southeastern North America showing extent of Osceola Arc (OA; defined by known or inferred Neoproterozoic intrusive (red dots) and extrusive (blue stars) rocks in the subsurface) in relation to the Brunswick Suture Zone (BSZ; green bands). Subcrop of younger Paleozoic Suwannee Basin strata (SBS) lying unconformably above both the OA and BSZ shown in yellow. Preserved lateral extent of the OA, BSZ, and SBS are limited by the younger Suwannee Suture Zone (SSZ), Basement Hinge Zone (BHZ), and Bahamas Fracture Zone (BFZ). Black solid lines identify seismic reflection data used in this study. Orange lines identify cross-sections A-A' and B-B' of Figure 3.6. White stars represent Suwannee Basin well penetrations tied to seismic reflection data in this study. C = COST GE-1, T = Transco 1005-1, a = J.W. Gibson-1, b = R.L. Henderson-1. (B) Magnetic anomaly map (same area as A) and labeled seismic reflection profiles (black lines). Images of bold portions of seismic reflection profiles are presented in subsequent figures. Note spatial coincidence of Brunswick Magnetic Anomaly (BMA) with locus of BSZ. (C) Enlarged Osceola Arc map with annotated Well ID numbers listed in Table. 1.

of these suspect terranes, the Suwannee terrane and Charleston terrane (Fig. 3.1B), have been the subject of considerable, but inconclusive, investigations. The present study draws on seismic reflection and well data to support a new interpretation of the age and nature of the boundary between these two terranes, as well as their tectonostratigraphic evolution, to provide new insights into the tectonic history of the southeastern North American margin.

The Charleston and Suwannee terranes were first distinguished on the basis of their differing aeromagnetic signatures (Williams and Hatcher, 1982), and while the terminology has evolved over time, these two terranes are both considered exotic to the Laurentia (Horton et al., 1989). The present study uses the nomenclature Charleston terrane and Suwannee terrane as described by Horton and others (1989) that is primarily based on aeromagnetic signatures and consistent with the boundaries of the Charleston terrane and North Florida terrane (respectively) of Higgins and Zietz (1983). The magnetic character of the Suwannee terrane consists of a series of high-amplitude, positive and negative, short-wavelength anomalies that contrast significantly with its northern boundary near the BMA (Fig. 3.1B). The Charleston terrane has a broader-wavelength, generally positive amplitude magnetic character that is > 200 gammas higher than, and distinct from, the shorter-wavelength NE-SW trending lineations of the Piedmont magnetic province (Carolina terrane) to the north and west (Fig. 3.1B) (Horton et al., 1989; Steltenpohl et al., 2013). The southern border of the Charleston terrane is typically delineated by the high, negative-amplitude component of the BMA (Higgins and Zietz, 1983; Tauvers and Muehlberger, 1987, Lizarralde et al., 1994). Higgins and Zietz (1983) suggested that while the two juxtaposed terranes are separated by a sharp boundary along the BMA, they appear nearly identical magnetically. Conversely, Daniels and others (1983) suggested that the trends of long wavelength anomalies in the Charleston terrane are generally E-W whereas in the Suwannee terrane the long wavelength anomalies trend NE-SW, implying the basement rocks of the Charleston and Suwannee terranes record two different orogenic imprints. The relationship between these two terranes and their tectonic origins remain elusive and were part of the motivation for this study.

Due to the Coastal Plain sedimentary cover of the Charleston and Suwannee terranes, researchers must rely heavily on geophysical data to draw inferences about the underlying basement. The limited elemental, isotopic, and radiometric age data from the Charleston terrane, combined with inferences from gravity and magnetic data, suggest that beneath the Coastal Plain, and in some cases below the overlapping Mesozoic rift sediments, the Charleston terrane largely consists of plutons and foliated mafic rocks (Daniels and Zietz, 1983; Horton et al., 1989). Rocks recovered from a few deep drill-holes also suggest a greenschist facies stratigraphic cover of meta-sedimentary and meta-volcanic rocks (Horton et al., 1989). Many of the inferred mafic plutons are thought to have intruded during Mesozoic rifting associated with the opening of the Atlantic Ocean (Daniels and Zietz, 1983), so that these shorter wavelength anomalies probably overprint the original Charleston terrane magnetic signature. The only other basement rocks that have been analyzed in detail within the Charleston terrane were cored at the Savannah River Laboratory and reported by Dennis and others (2004). These rocks are located in what some authors distinguish as a separate terrane, the Savannah River terrane (Maher et al., 1991; Maher et al., 1994; Mueller et al., 2014), near the northern boundary of the

Charleston terrane along the proposed Alleghanian suture zone (Fig. 3.1; SSZ; Boote and Knapp, 2016). The Savannah River terrane is distinct from the Carolina terrane, but is thought to be part of the Carolina zone and other infrastructural peri-Gondwanan terranes caught up in the Alleghanian suture zone (Maher et al., 1994; Hibbard, 2002; Dennis et al., 2004; Mueller et al., 2014). It is often included in the Charleston terrane because of its similar magnetic signature. Rocks from the Savannah River site have uranium-lead zircon ages of 619-626 Ma and greenschist to amphibolite facies metavolcanic rocks show Mesoproterozoic Sm-Nd depleted mantle model ages of 1.0 to 1.1 Ga (Dennis et al. 2004; Mueller et al., 2014). The Neoproterozoic ages of these volcanic rocks imply this terrane is exotic to Laurentia (Mueller et al., 2014); however, the stratigraphic cover records metamorphism not observed in the Suwannee terrane, so the relationship of these rocks to the Charleston terrane is still unclear.

Basement rocks of the Suwannee terrane are much better understood than those of the Charleston terrane, primarily because of extensive exploration drilling by oil and gas companies in Florida and adjacent states starting in the early 1900s. Deep boreholes in Florida, southern Georgia, and Alabama reveal a laterally extensive sequence of largely undeformed and unmetamorphosed Gondwanan Paleozoic sedimentary rocks (Fig. 3.1A) (Campbell, 1939; Applin, 1951; Wilson, 1966; Barnett, 1975; Pojeta et al., 1976; Chowns and Williams, 1983; Duncan, 1998) termed the Suwannee Basin by King (1961) (contracted from Suwannee River Basin of Braunstein (1957)). Offshore well penetrations of apparent Suwannee Basin rocks were integrated with seismic reflection data to create the first map documenting the extent of the Suwannee Basin strata offshore (Boote and Knapp, 2016). This offshore mapping implies these early- to mid- Paleozoic

Gondwanan strata can be traced continuously into the Charleston terrane. Well penetrations in the Suwannee terrane also reveal a series of Neoproterozoic layered volcanic rocks termed the North Florida Volcanic Series (NFVS) (Heatherington and Mueller, 1997; Duncan, 1998) underlying the Suwannee Basin, as well as numerous penetrations of intermediate to felsic intrusive rocks that probably represent the co-magmatic plutonic equivalent to the NFVS (Heatherington and Mueller, 1997; Duncan, 1998). The spatial extent and temporal evolution of the Suwannee terrane igneous rocks (volcanic and intrusive) and the overlying Suwannee Basin strata provide important age and tectonic constraints on the origin of the dipping crustal-scale fabric (BSZ) observed along the boundary between the Charleston and Suwannee terranes.

3.3 DATA

The data integrated in this study consist exclusively of information from the published literature (with the exception of the biostratigraphic report from the Transco 1005-1 well), and include geophysical (seismic reflection and refraction, well log, and aeromagnetic), stratigraphic, geochemical, and geochronologic data. The first comprehensive and regionally extensive aeromagnetic dataset in the southeastern U.S. was acquired by the United States Naval Oceanographic Office between 1964 and 1965, and interpreted in conjunction with the United States Geological Survey (USGS) (Taylor et al., 1968). Subsequent surveys have been collected and integrated into the Magnetic Anomaly Map of North America released to the public by the USGS (Bankey et al., 2002). Deep seismic reflection data for this study were acquired onshore by COCORP, beginning in 1983, followed by the offshore BA survey collected by the University of Texas Institute for Geophysics (UTIG) in 1988. Much of the geologic information is derived from oil exploration wells drilled in Florida, Georgia, and Alabama. Well data and lithological descriptions were reported in various publications beginning in the early 1950s and continued through the early 1990s as more wells were drilled. The wells presented in this study are identified in Table 1 with well ID numbers indicated in Figure. 3.1C. While various reports have conflicting rock descriptions, this study used a combination of the published reports, original well documentation archived in government databases, well logs, seismic reflection data, and geochronological studies, to make informed decisions on how to classify the basement rocks from each well.

The first regional synthesis and description of wells from Florida, Georgia, and Alabama classified basement rocks into three main groups: (1) Paleozoic strata, (2) Volcanic rocks, and (3) Granite (Applin, 1951). Numerous researchers continued to report on the basement rocks from deep boreholes in this region (Applin and Applin, 1965; Milton and Hurst, 1965; Milton, 1972) and conducted initial radiometric analyses for these rocks (Milton and Grasty, 1969; Bass, 1969). Neathery and Thomas (1975) produced a report on basement rocks in Alabama using a similar classification to Applin (1951). Barnett (1975) summarized previous work as well as described rocks from new well penetrations of the Florida basement. Throughout the investigation of the tectonic history of southeastern North America, researchers were proposing a Gondwanan connection for the Suwannee terrane, including the seminal paper that first proposed the theory of Wilson Cycles by Wilson (1966). The first faunal linkage to Gondwana was found in the Paleozoic strata penetrated by deep boreholes in Florida (Arden, 1974; Pojeta et al., 1976).

Table 3.1. Osceola Arc Wells.

Well ID	Well Name	State	County	Permit	Lat	Long	TD	Rock Type	Radiometric Age	Ref
	NFVS									
1	Buckeye Cellulose Corp #1	FL	Dixie	1129	29.732	-83.239	9075	Aphanitic Igneous Rock, Dacite	K-Ar 552 +/- 21	12
2	J.W. Campbell #1	FL	Flagler	44	29.554	-81.502	4644	Tuff & Volcanic Agglomerate		1, 5
3	St. Joe Paper Co. #6	FL	Gulf	762	29.798	-85.192	14570	Volcanic		logs
4	St. Joe Paper Co. #1	FL	Gulf	670	29.751	-85.209	14297	Dacite Porphyry, Ash Fall Tuff		6
5	P.C. Crapps #1	FL	Lafayette	1052	29.912	-83.223	10077	Volcanic rock		12
6	Henry N. Camp #1	FL	Marion	53	29.102	-82.008	4637	Volcanic Agglomerate, Tuff	U-Pb 552 +/- 8 Ma	1, 5, 6
7	Mattie Kelly Sims et al Trustees #1	FL	Okaloosa	970	30.389	-86.393	14919	Volcanic		logs
8	H.E. Westbury et al #1	FL	Putnam	96	29.524	-81.718	3892	Volcanic Ash, Tuff		1, 5
9	Johnson Malphure #1	FL	Putnam	607	29.519	-81.569	5506	Rhyolite		6
10	Retail Lumber Co. #1	FL	Volusia	78	29.230	-81.266	5424	Rhyolitic Volcanic Rock		1, 5
11	J R Sealy #1	FL	Walton	268	30.502	-86.042	11952	Rhyolite Porphyry Ash		5
12	First National Bank of Akron #28-3	FL	Washington	549	30.458	-85.753	11692	Rhyolite		7
13	D.W. Hendrix #1	AL	Butler	326	31.502	-86.675	9480	Rhyolite Tuff		9
14	Alger Sullivan "A" #1	AL	Conecuh	1747	31.271	-87.406	14417	Volcanic Agglomerate, Rhyolite		8, 9
15	D.W. McMillan Trust 20-6 #1	AL	Conecuh	3733	31.298	-87.186	15020	Felsic Tuff or Porphyritic Rhyolite		9, 12
16	D.R. Coley et al #1	AL	Conecuh	2170	31.262	-87.339	13895	Felsic Tuff		9
17	Alger-Sullivan Unit #29-3	AL	Conecuh	2212	31.288	-87.388	14342	Igneous Breccia		9
18	Scott Paper Co. et al 9-13 #1	AL	Escambia	1680	31.245	-87.472	14730	Volcanic Agglomerate		8, 9
19	Susie Wilson #1	GA	Early	3543	31.237	-84.964	9167	Volcanic Rock Identified as NFVS		11

