

ALLEGHANIAN PLUTONISM IN THE EASTERN BLUE RIDGE PROVINCE OF THE
SOUTHERN APPALACHIANS: ORIGIN AND TECTONIC SETTING

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Abstract

CRISTINE LYNN WINCHESTER: Alleghanian Plutonism in the Eastern Blue Ridge
Province of the Southern Appalachians: Origin and Tectonic Setting

(Under the direction of Dr. Kevin Stewart)

The Alleghanian orogeny was caused by the closing of the Theic ocean basin and subsequent collision of Gondwana with Laurentia. The orientation of the subducted Theic oceanic lithosphere is unknown but may be recorded in Carboniferous magmatism recently discovered in the southern Appalachians. The four Alleghanian plutons located in the eastern Blue Ridge are the oldest of the Alleghanian plutons and predate the estimated collision ca. 330 Ma. These plutons have ϵ_{Nd} values in between published values from the Grenville basement and the depleted mantle evolution line (~ 7.5 at 335 Ma), indicating that they derived from melting of juvenile and crustal sources. Mantle model and xenocrystic zircon ages from the EBR plutons are coeval with Grenville orogenesis suggesting that the crustal component was Grenville basement. Based on the zircon dates combined with the geochemical data, the EBR plutons were likely emplaced when the Theic oceanic lithosphere was subducting beneath Laurentia.

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Introduction

Igneous rocks in the southern Appalachians are typically associated with four orogenic events (Hatcher 2005): the Grenvillian orogeny (~1030 Ma plutons), the Taconian orogeny (490 – 440 Ma plutons), the Acadian orogeny (420 – 350 Ma plutons), and the Alleghanian orogeny (335 – 270 Ma plutons). Most of the Alleghanian plutons are located in the Carolina and Piedmont terranes and were emplaced during or after the collision of Gondwana with Laurentia between 326 Ma and 288 Ma (Speer et al. 1994). This timing coupled with available geochemical data suggested that the Piedmont and Carolina plutons are the result of syn-collisional heating of thickened crust (e.g. Price 1969, Speer et al. 1994). There are only four known Alleghanian plutons in the Eastern Blue Ridge: Stone Mountain, Mt. Airy, Walnut Creek, and Rabun. Recent geochronologic work (Miller and Stewart 2002, Stahr and Hatcher 2004, Miller et al. 2002) revealed that these plutons are significantly older than the Alleghanian plutons located in the Carolina and Piedmont terranes and predate the estimated collision of Gondwana with Laurentia at ca. 330 Ma (Hatcher 1987).

Proposed hypotheses for the origin of Alleghanian plutonism are based solely on the study of Piedmont and Carolina plutons (e.g. Coler et al. 1994, Speer et al. 1994). The competing hypotheses range from arc magmatism (e.g. Sinha and Zietz 1982 and Stahr 2008) to crustal melting induced by crustal thickening (e.g. Speer et al. 1994, Coler et al. 1997). If melting was caused by crustal thickening during the collision, one would expect to see the oldest plutons in the hinterland (southeast) and the youngest in the foreland (northwest); deformation in the

Alleghanian progressed from southeast to northwest as Gondwana collided with the eastern margin of Laurentia (Hatcher 2002).

An alternative model is that the Alleghanian plutons formed during subduction of Theic oceanic lithosphere prior to the Gondwanan collision (Sinha and Zietz 1982, Stahr 2008). This requires a west-dipping (modern-day orientation) subduction zone beneath Laurentia. The dominance of east-dipping northwest-vergent thrust faults throughout the Alleghanian orogen has been cited as evidence for an east-dipping subduction zone during the collision of Gondwana with Laurentia (Massey and Moecher 2005). East-dipping thrusts do not rule out an arc setting for the eastern Blue Ridge (EBR) plutons because they pre-date the estimated collision.

