Sourcing Neo-Acadian Inner Piedmont Granitoids within the Southern Appalachians

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A thesis submitted to the faculty at the University of North Carolina at Chapel Hill in partial fulfillment of the requirements for the degree of Earth Systems in the Geological Sciences Department in the UNC College of Arts and Sciences.

Chapel Hill

2022

Approved By:

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ABSTRACT

New whole-rock U/Th/Pb, Sm-Nd and Rb-Sr isotopic data are presented from meta-granitoids, gabbros, and meta-sedimentary rocks within the eastern Blue Ridge, Inner Piedmont, and Charlotte belts of the southern Appalachians. Data from this study, combined with published data from the Tugaloo and Carolina Super terranes, further demonstrate the character of the proposed "Neo-Acadian" Orogeny and its signature in the southern and central Appalachians. Radiogenic isotopic data support a crustal source for Neo-Acadian Inner Piedmont granitoids. Although Nd isotopic fingerprints from Tugaloo and Carolina Super terrane rocks overlap with Neo-Acadian Inner Piedmont granitoids, the range of compositions projected by the two sources is so wide that Nd isotopic compositions alone cannot test the hypothesis that the magmas were derived by anatexis of the Cat-Square terrane. The lack of published isotopic data for metasedimentary rocks, combined with a lack of radiogenic isotope data for Inner Piedmont granitoids, stifles any exploration of the anatexis hypothesis of the Cat-Square terrane. Moreover, radiogenic isotopic data support the idea that Eastern Blue Ridge rocks are derived from a mixed source of both crustal and mantle components. Mixing of a mafic component from the Charlotte belt, believed to have come from the depleted mantle, and felsic components from the eastern Blue Ridge produces an array of isotopic compositions observed in both belts.

INTRODUCTION

The history of Appalachian orogenies, including the origin of granitic rocks in southern Appalachia are debated (Fig. 1). Hypotheses for their origin that invoke crustal melting (e.g., Coler et al., 1997; Speer et al., 1994; Fullagar et al., 1997) gained traction within the last thirty years. Strontium isotope data (e.g., Odom and Fullagar, 1973) are widely available for rocks from the southern Appalachians; however, Sr systematics are susceptible to disruption during metamorphism and weathering. In contrast, Nd isotopes are less susceptible to disruption and data have recently been obtained and are being used to differentiate between crustal and mantle sources of granitic rocks in the southern Appalachians (Fullagar et al., 1997; Bream et al., 2002, 2008; Hatcher et al., 2004; Dasgupta et al., 2008; Quinn et al., 2012). Lead isotope data, that may be used to differentiate between upper crustal and lower crustal affinity (e.g., Zhang et al., 2016) and among crustal provenances (e.g., Blichert – Toft et al., 2016), have also recently been published (Fisher et al., 2010). Moreover, recent advances in geochronology are refining age controls on the rocks and helping to refine hypotheses for the origins of the granites (Miller et al.; 2006, Miller et al.; 2010; Gatewood et al.; 2006, Winchester ;2013, Merschat et al.; 2010).

What little Nd and Pb data are reported for southern Appalachian granitic rocks fail to provide a comprehensive and robust data set to confidently assess magma sources. Available data sets are biased with samples from the Blue Ridge, Carolina Slate, Raleigh, Charlotte, and Eastern Slate belts due to better exposure and abundance of plutonic rocks (e.g., Bream et al., 2002, 2004, 2008; Coler et al., 1997; Hatcher et al., 2004; Miller et al., 1997; Samson et al., 1995; Speer et al., 1994; Quinn et al., 2012). There is a dearth of isotopic data for rocks within the Inner Piedmont belt with the exception of the data in Fullagar et al. (1997).

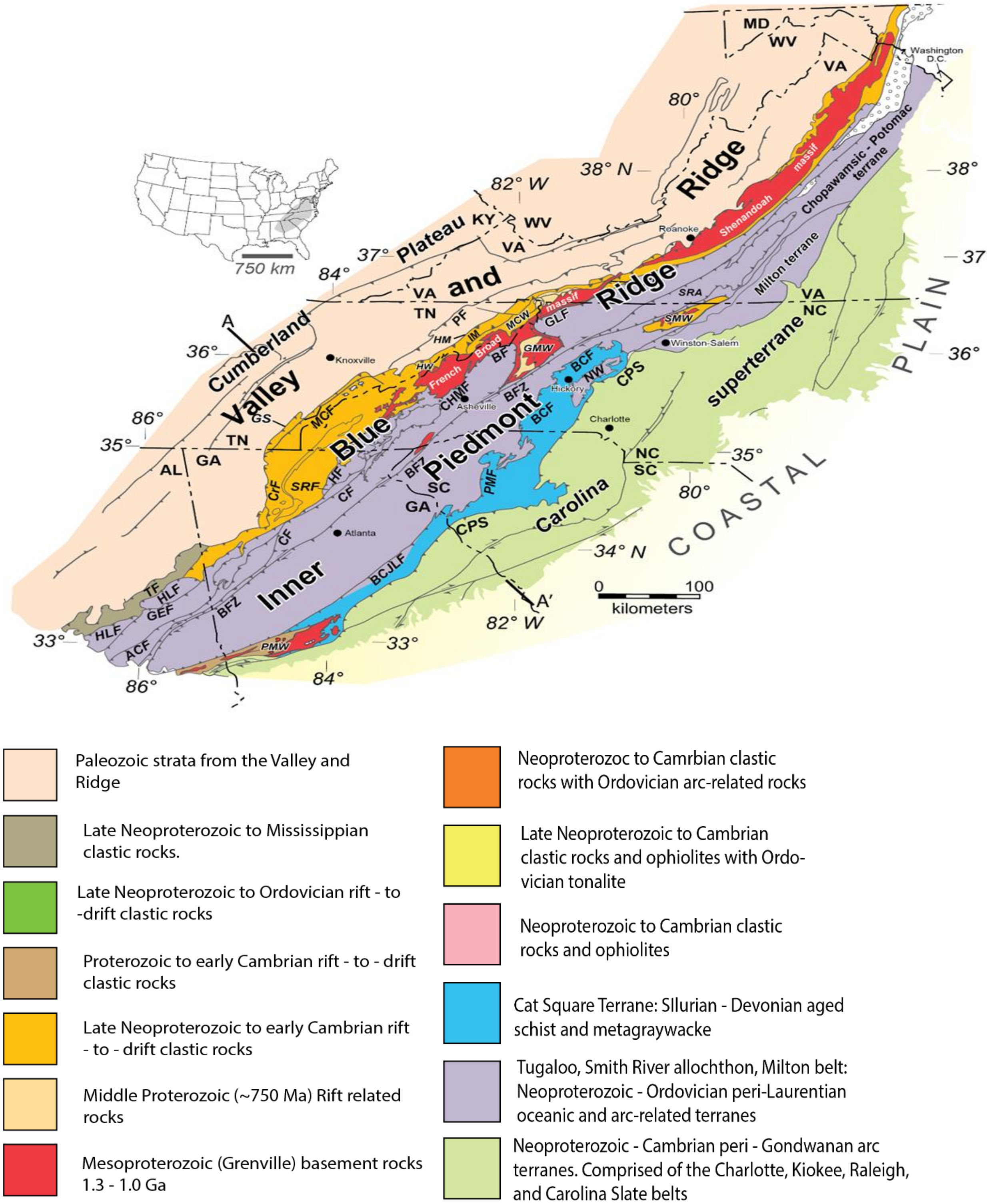

Fig. 1: Map of the geologic terranes of the southern Appalachians (after Merschat, 2017).

In this study I present Nd, Sr, and Pb isotope data for nine samples from the Eastern Blue Ridge, Inner Piedmont, and Charlotte belts (Fig. 2). Five samples come from Neo-Acadian aged granitoids in the Inner Piedmont, two samples come from Neo-Acadian to Alleghanian gabbros in the Charlotte belt, and two samples come from Neo-Acadian aged granitoids in the Eastern Blue Ridge. The goals of this study are to 1) evaluate a model for Neo-Acadian Inner Piedmont magmatism that suggests the magmas are the result of melting sedimentary rocks deposited in the Rheic Ocean (Merschat & Hatcher, 2007; Gatewood (2007); and 2) test the hypothesis that granitic rocks within the Eastern Blue Ridge belt and gabbroic rocks within the Charlotte belt are derived by mixing mantle and crustal melts.

BACKGROUND

Southern Maryland, western Virginia, western North and South Carolina, northeast Georgia, and eastern Alabama encompass the southern and central Appalachians (Fig. 1). The southern Appalachians, while known for Paleozoic provinces such as the Blue Ridge, the Foothills, and Piedmont regions find their origins in rocks with rich Proterozoic history (Hatcher 1987). Appalachian orogenies may be divided, roughly, into three periods, the Taconic, Acadian, and Alleghanian from oldest to youngest respectively.

Prior to the Appalachian orogenies were the Elzevirian and Grenvillian orogenies, occurring between 1.24 to 1.18 Ga and 1.15 to 1.0 Ga, respectively (Hatcher et al., 2007). These orogenies resulted in the assembly of the super continent of Rodinia (Fisher et al., 2010; Stewart, 2007). The formation of Rodinia also saw the formation of Grenvillian granitic orthogneisses that are between 1.15 and 1.0 Ga old (Carrigan et al., 2003; Bream et al., 2004; Hatcher et al., 2007, 1987). Following the assembly of Rodinia around 750 – 680 Ma it began to break up (Stewart, 2007).

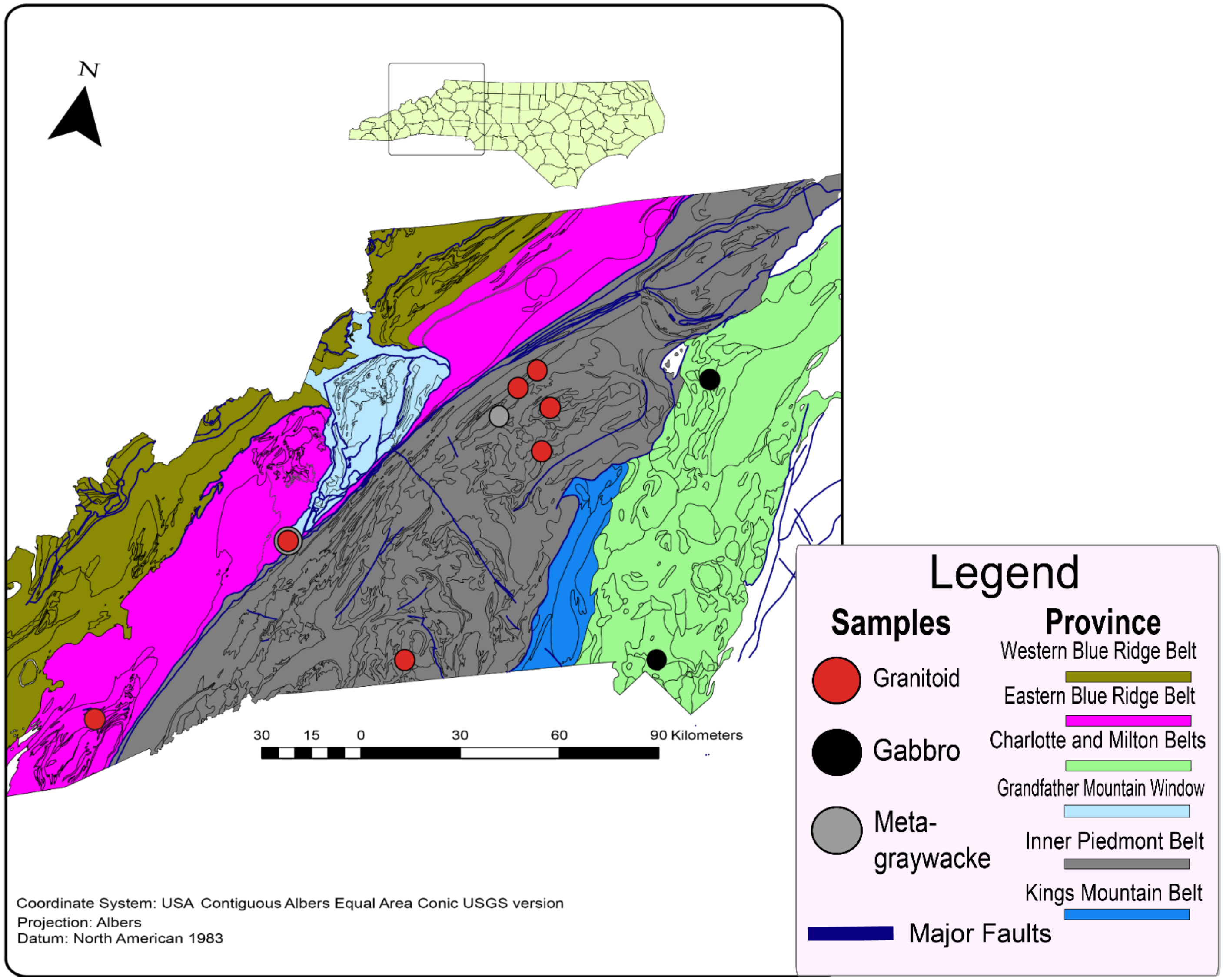

Fig. 2: Locations for samples collected from the Eastern Blue Ridge, Inner Piedmont, and Charlotte belts. Belts are primarily separated by faults. Belt delineations were provided by open source USGS shapefiles from Arthur Merschat.

The break-up finished around 620 – 570 Ma with the formation of the Iapetus Ocean, with Laurentia and Gondwana on either side becoming ancestral North America and Africa respectively (Hatcher et al., 2007; Stewart, 2007).