Table 3.1. Continued

Well ID	Well Name	State	County	Permit	Lat	Long	TD	Rock Type	Radiometric Age	Ref
	Intrusives									
20	International Paper 30-4 #1	FL	Gulf	746	30.191	-85.377	13284	Granodiorite	K-Ar 709 +/- 25 Ma	6
21	St. Joe Paper #2	FL	Bay	690	30.371	-85.938	12313	Granite		6
22	Southwest Forest Industries #13-3	FL	Bay	1010	30.309	-85.399	12486	Granite		10
23	St. Joe Paper #4	FL	Walton	721	30.373	-86.292	14515	Granite		6
24	N. Ray Carroll #1	FL	Osceola	8	28.148	-80.899	8045	Granite, Quartz Monzanite	U-Pb ~600 Ma	1, 3, 5, 6, 11
25	Bronson Inc #1	FL	Osceola	539	27.986	-81.203	7935	Granite		6
26	Bronson Inc #2	FL	Osceola	543	28.119	-81.369	6900	Granite		6
27	J.Ray Arnold #1	FL	Lake	N/A	28.389	-81.856	6129	Alaskite, Granite		1, 4
28	Arnold Industries Inc #1	FL	Lake	629	28.422	-81.833	5778	Alaskite	U-Pb 551+/- 6 Ma	6
29	George Terry #1	FL	Orange	230	28.470	-81.215	6589	Granite		2, 3, 4
30	Deseret Farms of Florida Inc #1	FL	Orange	441	28.479	-81.039	7119	Granite	U-Pb 551 +/- 10 Ma	6
31	Alger Tenants #1	AL	Escambia	1568	31.208	-87.525	15106	Granite		8, 9
32	ATIC 7-1 #6	AL	Escambia	3855	31.243	-87.500	14306	Hornblende Granodiorite		9
33	T.R. Miller Mill #1	AL	Escambia	1558	31.192	-86.950	12155	Granititc Igneous Rock		8
34	Beatrice and O.A. Gamble #1	AL	Henry	392	31.309	-85.178	6392	Quartz Diorite or Hornblende Diorite		8
35	Mabel Hall #1	AL	Monroe	1561	31.542	-87.571	13890	Granite	Pb-Pb 625 +/- 6 Ma	8, 13
36	Intl. Paper Co. #2	AL	Monroe	1352	31.728	-87.307	10367	Biotite Feldspathic Schist, Gneiss		8
37	Intl. Paper Co. #1	AL	Monroe	1340	31.618	-87.352	10033	Biotite Feldspathic Schist, Gneiss		8
38	B.C. Quimby 27-15 SWD #1	AL	Monroe	1599	31.276	-87.453	14193	Hornblende Granodiorite		9
39	Paper "B" #1	AL	Monroe	1624	31.667	-87.347	9408	Granite, Hornblende Biotite Phyllite		9
40	Woodrow Jackson Heirs #1	AL	Conecuh	1851	31.311	-87.213	12200	Granite		8

Table 3.1. Well ID correlates with annotation of wells in Figure 3.1C. References: (1) Applin, 1951; (2) Applin and Applin, 1965; (3) Bass, 1969; (4) Milton and Grasty, 1969; (5) Milton, 1972; (6) Barnett, 1975; (7) Arden, 1974; (8) Neathery and Thomas, 1975; (9) Guthrie and Raymond, 1992; (10) Winston, 1992; (11) Mueller et al., 1994; (12) Duncan, 1998; (13) Mueller et al., 2014

Additional geological syntheses produced by Chowns and Williams (1983) and by Duncan (1998), focused in Georgia and the Suwannee terrane respectively, made additional strides to further constrain the tectonic history of southeastern North America. Our study integrates previously reported elemental, isotopic, and geochronological data on these basement rocks (Mueller and Porch, 1983; Dallmeyer et al., 1987; Mueller et al., 1994; Heatherington and Mueller, 1996; Heatherington and Mueller, 1997; Mueller et al, 2014) with lithological descriptions to evaluate the tectonostratigraphic evolution of the Suwannee and Charleston terranes.

3.4 THE BRUNSWICK SUTURE ZONE

The BSZ is identified in deep seismic reflection data as a zone of southerly-dipping reflectivity and diffractions observed throughout the crust that we interpret as the boundary between the Charleston and Suwannee terranes. The BSZ ranges from 25-50 km wide and can be identified for more than 700 km along strike. The integration of these data with deep borehole penetrations both on and offshore resolves the considerable controversy surrounding the age and origin of the BSZ.

COCORP collected the first deep seismic reflection profiles in the southeastern United States in an effort to explore the crustal structure of the southeastern Atlantic margin. Three COCORP transects across the BMA in Georgia (Fig. 3.2) revealed a ~ 25 km wide zone of southerly dipping reflectivity observed in the crust between approximately 2-12 sec two-way travel time (TWTT) (approximately 2-34 km deep using estimated velocities of 2 km/s for Coastal Plain and an average crustal velocity of 6 km/s) that is truncated by the interpreted sub-horizontal Moho reflections around 12 sec TWTT (Fig. 3.2) (Nelson 1985 a, b; McBride and Nelson, 1988). While two of the transects (A, B; Fig. 3.2) reside in western Georgia in close proximity to the interpreted SSZ of Boote and Knapp (2016) (Fig. 3.1), the third transect (C; Fig. 3.2) resides over 180 km away to the east, demonstrating a consistent crustal fabric along the extent of the BMA.

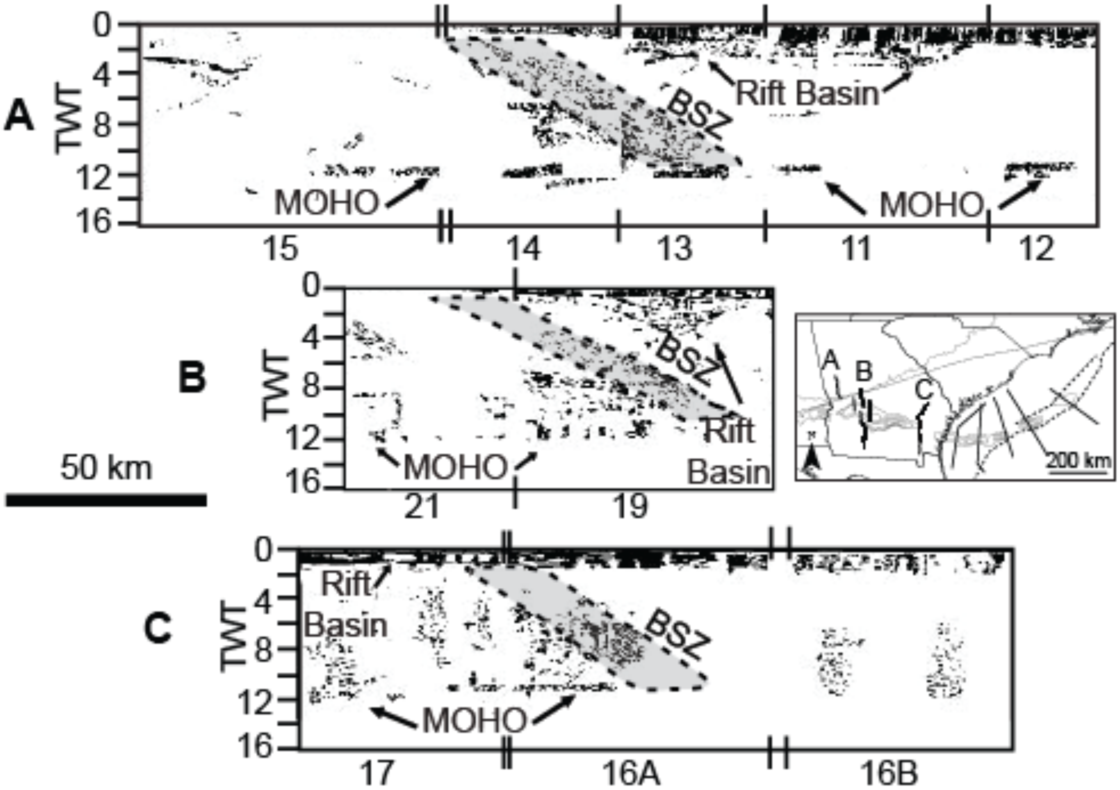

Figure 3.2. Reinterpreted line drawings of Georgia COCORP deep seismic reflection transects (modified from McBride and Nelson, 1988) that image a southerly-dipping zone of intracrustal reflectivity, originally interpreted as the Alleghanian Suwannee suture zone (SSZ), but identified in this study as the Neoproterozoic Brunswick Suture Zone (BSZ). Dipping reflectivity is apparent from the base of Coastal Plain (<2 km depth) to the Moho (~35 km depth), especially on transect A. Profile numbers indicated along bottom of transects. See inset and/or Figure 3.1 for locations.

A similar zone of S-SE dipping reflectivity can be observed in the upper- to mid-crustal levels (4-12 sec TWTT) in all five BA offshore seismic reflection transects (locations in

Fig. 3.1) that were previously documented by Oh and others (1991). While the original stacks no longer exist for the BA survey, herein we provide an appropriate reproduction from the published literature of profile BA-6, the most eastern profile acquired across the BMA (Fig. 3.3). BA-6 reveals a similar > 25 km wide zone of S-SE dipping reflectivity that is truncated at the base by the interpreted Moho around 12-13 sec TWTT (~36 km at 6 km/s). In the upper crust, the intracrustal reflectivity of the BSZ is capped by a sequence of sub-horizontal reflections around 4 sec TWTT (~ 12 km using average crustal velocity of 6 km/s) that lie below the post-rift unconformity (PRU). The southerly dipping crustal fabric offshore is similar to the zone of intracrustal reflectivity onshore in the COCORP profiles (Austin et al., 1990; Oh et al., 1991), all of which are consistently located on or just north of the BMA and may have implications for its origin.

The line drawings presented in Figures 3.2 and 3.3 were derived from unmigrated seismic reflection profiles. On these profiles, the BSZ appears to be dipping about 35-45° (Figs. 3.2 and 3.3), however, during the seismic migration process, reflections are translated along the wavefront, which in general would tend to shallow and steepen the observed reflectors that define the crustal fabric. This process would probably further highlight the discordance of the BSZ with the overlying sub-horizontal reflectivity below the PRU.

The three COCORP deep seismic reflection transects onshore as well as the five BA deep seismic reflection transects offshore document a consistent S-SE dipping crustal fabric that is truncated at depth by the Moho. At its western known extent, the BSZ is observed as shallow as ~2 km (Profile 14; Fig. 3.2), whereas at its eastern extent, it is truncated by a thick sequence of sub-horizontal reflections below the PRU at about ~8 km (Profile

BA-6, Fig. 3.3). A crustal-scale fabric of this extent is consistent with generation in a continental collision, lending support to the original conclusions that this zone of intracrustal reflectivity was produced in a suture zone (Nelson et al, 1985a, b; Tauvers and Muehlberger, 1987; McBride and Nelson 1988; Austin et al., 1990; Oh et al, 1991). While it is possible these seismic reflection profiles (onshore vs. offshore or west vs. east) are imaging similar intracrustal fabrics of different origins, the co-spatial association of the crustal-scale fabric with the BMA supports that they developed during a single tectonic event.

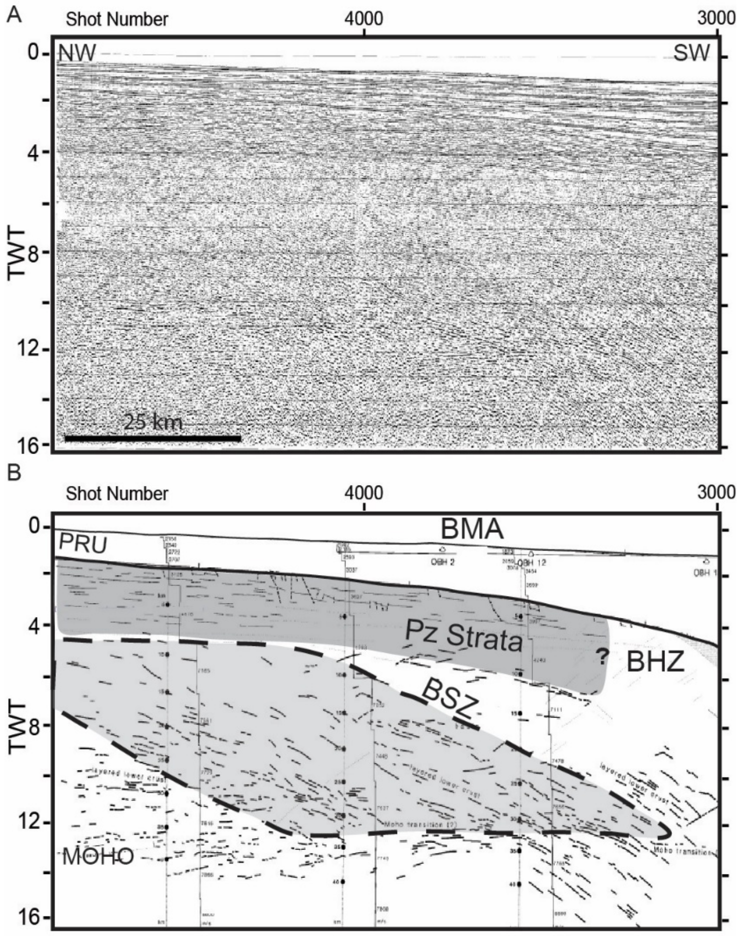

Figure 3.3. (A) Reproduction of the updip portion (shotpoints 3000-4880) of the seismic reflection stack and (B) reinterpreted unmigrated line drawing of profile BA-6 (see Fig. 3.1; modified from Austin and others, 1990). Sub-horizontal Suwannee Basin strata (Pz) mapped across the shelf of the southeastern U.S. overly with angular discordance the crustal-scale, SE-dipping reflectivity of the Brunswick Suture Zone (BSZ). Interpretation of Paleozoic strata limited to the east by the Basement hinge zone (BHZ).