Geologic Setting

Introduction to Southern Appalachian Tectonics

Appalachian mountain building began with the creation of Rodinia in the Proterozoic and continued episodically through the Paleozoic culminating with the creation of Pangaea (Hatcher 1987). Between orogenies there were periods of rifting that produced one failed and two successful rifts (Neoproterozoic and Triassic) responsible for creating the Iapetus and modern Atlantic Oceans, respectively (Hatcher 1987). As a result, rocks of the southern Appalachians record parts of each event and overprinting is widespread. Although the record of the different orogenic phases is variably preserved in the rocks of the southern Appalachians, basic information about the tectonic history, such as the polarity of the associated subduction zones, is commonly lacking.

Alleghanian Orogeny

The Alleghanian is the youngest of the Appalachian orogenies and marks the closing of the Theic ocean basin and the resulting collision of Gondwana with Laurentia beginning in the Late Mississippian and continuing into the Permian. The collision completed the assembly of Pangaea (Hatcher 1987; Figure 1). Magmatism was widespread in the southern Appalachians during the assembly of Pangaea but was mostly focused in the Piedmont and in Carolina (Charlotte and Carolina terranes; Figure 2). There are four Alleghanian plutons located in the EBR which formed pre- to syn-tectonically (Miller and Stewart 2002, Stahr and Hatcher 2004). Alleghanian plutons from beneath the Coastal Plain to the Piedmont formed synchronously with thrusting in the Valley and Ridge province (Samson et al. 1995a; Figure 2).

During the collision, deformation produced thrust faults, ramp anticlines, deformation fabrics, and dextral strike-slip faults (Hatcher 1989, Massey and Moecher 2005). In fact, most of the major thrust faults in the southern Appalachians are attributed to the Alleghanian orogeny (Trupe et al. 2004). The Piedmont and Blue Ridge terranes were transported together ~400 km northwestward (Hatcher 2002). Minimum estimates on the transport of Carolina terranes are 50 km but it is probable that thrusting was on the same order as transport of the BR and Piedmont terranes (Hatcher 2002). Despite the large amount of shortening westward, metamorphic conditions did not exceed greenschist facies (Miller et al. 2010). By 300 Ma, most of the region cooled below 500°C (Lux and Guidotti, 1985).

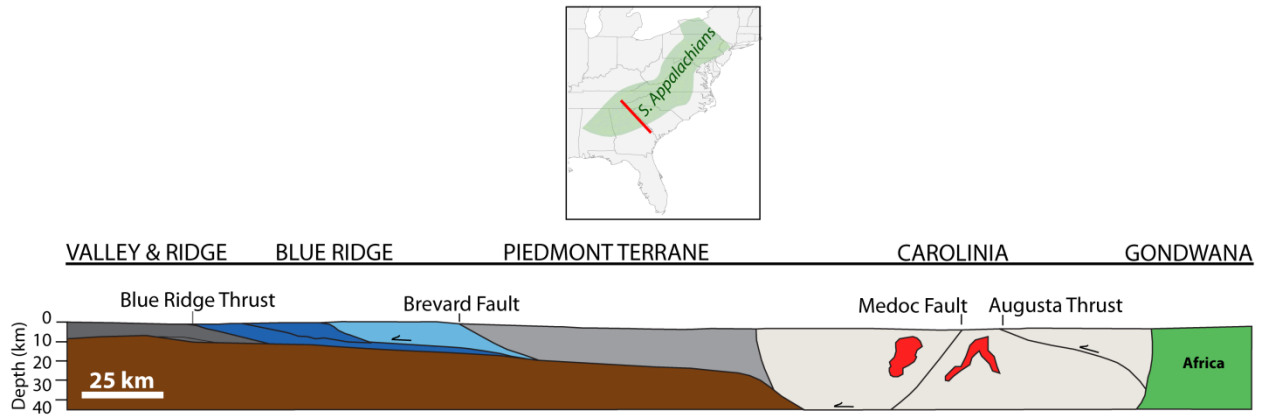


Figure 1. Cross-section of the Alleghanian orogeny (modified from Hatcher 1987).