Following the formation of the Iapetus Ocean, the eastern margin of Laurentia remained a passive margin for approximately 180 Ma until the start of the Appalachian orogenies, beginning with the Penobscot and Taconic orogenies from 500 to 430 Ma. The Taconic orogeny persisted throughout the Ordovician and featured deformation and metamorphism as high as granulite facies as a result of subduction and arc accretion onto Laurentia (Hatcher et al., 2007). It was followed by the Acadian orogeny, that occurred throughout the Silurian and Devonian. Whereas evidence for this orogeny appears in northern Appalachia (McLennan et al., 2001) there is still open debate as to the extent and nature of the Acadian's effect on Southern Appalachia (e.g, Hatcher & Merschat, 2006; Huebner & Hatcher, 2017; Hibbard et al., 2002; Stewart, 2007). Some propose that the orogeny may not have occurred at all in southern regions or that the term 'Neo-Acadian' be used to describe the effects of metamorphism and activity in southern Appalachia during this period (Merschat et al., 2012; Hatcher and Merschat, 2006; Trupe et al., 2003). The accepted end of the Acadian orogeny in northern Appalachia is ~ 380 Ma, (Osberg et al., 1989) the prefix 'Neo' refers to orogenic events that occurred between 380 – 340 Ma. The Alleghanian orogeny began in the Carboniferous and ended in the Permian with the closing of the Iapetus Ocean and the formation of Pangea (Stewart, 2007).

Rocks of the Southern Appalachian Orogenies

Geologists debate the subdivisions of rocks that define the Appalachian orogenies. Boundaries are primarily expressed as faults that separate significant changes in stratigraphy and rock type commonly referred to as 'belts' (Hatcher, 1987).

Western Blue Ridge

The western Blue Ridge comprises the oldest rocks within the southern Appalachians, including the approximately 1.8 Ga Mars Hill terrain; however, the majority of rocks in the western Blue Ridge are 1.0 to 1.2 Ga (Hatcher et al., 2005). The majority of sedimentary rocks in the western Blue Ridge are from the Ocoee super group, dates from detrital zircons support that these sedimentary rocks are older than the Ordovician (Hatcher et al., 2005). The western boundary of the western Blue Ridge is delineated by multiple small faults, including the Blue Ridge thrust, that separates the western Blue Ridge from the Valley and Ridge province located to the west (Hatcher et al. 2007). The eastern boundary of the western Blue Ridge is the Hayesville-Fries Fault that separates the eastern and western Blue Ridge terranes from one another (Hatcher 1987). The western Blue Ridge is distinguished from the eastern Blue Ridge by the occurrence of rift-facies sedimentary rocks on the Laurentian basement (Dallmeyer 1991).

Eastern Blue Ridge

The eastern Blue Ridge includes the western portion of the Tugaloo terrane and many plutons intruded during the middle to late Paleozoic, or middle Ordovician and Carboniferous (Hatcher et al., 2005). The majority of Paleozoic granitoids within the Blue Ridge occur within the eastern Blue Ridge and include the-Stone Mountain, Mt. Airy, Walnut Creek, Rabun, Pink Beds, Looking Glass, Yonah, White-side, Chalk Mountain, and Persimmon Creek plutons (Hatcher et al., 2005; Miller et al. 2006; Winchester, 2013). The plutons include trondhjemite, granodiorites, and tonalites with up to 25% modal K-feldspar (Miller et al., 1997). The dominant country rock of the Eastern Blue Ridge are highly aluminous schists of the Ashe-Tallulah Falls

Formation. The western boundary of the eastern Blue Ridge is defined by the Hayesville fault and the eastern boundary by the Brevard fault (Hatcher 1987).

Inner Piedmont

The Inner Piedmont includes the eastern portion of the Tugaloo terrain (the Tugaloo terrain to west and east of the Brevard fault are stratigraphically identical to one another) and the Cat Square terrain on the east. (Hatcher and Merschat, 2006). The Brindle Creek fault within the Inner Piedmont defines the boundary between the Tugaloo and Cat Square Basin terrains. A defining characteristic of the Inner Piedmont is its poly-phase deformational history, with stacks of crystalline thrust sheets, low-angle foliations, and sillimanite-grade metamorphism (Hatcher and Merschat 2006). It includes gneisses, schists, amphibolites, and granitoids that preserve the metamorphic history of the Taconic, Acadian (Hatcher and Merschat 2006), and Alleghenian orogenies (Fullagar et al., 1997). The Inner Piedmont is defined to the west by the Brevard fault and to the east by the Piedmont Suture (including the Lowndesville and Kings Mountain shear zones; Hatcher and Merschat 2006). The Inner Piedmont also exposes several granitic plutons that were intruded during either the middle or late Paleozoic (Hatcher et al., 2005). Relief within the Inner Piedmont is limited relative to the adjacent Blue Ridge. Thus, the granitic intrusions are not as well-exposed as those within the western Tugaloo and Cat Square Basin terrains.

Charlotte and Kings Mountain belts

Immediately east of the Inner Piedmont belt is the Kings Mountain belt. The Kings Mountain belt includes marble, mica schist, meta-conglomerate, and quartzite as its major rock types (Fullagar et al., 1997). East of the Kings Mountain belt is the Charlotte belt that includes Paleozoic intrusive rocks ranging from gabbro to granite (Fullagar et al., 1997; Hazlewood and

Bender 2012; McSween and Harvey 1997). Both the Charlotte and Kings Mountain belts experienced amphibolite facies regional metamorphism (Fullagar et al., 1997).

Origins of the Plutonic Rocks

A Neo-Acadian Model

Models proposed by Gatewood (2007) and Merschat & Hatcher (2007) for the origin of Neo-Acadian plutons in the Inner Piedmont Terrane suggest that sediments in the Cat-Square terrane were derived from the Carolina Super and Tugaloo terranes and melted during the Neo-Acadian orogeny (Fig. 3). The sediments are thought to have been deposited into the Rheic Ocean basin around 430 Ma, ceasing approximately 410 Ma as the Rheic Ocean closed. Neo-Acadian magmatism took place from 410 to 340 Ma as the Carolina Super Terrane over-rode the Tugaloo terrane.

Detrital zircon ages from rocks sampled within the Cat-Square terrane (Bream et al. 2004) and structural evidence near the boundaries of the Cat-Square terrane (Gatewood 2007; Merschat & Arthur, 2007) have been used to justify the source of sediments within the terrane. An isotopic approach has yet to be used to test the hypothesis that the Cat-Square terrane represents the erosional remnants of the Carolina Super and Tugaloo terranes and that melting of the Cat-Square terrane produced Neo-Acadian granitoids within the Inner Piedmont belt.

Mixing

On the basis of Nd isotopic data, Fullagar et al. (1997) proposed that Proterozoic granites within the Eastern Blue Ridge have significant mantle affinity but that the granites are not mantle-derived. Thus, they may reflect mixing between crustal and mantle components of different terranes.

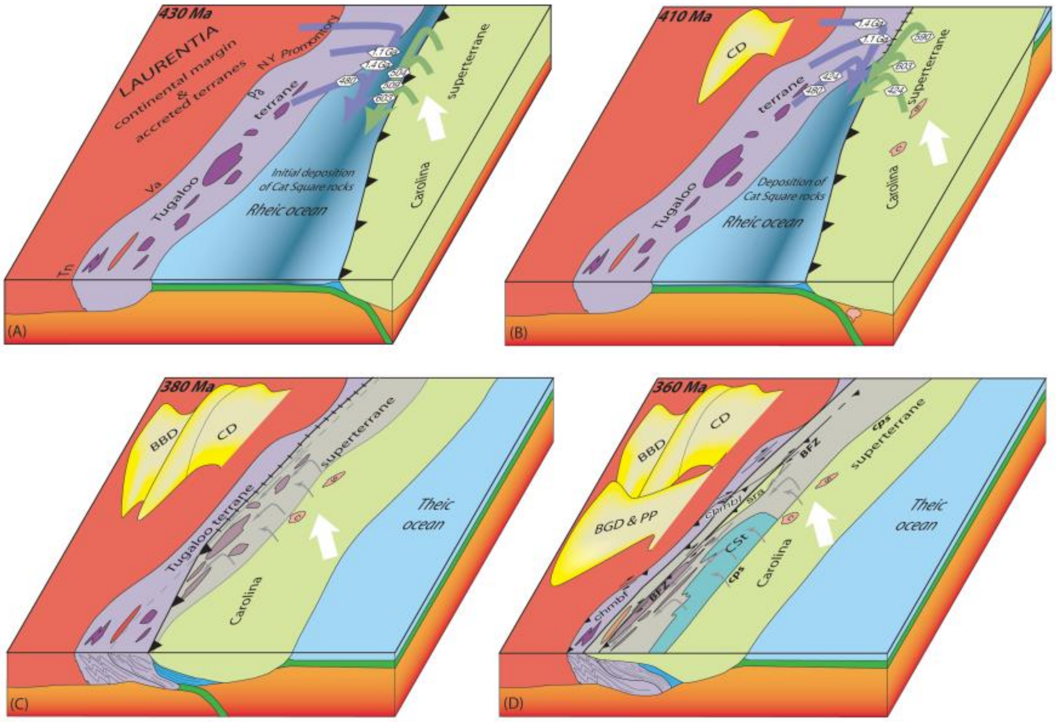

Fig. 3: A model from Merschat and Hatcher (2007) detailing their proposed view of Neo-Acadian tectonic synthesis within the Southern Appalachians. (A) Silurian configuration of Laurentia, Tugaloo terrane with mid-Ordovician plutons (dark purple), and Carolina super terrane separated by Rheic ocean. White arrows indicate motion of the Carolina super terrane. (B) Continued closure of the Rheic ocean and deposition of Cat Square terrane rocks during the Early Devonian. Magmatism in the Carolina super terrane, indicated by the Concord and Salisbury plutonic suites, is the product of subduction of the basin beneath the Carolina super terrane. (C) Closure of the Rheic ocean and suturing of Carolina super terrane by approximately 380 Ma. Gray lines indicate location of Brevard fault zone and ductile flow of Inner Piedmont material beneath the Carolina super terrane. (D) Neo-Acadian configuration resulting from dextral transpression. BBD—Bedford-Berea delta; BFZ—Brevard fault zone; BGD—Borden-Grainger delta; c—Concord Plutonic suite; CD—Catskill delta; chmbf—Chattahoochee–Holland Mountain–Burnsville fault; cps—central Piedmont suture; CSt—Cat Square terrane; PP—Price-Pocono delta; s—Salisbury Plutonic suite; sra—Smith River allochthon; Emb.—embayment.” Quoted directly from Merschat and Hatcher (2007)

Zircon ages from Huebner & Hatcher (2017) indicate that there were two discrete pulses of gabbroic magmatism in the Carolina Super terrane, one from 416 to 372 Ma and another from 311 to 308 Ma. Ages for gabbroic samples from the Eastern Blue Ridge are not available; however, they are believed to be late Proterozoic in age (Goldberg et al. 1994). Due to the roughly coeval nature of ages from Eastern Blue Ridge samples in this study (342.5 & 360 Ma) and Charlotte belt samples from this study (306 & 413 Ma), a direct comparison of both sets of samples across bulk compositions may yield insight into the sources of the gabbroic and granitic rocks.

Summary of Existing Isotopic Data

Western Blue Ridge

The majority of Western Blue Ridge depleted mantle model ages (T_{DM}) span the range of 2.0 to 1.1 Ga, with an outlier at 2.3 Ga for a sample from Roan Mountain (Fig. 4). These samples make up Grenvillian basement rock within the Blue Ridge and are believed to have signatures of Paleo- and Mesoproterozoic crust (Fullagar 1997 et al.) Initial ε_{Nd} values [$\varepsilon_{Nd}(t)$] for the western Blue Ridge plutons and orthogneisses range from -8.1 to 4.4; the majority of samples lie between -5 and 1. $(^{87}Sr/^{86}Sr)_i$ values for the western Blue Ridge belt range from 0.6908 – 0.71395. The only published Pb isotopic data that exist for the Southern Appalachians are present day values for the Western Blue Ridge and Eastern Blue Ridge belts. Present day radiogenic isotopic Pb data is not useful in intra-crust sourcing studies but may be used in conjunction with $\varepsilon_{Nd}(t)$ values to understand crustal provenance as demonstrated by Fisher et al. (2010).