3.5 OSCEOLA ARC

Volcanic and intrusive rocks have been reported from the subsurface of the southeastern U.S. for more than 100 years. Researchers used cuttings and core from deep borehole penetrations in Florida, Georgia, and Alabama to describe the basement rocks (Applin, 1951; Applin and Applin, 1965; Milton and Hurst, 1965; Milton and Grasty, 1969; Bass, 1969; Milton, 1972; Barnett; 1975; Neathery and Thomas, 1975; Winston, 1992a; Guthrie and Raymond, 1992; Chowns and Williams, 1983; Duncan, 1998) and perform geochemical (Milton and Grasty, 1969; Mueller and Porch, 1983) and geochronologic analyses (Milton and Grasty, 1969; Bass, 1969). These early reports recognized that the majority of the felsic igneous rocks found in southeastern North America represented early Paleozoic or Precambrian basement exotic to Laurentia. Less reliable techniques of Rb-Sr dating and whole rock K-Ar dating (unreliable based on altered nature of many of the rocks) were followed by more recent analyses using ^{40}Ar/^{39}Ar (Dallmeyer, 1987), and U-Pb in zircon (Mueller et al., 1994; Heatherington and Mueller, 1996; Mueller et al., 2014) dating techniques that revealed an extensive Neoproterozoic igneous province beneath the pre-Mesozoic sedimentary cover in Florida, Alabama, and Georgia. This study assimilates the geologic, geochemical, and geochronologic data on igneous rock penetrations in southeastern North America to define the extent and tectonic evolution of these rocks as the Osceola Arc.

The Osceola Arc is comprised of Neoproterozoic volcanic and plutonic rocks identified in the subsurface of the Suwannee terrane. In addition to the Coastal Plain, Osceola Arc rocks are often buried beneath the overlying passive margin sequence of the Suwannee Basin and appear to sub-crop at the edges of the basin or along broad antiforms within the Suwannee Basin. To determine the extent of the Osceola Arc, this study integrates deep borehole penetrations with seismic reflection data that reveal Neoproterozoic arc igneous rocks are preserved along a broad arcuate belt through the central Suwannee terrane. The preserved extent of the Osceola Arc continues > 750 km from west to east and is at least 230 km wide. The extent of the Osceola Arc is limited to the east by the basement hinge zone (BHZ) and to the west by the Alleghanian suture (SSZ of Boote and Knapp, 2016) (Fig. 3.1). The southern limit of the Osceola Arc is not well constrained because of overlying Mesozoic volcanic rocks; therefore, the BFZ is used as the southern boundary. The northern boundary of the Osceola Arc is poorly defined as a result of limited well penetrations, the majority of which bottom in Triassic rift-related sediments or inferred Jurassic igneous rocks. Radiometric, elemental, and isotopic data reported for the NFVS and felsic intrusive rocks found within the Suwannee terrane suggest these rocks were formed in a continental arc setting during the Neoproterozoic (Mueller and Porch, 1983; Heatherington and Mueller, 1996; Heatherington et al., 1997; Duncan, 1998, Mueller et al., 2014). The lithostratigraphic relationship between the plutonic rocks, layered volcanic rocks, and overlying clastic

Suwannee Basin sequence provides new insight into the tectonic history of the BSZ and associated Gondwanan continental margin.

3.5.1 The North Florida Volcanic Series (NFVS)

Felsic volcanic rocks of late Precambrian or early Paleozoic age were drilled in Florida as early as 1946. Based on proximity, composition, and age, these rocks are thought to be of a single volcanic province termed the North Florida Volcanic Series (NFVS) by Heatherington and Mueller (1996). The NFVS sits stratigraphically below Suwannee Basin sedimentary rocks and consists of layered volcanic rocks generally representing the more felsic end of the compositional spectrum (Applin, 1951; Milton, 1972; Bass, 1969; Barnett, 1975; Chowns and Williams, 1983; Heatherington et al., 1996; Duncan, 1998). The NFVS can be identified by both lithology and stratigraphic position in 19 deep well penetrations in southern Alabama, western Georgia, the Florida panhandle, and central Florida (Fig. 3.1A). This study interprets a greater extent for the NFVS than originally defined after integrating additional well data from western Florida, western Georgia, and Alabama that penetrated similar lithologies to the NFVS at an appropriate structural level.

NFVS rocks range in composition from basaltic andesite to rhyolite, often with preserved textures consistent with lava and pyroclastic flows. Volcanic ash-fall tuffs and ash-flow tuffs of rhyolitic or dacitic composition are identified in 7 of the 19 NFVS wells and often exhibit distinguishing features such as graded laminations or flow foliations (Applin, 1951; Barnett, 1975; Chowns and Williams, 1983). The mafic end of the spectrum is decidedly under-represented in NFVS rocks; therefore, the NFVS contrasts significantly with the younger Triassic and Jurassic basalts and diabases commonly observed throughout the southeastern United States, including the Southwest Florida Volcanic Series (Milton, 1972; Mueller and Porch, 1983; Heatherington and Mueller, 1997). A cluster of wells in southeastern Georgia penetrated felsic volcanic rocks at the base of the Coastal Plain that were previously identified as early Paleozoic or Precambrian (Chowns and Williams, 1983), but we believe are actually Mesozoic and are not included in the mappable extent of the Osceola Arc. These inferred younger volcanic rocks are in close proximity to a Jurassic felsic intrusive (Heatherington et al., 1999), suggesting there may be a younger, and more felsic province in this region. Additionally, these proposed Jurassic igneous rocks were penetrated at the base of the Coastal Plain where one would expect to find Suwannee Basin strata, suggesting that these volcanic rocks are probably younger and overlie the Suwannee Basin. Distinguishing NFVS rocks from younger volcanism is imperative, but pose a challenge because the NFVS rocks often exhibit some degree of hydrothermal alteration and/or weathering (Applin, 1951; Milton and Hurst, 1965; Milton and Grasty, 1969; Bass, 1969; Milton, 1972; Barnett; 1975; Chowns and Williams, 1983; Duncan, 1998). Another challenge when identifying NFVS rocks is that this layered volcanic sequence is frequently interbedded with thin clastic intervals, with one well in Florida penetrating a marker limestone bed within the NFVS (Milton, 1972; Chowns and Williams, 1983; Duncan et al., 1998). The basal member of the Suwannee Basin consists of a volcanic-clastic sandstone thought to have been derived from the Osceola Arc rocks (Duncan, 1998), introducing some complexity in distinguishing the Paleozoic sedimentary section from the older layered volcanic sequence using well cuttings.

The NFVS is laterally extensive beneath the Coastal Plain throughout northern Florida and southern Alabama, where the overlying Suwannee Basin sequence is thin or missing. The previously documented extent of the NFVS was limited to northwestern Florida based on five well penetrations (Heatherington and Mueller, 1996). The present study identifies 14 additional wells in the Florida Panhandle and southwestern Alabama that penetrated lithologically similar layered felsic volcanic rocks. Stratigraphically, the NFVS appears to reside consistently above intermediate to felsic intrusive rocks and below the Suwannee Basin strata. Generally, NFVS penetrations appear to cluster where the Suwannee Basin is missing and often in proximity to intrusive rocks of a known or inferred similar age. The consistent spatial relationship between NFVS rocks and plutons, in addition to geochronologic age constraints, suggests these rocks are pene-contemporaneous intrusive and extrusive igneous rocks (Chowns and Williams, 1983; Heatherington et al., 1996; Duncan, 1998) that record the construction of the Osceola Arc. In at least six wells (Well ID # 1, 5, 6, 12, 15, 19; Table 1; Fig. 3.1C) Paleozoic strata of the Suwannee Basin unconformably overlie volcanic rocks of the NFVS, providing a relative age of Cambrian-Precambrian for the NFVS. The westernmost penetration of the Suwannee Basin in well #15 (Table 1) has paleontological control documenting that the Suwannee Basin overlie rock identified as rhyolite (Neathery and Thomas, 1975; Guthrie and Raymond, 1992). This stratigraphic relationship of Suwannee Basin strata overlying NFVS is consistent from Florida to Alabama. Well #1 (Table 1) drilled the thickest succession of NFVS rocks penetrating more than 1,300 ft of layered volcanic rocks. Dip meter logs from this well document an angular unconformity between the underlying 58-60º dipping NFVS rocks and the overlying 6-8º dipping rocks of the Suwannee Basin. This angular unconformity is also apparent in seismic reflection data along COCORP profiles FL-1 and FL-2 where the Suwannee Basin strata thin towards the north (FL-1, Fig. 3.4) and south (FL-2) and the underlying reflections of the proposed NFVS (Arden, 1974) dip more steeply. The seismic reflection data support that the NFVS is laterally extensive with varying thicknesses; however, many of the industry boreholes were not deep enough to penetrate through the Suwannee Basin sequence into the NFVS. Most NFVS well penetrations are located along the edges of the preserved Suwannee Basin or along the axes of broad antiforms previously mapped (Duncan, 1998) within the Suwannee Basin. The NFVS rocks appear to reside consistently south of the BSZ and there is no indication of a major unconformity in offshore seismic reflection data, suggesting that if the NFVS was laterally continuous eastward it has been removed and/or deformed during the extension associated with the BHZ.

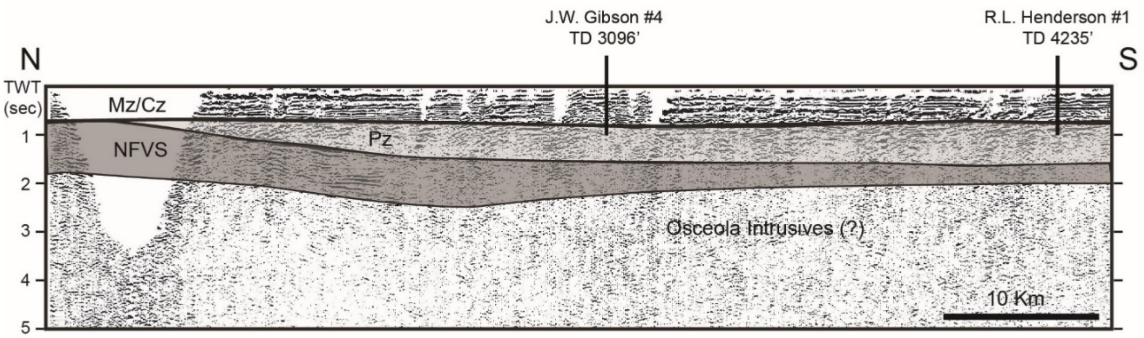

Figure 3.4. Reinterpreted shallow portion (upper 5 seconds; ~12 km) of COCORP FL-1 deep seismic reflection profile (Fig. 3.1) indicating angular unconformity between Paleozoic Suwannee Basin strata (Pz) and underlying layered volcanic rocks of the NFVS (modified after Nelson et al 1985a). MS/CZ denotes the Coastal Plain. Well locations encountering Suwannee Basin strata correspond to (a) and (b) in Figure. 3.1.

3.5.2 Osceola Arc Intrusive Rocks

Petroleum exploration efforts in the 1940's in central Florida revealed a large intrusive complex beneath the Coastal Plain in Osceola County, Florida. Subsequent exploration throughout the southeast established numerous plutons of inferred Precambrian age in the Suwannee terrane basement (Applin, 1951; Milton and Hurst, 1965; Milton and Grasty, 1969; Bass, 1969; Milton, 1972; Barnett; 1975; Neathery and Thomas, 1975; Winston, 1992a; Chowns and Williams, 1983; Dallmeyer et al., 1987; Winston, 1992; Mueller et al., 1994; Heatherington et al., 1996; Heatherington and Mueller, 1997; Duncan, 1998). While often generically labeled as “granite”, a closer evaluation of reported lithologies suggests many of the intrusive rocks cover a broader range in composition. This study integrates the distribution of inferred contemporaneous intrusive rock well penetrations with NFVS well penetrations to infer Osceola Arc magmatism comprises much of the Suwannee terrane basement.