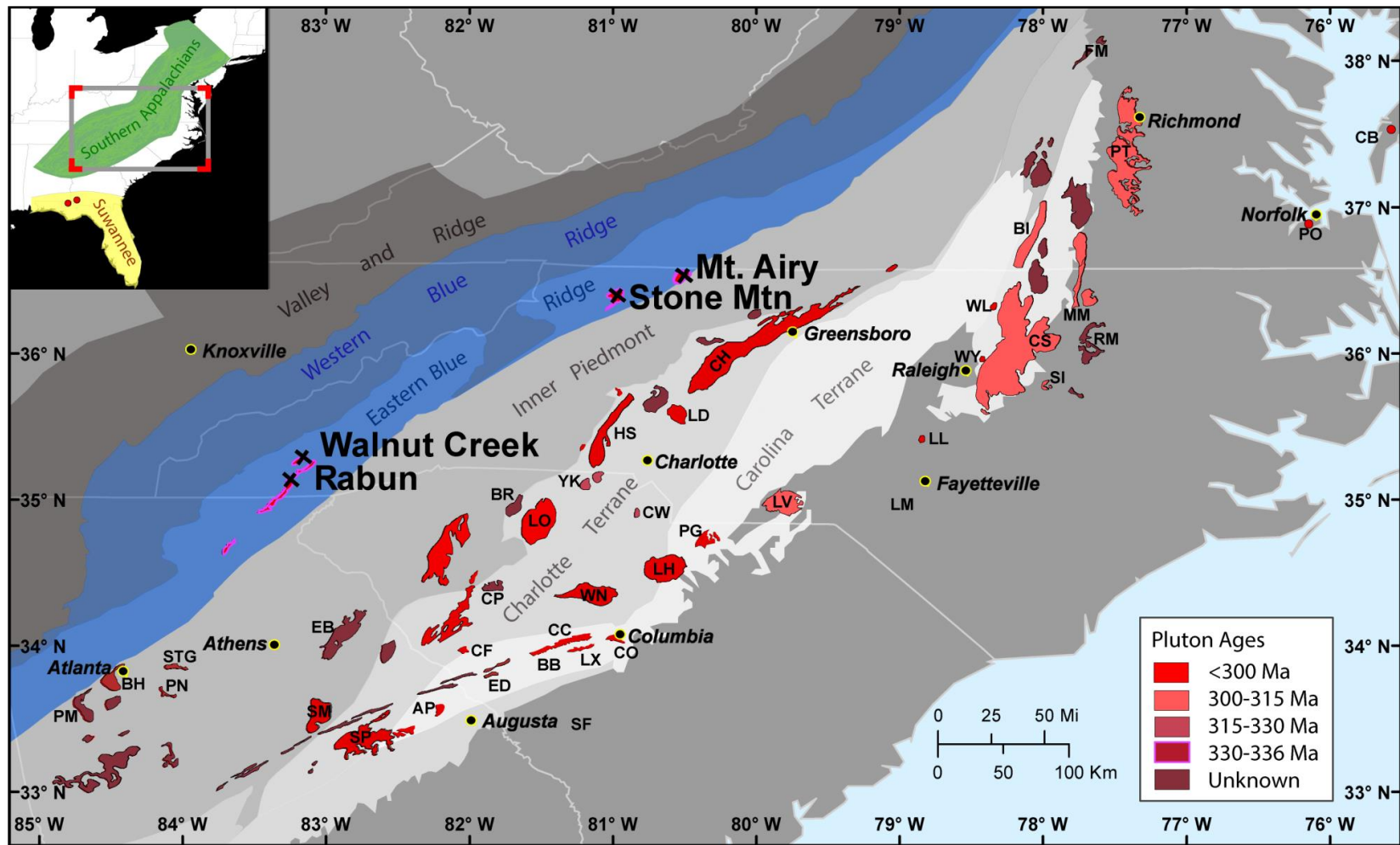


Figure 2. Location map of the southern Appalachian Alleghanian plutons. Plutons with reported Alleghanian ages are identified by initial; AP-Appling Granite, BR-Bald Rock, BB-Batesburg, BH-Ben Hill, BI-Buggs Island, CS-Castalia, CW-Catawba-Roddey, CB-Chesapeake Bay*, CH-Churchland, CC-Cloud's Creek, CP-Cold Point, CO-Columbia, CF-Cuffytown Creek, EB-Elberton, ED-Edgefield, FM-Falmouth, HS-High Shoal's, LD-Landis, LX-Lexington, LH-Liberty Hill, LV-Lilesville, LL-Lillington, MM-Medoc Mountain, PG-Pageland, PM-Palmetto-Tyrone, PN-Panola, PT-Petersburg, PO-Portsmouth*, RM-Rocky Mount, SM-Siloam, SI-Sims, SP-Sparta, STG-Stone Mountain(GA), WL-Wilton, WN-Winnsboro, WY-Wyatt, YK-York. * Indicates sample was obtained from a drill core.

Origin of the Alleghanian Plutons

Introduction

Historically, researchers believed that Alleghanian magmatism occurred during or after continental collision without any subduction-induced melting (Price 1969, Speer et al. 1994, Samson et al. 1995a, Hatcher 2005). With the exception of the EBR plutons - which predate the 330 Ma estimated collision of Laurentia and Gondwana (Hatcher 1989) - the geochronological and geochemical analyses for many of the plutons support crustal melting. In order to determine whether plutonism occurred before the collision in a continental arc setting or due to crustal melting during or after the collision, the geochemical data has to be compared and explored for signatures of mantle-derived melting.

Crustal Melting

Coler et al. (1997) interpreted the dominantly felsic composition of the Alleghanian plutons to indicate exclusively crustal melting. Cited as evidence were the characteristic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios higher than 0.7045 - indicative of a chemically evolved magma due to partial melting of a crustal source. Although crustal melting is a substantiated and widely accepted hypothesis, an accepted heat source remains unidentified. Commonly proposed heat mechanisms are crustal thickening, delamination of the lower crust, decompression melting due to crustal arching or orogenic collapse, and frictional melting due to faulting (Speer et al. 1994, Samson et al. 1995a). Of the listed possibilities, frictional