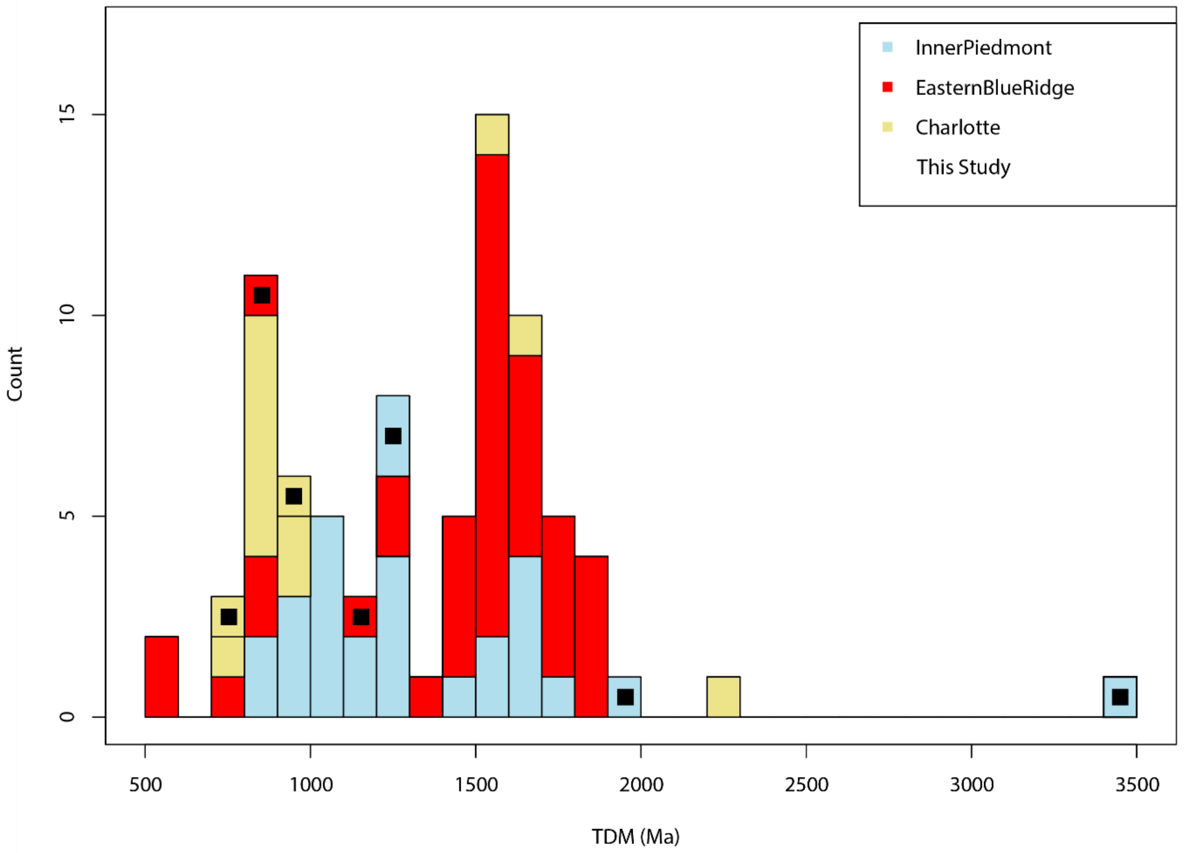

Fig. 4: Histogram of T_{DM} ages in Ma. Rectangles with black squares show data from this study.

Eastern Blue Ridge

T_{DM} values for the eastern Blue Ridge form two clusters, one from 1.9 Ga to 1.2 Ga and another from 0.9 to 0.5 Ga. Western Blue Ridge T_{DM} values do not overlap the younger cluster of eastern blue Ridge T_{DM} ages, implying that the eastern Blue Ridge is characterized by a juvenile component. $\varepsilon_{Nd}(t)$ values for the western Blue Ridge plutons and orthogneisses range from -10.51 to 7.24. There is a gap in the overlap between western and eastern Blue Ridge T_{DM} ages between 1.1 to 0.9 Ga. The highest and lowest $\varepsilon_{Nd}(t)$ values come from amphibolites and a pluton from Spruce Pine NC. Amphibolites are believed to represent mafic additions from Proterozoic oceanic crust (Goldberg et al., 1994). The majority of plutons and orthogneisses in the Eastern Blue Ridge province fall between -4 and 2. $(^{87}Sr/^{86}Sr)_i$ values for the eastern Blue Ridge belt range from 0.6980 – 0.71280.

Inner Piedmont

T_{DM} ages for the Inner Piedmont form two clusters, one from 1.3 to 0.8 Ga and another from 1.8 to 1.4 Ga. T_{DM} ages which define the gap between the eastern and western Blue Ridge belts are present in the Inner Piedmont belt. $\varepsilon_{Nd}(t)$ values for the western Blue Ridge plutons and orthogneisses range from -8.2 to 0.93. The majority of initial $\varepsilon_{Nd}(t)$ values are from -6 to 0. $(^{87}Sr/^{86}Sr)_i$ values for the Inner Piedmont belt range from 0.7037 – 0.7279

Charlotte Belt and Kings Mountain

T_{DM} ages for the Charlotte belt and Kings Mountain belts are from 2.22 to 0.711 and .96 to .9 Ga respectively. T_{DM} values for the Charlotte belt define 2 clusters from 1.0 to 0.7 and 1.7 to 1.5 Ga. The highest T_{DM} value is from the Southmount-B unit. T_{DM} values from the 1.0 to 0.7 Ga cluster overlap with the youngest cluster of ages from the eastern Blue Ridge and Inner Piedmont. T_{DM} values from the 1.7 – 1.5 Ga cluster overlap with the oldest cluster of ages from the eastern Blue Ridge and Inner Piedmont. The Kings Mountain belt values overlap the Charlotte and Inner Piedmont belts respectively. The $\varepsilon_{Nd}(t)$values for the Charlotte and Kings Mountain plutons are -1.71 to 4.88 and -2.59 to -1.78 respectively. The Charlotte belt has the highest number of mafic plutonic rocks of any belt in this study. $(^{87}Sr/^{86}Sr)_i$ values for the Charlotte and Kings Mountain belts range from 0.7023 – 0.7084 and 0.7046. There is only one published initial radiogenic Sr ratio for the Kings Mountain belt.

METHODS

Samples

Samples were collected from the Eastern Blue Ridge, Piedmont and Charlotte belts. Six of the samples are from the tonalite-trondhjemite-granodiorite suite of protoliths outlined by Miller et al. (1997), two are gabbros, and two are metagraywackes (Table 1).

Eastern Blue Ridge

Three samples (CcrkmGn, CcrkmGn2ndvar, and RMmGn) were collected in the Eastern Blue Ridge. CcrkmGn and CcrkmGn2ndvar were collected near Old Fort NC and RMmGn was collected 22 km west of Brevard NC.

Inner Piedmont

Six samples (WTmGn, WTmGn#2, HqmGn, RF, and Ggn) were collected in the Inner Piedmont belt. Sample HqmGn was collected from Henrietta quarry within the Sandy Mush pluton, 20 km southeast of Rutherfordton NC. Samples WTmGn, WTmGn#2, RF, and Ggn were collected within Alexander County NC. Sample Ggn was collected 3 km southeast of Morovian Falls NC.

TABLE 1. SAMPLE NAMES, AGES, AND LOCATIONS

Sample names	10_1_21_1_WTmGn	10_1_21_5_WTmGn	10_2_21_3_RFmGn
Shortened names	WTmGn	WTmGn#2	RF
Belt	Inner Piedmont	Inner Piedmont	Inner Piedmont
Lat (N)	36.0304739	35.8229972	35.963758
Long (W)	-81.2358137	-81.1883446	-81.119942
Full names	Walker Top meta Granitoid	Walker Top meta Granitoid #2	Rocky Face meta Granitoid
Rock Type	meta-Granitoid	meta-Granitoid	meta-Granitoid
Magmatic Age	408	408	380
Age uncertainty	2.1	2.1	-
Age References	a	a	b

TABLE 1. SAMPLE NAMES, AGES, AND LOCATIONS cont.

Sample names	10_17_21_1_HqMetMegGn	10_2_21_2_Ggn	10_2_21_4_mGw
Shortened names	HqmGn	Ggn*	MGW
Belt	Eastern Blue Ridge	Inner Piedmont	Inner Piedmont
Lat (N)	35.2409934	36.0780807	35.9519226
Long (W)	-81.813427	-81.1556683	-81.3238482
Full names	Henrietta Quarry meta Granitoid	Granitic dike	meta Graywacke
Rock Type	meta-Granitoid	dike	meta-Graywacke
Magmatic Age	383	362.9	430
Age uncertainty	-	1.8	-
Age References	c	d	e

TABLE 1. SAMPLE NAMES, AGES, AND LOCATIONS cont.

Sample names Shortened names	9_22_21_1_RMmGn RMmGn	10_16_21_2_CcrkGr (2ndvariation CcrkmGn2ndvar	10_16_21_3_CcrkMetaGn CcrkmGn
Belt	Eastern Blue Ridge	Eastern Blue Ridge	Eastern Blue Ridge
Lat (N)	35.194917	35.65602	35.65602
Long (W)	-82.974389	-82.1795	-82.1795
Full names	Round Mountain meta Granitoid	Curtis Creek Meta Granitoid (2nd variation)	Curtis Creek meta Granitoid
Rock Type	meta-Granitoid	meta-Graywacke	meta-Granitoid
Magmatic Age	342.5	359.9	359.9
Age uncertainty	2.4	1.1	1.1
Age References	f	g	g

TABLE 1. SAMPLE NAMES, AGES, AND LOCATIONS cont.

Sample names Shortened names	10_16_21_1_FrmGb FrmGb	10_17_21_2_McklnbrgGb MckmGb
Belt	Charlotte	Charlotte
Lat (N)	35.9646042	35.1266042
Long (W)	-80.5291981	-80.8943433
Full names	Farmington Gabbro	Mecklenburg meta-Gabbro
Rock Type	Gabbro	meta-Gabbro
Magmatic Age	306	413
Age uncertainty	6	10
Age References	h	h

a	Gatewood (2007)
b	Wilson et al., (2006)
c	Mapes et al., (2002)
d	Gatewood (2007)
e	Merschat et al., (2010)
f	Jubb (2010)
g	Ryan McAleer, personal communication
h	Huebner and Hatcher (2017)

Charlotte belt

Two samples (FrmGb and MckGb) were collected in the Charlotte belt. Sample MckGb was collected in Mecklenburg County at a quarry owned by Vulcan Materials 8.2 km southwest of Charlotte. Sample FrmGb was collected from a quarry owned by Vulcan Materials 16.4 km north of Mocksville.

Sample Preparation and Standards

Samples were collected from outcrops and road cuts for petrographic and geochemical analysis. Except for a hand-sample, all samples were reduced to less than 5 cm pieces on the outcrop. Weathering rinds were removed in the field. A rock saw with diamond grit was used to cut billets needed for thin sections. Billets were cut to 40 x 21 x 15 mm and sent to Spectrum Petrographics in Seattle WA. All thin sections were polished and cut to down to 30 µm. Sample descriptions were made using a Leica petrographic microscope.

Sample pieces were crushed using a Bico Incorporated WD-Chipmunk Crusher and powdered using the SPEX SamplePrep Shatterbox 8530 with an alumina ceramic mill and puck. Whole-rock powder (50 – 100 mg) was dissolved in Teflon dissolution vessels using a 1:3.4 mixture of $HF:HNO_3$. Dissolution vessels were placed in a 180C° oven for 72 hours to ensure complete dissolution. Following dissolution, samples were evaporated to dryness and fluxed with 3 mL 6N HCL for 24 hours to remove residual fluoride precipitates. Samples were aliquoted for Nd, Pb, and Sr isotope analysis to yield approximately 100 ng Nd, 2 ng Pb, and 2 µg Sr. The remainder of the dissolved sample was used for whole-rock elemental analysis by inductively-coupled plasma mass spectrometry (ICP-MS).

ICP-MS

Remaining dissolved samples were dried down and redissolved in 2% HNO_3. Samples were fluxed for 24 hours at 130°C to ensure complete dissolution. Solutions were diluted to 10,000 times their original concentrations with 2% HNO_3 to ensure compatibility with detection limits.

Whole-rock elemental analysis was performed at the University of North Carolina at Chapel Hill. All samples were analyzed on an Agilent^{TM} 7900 ICP-MS set with normal operational parameters. Helium gas was used as a carrier to reduce interferences. An internal standard solution including Be, Ge, In, Ir, Rh, and Bi was added to correct for instrumental drift. A 2% HNO_3 blank was measured before and after each analysis to provide background intensities. Two standards – a basalt standard BHVO-2, and a granodiorite standard GSP-2, were measured to evaluate the accuracy and reproducibility of elemental analyses. Standard measurements yielded precisions of less than 3% (relative standard derivation, RSD) were achieved for most major and trace element analyses. Trace elements used for radiogenic isotope analysis (Rb, Sr, Sm, Nd, U, Th, Pb) routinely achieved RSD values less than 2.5%.

Radiogenic Isotope Geochemistry

Separation of Nd was completed with a three-column technique outlined by Fullagar (1997). The first stage used AG50wx-4 resin and HCl for separation of Fe from the rest of the matrix in order to improve REE yield on the second-stage column. The second stage used REE-spec resin with HNO_3 reagent to isolate REE's from the remaining sample matrix. The third stage used AG50wx-4 resin and methylactic acid to isolate Nd from the remaining REEs. Anion exchange chromatography utilizing AG1X-8 resin was used to isolate Pb. Lead columns were repeated twice to ensure full separation of Ca. Methods are outlined in Manhes et al. (1984) and

Baker et al. (2004). Strontium was separated using Sr-spec resin according to methods outlined by Lundblad (2019).

Strontium column separates were dried onto Re filaments suspended with a TaF_5 activator and analyzed on a VG Sector 54 thermal ionization mass spectrometer (TIMS). Strontium was analyzed using a multi-collector method. Replicate analyses of NBS-987 during the period of sample analysis produced $^{87}Sr/^{86}Sr = 0.710268 \pm 0.000020$ (2σ, $n = 97$). Mass fractionation was corrected using an exponential law and normalization to $^{86}Sr/^{84}Sr = 0.1194$. A PhoeniX-X62 TIMS was used in dynamic multi-collector mode to analyze Nd. All analyses were corrected for fractionation using $^{146}Nd/^{144}Nd = 0.7219$. Replicate analyses of JNdi through the period of sample analysis yielded $^{143}Nd/^{144}Nd = 0.512104 \pm 0.000012$ (2σ, $n = 12$). Purified Pb was loaded onto Re filaments with silica-gel and analyzed as a metal in static multi-collector mode on a PhoeniX-X62 TIMS. Replicate analyses of the NBS-981 standard were used to determine mass fractionation for Pb analyses (0.14%/amu) assuming linear fractionation behavior.

RESULTS

Sample Descriptions

MckGb

This sample is a fine- to medium-grained, equigranular, hornblende metagabbro. The rock consists of approximately 45% sub/anhedral plagioclase, 25% an/euhedral hornblende, 15% an/subhedral biotite, approximately 5% accessory minerals including epidote, chlorite, and serpentine, and 5% of an opaque mineral. Plagioclase grains have Carlsbad and albite twins along with undulatory extinction. Plagioclase in some thin sections showed evidence of zoning. Some large plagioclase grains have undergone sericitic alteration (Huebner & Hatcher 2017).