Known or inferred Neoproterozoic plutons were encountered in 20 wells within the Suwannee terrane and record intrusive magmatism of the Osceola Arc. These intrusive rocks include the Osceola “Granite” in central Florida, the Gaskin “Granite” located in the Florida panhandle, and two previously unnamed plutonic complexes in southern Alabama. While these official names are consistent with published literature, the term granite is misleading because these intrusive rocks exhibit a variety of compositions from quartz monzonite to diorite to granodiorite. The Osceola intrusive complex in central Florida has compositions ranging from diorite to granodiorite and subcrops beneath the Mesozoic post-rift unconformity (PRU) in seven different boreholes (Fig. 3.1; Applin and Applin, 1965; Bass 1969; Milton and Grasty. 1969; Milton, 1972; Mueller et al., 1994; Heatherington and Mueller, 1996). The Gaskin granite of Winston (1992), encountered in well #20 (Table 1) in Gulf county, FL, was originally described as a granodiorite (Barnett, 1975). Three wells west of the Gaskin granite type well (well

#20) reportedly encounter felsic intrusive rocks (Barnett, 1975; Winston, 1992a) at similar depths, and based on proximity and structural level are interpreted to be part of the Gaskin intrusive complex named here. An unnamed intrusive in southwestern Alabama was drilled by well #35 (Table 1) and was described as an undeformed granodiorite by Mueller and others (2014) who conducted geochronological analyses. Three boreholes northeast of well #35 in Monroe County are documented to have compositions consistent with the well #35 intrusive (Neathery and Thomas, 1975; Guthrie and Raymond, 1992), but record significant strain, perhaps as a result of their proximity to the Alleghanian suture. Five wells southeast of the well #35 also encountered felsic intrusive rocks (Neathery and Thomas, 1975; Guthrie and Raymond, 1992) and all nine well penetrations are considered to delineate a large intrusive complex here named the Monroeville intrusive complex. A diorite in southeastern Alabama (Neathery and Thomas, 1975), here named the Dothan intrusive complex, is considered part of the Osceola Arc based on composition, proximity to an NFVS penetration, and most importantly observed nonconformity with overlying Suwannee Basin strata. Well #34 (Table 1) drilled through Suwannee Basin strata that was described as showing initial stages of low grade metamorphism into the Dothan intrusive complex, providing a relative age constraint of pre-Suwannee Basin deposition (Neathery and Thomas, 1975). While we cannot rule out a younger age for the Dothan intrusive complex, the lack of significant contact metamorphism in the overlying Suwannee Basin rocks implies a probable Precambrian age.

Intrusive rocks of the Osceola Arc are found within the Suwannee terrane and appear to be spatially associated with NFVS rocks. All of the Osceola Arc intrusive complexes are in close proximity to NFVS rocks and appear to construct the basement of the Suwannee terrane underlying the Suwannee Basin strata. The intrusive rocks consistently subcrop below the Coastal Plain where the NFVS and/or the Suwannee Basin strata are missing. These lithostratigraphic relationships between the intrusives, layered volcanic rocks, and overlying passive margin sequence of the Suwannee Basin provide spatial and temporal constraints on the evolution of the Osceola Arc system.

3.5.3 Geochemical Evidence for Continental Margin Arc

Published elemental analyses for the NFVS rocks (Milton and Grasty, 1969; Chowns and Williams, 1983; Mueller and Porch, 1994; Heatherington and Mueller, 1996) document calc-alkaline compositions, consistent with generation in an arc environment. The calc-alkaline compositions of the NFVS rocks distinguish them from the younger South Florida Volcanic Series (SFVS) (Heatherington and Mueller, 1997), as the latter are consistently richer in alkali elements (Mueller and Porch, 1983; Heatherington and Mueller, 1997).

Similarly, isotopic analyses of the NFVS rocks are compatible with development in a continental margin arc. Heatherington and Mueller (1996) documented the involvement of an enriched source for the NFVS rocks, indicating the arc formed on pre-existing continental lithosphere of at least Mesoproterozoic age. Osceola intrusive complex rocks have Sm-Nd depleted mantle model ages (Tdm) of 974, 1470, and 1531 Ma; Tdm for the Monroeville intrusive complex is 1023 Ma (well #34, Table.1), consistent with model ages reported for the NFVS (Heatherington and Mueller, 1996). One sample from the Osceola intrusive complex (well #24; Table.1) yielded U-Pb ages of 3.0 Ga for pre-magmatic zircons, consistent with calculated whole-rock Sm-Nd model ages of 3.36 Ga (Mueller et al., 1994; Heatherington and Mueller, 1996), suggesting the Suwannee basement may be a composite of Mesoproterozoic and Archean lithosphere (Heatherington and Mueller, 1996). Correlative elemental and isotopic signatures between NFVS volcanic rocks and the proximal intrusive complexes suggest that these rocks collectively constrain the location and evolution of the Osceola Arc along the Gondwanan continental margin.

3.5.4 Geochronologic Constraints

Radiometric dates for extrusive and intrusive rocks of the Osceola Arc provide critical evidence for the age and minimum life span of the arc. Initial efforts to date the igneous rocks of the Suwannee terrane began in the late 1960s using whole-rock Rb-Sr and K-Ar geochronologic methods (Bass, 1969). Early studies produced a range of dates from Neoproterozoic to early Paleozoic for NFVS and Osceola intrusive complex rocks (Bass, 1969; Milton and Grasty, 1969; Milton, 1972). However, significant alteration of some of the Osceola Arc rocks suggest that these whole-rock K-Ar dates do not provide reliable crystallization ages; however, the $^{40}Ar/^{39}Ar$ results likely do provide reliable cooling ages (Mueller and Porch, 1983; Dallmeyer, 1987; 1989b). Studies using $^{40}Ar/^{39}Ar$ (Dallmeyer, 1987) and U-Pb in zircon (Mueller et al., 1994; Heatherington and Mueller, 1996; Mueller et al., 2014) dating techniques produce more reliable age determinations. Published ages of the intrusive and extrusive rocks interpreted as part of the Osceola Arc range from approximately 625 Ma – 550 Ma, indicating a Neoproterozoic Osceola Arc.

Geochronologic data for the NFVS suggest a ~550 Ma age from two different localities in Florida. Heatherington and others (1996) determined an age of 552 ± 8 Ma for a dacite in the NFVS (well #6, Table. 1) using U-Pb zircon geochronology. Duncan

(1998) documented that these volcanic rocks underlie a section of ~350 feet of Suwannee Basin strata, although he inferred that the contact was structural based on the apparent missing stratigraphy between the two units. Whole rock K-Ar dating was completed on a probable andesite from the NFVS in a nearby well (well #1, Table. 1) for which Duncan (1998) reported a comparable age of 552 ± 21 Ma (Lloyd, 1985), although this age likely represents a cooling age minima.

Osceola Arc intrusive rocks have Neoproterozoic crystallization ages and are inferred to be the intrusive counterpart of the Osceola arc to the volcanic rocks of the NFVS. U-Pb geochronology on the Osceola intrusive complex yielded crystallization ages of ~600 Ma, 551± 6 Ma, and 551 ± 10 Ma for three well penetrations (wells 24, 26, and 30; Table. 1). An age of 551 Ma is considered the most well constrained crystallization age (Mueller et al., 1994; Heatherington and Mueller, 1996). ^{40}Ar/^{39}Ar dating of biotite concentrates reported for the Osceola intrusive complex suggest cooling ages of ~535-527 Ma (Dallmeyer et al.,1987). Other granitoids that may record an earlier phase of magmatism of the Osceola Arc or represent some older, unrelated, magmatic event include the Gaskin Intrusive complex (well #20, Table. 1) and the Monroeville intrusive complex (well #35; Table 1). The Gaskin intrusive complex was dated using K-Ar dating and had a reported age of 709 ± 24 Ma (Lloyd, 1985; Winston, 1992; Duncan, 1998). Mueller and others (2014) reported a ^{207}Pb/^{206}Pb age of 625 ± 6 Ma for Monroeville intrusive complex (well #35; Table 1) in southwestern Alabama.

The consistent Neoproterozoic ages of the Osceola Arc intrusive rocks and NFVS rocks suggest these rocks are the pene-contemporaneous intrusive and volcanic parts of the Osceola Arc that was active between ~625 - 550 Ma (Heatherington and Mueller, 1996; Duncan, 1998). The significantly older date from the Gaskin intrusive complex presents a few possibilities that: (1) if it cooled quickly the Gaskin intrusive complex may represent some unrelated, older magmatic event, (2) the Gaskin intrusive complex may actually represent the much older continental crust on which the Osceola Arc formed, or (3) the Osceola Arc may have been a long-lived subduction zone. At this time we have no reason to distinguish between the three scenarios, but the Gaskin intrusive complex is currently included in the extent of the Osceola Arc based on proximity to the laterally extensive NFVS rocks. Furthermore, a late Neoproterozoic origin for the Osceola Arc magmatic activity is stratigraphically consistent with the overlying, unconformable late Cambrian – early Ordovician to Devonian Suwannee Basin sequence. The spatial distribution of these Neoproterozoic arc rocks provides additional constraints on the age and origin of the BSZ.

3.6 CORRESPONDING SUBDUCTION ZONE AND CONTINENTAL MARGIN ARC

Evaluating the spatial relationship between the Osceola Arc rocks, BSZ, and overlapping Paleozoic Suwannee Basin sequence provides new insight into the tectonostratigraphic evolution of the Charleston and Suwannee terranes. Historically the age and origin of the structures associated with the BSZ have been the subject of considerable controversy. Integration of deep borehole penetrations within the Suwannee terrane and offshore seismic reflection data provides new constraints on the age of the BSZ. Two offshore wells (Transco 1005-1 and COST GE-1; T, C, Fig. 3.1) penetrate the PRU into Paleozoic sedimentary rocks that have been correlated with the onshore Suwannee Basin rocks (Poppe and Dillon, 1989) and substantiated by a previously unpublished proprietary palynological report (supplemental material of this study). The

Transco 1005-1 and COST GE-1 wells tie directly to seismic reflection line BA-3 offshore where the Suwannee Basin strata appear as sub-horizontal layered reflectivity below the PRU. The 1.5-2 sec TWTT of layered reflectivity below the PRU that is tied to the Gondwanan Paleozoic strata was mapped across the continental shelf (Boote and Knapp, 2016) and overlaps the BSZ (Fig. 3.3). The truncation of the BSZ in the upper crust by undeformed layered reflectivity tied to the Suwannee Basin sequence implies the formation of the BSZ must predate the early- to mid- Paleozoic Suwannee Basin passive margin sequence. Onshore in the Suwannee terrane, a detailed study of the lateral and stratigraphic changes of Suwannee Basin rocks and underlying Osceola Arc rocks provides additional insight into the likely age and tectonic origin of the BSZ. The Osceola Arc rocks were produced in a continental margin arc setting and the dip and location of the BSZ is consistent with recording the strain accommodated in the overriding plate of a subduction zone that produced the Osceola Arc magmatism. The integration of these data imply that the BSZ records a Neoproterozoic collision between the Charleston terrane and the Gondwanan (Suwannee) margin that was subsequently buried by the early Paleozoic Suwannee Basin passive margin sequence.

3.6.1 Early- to Mid- Paleozoic Suwannee Basin Strata Overlapping BSZ

Two offshore well penetrations (Transco 1005-1 and COST GE-1) and coincident seismic reflection data provide critical new age constraints on the BSZ. The Transco 1005-1 well penetrated the PRU at ~8,750 ft (2667 m) (Poppe and Dillon, 1989; Poppe et al., 1995; Boote and Knapp 2016; supplemental well report) and continued into a sequence of Paleozoic sedimentary rocks. The upper section of Paleozoic sedimentary rocks consists of Silurian (undifferentiated) strata that are constrained by several species of chitinozoans and acritarchs as well as the lack of trilete spores that indicate a pre-Devonian age (Poppe and Dillon, 1989; supplemental well report). Below the Silurian strata, Transco 1005-1 penetrated a lower Ordovician sequence around ~9,900 ft (3018 m) and the basal rocks at a TD of 11,635 ft (3,546 m) were constrained to be no older than early Ordovician based on the few palynomorph specimens observed (Poppe and Dillon, 1989; supplemental well report). The COST GE-1 well lacks biostratigraphic data below the PRU; however, seven whole rock samples yielded a Rb-Sr isochron age of 363± 7 Ma and K-Ar ages ranging between 346± 12 - 374± 14 Ma, providing what we suggest is a minimum age constraint on the Suwannee Basin rocks in this well (Scholle, 1979; Poppe et al., 1995). There appear to be lateral variations in age and thickness throughout the Suwannee Basin including the offshore; nevertheless, correlating the layered reflectivity below the PRU offshore to the Suwannee Basin has important implications for the underlying BSZ.