melting is the most substantiated; several of the Alleghanian plutons are elliptical and have flow foliation parallel to adjacent shear zones (e.g. Batesburg, Buggs Island, Lexington, High Shoals, Palmetto, Petersburg, Clouds Creek, and Siloam plutons; Speer et al. 1994). Many plutons are also weakly foliated and located adjacent to or are cut by

known Alleghanian faults (e.g. Batesburg, Buggs Island, Rabun, Walnut Creek) suggesting syn-collisional emplacement (Speer et al. 1994). All of these hypotheses are viable explanations for the Alleghanian plutonism. Regardless, this research does not attempt to identify melting mechanisms but rather whether or not it was subduction driven.

Continental arc

Although the origin of Alleghanian plutonism is widely accepted as crustal melting, syn- and post-collisional mechanisms do not explain several patterns observed in the Alleghanian plutons. Sinha and Zietz (1982) proposed that the Carolina and Piedmont plutons formed in an arc setting because the plutons outcrop in an arcuate pattern similar to modern-day continental arcs in the Andes and West Indies. Sinha and Zietz (1982) also noted that geochemical signatures vary transitionally across strike, with compositions becoming increasingly felsic toward the hinterland, another pattern consistent in modern continental arcs. Specifically, Carolina and eastern Piedmont plutons are characterized by SiO_2 content greater than 72% and K_2O values greater than 5% while western Piedmont plutons are characterized by SiO_2 content between 68-72% and K_2O values between 4-5% (Sinha and Zietz 1982). Stahr (2008) also proposed that the EBR Rabun and Walnut Creek plutons derived from mantle- and crustal-derived melt when analysis of their isotopic compositions of the Rabun and Walnut Creek trondhjemites indicated the role of crustal material was minimal (Stahr 2008). Despite their arcuate pattern and transitional geochemistry across strike, an arc origin has typically been ruled out for the Carolina and Piedmont plutons because of the lack of plutons with an intermediate-to-mafic composition and abundance of syn-tectonic plutons (Speer et al. 1994) and ϵ_{Nd} values similar to the Grenville basement and the Carolina terranes (Coler et al. 1997).