Hornblende grains have light – grey green pleochroism, and opaque mineral inclusions. Biotite is pleochroic and possesses distinct birds eye extinction. Although the identity of the opaque mineral is unknown, magnetism of the sample and mineral associations suggest that a significant portion of the opaque mineral is magnetite. Foliation is defined by amphibole, biotite, and plagioclase.

FrmGb

This sample is a medium-grained, two-pyroxene hornblende gabbro. The sample consists of approximately 50% sub/euhedral plagioclase, approximately 20% sub/euhedral orthopyroxene, approximately 20% sub/euhedral clinopyroxene, approximately 5% an/euhedral hornblende, approximately 5% sub/euhedral biotite, and less than 1% of an unidentified high-relief, high-birefringence mineral (olivine?). Plagioclase is albite twinned. Plagioclase encloses some pyroxene grains, giving a poikilitic texture.

MGW

This is a sample of fine-grained meta-graywacke. This sample features 40% an/subhedral quartz, 20% an/subhedral plagioclase, 15% an-subhedral biotite, 10% an/euhedral hornblende, 5% an/subhedral muscovite, approximately 5% opaque mineral, 5% an/subhedral chlorite, and less than 1% rutile and titanite. Plagioclase and quartz are equigranular. Some biotite is altered to chlorite. The greywacke is cut by calcite and quartz veins. Weathering rinds have a distinct rust-red coloration.

Ggn

This sample is a medium- to coarse-grained felsic /rhyolitic dike. It contains approximately 45% an/euhedral quartz, approximately 25% an/subhedral plagioclase, approximately 15% anhedral K-feldspar, approximately 10% an/euhedral biotite, less than 5% an/subhedral muscovite, and less than 1% chlorite. The sample has myrmekitic texture.

HqmGn

This is a medium- to coarse-grained phenocrystic meta-granitoid. This sample contains 25% an/subhedral K-feldspar, 15% an/subhedral plagioclase, 45% an/euhedral quartz, 10% an/euhedral biotite, approximately 5% an/subhedral muscovite, and less than 1% garnet. Phenocrysts of K-feldspar range from 1 to 2.5 cm in length, the largest of which show perthitic exsolution. Myrmekite texture is observed on the boundary of K-feldspar phenocrysts. The biotite, plagioclase, and quartz define foliation.

RMmGn

This sample is a fine- to medium-grained meta-granitoid. This sample contains approximately 50% an/euhedral quartz, approximately 10% an/euhedral biotite, approximately 15% an/subhedral plagioclase, approximately 5% anhedral K-feldspar, approximately 5% an/euhedral muscovite, and approximately 5% accessory minerals. Plagioclase has sericite alteration. Myrmekite is observed along the boundaries of feldspars. Biotite includes plagioclase. Biotite defines the foliation.

WTmGn:

This is a medium- to coarse-grained mylonitic meta-granitoid with approximately 40% an/euhedral quartz, approximately 30 % an/euhedral K-feldspar, approximately 5 % an/subhedral plagioclase, approximately 20% an/euhedral biotite, approximately 5% muscovite, approximately 1% zircon with pleochroic halos in biotite, and less than 5% chlorite. Myrmekite texture is observed near the boundary of feldspars and quartz. Exsolution textures are prevalent within K-feldspar porphyroblasts. Feldspar porphyroblasts are from 4 to 30 mm in length and have nearly ubiquitous simple/Carlsbad twinning.

WTmGn 2nd variation

This sample is a medium- to coarse-grained mylonitic meta-granitoid. This sample contains approximately 30 to 35% altered feldspar (sericite), approximately 25 % an/subhedral quartz, approximately 10% an/euhedral chlorite, approximately 15% an/euhedral biotite, approximately 10% an/subhedral K-feldspar, approximately 10% an/subhedral plagioclase, approximately 2% an/subhedral muscovite, approximately 2 % opaque minerals, approximately 1% zircon with pleochroic halos in biotite. Porphyroblasts are altered and are 2 to 35 mm in length.

CcrkmGn:

This sample is a porphyritic granodiorite. It has 35 to 40% an/euhedral quartz, 15 to 20% an/subhedral biotite, 10 to 15% an/euhedral muscovite, 20% an/subhedral plagioclase, 5% an/subhedral K-feldspar, 5% an/euhedral epidote, 5% an/subhedral chlorite, and 5% allanite plus apatite. Plagioclase porphyroblasts have exsolution textures and inclusions of biotite, quartz, and apatite. The matrix of the rock includes quartz, plagioclase, biotite, and chlorite (after biotite). There are veins/lenses of euhedral quartz in the matrix as well. The porphyroblasts are between 2 and 10 mm. The matrix is gray.

CcrkmGn 2nd var

This unit is a fine- to medium-grained mylonitic meta-graywacke. This sample contains approximately 50% an/subhedral quartz, 10% an/subhedral plagioclase, 5% anhedral K-feldspar, 20% an/subhedral muscovite, 10% anhedral biotite, and 5% an/subhedral staurolite. The matrix of this rock consists of bands of quartz and feldspars alternating with muscovite. Mylonitic bands of approximately nearly pure quartz are common. Plagioclase porphyroblasts (2-15 mm) have inclusions of muscovite, biotite, K-feldspar, and quartz.

RF

This sample is a medium- to coarse-grained meta-granitoid. This rock contains approximately 40% sub/euhedral quartz, approximately 40% sub/euhedral potassium feldspar, approximately 5% sub/euhedral plagioclase, approximately 5% sub/euhedral muscovite, approximately 5% sub/euhedral biotite, approximately 2% zircon with pleochroic halos in biotite, approximately 2% an/subhedral garnet, approximately 1% opaque mineral. Feldspars are characterized by minor alteration to sericite.

Summary of New Major Oxide and Trace Element Data

Major elements from samples collected from the Eastern Blue Ridge, Inner Piedmont, and Charlotte belts fall in line within established rock types observed by other authors (Huebner and Hatcher, 2017; Mapes et al., 2002; Miller et al., 1997). Concentrations of SiO_2 (wt.%) were not determined in this study and are estimated from literature values (CcrkmGn2ndvar, Ggn, and HqmGn; Mapes, 2002) and, educated inference on the basis of rock type. Many major oxide and trace elements are reported for the samples in this study; however, only parent/daughter pairs (Rb/Sr, Sm/Nd and U-Th/Pb) were used for analysis in this study. The complete set of results is presented so that they may be used in other studies.

TABLE 2. MAJOR ELEMENT CONCENTRATIONS (wt.%)

Sample	WTmGn	WTmGn#2	RF	HqmGn**	Ggn**	MGW
SiO_2	67.96	67.96	73.21	68.90	73.00	68.84
TiO_2	0.19	0.46	0.03	0.11	0.10	0.31
Al_2O_3	16.67	17.33	14.84	13.10	17.73	10.90
Fe_2O_3	3.05	6.42	0.71	2.33	1.69	3.93
FeO	-	-	-	-	-	-
MnO	0.03	0.06	0.02	0.04	0.01	0.05
MgO	0.59	0.96	0.08	0.26	0.34	1.41
CaO	0.90	1.16	0.39	0.75	1.62	2.78
Na2O	2.58	2.60	2.86	2.09	3.78	0.75
K2O	5.04	4.05	5.80	3.49	2.52	0.78
P_2O_5	0.16	0.30	0.08	0.05	0.07	0.16
LOI	-	-	-	-	-	-
Total*	97.18	101.30	98.03	91.12	100.87	89.91
SiO_2 Ref.	a	a	b	-	-	e

TABLE 2. MAJOR ELEMENT CONCENTRATIONS (wt.%) cont.

Sample	RMmGn	**CcrkmGn2ndvar	CcrkmGn	FrmGb	MckmGb
SiO_2	72.09	70.92	70.92	51.09	48.55
TiO_2	0.12	0.09	0.27	0.23	0.98
Al_2O_3	16.70	13.01	17.39	18.96	16.52
Fe_2O_3	1.77	1.52	4.57	8.25	12.22
FeO	-	-	-	-	-
MnO	0.01	0.01	0.05	0.07	0.10
MgO	0.30	0.20	0.83	4.17	2.28
CaO	1.33	0.34	1.23	4.31	3.39
Na2O	4.35	1.80	4.10	2.57	3.61
K2O	1.57	3.37	2.66	0.19	1.07
P_2O_5	0.09	0.05	0.30	0.03	0.88
LOI	-	-	-	-	-
Total	98.32	91.31	102.31	89.88	89.60
SiO_2 Ref.	f	-	g	h	h

** SiO_2 values were assumed from nearby intrusions. SiO_2% reported by Mapes(2002) for the Toluca intrusion was used for HqmGn. CcrkmGn2nd Var assumed the same value as CcrkmGn. Personal communication with Drew Coleman was used for Ggn

TABLE 3. TRACE ELEMENT CONCENTRATIONS (ppm)

Sample	WTmGn	WTmGn#2	RF	HqmGn	Ggn	MGW	RMmGn	CcrkmGn2ndvar
Ni	7.99	14.95	0.73	16.07	2.64	59.26	2.18	1.74
Cu	3.22	12.14	-	19.38	1.71	31.56	0.03	3.81
Zn	61.43	99.21	13.07	55.91	38.89	30.28	52.75	34.89
Ga	-	-	-	-	-	-	-	-
Y	22.70	30.00	18.49	14.11	2.61	31.84	4.33	2.51
Zr	111.61	128.70	40.33	107.70	82.22	240.59	192.38	120.85
Nb	9.57	5.41	4.57	9.77	2.75	11.19	1.84	6.66
Ba	646.33	939.39	145.00	356.38	810.24	268.81	619.02	399.12
La	58.25	48.78	6.31	13.11	10.17	34.08	37.31	6.68
Ce	123.50	127.00	13.84	24.97	19.67	66.68	62.68	8.62
Pr	13.66	12.75	1.62	3.00	2.25	8.31	6.74	1.64
Eu	1.56	2.16	0.46	0.82	0.89	1.51	1.12	0.56
Gd	11.06	10.94	2.60	2.86	1.54	7.95	3.71	1.25
Tb	1.16	1.15	0.49	0.37	0.14	1.05	0.26	0.15
Dy	5.30	5.94	3.23	2.39	0.60	6.17	0.96	0.75
Ho	0.95	1.25	0.63	0.55	0.11	1.20	0.16	0.15
Er	2.44	3.72	1.97	1.85	0.31	3.57	0.44	0.45
Tm	0.34	0.59	0.33	0.29	0.04	0.53	0.07	0.07
Yb	2.00	3.94	2.43	1.99	0.27	3.50	0.44	0.50
Lu	0.31	0.61	0.36	0.31	0.05	0.54	0.08	0.09
Ta	0.53	0.20	0.60	1.08	0.24	3.13	2.57	1.07

TABLE 3. TRACE ELEMENT CONCENTRATIONS (ppm) cont.

Sample	CcrkmGn	FrmGb	MckmGb
Ni	13.60	105.49	24.14
Cu	25.61	76.92	44.40
Zn	82.50	67.00	107.50
Ga	-	-	-
Y	24.44	7.60	42.75
Zr	186.71	15.14	43.59
Nb	24.57	0.65	20.27
Ba	209.60	71.95	475.63
La	36.60	4.13	47.63
Ce	73.50	8.95	104.78
Pr	8.05	1.19	14.27
Eu	1.10	0.67	3.42
Gd	7.92	1.74	13.81
Tb	0.97	0.26	1.71
Dy	5.10	1.58	9.10
Ho	0.93	0.31	1.80
Er	2.59	0.91	4.89
Tm	0.35	0.13	0.70
Yb	2.23	0.84	4.15
Lu	0.37	0.13	0.61
Ta	1.23	0.20	1.71

Summary of New Isotopic Data

Eastern Blue Ridge

T_{DM} values obtained for two granitoids within the Eastern Blue Ridge belt fall within and expand the established range of T_{DM} values determined in earlier studies. CcrkmGn yields a T_{DM} age of 1152 Ma that expands the younger bound of the older cluster of T_{DM} ages defined in previous studies (e.g., Fullagar et al., 1997). RMmGn has a T_{DM} age of 850 Ma. $\varepsilon_{Nd}(t)$ values within the Eastern Blue Ridge belt (-2.5 - -1) fall within the range of values established by other studies (Table 4; e.g., Fullagar et al., 1997). $(^{87}Sr/^{86}Sr)_i$ values for samples within the Eastern Blue Ridge belt (0.7060 – 0.7063) also fall within the range of values established by other authors(Table 5). Strontium and Nd isotopic data plot near bulk earth (Fig. 5).

$(^{206}Pb/^{204}Pb)_i$ values for Eastern Blue Ridge samples range from 18.54 – 18.66 (Table 6). $(^{207}Pb/^{204}Pb)_i$ values range from 15.64 – 15.66. $(^{208}Pb/^{204}Pb)_i$ values range from 38.93 – 38.98. These values are slightly more radiogenic than Inner Piedmont samples from this study (Table 6).