The Suwannee Basin strata can be identified in seismic reflection profile BA-3 as a sub-horizontal package of reflectivity below the PRU using the COST GE-1 and Transco 1005-1 well ties. There is a ~ 1.5 - 2 sec TWTT thick package of sub-horizontal reflectivity below the PRU landward of the BHZ that overlaps both the BSZ and BMA (Fig. 3.3, 3.4). The extent of the Suwannee Basin rocks seaward is limited by the BHZ, which is interpreted to be a major structural boundary formed by Mesozoic rift-related processes (Sheridan, 1974; Hutchinson et al., 1995). The sub-horizontal Gondwanan Paleozoic sequence can be identified as a relatively flat-lying sequence below the PRU in six of the BA profiles as shown on BA-6 (Fig. 3.3) this sequence lacks any significant compressional structures near the BSZ, suggesting it remained relatively undeformed throughout the Alleghanian collision.

The BSZ appears to be truncated in the upper crust by sub-horizontal reflectivity tied to the Suwannee Basin strata across all five BA profiles (example in Fig. 3.3; Oh et al., 1991) implying that the BSZ must, at minimum, pre-date the deposition of the early- to mid- Paleozoic sequence as originally suggested by Oh and others (1991). The tie between the Gondwanan Paleozoic rocks offshore and the Suwannee Basin onshore further suggest that there could be a significant succession of older Suwannee Basin strata below the well penetrations offshore. A schematic cross-section (B-B’, Fig. 3.6) highlights the relationship between the overlapping Suwannee Basin rocks and BSZ.

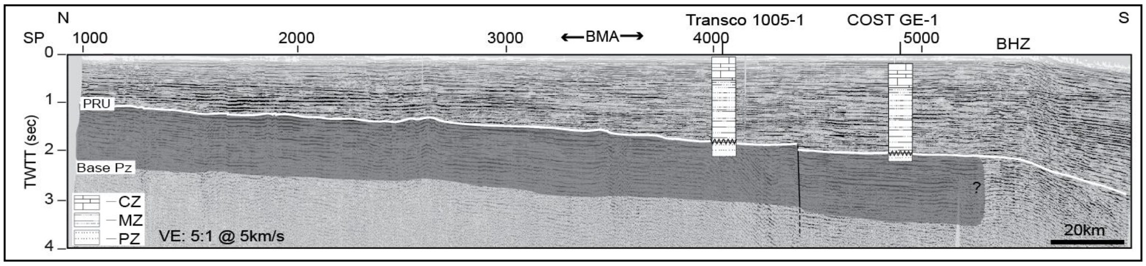

Figure 3.5. Reproduction of upper 4 seconds of BA-3 profile (modified after Boote and Knapp, 2016) showing correlation of Paleozoic strata in offshore wells (Transco 1005-1 and COST-GE1) with layered sequence of reflectors beneath the PRU. BMA marks position of Brunswick Magnetic Anomaly on profile. BHZ is Basement Hinge Zone. Zone.

3.6.2 Neoproterozoic Igneous Rocks of the Osceola Arc

The laterally extensive Neoproterozoic igneous rocks of the Osceola Arc in the Suwannee terrane provide additional important constraints on the age and origin of the BSZ. The spatial relationship between the southerly-dipping (present day coordinates) BSZ beneath the Suwannee terrane and the overlying arc-derived volcanic and plutonic rocks suggest that the BSZ represents the strain accommodated in the overriding plate

(Suwannee) following subduction and subsequent collision with the Charleston terrane along the Gondwanan margin (Fig. 3.6). A Neoproterozoic age for the BSZ is also consistent with the Suwannee Basin strata overlying the Osceola Arc rocks and continuing laterally across the Suwannee and Charleston terrane boundary (B-B’, Fig. 3.6). The integration of these data imply that the Neoproterozoic subduction zone beneath Gondwana and associated continental magmatic arc (Osceola Arc) are now preserved along the North American margin.

The geometry and location of the BSZ and spatial relationship with the presently mapped Osceola Arc rocks suggests a single genetic origin. The first appearance of dipping reflectivity associated with the BSZ is generally located north of the BMA and is inferred to record a zone of strain 25-50 km wide. The BSZ dips ~ 45º towards the south which is inferred to record the strain accommodated in the hanging wall (Suwannee terrane) during collision and reflect a geometry similar to the original subduction zone. Osceola Arc rocks are located approximately 100-350 km south of the BSZ within the Suwannee terrane, which is consistent with magmatism generated in a subduction zone located along or north of the BSZ with a similar southeast-dipping geometry. The age of Osceola Arc rocks range from ~625-550 Ma with suggested cooling ages as young as ~530 Ma (Bass, 1969; Dallmeyer et al., 1987; Mueller et al., 1994; Heatherington and Mueller, 1996; Heatherington and Mueller, 1997; Mueller et al., 2014). In this model, these rocks provide minimum age constraints of ~550 Ma for active subduction and melting and approximate the age of collision to be sometime in the late Neoproterozoic.

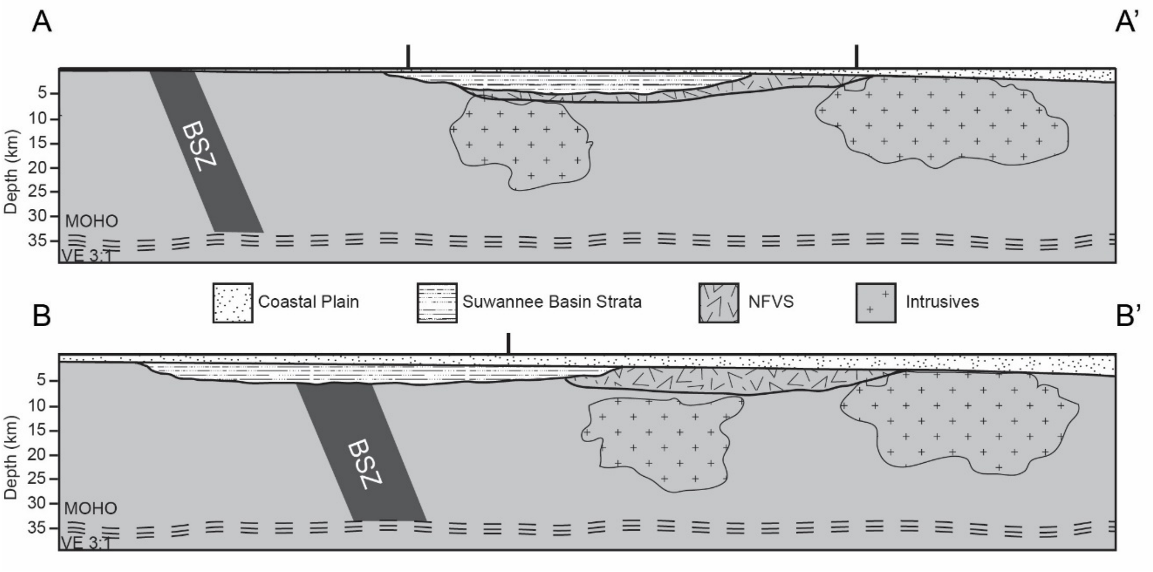

Figure 3.6. Schematic ~N-S cross-sections (A-A' and B-B') nominally perpendicular to Brunswick Suture Zone (BSZ) and Osceola Arc (NFVS and intrusives), illustrating relationship with younger Suwannee Basin strata (SBS). Offshore (B-B') SBS clearly overly BSZ; onshore (A-A') a similar relationship may exist but has not been confirmed with existing data. Refer to Figure. 3.1A for locations of cross-sections. Tick marks represent bends in section.

3.7 DISCUSSION

Re-evaluation of the tectonostratigraphic evolution of the Suwannee and Charleston terranes from seismic reflection and well data suggest a Neoproterozoic continental collision and that the associated continental margin arc is preserved in southeastern North America. Deep borehole penetrations in Florida, Alabama, and Georgia document a stratigraphic succession of Neoproterozoic intrusive rocks and coeval layered volcanic rocks of the NFVS, unconformably overlain by the passive margin sequence of the Suwannee Basin. The overlap of Suwannee Basin rocks across the BSZ offshore provides a minimum age constraint on the BSZ. Furthermore, the location and geometry of the BSZ demonstrate a consistent spatial relationship with the Neoproterozoic Osceola Arc rocks, providing additional constraints on the timing and tectonic origin of the BSZ.

3.7.1 Tectonic Reconstruction of the BSZ

The BSZ and associated Osceola Arc record a Neoproterozoic collision between the Charleston terrane and the Gondwanan continental margin (Suwannee). Three main phases of tectonism can be inferred from the strain recorded by the BSZ and the distribution of Osceola Arc and Suwannee Basin sedimentary rocks. These three phases are depicted in an evolutionary cartoon (Fig. 3.7) and include: (1) subduction and generation of arc magmatism, (2) collision and accommodation of strain during the formation of the BSZ, and (3) tectonic quiescence and deposition along Gondwanan passive margin.

Subduction and formation of the Osceola Arc initiated in the mid-Neoproterozoic and continued to generate arc magmatism until ~ 550 Ma ago (Fig. 3.7a). Elemental and isotopic data collected from Osceola Arc rocks suggest these rocks document the intrusive and volcanic magmatism of a continental margin arc (Mueller an Porch, 1994; Heatherington and Mueller, 1996). The Osceola Arc appears to define an arcuate belt within the Suwannee terrane indicating that this piece of crust resided along the Gondwanan continental margin as the overriding plate in a subduction zone (Fig. 3.7a). Osceola Arc rocks generally reside 100-350 km south of the BSZ. The location and southerly-dip of the BSZ is consistent with the expected location and geometry of a subduction zone that produced the Osceola Arc magmatism. Age constraints from Osceola Arc rocks suggest the arc was active from approximately 625 to 550 Ma. Once the Charleston terrane collided with Gondwana arc magmatism would have ceased.

The BSZ records strain accommodated in the overriding plate during the collision between the Charleston terrane and Gondwanan margin (Fig, 7b). Deep seismic reflection data reveal a S-SE dipping crustal-scale fabric that defines the location of the BSZ along the leading edge of the BMA. Therefore, the BSZ is inferred to record the collisional processes that occurred sometime between the cessation of magmatism around 550 Ma and the deposition of the basal sequence of the Suwannee Basin in the late Cambrian - early Ordovician. The timing of collision is consistent with the timing of two Gondwanan orogenic events, the Pan-African and Brasiliano orogenies, on the potential conjugate margins of West Africa and South America respectively (Dallmeyer et al., 1987; Heatherington and Mueller, 1997).

Deposition of the Suwannee Basin sequence began in the late Cambrian – early Ordovician and documents the formation of a passive margin along Gondwanan (Fig. 7c). The Suwannee Basin strata continue as a sub-horizontal sequence across the Suwannee and Charleston terranes demonstrating the quiescence of tectonic activity between the late Cambrian and early Devonian prior to the late Paleozoic Alleghanian collision. The early- to mid- Paleozoic strata contain faunal records exotic to the Laurentia that have previously been tied to the Bové basin along the conjugate West African margin (Dillon and Sougy, 1974; Chowns and Williams, 1983; Dallmeyer et al., 1987). Additionally, detrital zircon records from the Suwannee Basin indicate two dominant age groups that correspond to the Pan-African and Brasiliano orogenic cycles (~550-650 Ma) and the Birimian and Trans-Amazonian orogenic cycles (2100-2300 Ma) (Heatherington and Mueller, 1997; Mueller et al., 2014). While distinguishing between a West African or South American provenance is not yet possible, the Suwannee Basin detrital zircon record requires a Gondwanan origin.

The spatial distribution of the Neoproterozoic Osceola Arc rocks and overlapping Suwannee Basin strata constrain the formation of the BSZ to the late Neoproterozoic. Elemental and isotopic data from Osceola Arc rocks suggest a continental margin origin and information recorded in the Suwannee Basin rocks imply a Gondwanan origin. The synthesis of all these data indicate a Neoproterozoic Gondwanan continental margin arc and associated suture zone have been preserved throughout 1.5 Wilson cycles and now reside along the southeastern North American continental margin.