Analytical Methods

Samples from the EBR plutons were collected and analyzed for geochemical and isotopic ratio analysis. Two samples each of the Mt. Airy pluton from the North Carolina Granite Company quarry (Figure 3), the Rabun pluton from Vulcan Materials quarry (Figure 4), and the Stone Mountain pluton from Stone Mountain State Park in North Carolina (Figure 5) were collected totaling six samples (Appendix II). Samples were not collected from the Walnut Creek pluton because of its proximity and geochemical similarity to the Rabun pluton (Stahr 2008). Samples ranged in size from 5 to 10 kg and were fractured by hand into fist-sized samples. The samples were then broken into chips with a chipmunk and ground to a fine powder using a shatter box.

Washington University in St. Louis, Missouri analyzed two samples of the Mt. Airy pluton and one sample of the Stone Mountain pluton for major and trace element concentrations. Major elements along with Sr, Ba, Y, and Zr were measured by inductively coupled plasma (ICP) emission spectroscopy employing lithium metaborate/tetraborate fusion (FUS-ICP). Lead concentrations were obtained by total digestion methods (TD-ICP). Trace and rare earth elements (REE) were measured by instrumental neutron activation analysis (INAA) and fusion methods (FUS-MS). Major element data were used to calculate the normative mineralogy (CIPW norm) of the samples. Rock classification was done using a normative feldspar diagram (An-Ab-Or) created by O'Connor (1965) and modified by Barker (1979). Trace elements were used to test provenance.

Sm-Nd isotopic ratios were obtained using the University of North Carolina thermal ionization mass spectrometer. Two samples were analyzed from each pluton for Sm-Nd isotopic

ratios. Two samples of Mt. Airy and Rabun were also analyzed for Rb-Sr ratios but only one sample of Stone Mountain was pristine enough to analyze for Rb-Sr isotopic ratios.