TABLE 4. Sm - Nd ISOTOPIC DATA

Sample	WTmGn	WTmGn#2	RF	HqmGn	Ggn	MGW
Sm (ppm)	9.17	8.67	1.87	2.34	1.31	6.14
Nd (ppm)	50.51	49.03	6.10	11.08	8.22	31.23
$(^{147}Sm/^{144}Nd)$	-	-	-	-	-	-
$(^{143}Nd/^{144}Nd)$	0.5122	0.512142	0.512447	0.51197	0.512258	0.511989
$2\sigma(^{143}Nd/^{144}Nd)$	0.0003	0.0005	0.0006	0.0002	0.0003	0.0002
$^{143}Nd/^{144}Nd)i$	0.511907	0.511857	0.511985	0.511650	0.512029	0.511654
$\varepsilon_{Nd}0$	-8.54	-9.68	-3.73	-13.03	-7.41	-12.66
$\varepsilon_{Nd}t$	-4.01	-5.00	-3.19	-9.66	-2.77	-8.39
ε_{Nd}340Ma	-	-	-	-	-	-9.29
ε_{Nd}410Ma	-	-	-	-	-	-8.59
T_{DM}	1235.31	1284.12	3451.36	1900.51	1023.84	1690.92
T_{ChUR}	770.22	844.18	2654.7	1481.85	579.89	1275.6

TABLE 4. Sm - Nd ISOTOPIC DATA cont.

Sample	RMmGn	CcrkmGn2ndvar	CcrkmGn	FrmGb	MckmGb
Sm (ppm)	2.94	1.18	5.68	1.30	11.87
Nd (ppm)	22.06	6.34	28.81	5.29	59.05
$(^{147}Sm/^{144}Nd)$	-	-	-	-	-
$(^{143}Nd/^{144}Nd)$	0.512306	0.512302	0.512329	0.512632	0.512621
$2\sigma(^{143}Nd/^{144}Nd)$	0.0002	0.0005	0.0002	0.0004	0.0005
$^{143}Nd/^{144}Nd)i$	0.512126	0.512037	0.512048	0.512335	0.512292
$\varepsilon_{Nd}0$	-6.48	-6.55	-6.03	-0.12	-0.33
$\varepsilon_{Nd}t$	-1.39	-2.68	-2.46	1.78	3.51
ε_{Nd}340Ma	-	-	-	-	-
ε_{Nd}410Ma	-	-	-	-	-
T_{DM}	849.18	1115.86	1151.92	962.07	710.99
T_{ChUR}	436.68	609.29	609.6	18.91	34.59

TABLE 5. Rb - Sr ISOTOPIC DATA

Sample	WTmGn	WTmGn#2	RF	HqmGn	Ggn	MGW
Sr (ppm)	234.60	241.48	90.37	121.97	465.91	248.60
Rb (ppm)	191.96	143.14	229.09	135.95	58.01	37.80
(^{87}Sr/^{86}Sr)	0.7220	0.7183	0.7562	0.7265	0.7092	0.7165
2σ(^{87}Sr/^{86}Sr)	0.0012	0.0010	0.0009	0.0010	0.0010	0.0009
(^{87}Sr/^{86}Sr)$_i$	0.7082	0.7083	0.7163	0.7089	0.7074	0.7138
(^{87}Sr/^{86}Sr)$_{340Ma}$	-	-	-	-	-	0.7143
(^{87}Sr/^{86}Sr)$_{410Ma}$	-	-	-	-	-	0.7139

TABLE 5. Rb - Sr ISOTOPIC DATA cont.

Sample	RMmGn	CcrkmGn2ndvar	CcrkmGn	FrmGb	MckmGb
Sr (ppm)	801.21	177.02	225.87	784.05	940.03
Rb (ppm)	41.48	67.98	149.01	1.94	16.07
(^{87}Sr/^{86}Sr)	0.7068	0.7127	0.7160	0.7039	0.7039
2σ(^{87}Sr/^{86}Sr)	0.0008	0.0010	0.0009	0.0010	0.0007
(^{87}Sr/^{86}Sr)$_i$	0.7061	0.7070	0.7062	0.7039	0.7036
(^{87}Sr/^{86}Sr)$_{340Ma}$	-	-	-	-	-
(^{87}Sr/^{86}Sr)$_{410Ma}$	-	-	-	-	-

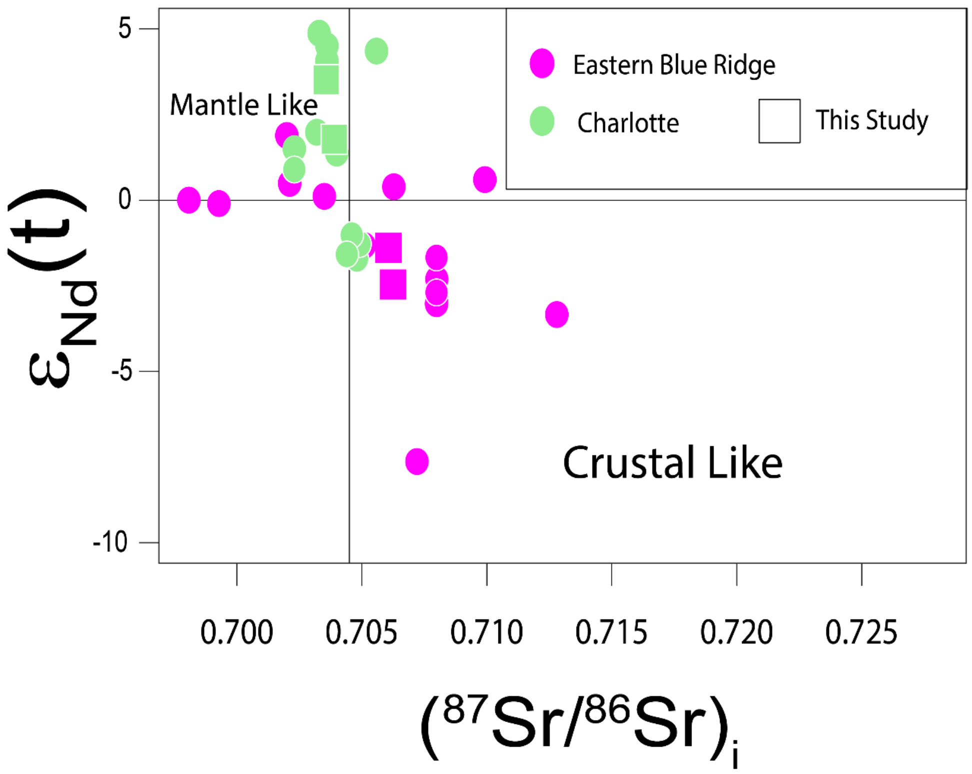

Fig. 5: $(^{87}Sr/^{86}Sr)_i$ vs. $\varepsilon_{Nd}(t)$ showing a decrease in $\varepsilon_{Nd}(t)$ as $(^{87}Sr/^{86}Sr)_i$ increases. Lines represent the composition of bulk earth. Samples which lie near the bulk earth suggest that they possess a significant mantle component

TABLE 6. U/Th/Pb ISOTOPIC DATA

Sample	WTmGn	WTmGn#2	RF	HqmGn	Ggn	MGW
Pb (ppm)	34.76	22.78	66.36	26.35	24.20	6.09
Th (ppm)	9.01	7.43	1.37	2.44	1.07	2.75
U (ppm)	3.47	0.92	4.83	3.23	0.80	2.14
(^{206}Pb/^{204}Pb)	18.810	18.679	19.677	18.967	18.666	20.089
2σ(^{206}Pb/^{204}Pb)	0.006	0.006	0.006	0.006	0.006	0.006
(^{206}Pb/^{204}Pb)$_i$	18.387	18.510	19.391	18.484	18.544	18.482
(^{207}Pb/^{204}Pb)	15.671	15.677	15.733	15.693	15.653	15.723
2σ(^{207}Pb/^{204}Pb)	0.007	0.007	0.007	0.007	0.007	0.007
(^{207}Pb/^{204}Pb)$_i$	15.648	15.667	15.717	15.667	15.646	15.634
(^{208}Pb/^{204}Pb)	39.683	38.900	38.373	38.680	38.449	39.975
2σ(^{208}Pb/^{204}Pb)	0.024	0.023	0.023	0.023	0.023	0.024
(^{208}Pb/^{204}Pb)$_i$	39.329	38.459	38.346	38.562	38.396	39.310

TABLE 6. U/Th/Pb ISOTOPIC DATA cont.

Sample	RMmGn	CcrkmGn2ndvar	CcrkmGn	FrmGb	MckmGb
Pb (ppm)	17.39	16.11	15.82	1.77	5.16
Th (ppm)	3.99	3.40	4.59	0.10	0.65
U (ppm)	1.68	0.82	1.72	0.06	0.60
(^{206}Pb/^{204}Pb)	19.010	18.639	18.947	18.512	18.602
2σ(^{206}Pb/^{204}Pb)	0.006	0.006	0.006	0.006	0.006
(^{206}Pb/^{204}Pb)$_i$	18.669	18.451	18.543	18.408	18.110
(^{207}Pb/^{204}Pb)	15.662	15.670	15.682	15.675	15.633
2σ(^{207}Pb/^{204}Pb)	0.007	0.007	0.007	0.007	0.007
(^{207}Pb/^{204}Pb)$_i$	15.644	15.660	15.661	15.669	15.606
(^{208}Pb/^{204}Pb)	39.194	39.391	39.333	38.417	38.435
2σ(^{208}Pb/^{204}Pb)	0.023	0.024	0.023	0.023	0.023
(^{208}Pb/^{204}Pb)$_i$	38.933	39.138	38.984	38.364	38.265

Inner Piedmont

T_{DM} values obtained for granitoids within the Inner Piedmont fall within and expand the range of T_{DM} values observed by other authors. Sample RF features an extremely high T_{DM} age of 3451 Ma, other samples (WTmGn, WTmGn#2, & HQmGn) range from 1900 to 1235 Ma. $\varepsilon_{Nd}(t)$ values for samples from the Inner Piedmont range from -10 to -3. Sample HqmGn expands the lower range of $\varepsilon_{Nd}(t)$ values reported by other authors (Fig. 4). $(^{87}Sr/^{86}Sr)_i$ values (0.7074 – 0.7163) fall within ranges reported by other authors. Strontium and Nd isotopic data for samples from the Inner Piedmont plot near samples with increased crustal affinity (Fig. 6)

$(^{206}Pb/^{204}Pb)_i$ values for Inner Piedmont Belt samples from this study range from 18.39 – 19.39. $(^{207}Pb/^{204}Pb)_i$ values range from 15.646 – 15.717. $(^{208}Pb/^{204}Pb)_i$ values range from 38.35 – 39.33. Lead isotopic compositions of samples from the Inner Piedmont belt are more radiogenic than samples from the Blue Ridge that may have been potential sources for the Cat Square Terrane (Fig. 7).

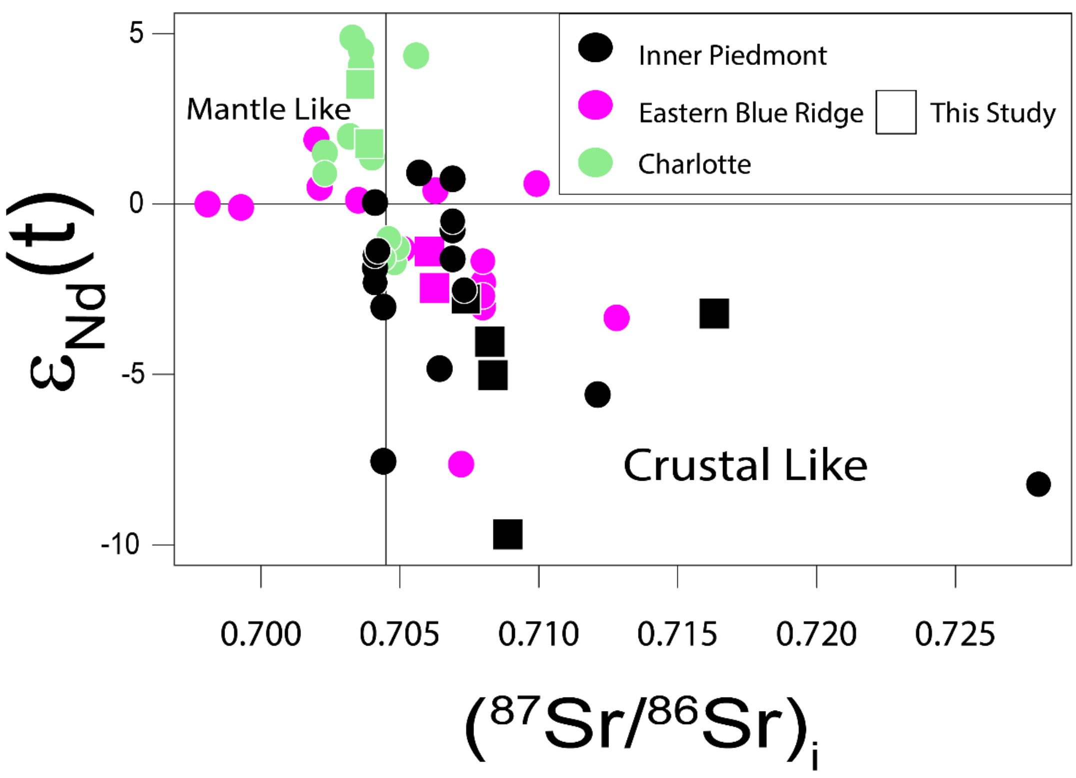

Fig. 6: $(^{87}Sr/^{86}Sr)_i$ vs. $\varepsilon_{Nd}(t)$ showing a decrease in $\varepsilon_{Nd}(t)$ as $(^{87}Sr/^{86}Sr)_i$ increases. Inner Piedmont samples have far more crustal affinity than other samples, consistent with the hypothesis that Neo-Acadian Inner Piedmont granitoids came from melting sediments.