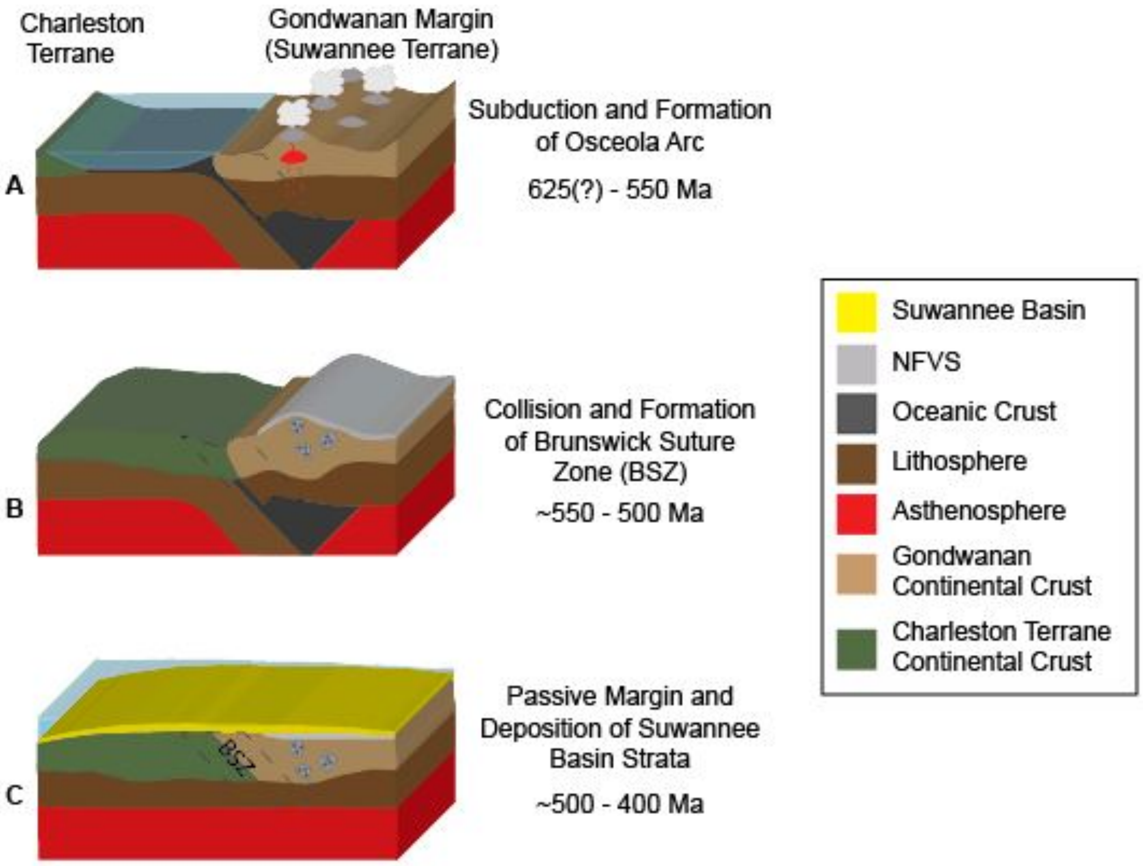

Figure 7. Cartoon depicting tectonic evolution of a Gondwanan continental margin (present day Suwannee) from mid-Neoproterozoic through early Devonian time. The Osceola continental margin arc evolved above a south-dipping (present coordinates) subduction zone, culminating in collision of the Charleston terrane with Gondwana/Suwannee and formation of the Brunswick Suture Zone. Subsequently, passive margin sediments (Suwannee Basin) buried the margin and suture zone.

3.7.2 Osceola Arc Provenance and Distribution

The tectonostratigraphic relationships and ages of the Osceola Arc and Suwannee Basin rocks appear consistent with those observed along present day conjugate margins that were once a part of the single supercontinent Gondwana (Dallmeyer 1987; Dallmeyer 1989a, b; Heatherington and Mueller, 1997; Duncan, 1998; Mueller et al., 2014). While the preserved Osceola Arc and associated BSZ should be correlable with other parts of Gondwana, such an analysis is beyond the scope of this paper. Nevertheless, late Neoproterozoic volcanic rocks are exotic to Laurentia, but coeval with the orogenic events of Gondwana (Pan-African and Brasiliano orogenic cycles) (Heatherington et al., 1996). The age and nature of these orogenic events are consistent with elemental and isotopic signatures of NFVS that indicate a continental arc setting (Heatherington et al., 1996; Heatherington and Mueller, 1997; Duncan, 1998). While it is difficult to make direct correlations to either West Africa or South America, the tectonic reconstruction proposed in this study is consistent with Pan-African or Brasiliano orogenic activity and is supported by dominant Pan-African or Brasiliano detrital zircons ages obtained from the Suwannee Basin strata (Heatherington and Mueller, 1997; Mueller et al., 2014). While this study is limited to the North American margin, correlation of Osceola Arc rocks with Neoproterozoic igneous rocks along conjugate margins could provide insight into the geometry of the Gondwanan margin prior to the Alleghanian collision. Additionally, recognition of these Neoproterozoic tectonic elements (BSZ and/or Osceola Arc) in other parts of Gondwana could place important new constraints on Neoproterozoic plate reconstructions.

3.8 CONCLUSIONS

The integration and synthesis of geological and geophysical data from deep boreholes and deep seismic reflection data provides new information about the tectonostratigraphic evolution of the Suwannee and Charleston terranes. Neoproterozoic intrusive and extrusive rocks of the Osceola Arc formed above the basement of the Suwannee terrane and are limited to the north by the BSZ. The Osceola Arc in conjunction with the BSZ record the magmatism and strain associated with subduction and subsequent collision of the Charleston terrane with the Gondwanan continental margin. The passive margin sequence of the Suwannee Basin can be mapped continuously from the Suwannee terrane to the Charleston terrane, overlapping the BSZ, providing a minimum early-Cambrian to late-Neoproterozoic age for the collision. These findings appear to resolve the debate surrounding an Alleghanian age for the BSZ.

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CHAPTER 4

PANGEAN TRANSCURRENT FAULT SYSTEM (PTFS) TRANSECTS ALLEGHANIAN SUTURE

The Late Paleozoic collision between Gondwana and Laurentia resulted in both thin-skinned tectonics accommodating significant shortening as well as the formation of transcontinental shear zones. The temporal and spatial relationships between these tectonic features remain critical to understanding the evolution of the Appalachian orogen. For more than 40 years, researchers have recognized the Eastern Piedmont Fault System (EPFS) as a network of late-stage Alleghanian dextral-slip shear zones. Integration of known structural measurements and geochronologic data with observations from aeromagnetic and seismic reflection data suggest that the Pangean Transcurrent Fault System (PTFS), that largely includes the previously identified EPFS, extends for at least 1500 km from Mississippi to Virginia representing one of the largest fault systems in eastern North America. The PTFS appears to represent a post-collisional tectonic boundary based on geochronologic data and observations of the PTFS crosscutting all of the Alleghanian tectonic boundaries of the Appalachian orogen. Lineations characteristic of structural features in aeromagnetic data appear to continue southwest from the originally interpreted EPFS along the PTFS and truncate both, magnetic anomalies and associated tectonic boundaries within Gondwanan continental crust, as well as the magnetic signature of the Appalachian orogen. Re-interpretation of seismic reflection data across the PTFS reveals new observations that mapped mylonitic shear zones at the surface correlate to a zone of moderately dipping reflectivity that penetrates the full thickness of the crust, supporting observations from aeromagnetic data that the PTFS represents a significant crustal boundary. Additionally, while the PTFS in Alabama and Georgia appears to separate Laurentian crust from Gondwanan crust, to the northeast the PTFS resides within the Carolina zone of Peri-Gondwanan origin, implying that this transcurrent fault network cannot represent the Alleghanian suture. The integration of these observations suggests that the PTFS represents a post-collisional feature that crosscuts regional structures internal to the Appalachian orogen and likely transects the previous plate boundary between Gondwana and Laurentia.

4.1 INTRODUCTION

Numerous proposed models for the tectonic evolution of the southern Appalachians try to address observations of significant shortening as well as dextral, strike-slip displacement and relate those tectonic features to the former plate boundary between Gondwana and Laurentia. Orogen-scale strike-slip shear zones are thought to form from either: (1) oblique movement between the two plates during initial collision (Hatcher, 2010), (2) “escape” tectonics at the periphery of a head-on collision that may or may not include a rigid “indenter” (Bobyarchick, 1981), or (3) post-collisional “dispersal” resulting from changes in stress and/or plate motion following accretion (Bobyarchick, 1988). Throughout the Appalachian orogen dextral, strike-slip fault networks have been recognized for decades; however, they have been interpreted to form in a full range of tectonic scenarios resulting in considerable scientific debate surrounding the evolution of the Appalachian orogen. This study integrates known structural and geochronologic constraints with new observations from aeromagnetic data and seismic reflection data to demonstrate that the eastern-most transcurrent fault network, here termed the Pangean Transcurrent Fault System (PTFS), represents a post-collisional network of dextral shear zones that modify the southern Appalachians and likely transects the long-sought-after Alleghanian suture.

4.1.1 Alleghanian Structural Features in the Southern Appalachians

Both geological and geophysical observations document a strong overprint of polyphase Alleghanian deformation throughout the southern Appalachians. For more than 40 years, researchers have recognized three main transcurrent fault zones internal to the Appalachian orogen in the southeastern United States, including the Brevard Zone (Reed and Bryant, 1964; Vauchez, 1987; Bobyarchick, 1988; Gates et al., 1988), a zone in the central Piedmont that includes the Towaliga fault, Central Piedmont Suture (CPS), and Brookneal zone (Bobyarchick, 1988; Gates et al., 1988), and lastly, the Eastern Piedmont Fault System (EPFS) (Hatcher et al., 1977; Bobyarchick, 1981; Bobyarchick, 1988; Gates et al., 1988). In addition to the regionally extensive shear zones, the Master Appalachian Decollement (MAD) is interpreted to reside in the upper crust beneath the Valley and Ridge fold and thrust belt, the Blue Ridge, and most of the Piedmont (Cook et al., 1979; Cook et al., 1981; Behrendt, 1985; Nelson et al., 1985a; Behrendt, 1986; McBride and Nelson, 1988; McBride, 2005; Hatcher et al., 2007). The MAD is thought to accommodate estimates of more than 1000 km of NW directed shortening along the detachment and associated thrust faults (Hatcher, 1987; Gates et al., 1988), including at least 210 km of documented shortening in the Valley and Ridge province (Hatcher et al., 2007). Many of the structures that were active during the Alleghanian, which include the reactivation of early- to mid- Paleozoic structures, record a polyphase deformational history in the late Paleozoic (Bobyarchick, 1981; Secor et al., 1986a, b; Hatcher, 1987; Gates et al., 1988; Bobyarchick, 1988). Understanding the timing and type of deformation in the southern Appalachians is critical to understanding the evolution of this margin and the location of the former plate boundary.

The Alleghanian orogeny occurred between the Late Carboniferous and Permian (~325-260 Ma), with evidence for initial deformation of the North American plate starting as early as 327 +/- 21 Ma inferred from the development of clastic wedges (Secor et al., 1986b; Chestnut,1991). The transcurrent fault systems (Brevard, Central Piedmont, EPFS) in the southern Appalachians appear to have been penecontemporaneous with or post-date the observed shortening since activity along the shear zones generally clusters between 300-260 Ma, representing post-collisional activity (Secor et al., 1986a, b; Bobyarchick, 1981; Hatcher, 1987; Bobyarchick, 1988). This timeline constrained by geochronologic data is in direct conflict with recent tectonic models that suggest these transcurrent fault systems formed during oblique collision between Gondwana and Laurentia that then rotated into a head-on collision (Hatcher et al., 2010; Hopper et al., 2017). Other tectonic models suggest that the collision between Gondwana and Laurentia was largely a transpressional boundary and have identified the suture in eastern Alabama and western Georgia along faults constructing the previously identified EPFS (now included in the PTFS) (Steltenpohl et al., 2008; Mueller et al., 2014; Boote and Knapp, 2016). While identifying the Alleghanian suture zone is out of the scope of this study, integration of known structural and geochronologic data with new observations from geophysical data suggests that the transcurrent fault systems are post-collisional and actually truncate the southern Appalachian orogen. These results imply the newly define PTFS is not the Alleghanian suture and likely transects the former plate boundary, providing new constraints on future tectonic models and plate reconstructions.