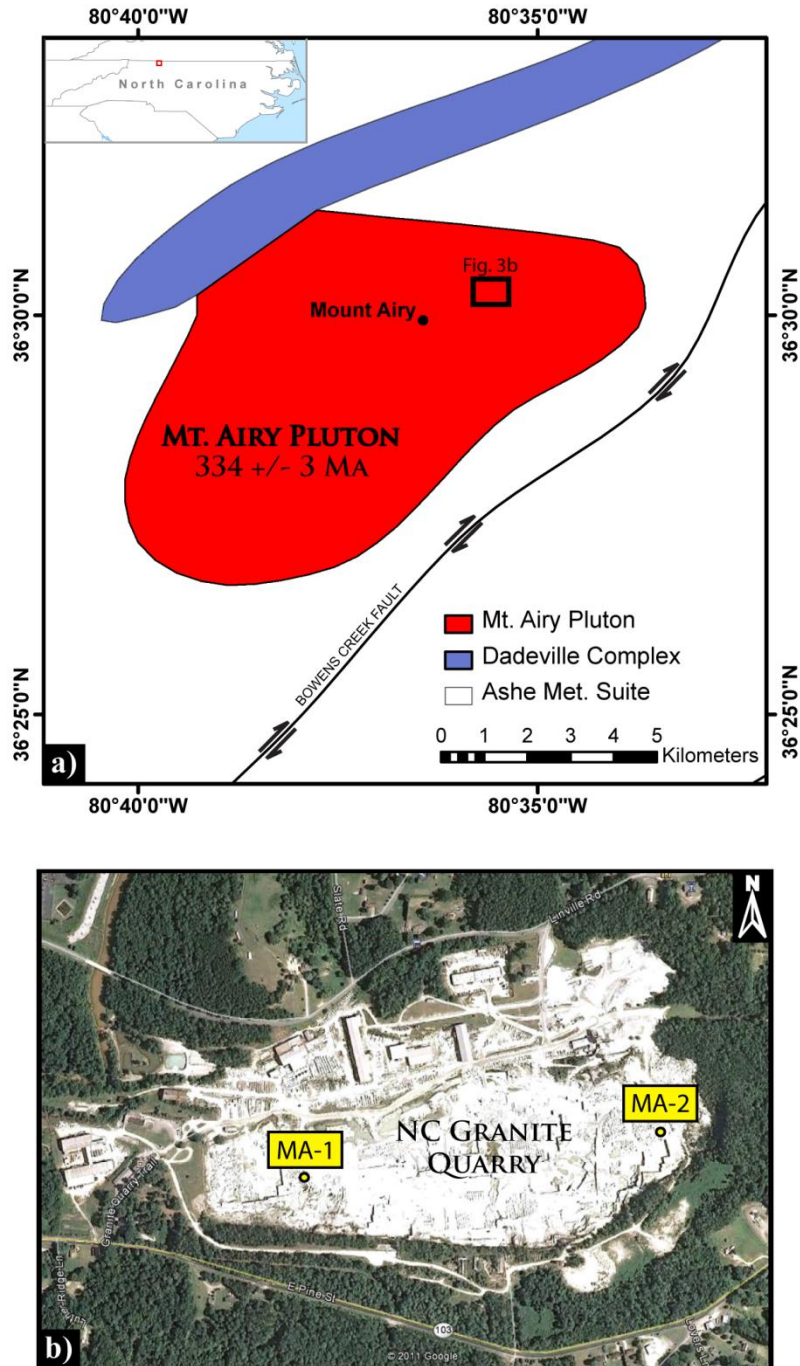


Figure 3. Mt. Airy pluton map. Figure 3A shows Mt. Airy pluton outcrop (Hibbard et al. 2006). Both samples (MA-1 and MA-2) were collected within the NC Granite Quarry shown in Figure B (www.earth.google.com). UTM coordinates for sample locations are given in Appendix II.