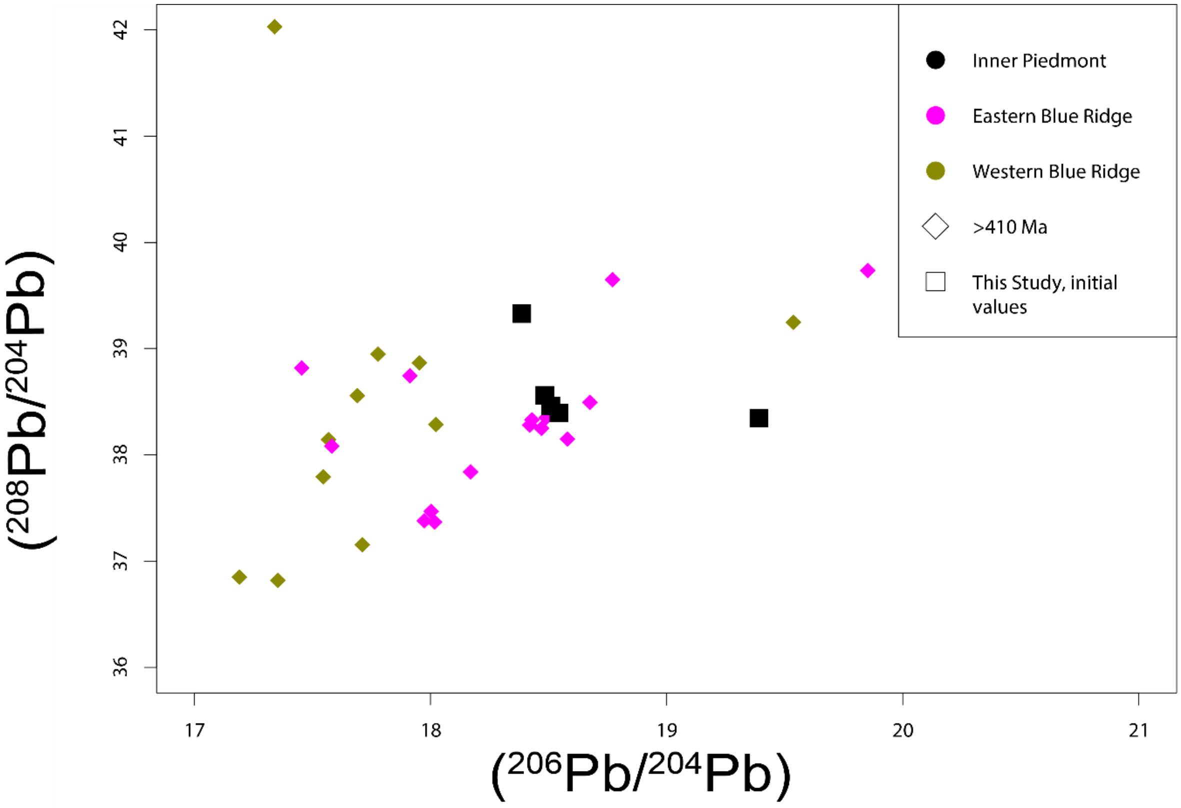

Fig. 7: (^{206}Pb/^{204}Pb) vs. (^{208}Pb/^{204}Pb) showing present day ratios of samples reported in Fisher et al. (2010). Black samples are data from this study but shown on the plot as (^{206}Pb/^{204}Pb)$_i$ and (^{208}Pb/^{204}Pb)$_i$. Once corrected to 410 to 340 Ma, samples from Fisher et al. 2010 would be even less radiogenic than Inner Piedmont samples presented in this study.

Charlotte

T_{DM} values obtained for two gabbroic samples within the Charlotte belt fall within the established range of T_{DM} values observed by other authors. FrmGb and MckmGb feature T_{DM} ages of 962 and 710 Ma respectively (Fig. 4). $\varepsilon_{Nd}(t)$ values within the Charlotte belt (2 – 3.5) fall within the established range of $\varepsilon_{Nd}(t)$ values reported by other authors. $(^{87}Sr/^{86}Sr)_i$ values for samples within the Charlotte belt from this study range from 0.7036 – 0.7039, and fall within observed ranges from earlier studies.

$(^{206}Pb/^{204}Pb)_i$ values for Charlotte belt samples from this study range from 18.11 – 18.41. $(^{207}Pb/^{204}Pb)_i$ values range from 15.61 – 15.67. $(^{208}Pb/^{204}Pb)_i$ values range from 38.27 – 38.36. Lead values for Charlotte belt samples are the least radiogenic of all samples reported in this study (Table 6).

DISCUSSION

Sources for Neo-Acadian granitoids within the Inner Piedmont

A simple way to test the model that Neo-Acadian plutons in the Inner Piedmont were derived via melting sedimentary rocks such as those exposed in the Cat-Square terrane (Hatcher & Merschat, 2007; Gatewood, 2007) is to directly compare the isotope geochemistry of a sample of sediment from the terrane with granitic rock believed to have been produced via melting the sediment (Fig. 8). Sample MGW from the Inner Piedmont belt is believed to have been a sample of sediment directly from the Cat-Square Terrane (Merschat et al., 2010). Neither published data nor data from this study overlap with MGW with a reprojected isotopic composition between 410 to 340 Ma. This observation has one implication: Not enough sedimentary samples with whole-rock isotopic data exist to adequately evaluate the hypothesis, and therefore this method is insufficient in evaluating the first hypothesis.

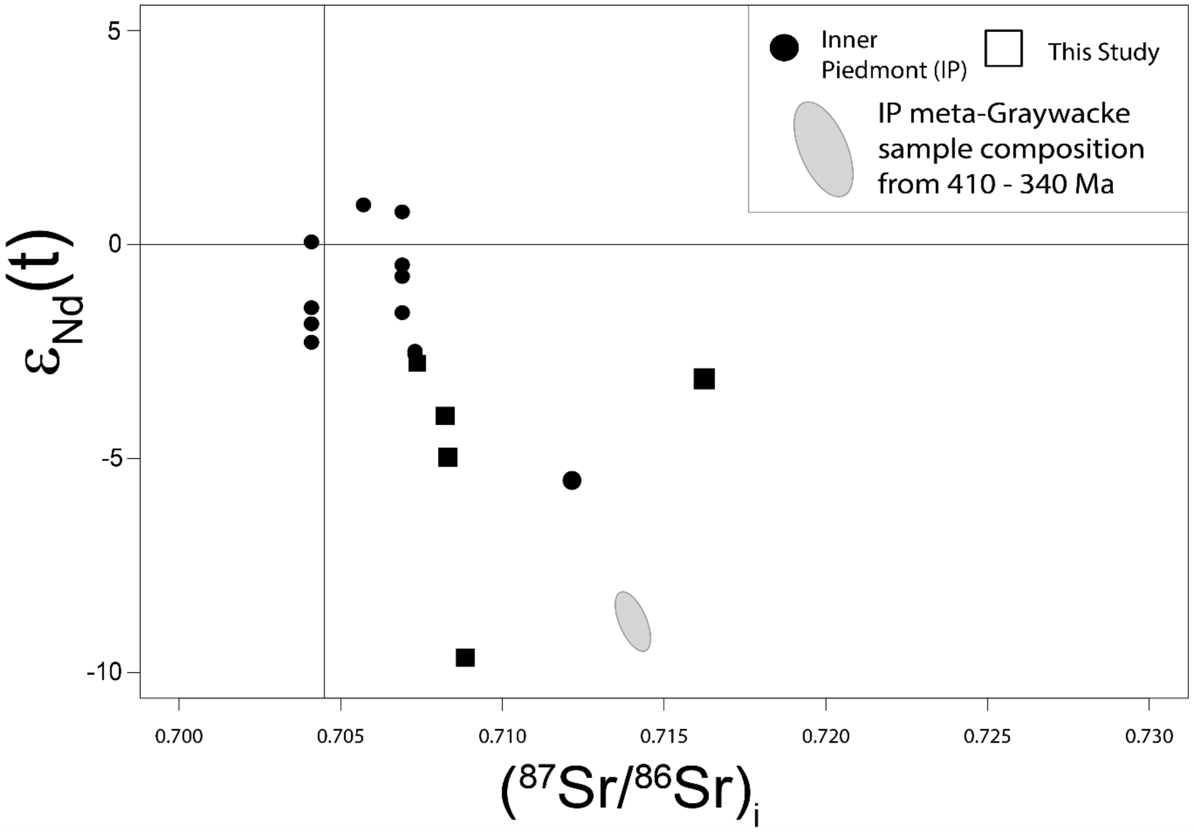

Fig. 8: ε_{Nd}(t) vs $(^{87}Sr/^{86}Sr)_i$ plot representing Inner Piedmont belt samples (black). Circles are data from published studies. Squares represent Neo-Acadian aged samples from this study. The ellipse is MGW with reprojected isotopic compositions from 410 to 340 Ma. Horizontal and vertical lines reflect isotopic compositions of bulk earth. Additional whole rock isotopic data are needed for meta-sedimentary samples from the Cat-Square terrane.

Another approach to evaluating the model proposed by Arthur & Hatcher (2007) and Gatewood (2007) is to determine if plutonic rocks that were potentially the sources of sediment from the Tugaloo and Carolina Super terrane overlap with the isotopic compositions of the granitoids (Fig. 9). By recalculating the Nd isotopic compositions of the potential source rocks to the age of Neo-Acadian Inner Piedmont granitoids it appears as if they could have been sourced from a mix of Tugaloo and Carolina Super terrane rocks (Fig. 10). Back calculation of Sr isotopic compositions is consistent with this possibility as well. Reprojected Nd isotopic compositions, however, cover such a broad range of compositions that they do not provide a particularly discerning test of the anatexis hypothesis.

There are no published data for the U-Th/Pb system that can be used to calculate ratios for potential Cat-Square terrane sediment sources in the past. However, Fisher et al. (2010) provide present-day Pb isotopic data for the rocks and some qualitative observations can be made. Present-day isotopic ratios for potential sediment in the Tugaloo source terranes are generally less radiogenic than initial values for Inner Piedmont plutons (Fig. 7). After correction for *in situ* decay back to 410 to 340 Ma, rocks from the Tugaloo terrane will be even less radiogenic than Neo-Acadian aged Inner Piedmont values. A lack of overlap between these rocks implies that far less Tugaloo terrane was incorporated than Carolina Super terrane (for which there are no available data) during the formation of the Cat-Square terrane. Additional Pb data from the Tugaloo, Cat-Square, and Carolina Super terranes are necessary for further assessment of Arthur & Hatcher (2007) and Gatewood's (2007) hypothesis.

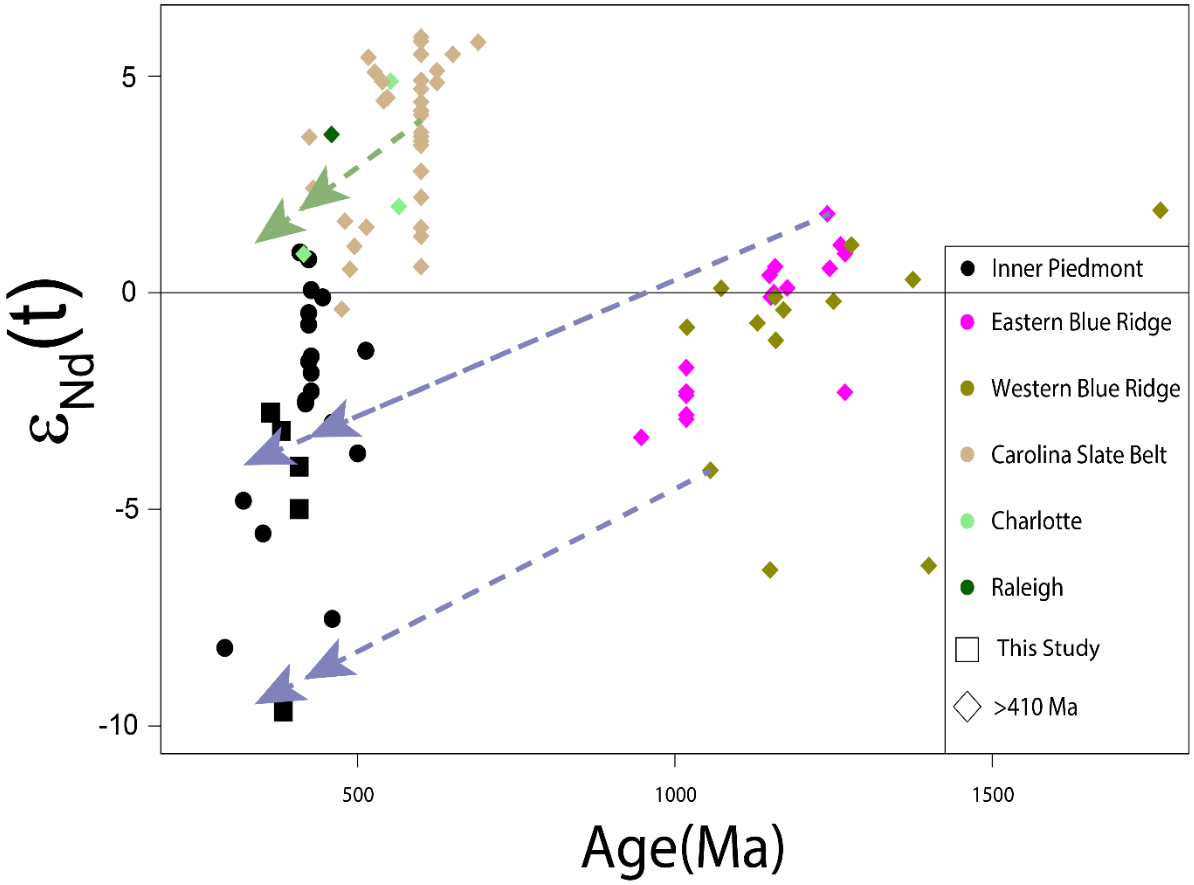

Fig. 9: ε_{Nd}(t) vs. age plot showing the projection of isotopic compositions of rocks greater than 410 Ma to the suggested age range of the Neo-Acadian Orogeny (410-340 Ma). Arrows indicate trend of isotopic compositions through time.