4.2 PANGEAN TRANSCURRENT FAULT SYSTEM (PTFS)

The PTFS extends for more than 1500 km along the eastern North America margin as a series of Alleghanian dextral shear zones, making it one of the largest fault systems in North America (Fig. 1). Integration of known structural and geochronologic data with new observations from aeromagnetic and seismic reflection data document the location, extent, geometry, and age of the orogen-scale fault network. The surficial expression of the PTFS includes the majority of the structures previously identified as the EPFS (Hatcher et al., 1977) and can be readily identified in aeromagnetic data as a zone of higher frequency, linear magnetic anomalies. Towards the southwest, the PTFS narrows and appears to truncate the magnetic signatures of features internal to Laurentian and Gondwanan crust. Prolific late Paleozoic magmatism in this region provides age constraints documented in the literature on the kinematic evolution of PTFS providing additional documentation that these shear zones formed during the latest stages of the Alleghanian (Bobyarchick, 1981; Gates et al., 1988) and likely document post-collisional "dispersal" processes (Bobyarchick, 1988). Re-interpretation of six regional seismic reflection transects reveal a consistent SE-dipping crustal fabric penetrates the entire thickness of the crust and correlates to the PTFS and previously identified shear zones at the surface. Both in seismic reflection data and aeromagnetic data, PTFS appears to truncate all of the Alleghanian (and older) tectonic boundaries internal to Laurentian and

Gondwanan crust, supporting that the transcurrent fault network documents post-collisional activity.

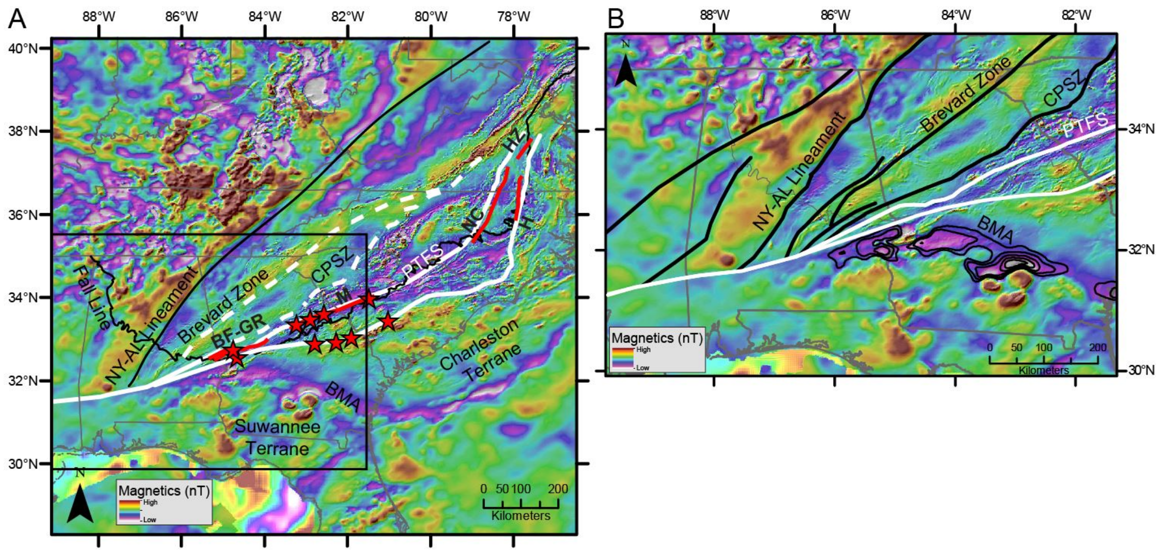

Figure 4.1: (A) Magnetic anomaly map of southeastern North America identifying Pangean Transcurrent Fault System (PTFS; white solid lines) and control points (red stars) from seismic reflection data (line locations indicated in Figure. 2 inset map).. Shear zones identified at the surface bounding the PTFS identified as red lines (BF-GR = Bartletts Ferry-Goat Rock, M=Modoc, NC= Nutbush Creek, H=Hollister, HZ=Hylas). White dotted lines indicated other transcurrent fault systems internal to the orogen including the Brevard Zone and Central Piedmont Shear Zone (CPSZ). BMA= Brunswick Magnetic Anomaly. NY-AL Lineament = New York-Alabama Lineament. Black box indicates extent of zoomed-in location map (Fig. 4.1B). (B) Large-scale magnetic anomaly map highlighting truncation of Appalachian and Gondwanan (i.e. BMA) magnetic anomalies (outlined in black) and associated structural features by the PTFS (white).

4.2.1 Known Faults and Geochronologic Data

Previously identified shear zones of the EPFS associated with the PTFS include the: Goat Rock shear zone, Bartlett's Ferry shear zone, Modoc shear zone, Nutbush Creek shear zone, Hollister shear zone, Hylas shear zone, and various unnamed high strain zones (Fig. 1) (Hatcher, 1977; Bobyarchick and Glover, 1979; Bobyarchick, 1981; Bobyarchick, 1988; Gates et al., 1988; Gates and Glover, 1989). The EPFS extends from

Alabama to Virginia, but has historically been limited to linear magnetic anomalies associated with structures that outcrop at the surface (north and west of the Fall Line) (Hatcher et al., 1977). While nearly the entire EPFS is included within the PTFS, this study uses additional observations from seismic reflection and aeromagnetic data to extend the interpreted transcurrent system south and east of the Piedmont, requiring the abandonment of the term EPFS.

The known faults of PTFS at the surface define major lithotectonic boundaries that record late-stage dextral, strike-slip displacement constrained by syn- and post-kinematic plutons (Hatcher, 1977; Bobyarchick and Glover, 1979; Secor et al., 1986a, b; Bobyarchick, 1988). Geochronologic constraints for dextral shearing provided by intrusions are as follows: Modoc deformation constrained between 290-268 Ma, Nutbush Creek deformation constrained between 312-285 Ma, Hollister deformation syn-kinematic with 292 Ma pluton, Hylas shear zone post-dates 330 Ma and continued through 260-250 Ma (Secor et al., 1986a; Gates et al., 1988). While detailed geologic mapping suggests many of these structures formed prior to or during the early stages of the Alleghanian and often record earlier deformation, they all record a consistent late-stage Alleghanian, dextral, strike-slip strain (Hatcher et al., 1977; Bobyarchick, 1981; Secor et al., 1986a, b; Bobyarchick, 1988; Gates et al., 1988; Gates and Glover, 1989).

4.2.2 Aeromagnetic Data and Temporal Constraints

Temporal constraints on the PTFS provided by geochronologic data are consistent with the crosscutting relationships observed in the magnetic anomaly map (Fig. 1). A zone of linear magnetic anomalies of variable strike characterized the PTFS in aeromagnetic data. These linear anomalies denote a boundary that is largely discordant with the magnetic lineations both in Gondwanan and Laurentian crust that define major tectonic boundaries. Towards the southwest, the PTFS and associated magnetic anomalies truncate that Appalachian orogen's magnetic signature, as well as the Brunswick Magnetic Anomaly (BMA) at a high angle. The higher-frequency pattern of the inferred structures associated with the PTFS range in strike from NE-SW (parallel to the origin), to nearly E-W in South Carolina, to nearly N-S in North Carolina and Virginia (Fig. 1). However, the expression of the PTFS does not appear to be limited to the upper-most crust in aeromagnetic data.

Broader wavelength magnetic anomalies associated with major tectonics boundaries, similar to the ones discussed herein, are thought to be produced from within the mid- to upper-crust (in particular, above the Curie temperature). In the southeast, the trace of the PTFS in aeromagnetic data appears to truncate both the N-NE to S-SW anomaly pattern of the orogen and the Brunswick Magnetic Anomaly BMA, implying the PTFS represents a major crustal boundary (Fig. 1). The magnetic features characteristic of the Blue Ridge and inner Piedmont along with other major fault systems including the New York-Alabama (NY-AL) lineament (King and Zietz, 1978; Horton et al., 1984), Brevard zone, Central Piedmont shear zone are truncated by the nearly orthogonal trace of the PTFS in western Alabama (Fig. 1), consistent with previous interpretations (Horton et al., 1984; Steltenpohl et al., 2013). This crosscutting relationship suggests that the transcurrent features that construct the PTFS largely post-date the formation of the Appalachian orogen and transect many those features during the late-stages of the Alleghanian.

Similarly, the PTFS truncates the BMA at a high angle in western Georgia and eastern Alabama. Previous work suggests the BMA is internal to Gondwanan continental crust based on the overlapping early- to mid- Paleozoic Gondwanan Suwannee basin strata offshore (Oh et al., 1991; Boote and Knapp, 2016). The PTFS sharply truncates the prominent magnetic low associated with the BMA which is also supported by interpretations from seismic reflection data in this region. The combination of geochronologic data with observed crosscutting relationships in the magnetic anomaly map, strong support a post-collisional origin for the PTFS.

4.2.3 Seismic Reflection Data

Seismic reflection data plays an important role in interpreting tectonic boundaries in southeastern North America where the Coastal Plain covers a significant amount of the region. Re-interpretation of six seismic reflection transects across the PTFS, reveals a previously un-recognized southeast-dipping crustal fabric that penetrates the full thickness of the crust (Fig. 2). While not presented in this study, Gates and others (1989) identified a similar zone of east-dipping reflectivity beneath the Hylas shear zone in Virginia that appears to be consistent with the fabric identified along the PTFS in southeastern North America. Alleghanian transcurrent faults identified further northwest (Brevard Zone and Central Piedmont) appear to sole into the MAD, consistent with previous interpretations (Cook et al., 1979; Cook et al., 1981; Behrendt, 1985; 1986; Bobyarchick, 1988) whereas the PTFS appears to represent a fundamentally different boundary, extending all the way to the Moho.

The seismic reflection transects that image the proposed PTFS include three Seisdata lines (S4, S6, S8; Figs. 1 and 2) collected by the United States Geological

Survey (USGS) with record lengths of six or eight seconds (Behrendt, 1985; 1986) and three crustal-scale Consortium for Continental Profiling (COCORP) transects (Figs. 1 and 2), COCORP GA-5 and GA-8 (Cook et al., 1981; Cook and Vasudevan, 2006), COCORP GA 21 and 19, and COCORP GA 15, GA-14, and GA-13 (Nelson et al., 1985a,b; McBride and Nelson 1988; McBride et al., 2005). All six of these transects traverse a region from the northwest, where autochthonous Laurentian crust is interpreted, to the southeast, where the regional transects cross into Gondwanan continental crust of the Charleston and Suwannee terranes (Boote and Knapp, 2016). This study re-interprets the previously published line drawings created from the unmigrated seismic reflection profiles for all six transects and includes portions of these lines in Figure 2. While line drawings are interpretive by nature, they provide a good way to capture and present the principal features observed in seismic reflection data.

Integration of these legacy seismic reflection data with previously mapped surface geology (Hatcher, 1977; Bobyarchick, 1981; Secor et al., 1986a, b; Gates et al., 1988; Secor et al., 1986a, b; West et al., 1995; Hibbard et al., 2002; Steltenpohl et al., 2008) suggests that the northwestern boundary of a SE dipping crustal-scale fabric is largely coincident with the series of Alleghanian mylonitic shears zones that construct the PTFS. Along strike, the Modoc shear zone and the Bartletts Ferry-Goat Rock shear zones consistently limit the northwestern boundary of the dipping crustal fabric interpreted to represent the PTFS in the subsurface. The seismic reflection data (Fig. 2) is aligned on the northwestern edge of the tectonic boundary associated with the outcropping of these shear zones to compare and contrast changes observed in the identified dipping crustal fabric. Eastern and western boundaries of the PTFS derive from projecting the dipping crustal fabric of the observed PTFS to the near surface location and then plotting those points on the location maps (star symbols, Figs. 1 and 2). Mesozoic modification of the upper crust can be observed in a few of the profiles, specifically GA-8 where the Triassic Riddleville basin overprints the PTFS beneath the Coastal Plain (Cook et al., 1981; Cook and Vasudevan, 2006), requiring the projection of the dipping fabric to a consistent near-surface location for plotting on the location map (Fig.1 and 2). Additionally, the base of the Coastal Plain is indicated on all six-seismic reflection transects (Fig. 2) as a gently dipping surface southeast of the fall line, highlighting that along strike towards the northeast a good portion of this tectonic boundary is buried beneath the Coastal Plain sedimentary package, emphasizing the need for alternative geophysical methods, such as aeromagnetic data.

In addition to providing control points for the western and eastern boundaries of the PTFS (Figs. 1 and 2), seismic reflection data provides a good estimation for the dip of the PTFS. The seismic reflection profiles are presented (Fig. 2) at an approximate vertical to horizontal ratio of 1:1 using a constant average velocity of 6 km/s to convert time (sec) into depth (km). Without any vertical exaggeration, these features should be displayed at their approximate true dip; however, these data are unmigrated so some of the features may shallow and steepen slightly after migration and the dips presented in this study should be taken as minimum estimates.