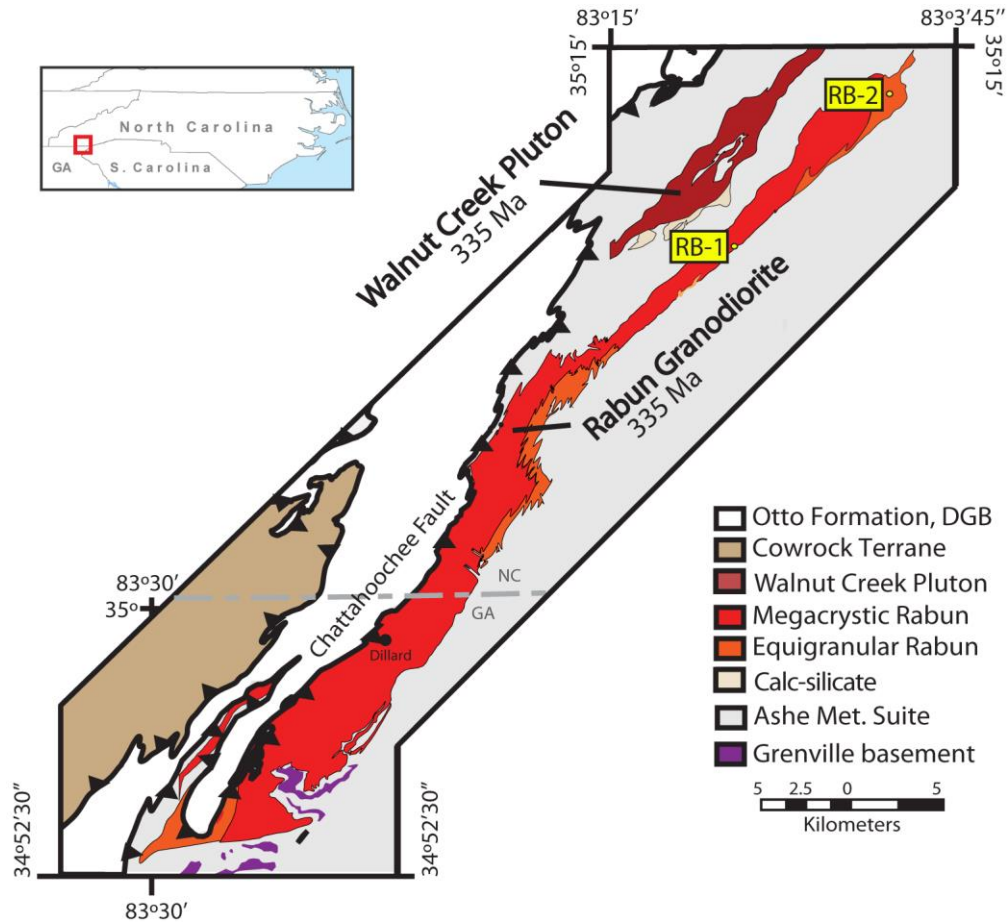


Figure 4. Geologic map of Walnut Creek and Rabun plutons. The Rabun is shown here with its two textural phases identified; a dominant megacrystic to porphyritic phase with an equigranular phase concentrated at the tips and in the center (modified from Stahr 2008). Two samples were collected from the Rabun pluton (RB-1 and RB-2), one sample was collected per textural phase. UTM coordinates for sample locations are given in Appendix II.

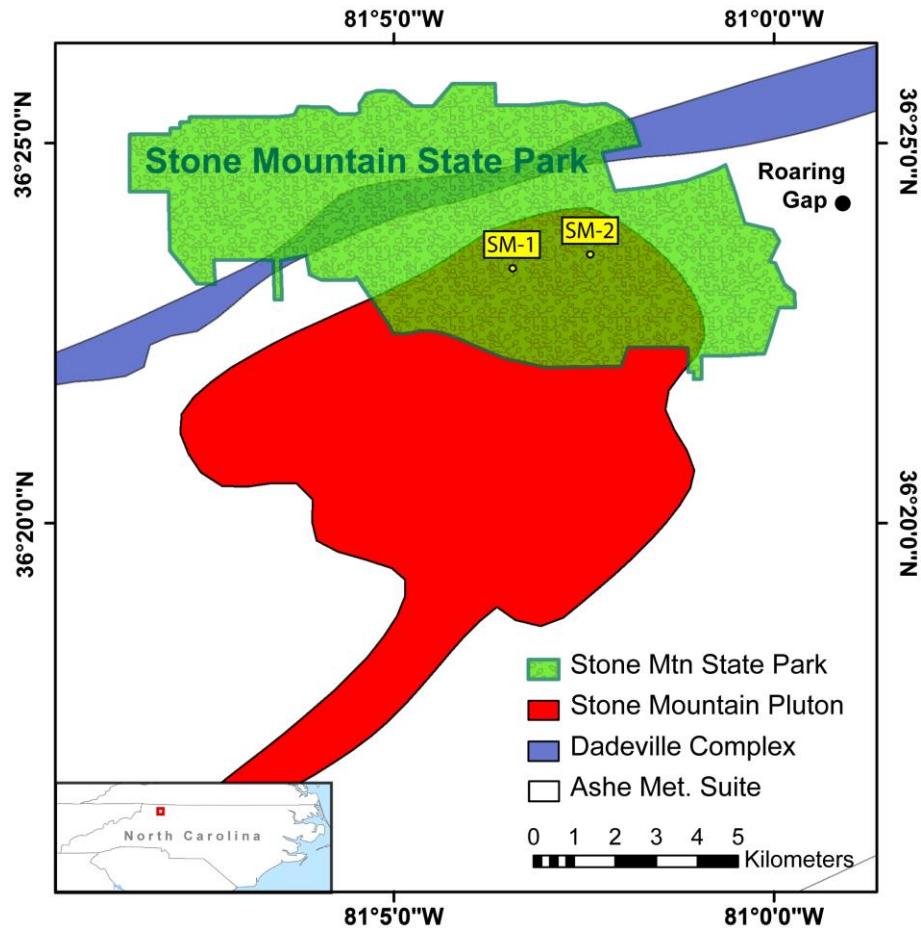


Figure 5. Geologic map of the Stone Mountain pluton. UTM coordinates for Stone Mountain sample locations are in Appendix II). Geology from Hibbard et al. 2006.