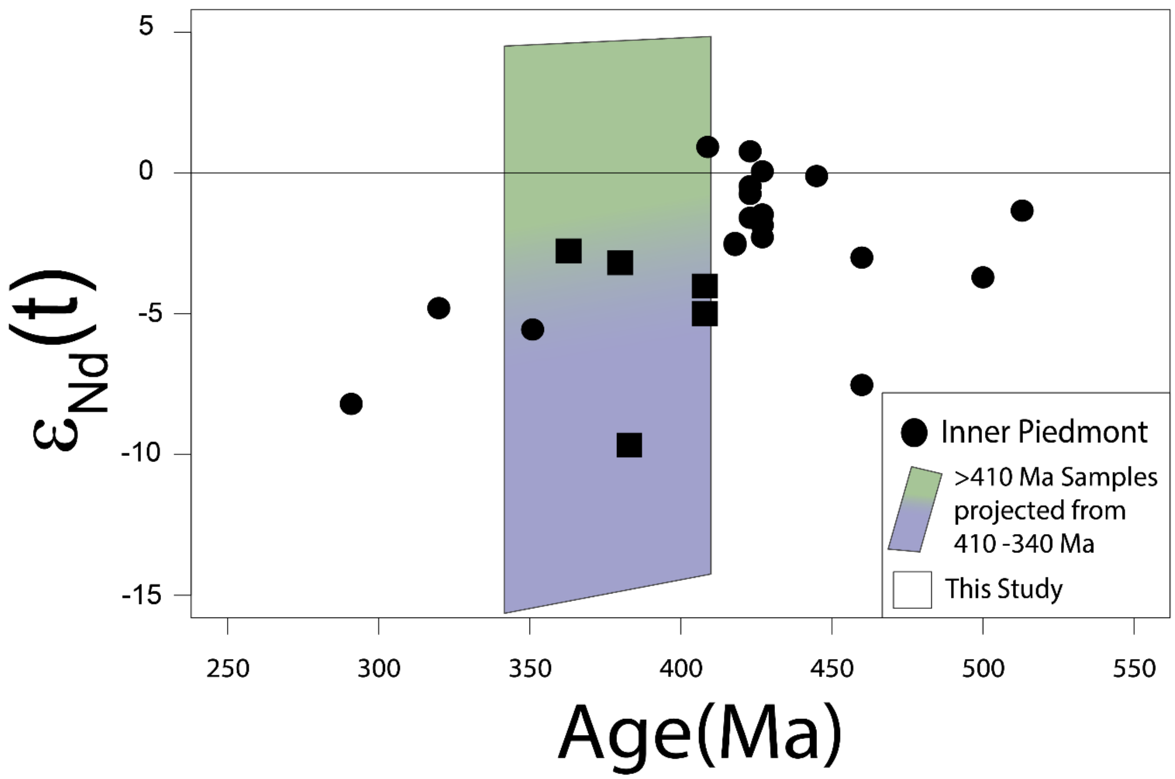

Fig. 10: The width of the polygon spans the age of the Neo-Acadian Orogeny, representing the boundaries of $\varepsilon_{Nd}(t)$ compositions from reprojected samples that could have supplied sediment to the Cat-Square terrane. Neo-Acadian Inner Piedmont granitoids may be derived from a mix of Tugaloo and Carolina Super terranes.

Crustal and Mantle Mixing within the Tugaloo and Charlotte Terranes

It is believed that samples from the Eastern Blue Ridge contain a juvenile mantle component that is not observed in the Western Blue Ridge belt (Fullagar et al. in 1997). T_{DM} for rocks in the Eastern Blue Ridge belt define a juvenile component that is also seen in the Charlotte belt (Fig. 4). This overlap in T_{DM} values between regions implies an overlap in isotopic signatures from the depleted mantle (Fullagar et al., 1997). There is no overlap in the Nd isotopic compositions of mafic and felsic rocks in the dataset, however (Fig. 11). A potential explanation for this behavior may lie in crustal and mantle mixing between the depleted mantle and crustal components of the Tugaloo and Carolina Super terranes. Exploring the relationship with Sr isotopic compositions is hampered by a lack of data; however, a linear relationship between roughly coeval Charlotte and Eastern Blue Ridge belt rocks suggests that a mixing model may explain the variation we see in Charlotte and Eastern Blue Ridge belt rocks (Fig. 12). A similar pattern is observed for samples older than Neo-Acadian samples presented in this study (Fig. 12). There are insufficient Pb isotopic data to evaluate this interpretation.

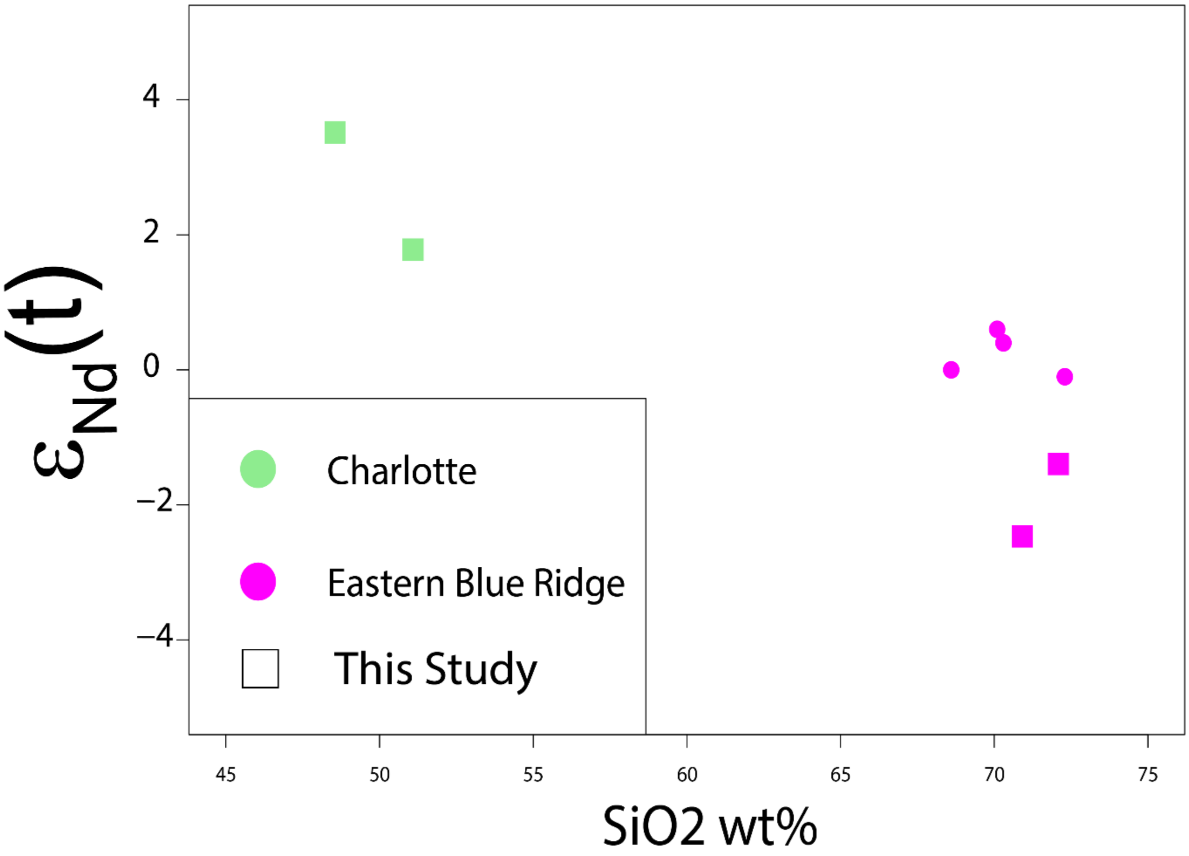

Fig. 11: SiO_2 vs. $\varepsilon_{Nd}(t)$ showing a decrease in $\varepsilon_{Nd}(t)$ with increasing SiO_2, consistent with mixing of mantle (low-SiO_2) and crustal (high SiO_2) magmas.

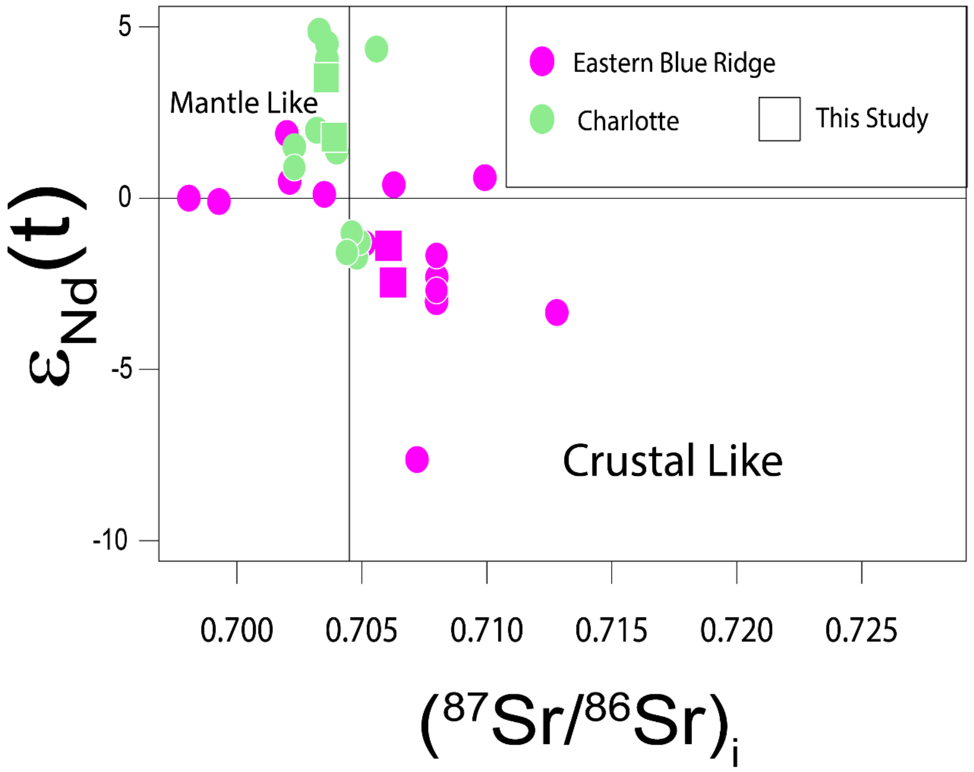

Fig. 12: $(^{87}Sr/^{86}Sr)_i$ vs. $\varepsilon_{Nd}(t)$ showing a decrease in $\varepsilon_{Nd}(t)$ as $(^{87}Sr/^{86}Sr)_i$ increases. Lines represent the composition of bulk earth. Samples which lie near bulk earth suggest that they possess a significant mantle component.

CONCLUSIONS

1. The majority of Neo-Acadian Inner Piedmont granitoids have an increased crustal affinity relative to other plutonic rocks from the Blue Ridge and Carolina terranes, supporting the hypothesis that Neo-Acadian Inner Piedmont granitoids come from the melting of crustal sediments. One source of which may have been from the eroded sediments of the Tugaloo and Carolina Super terranes. However, Pb data suggest a limited role for rocks from the Tugaloo Terrane.
2. Additional whole-rock Nd and Sr data for metasedimentary rocks from the Cat-Square terrane would also help test the sediment anatexis hypothesis for the origin of Neo-Acadian Inner Piedmont granitoids.
3. Limited data for rocks within the Eastern Blue Ridge and Charlotte belts reveal that mixing of a mafic component, similar to that identified in the Charlotte belt, and a felsic component from the Eastern Blue Ridge may yield isotopic compositions observed in both belts.
4. There is an acute lack of U-Th/Pb data for samples within the Southern Appalachians. Present ratios without elemental concentrations for U, Th and Pb are of limited use for assessing magma sources.
5. Neo-Acadian Inner Piedmont samples that did not overlap with eastern and western Blue Ridge rocks isotopically may be derived from a heterogenous of mantle and crustal source rocks such as those in the Carolina Super and Tugaloo terranes. A wide range in $(^{87}Sr/^{86}Sr)_i$ values within Neo-Acadian Inner Piedmont samples of this study across support this idea (Fig. 6).

ACKNOWLEDGEMENTS

Drew Coleman, Arthur Merschat, and Ryan Mills offered invaluable guidance throughout this process without which I would not have a thesis. Xiaoming Liu and Xikai Wang provided the use of their ICP-MS and instructed me on loading and dilution procedures. Han Truong provided vital assistance with lab procedures and techniques. Jonathan Lees helped draft the stacked histogram figure (Fig. 4). Mark Carter was there the day I proposed my original idea to do an honors thesis examining granitoids using Sm-Nd isotope systematics and got me excited to hit the ground running. Eli Bird, Sam Rivers, Douglas Hill, Mike Sandstrom, Alexis Lopez, Ami Ward, Sarah Wells, Ashley Lynn, and Ahmad Isaac provided copious amounts of empathy and fresh perspectives when they were needed the most. Gus Winiker, Members of the 703 Society, Elliot, Kaiya, Woods, Hayden, Daniella, and my parents are the reason where I am today, without their influence I doubt I would have chosen to complete a thesis. Review by Drew Coleman is responsible for the shape of the manuscript you see here today.

REFERENCES CITED

Blichert-Toft, J., Delile, H., Lee, C.-T.A., Stos-Gale, Z., Billstrom, K., Andersen, T., Hannu, H., and Albarede, F., 2016, Large-scale tectonic cycles in Europe revealed by distinct Pb isotope provinces: Geochemistry, Geophysics, Geosystems - G3, v. 17, p. 3854–3864, doi:http://dx.doi.org/10.1002/2016GC006524.

Bream, B.R. Tectonic implications of para- and orthogneiss geochronology and geochemistry from the southern Appalachian crystalline core [Ph.D.]: The University of Tennessee, 310 p., http://www.proquest.com/docview/305306876/abstract/8478A56095824ABCPQ/4 (accessed August 2021).