The observations from seismic reflection data suggest the proposed PTFS can be identified as a continuous crustal-scale tectonic mélange with a consistent dip towards the SE for approximately 350 km from the southwestern-most COCORP transect to transect S4. The PTFS in the upper crust observed in all three Seisdata profiles has fairly similar dips ranging between ~15-30º. While the Seisdata profiles are limited in record length, there is little reason to believe that the PTFS significantly changes dip at depth, therefore, we suggest these dips are representative of the entire tectonic boundary, including the lower crust. The three COCORP transects image a transparent upper crust, and therefore

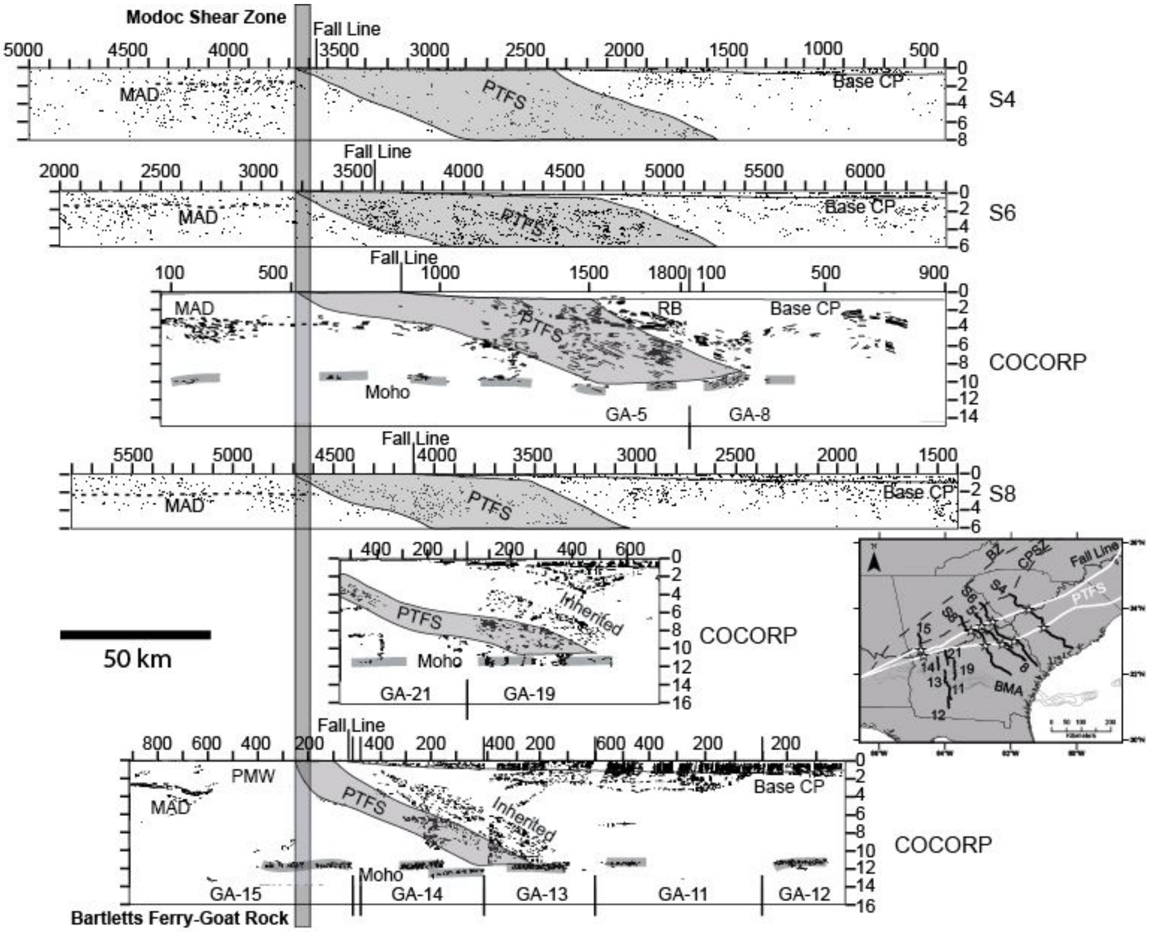

Figure 4.2: Six seismic reflection transects displayed at 1:1 vertical to horizontal scale with interpretation of the PTFS (gray overlay). Seismic reflection data is aligned on the northwestern boundary of the PTFS coincident with the Modoc and Bartletts Ferry-Goat Rock shear zones. Inset map identifies location of transects in relationship to PTFS. MAD = Master Appalachian Decollement, CP = Coastal Plain, RB = Riddleville Basin. BMA = Brunswick Magnetic Anomaly.

the interpretation is non-unique; however, constraints from the mid- to lower-crust suggest the PTFS dips moderately towards the southeast 20-40º on all three transects.

These data also support the interpretation that the transcurrent systems further northwest (Brevard zone and Central Piedmont Suture) sole into a sub-horizontal detachment. A sub-horizontal feature identified between 2-3 sec two-way travel time (TWTT) northwest of the PTFS in profiles GA-15, GA-5, S8, and S6, is consistent with previous interpretations of the MAD in these reflection data (Cook et al., 1979; Cook et al., 1981; Behrendt, 1985, 1986). The MAD has previously been interpreted to continue southeast beneath the Charleston and Suwannee terranes (Hatcher, 2010; Hopper et al., 2017), which this study does not support nor refute; however, we would suggest the PTFS must post-date and overprint the detachment if it were to continue towards the southeast.

Not only does the PTFS appear to overprint the MAD in seismic reflection data, but it also appears to truncate the inherited tectonic boundary observed in Gondwanan continental crust associated with the Brunswick Magnetic Anomaly (BMA). The two southern most COCORP transects (GA 15-14-13 and GA 21-19) image two discordant zones of dipping crustal reflectivity. The surface location of the PTFS in eastern Alabama and western Georgia correlates to the more shallowly dipping package of reflectivity, which we suggest is overprinting the older crustal fabric that is overlapped and constrained by the sub-horizontal early- to mid- Paleozoic Gondwanan rocks offshore (Boote and Knapp, 2016).

4.3 PTFS MODIFICATION OF PANGEA AND IMPLICATIONS FOR ALLEGHANIAN SUTURE

Observations from both geological and geophysical data suggest the PTFS represents a crustal-scale post-collisional transcurrent fault system that truncates all tectonic features southern Appalachian orogen. These observations are consistent with the previous tectonic model purposed by Bobyarchick (1988) that orogen-scale transcurrent fault systems can be attributed to “dispersal” tectonics following the initial accretion phase during collisional. Age and tectonostratigraphic constraints imply the PTFS cannot be the Alleghanian suture and likely transects the former Gondwanan-Laurentian plate boundary. These new findings create additional challenges for identifying the Alleghanian suture and creating future plate reconstructions.

Age constraints provided by syn-deformational and post-deformational plutons suggests the shear zones that comprise the PTFS record late-stage Alleghanian dextral strike-slip movement. These observations at the surface are consistent with observations from aeromagnetic data that suggest both magnetic anomalies internal to Gondwanan continental crust as well as the N-NE to S-SW trending features of the Appalachian orogen (ex. NY-AL lineament) are truncated by PTFS in southeastern North America. Seismic reflection data further supports the interpretation from that the PTFS truncates both Laurentian continental crust and Gondwanan continental crust. The crustal-scale dipping reflectivity of PTFS appears to overprint and/or truncate the sub-horizontal feature interpreted to represent the MAD that formed within Laurentian continental crust. Additionally, the crustal fabric of the PTFS appears to overprint the dipping crustal-fabric previously associated with the BMA (Nelson and McBride, 1988; Oh et al., 1991), in Georgia.

Previous researchers have interpreted this tectonic boundary in eastern Alabama and western Georgia to represent the Alleghanian suture; however, this study's results suggest the PTFS cannot be the Alleghanian suture. Interpretations of this tectonic boundary as the Alleghanian suture were largely based on similar observations from aeromagnetic data (Horton et al., 1984) as well as the juxtaposition of Grenville-age crust interpreted to be Laurentian against Gondwanan continental crust of the Suwannee terrane (Steltenpohl et al., 2008; Mueller et al., 2014; Boote and Knapp, 2016). While this interpretation appears valid at this location, along strike the PTFS separates crust of a decidedly different tectonostratigraphic origin. For example, in North Carolina, the PTFS lies entirely within the Carolina Zone as defined by Hibbard and others (2002), which is a collage of tectonostratigraphic terranes accreted prior to the collision between Laurentia and Gondwanan in the late Paleozoic. Therefore, while the PTFS appears to represent the boundary between Gondwana and Laurentia in the southeast, somewhere along strike it must transect the plate boundary between Gondwana and Laurentia before becoming a post-collisional boundary within the Carolina Zone. The PTFS appears to capitalize on previous zones of weakness that are optimally oriented to accommodate the changes in stress and/or plate motion following accretion, but transects other major tectonic boundaries, including the former plate boundary between Gondwana and Laurentia.

These finding suggest that locating the Alleghanian suture may be more challenging than previously thought, if an intracontinental transcurrent fault system has subsequently modified early-Alleghanian tectonic features. While estimates of displacement along individual faults is generally < 50 km (Gates et al., 1988), the PTFS as a system may have displaced the former plate boundary a significant distance away from where the observed juxtaposition of Gondwana and Laurentia appears today in western Georgia and Alabama. Identifying key equivalent tectonostratigraphic terranes and/or tectonic features on either side of the PTFS, including the Alleghanian suture, could provide estimations of the amount of offset on the PTFS.

4.4 CONCLUSIONS

The PTFS is one of the largest fault systems in eastern North America reaching > 1500 km that formed in the late Paleozoic and truncates multiple tectonic boundaries in southeastern North America. New observations from aeromagnetic data and seismic reflection data suggest this boundary extends throughout the full thickness of the crust and crosscuts that Appalachian magnetic signature, as well as truncates the BMA internal to Gondwana continental crust. While previously thought to be the Alleghanian suture in eastern Alabama and Georgia, this boundary resides solely in Peri-Gondwanan crust to the northeast implying: (1) it cannot be the Alleghanian suture and (2) somewhere along strike this tectonic boundary must transect the former plate boundary between Gondwana and Laurentia.

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CHAPTER 5

CONCLUSIONS

The three tectonic studies presented in Chapters 2-4 resolve a number of long-standing controversies concerning the crustal and lithospheric evolution of southeastern North America. New interpretations derived from legacy seismic reflection, seismic refraction, well, and aeromagnetic data document the age and origin of two tectonic boundaries, the BSZ and PTFS, as well as explore the relationship between boundaries and the Osceola Arc and Suwannee Basin rocks. These features provide new constraints on the tectonostratigraphic evolution of southeastern North America and document that while > 800,000 km^2 of Gondwanan continental crust survived a full Wilson cycle and is still identifiable along the United States Atlantic margin, post-collisional transcurrent faulting has subsequently modified the southern Appalachian orogen.

The revised extent of the Suwannee Basin strata presented in Chapter 2 implies that both the Charleston and Suwannee terranes represent Gondwanan continental crust and must have been amalgamated prior to the Alleghanian collision. As a result, the revised extent of Gondwanan continental crust preserved in southeastern North America is > 800,000 km^2, nearly doubling the size of previously interpreted Gondwanan continental crust. Moreover, this study suggests the late Paleozoic suture between Gondwanan and Laurentia must be located further to the northwest and the previously interpreted suture between the Charleston and Suwannee terranes (BMA), must pre-date the deposition of the Suwannee Basin passive margin sequence.

Further investigation into the boundary between the Charleston and Suwannee terranes in Chapter 3 demonstrates that the preserved dipping reflectivity of the BSZ along their boundary, long-interpreted to be the Alleghanian suture, represents a Neoproterozoic suture zone. The Suwannee Basin strata overlap the BSZ providing minimum age constraints of early Cambrian on the tectonic boundary. Additional investigation into the Suwannee terrane basement rocks suggest that the BSZ has a consistent geometry and spatial relationship with the generation of a series of Neoproterozoic volcanic and intrusive rocks, identified as the Osceola Arc. As a result, the BSZ is inferred to represent the Neoproterozoic subduction zone that generated the Osceola Arc magmatism and the associated collision between the Charleston terrane and Gondwana. These findings provide a plausible explanation for the tectonic fabric associated with the BMA and resolve the debate surrounding an Alleghanian age for the BSZ.

Synthesis of onshore seismic reflection data and aeromagnetic data with published geochronologic and geologic data reveals a post-collisional transcurrent fault system, termed the PTFS, transects the BSZ as well as the Alleghanian suture in southeastern North America. The PTFS represents one of the largest fault systems in eastern North America stretching more than 1500 km and crosscutting the NE-SW Appalachian magnetic signature in Mississippi and Alabama. Contrary to previous interpretations, this study demonstrates the PTFS traverses crust of various affinity (Laurentia, Gondwanan, and Peri-Gondwanan), cannot represent the Alleghanian suture, and likely transects the

Alleghanian suture. The results of the research presented in this dissertation provide new temporal and spatial constraints on future tectonic models as well as plate reconstructions for the late Paleozoic.

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