Bream, B.R., Hatcher, R.D., and Anonymous, 2002, Southern Appalachian terranes amended; timing of accretion and delimiting provenance from new detrital zircon and Nd isotopic data: Abstracts with Programs - Geological Society of America, v. 34, p. 41.

Bream, B.R., Hatcher, R.D., Miller, C.F., and Fullagar, P.D., 2004, Detrital zircon ages and Nd isotopic data from the southern Appalachian crystalline core, Georgia, South Carolina, North Carolina, and Tennessee: New provenance constraints for part of the Laurentian margin:, doi:10.1130/0-8137-1197-5.459.

Bream, B.R., Loewy, S.L., Merschat, A.J., Hatcher, R.D., Miller, C., and Anonymous, 2008, Constraints on Blue Ridge and Inner Piedmont paragneiss provenance; synthesis of detrital zircon and whole-rock Pb isotopic data: Abstracts with Programs - Geological Society of America, v. 40, p. 28.

Cao, C., Liu, X.-M., Bataille, C.P., and Liu, C., 2020, What do Ce anomalies in marine carbonates really mean? A perspective from leaching experiments: Chemical Geology, v. 532, p. 119413, doi:10.1016/j.chemgeo.2019.119413.

Carrigan, C.W., Miller, C.F., Fullagar, P.D., Bream, B.R., Hatcher, R.D., and Coath, C.D., 2003, Ion microprobe age and geochemistry of southern appalachian basement, with implications for Proterozoic and Paleozoic reconstructions: Precambrian Research, v. 120, p. 1–36, doi:10.1016/S0301-9268(02)00113-4.

Coler, D.G., Samson, S.D., and Speer, J.A., 1997, Nd and Sr isotopic constraints on the source of Alleghanian granites in the Raleigh metamorphic belt and Eastern slate belt, southern Appalachians, U.S.A.: Chemical Geology, v. 134, p. 257–275, doi:10.1016/S0009-2541(96)00063-0.

Dallmeyer, R.D., 1991, Exotic Terranes in the Central-Southern Appalachian Orogen and Correlations With West Africa, *in* Dallmeyer, R.D. and Lécorché, J.P. eds., The West African Orogens and Circum-Atlantic Correlatives, Berlin, Heidelberg, Springer, IGCP-Project 233, p. 335–371, doi:10.1007/978-3-642-84153-8_15.

Dasgupta, T. Geochemistry and geochronology of Alleghanian and "atypical" Alleghanian granites from south-central Appalachians: Implications for magma evolution and Late Paleozoic terrane accretionary history in the southern Appalachians [Ph.D.]: Syracuse University, 332 p., https://www.proquest.com/docview/821864533/abstract/D5D5315156474CE9PQ/1 (accessed December 2021).

Dasgupta, T., Samson, S., and Anonymous, 2008, Geochronology and geochemistry of Alleghanian and "atypical" Alleghanian granites in the Carolina Terrane, Southern Appalachians; implications for sources and terrane accretionary history: Abstracts with Programs - Geological Society of America, v. 40, p. 69.

Fisher, C.M., Loewy, S.L., Miller, C.F., Berquist, P., Van Schmus, W.R., Hatcher, R.D., Jr., Wooden, J.L., and Fullagar, P.D., 2010, Whole-rock Pb and Sm-Nd isotopic constraints on the growth of southeastern Laurentia during Grenvillian orogenesis: GSA Bulletin, v. 122, p. 1646–1659, doi:10.1130/B30116.1.

Fullagar, P., Goldberg, S., and Butler, J., 1997, Nd and Sr isotopic characterization of crystalline rocks from the Southern Appalachian Piedmont and Blue Ridge, North and South Carolina, *in* Memoir of the Geological Society of America, v. 191, p. 165–179, doi:10.1130/0-8137-1191-6.165.

Gatewood, M., 2007, Tectonics of the Northeastern Inner Piedmont, Northwestern NC, from Detailed Geologic Mapping, Geochronologic, Geochemical, and Petrologic Studies with Structural Analyses of Ductile Fault Zones: Masters Theses, https://trace.tennessee.edu/utk_gradthes/132.

Gatewood, M.P., Hatcher, R.D., Miller, C.F., Wooden, J.L., and Anonymous, 2006, Timing of inner Piedmont terrane accretion; new structural and geochronologic data provide important timing relationships: Abstracts with Programs - Geological Society of America, v. 38, p. 21.

Hatcher, J., Robert, 1987, Tectonics of the Southern and Central Appalachian Internides: Annual review of earth and planetary sciences. Vol. 15, v. 15, p. 337–362, doi:10.1146/annurev.ea.15.050187.002005.

Hatcher, R.D., Bream, B.R., Merschat, A.J., Carlson, M.P., McBride, J.H., and Martinez Catalan, J.R., 2007, Tectonic map of the Southern and Central Appalachians; a tale of three orogens and a complete Wilson cycle: Memoir - Geological Society of America, v. 200, p. 595–632, doi:http://dx.doi.org.libproxy.lib.unc.edu/10.1130/2007.1200(29).

Hatcher, R.D., Bream, B.R., Miller, C.F., Eckert, J.O., Fullagar, P.D., Carrigan, C.W., Tollo, R.P., Corriveau, L., McLelland, J., and Bartholomew, M.J., 2004, Paleozoic structure of internal basement massifs, Southern Appalachian Blue Ridge, incorporating new geochronologic, Nd and Sr isotopic, and geochemical data: Memoir - Geological Society of America, v. 197, p. 525–547.

Hatcher, R.D., Jr., and Merschat, A.J., 2006, The Appalachian Inner Piedmont: an exhumed strike-parallel, tectonically forced orogenic channel, *in* Law, R.D., Searle, M.P., and Godin, L. eds., Channel Flow, Ductile Extrusion and Exhumation in Continental Collision Zones, Geological Society of London, v. 268, p. 0, doi:10.1144/GSL.SP.2006.268.01.24.

Hatcher, R.D., Jr., Merschat, A.J., and J. Ryan, T., 2005, Blue Ridge Geology Geotraverse East of the Great Smoky Mountains National Park, Western North Carolina, *in* Carolina Geological Society Annual Field Trip, p. 1–12.

Hazlewood, L.E., Bender, J.F., and Anonymous, 2012, Petrogenesis of the Concord Syenite; partial melting of an alkalic gabbro: Abstracts with Programs - Geological Society of America, v. 44, p. 543.

Hibbard, J., 2000, Docking Carolina: Mid-Paleozoic accretion in the southern Appalachians: Geology, v. 28, p. 127–130, doi:10.1130/0091-7613(2000)28<127:DCMAIT>2.0.CO;2.

Hibbard, J., Stoddard, E., Secor, D., and Dennis, A., 2002, The Carolina Zone: overview of Neoproterozoic to Early Paleozoic peri-Gondwanan terranes along the eastern Flank of the southern Appalachians: Earth-Science Reviews, v. 57, p. 299–339, doi:10.1016/S0012-8252(01)00079-4.

Huebner, M.T., and Hatcher, R.D., 2017, Transition from B- to A-type subduction during closing of the Rheic remnant ocean: New geochronologic and geochemical data marking Acadian-Neoacadian orogenesis and accretion of the Carolina superterrane, southern Appalachians:, doi:10.1130/2017.1213(12).

Jr, J.W.H., and Zullo, V.A., 1991, Geology Of Carolinas: Carolina Geological Society 50Th Anniversary Volume: Knoxville, Univ Tennessee Press, 424 p.

Jubb, M.G., 2010, Paradoxes in the deformational and metamorphic history of the eastern Blue Ridge: Evidence from the Lake Toxaway and eastern Big Ridge quadrangles, North Carolina: Masters Theses, https://trace.tennessee.edu/utk_gradthes/638.

Li, W., Liu, X.-M., and Godfrey, L.V., 2019, Optimisation of Lithium Chromatography for Isotopic Analysis in Geological Reference Materials by MC-ICP-MS: Geostandards and Geoanalytical Research, v. 43, p. 261–276, doi:10.1111/ggr.12254.

Li, W., Liu, X.-M., Hu, Y., Teng, F.-Z., and Hu, Y., 2021, Potassium isotopic fractionation during clay adsorption: Geochimica et Cosmochimica Acta, v. 304, p. 160–177, doi:10.1016/j.gca.2021.04.027.

Mapes, R.W., Maybin, A.H., Miller, C.F., Fullagar, P.D., Bream, B.R., and Anonymous, 2002, Geochronology and geochemistry of mid Paleozoic granitic magmatism, central and eastern Inner Piedmont, NC & SC: Abstracts with Programs - Geological Society of America, v. 34, p. 92.

McLennan, S.M., Bock, B., Compston, W., Hemming, S.R., and McDaniel, D.K., 2001, Detrital Zircon Geochronology of Taconian and Acadian Foreland Sedimentary Rocks in New England: Journal of Sedimentary Research, v. 71, p. 305–317, doi:10.1306/072600710305.

McSween, H.Y., and Harvey, R.P., 1997, Concord Plutonic Suite: Pre-Acadian gabbro-syenite intrusions in the southern Appalachians:, doi:10.1130/0-8137-1191-6.221.

Merschat, A.J., Bream, B.R., Hatcher, R.D., Huebner, M.T., and Anonymous, 2012, Provenance of Blue Ridge and Inner Piedmont terranes from detrital zircon geochronology and whole-rock isotopic data, NC-SC-GA-TN: Abstracts with Programs - Geological Society of America, v. 44, p. 173.

Merschat, A.J., and Hatcher, R.D., 2007, The Cat Square terrane: Possible Siluro-Devonian remnant ocean basin in the Inner Piedmont, southern Appalachians, USA:, doi:10.1130/2007.1200(27).

Merschat, A.J., Hatcher, R.D., Bream, B.R., Miller, C.F., Byars, H.E., Gatewood, M.P., and Wooden, J.L., 2010, Detrital zircon geochronology and provenance of southern Appalachian Blue Ridge and Inner Piedmont crystalline terranes:, doi:10.1130/2010.1206(26).

Miller, B.V., Fetter, A.H., and Stewart, K.G., 2006, Plutonism in three orogenic pulses, Eastern Blue Ridge Province, southern Appalachians: GSA Bulletin, v. 118, p. 171–184, doi:10.1130/B25580.1.

Miller, C.F., Fullagar, P., Sando, T.W., Kish, S., Solomon, G., Russell, G.S., and Steltenpohl, L., 1997, Low-potassium, trondhjemitic to granodioritic plutonism in the eastern Blue Ridge, southwestern North Carolina-northeastern Georgia:, doi:10.1130/0-8137-1191-6.235.

Miller, B.V., Stewart, K.G., and Whitney, D.L., 2010, Three tectonothermal pulses recorded in eclogite and amphibolite of the Eastern BlueRidge, Southern Appalachians, *in* From Rodinia to Pangea, Geological Society of America, Memoir of the Geological Society of America, p. 701–724, doi:10.1130/2010.1206(27).

Odom, A.L., and Fullagar, P.D., 1973, Geochronologic and tectonic relationships between the Inner Piedmont, Brevard Zone, and Blue Ridge belts, North Carolina: American Journal of Science, v. 273-A, p. 133–149.

Osberg, P.H., Tull, J.F., Robinson, P., Hon, R., and Butler, J.R., 1989, The Acadian orogen, Chapter 4, in Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 179–232.

Quinn, R.J., Moecher, D.P., Satkoski, A.M., Samson, S.D., Tohver, E., and Anonymous, 2012, Nd-Pb isotope systematics and zircon U-Pb geochronology support a native crustal component within Grenville basement, eastern Great Smoky Mountains: Abstracts with Programs - Geological Society of America, v. 44, p. 281.

Samson, S.D., Coler, D.G., and Speer, J.A., 1995, Geochemical and NdSrPb isotopic composition of Alleghanian granites of the southern Appalachians: Origin, tectonic setting, and source characterization: Earth and Planetary Science Letters, v. 134, p. 359–376, doi:10.1016/0012-821X(95)00124-U.

Speer, J.A., McSween, H.Y., and Gates, A.E., 1994, Generation, Segregation, Ascent, and Emplacement of Alleghanian Plutons in the Southern Appalachians: The Journal of Geology, v. 102, p. 249–267.

Stewart, K.G., 2007, By Kevin G. Stewart - Exploring the Geology of the Carolinas: A Field Guide to Favorite Places from Chimney Rock to Charleston: 1st (first) Edition:

Trupe, C.H., Stewart, K.G., Adams, M.G., Waters, C.L., Miller, B.V., and Hewitt, L.K., 2003, The Burnsville fault: Evidence for the timing and kinematics of southern Appalachian Acadian dextral transform tectonics: GSA Bulletin, v. 115, p. 1365–1376, doi:10.1130/B25256.1.

Wilson, C.G., Hatcher, R.D., Bream, B.R., and Anonymous, 2006, The nature and origin of Inner Piedmont Taconian and Neoacadian magmatism; synthesis of recent and new geochemical data: Abstracts with Programs - Geological Society of America, v. 38, p. 73.

Winchester, C.L., 2013, Alleghanian plutonism in the eastern Blue Ridge province of the southern Appalachians: Origin and tectonic setting [M.S.]: The University of North Carolina at Chapel Hill, 45 p., http://www.proquest.com/docview/1438865843/abstract/E625DF20B9BE46C0PQ/1 (accessed August 2021).

Zhang, Y.-L., Zhang, H.-F., Bao, Z.-A., Santosh, M., and Yuan, H.-L., 2016, Heterogeneous Pb isotope composition in the Archean lower crust of the North China Craton induced by Cenozoic basaltic magma underplating: Journal of Asian Earth Sciences, v. 125, p. 71–86, doi:10.1016/j.jseaes.2016.05.016.