Petrology

Alleghanian plutons located in the Piedmont and Carolina terranes are commonly equigranular granites to granodiorites (Appendix I). Speer and Hoff (1997) stated that less than 5% of the plutons are intermediate to mafic and equate to less than 1% of the total volume of plutonism east of the Blue Ridge (e.g. Clouds Creek and Lilesville-Peedee plutons; Speer et al. 1994). The Alleghanian plutons located in the EBR are granitic to trondhjemitic (Figure 6). The Mt. Airy pluton is white, coarse-grained, equigranular quartz-rich granite (Figure 7). The Rabun pluton consists of two texturally distinct phases – a dominant porphyritic to megacrystic phase and an equigranular phase (Stahr 2004; Figure 8). The porphyritic to megacrystic phase is white

to tan, medium- to coarse-grained granodiorite with potassic feldspar phenocrysts 1-2 cm long. The equigranular phase of the Rabun pluton is gray to tan, medium-grained, biotite granodiorite to trondhjemite. The Stone Mountain pluton is tan, medium- to coarse-grained equigranular granite (Figure 9). The Mt. Airy and Stone Mountain plutons are weakly foliated. The Rabun and Walnut Creek plutons are strongly elongated and locally foliated parallel to the Chattahoochee fault, an Alleghanian thrust fault.

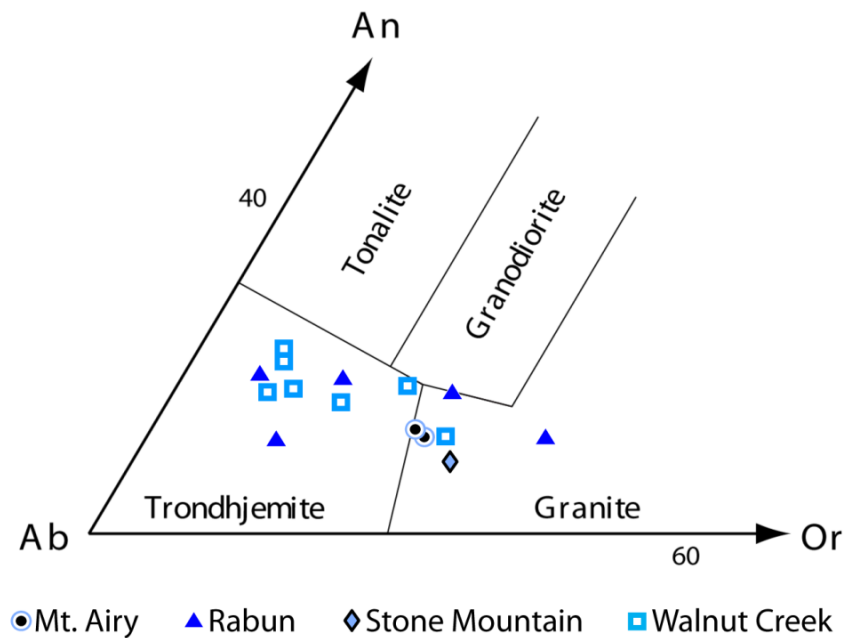


Figure 6. Normative feldspar classification of EBR Alleghanian plutons (Barker 1979). Figure modified from Stahr (2008). Note how the EBR plutons are either trondhjemitic to granitic in composition.

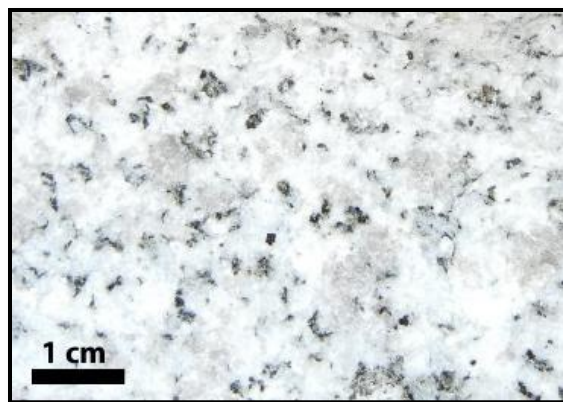


Figure 7. Mt. Airy granite. The Mt. Airy pluton is white, coarse-grained, equigranular quartz-rich granite.

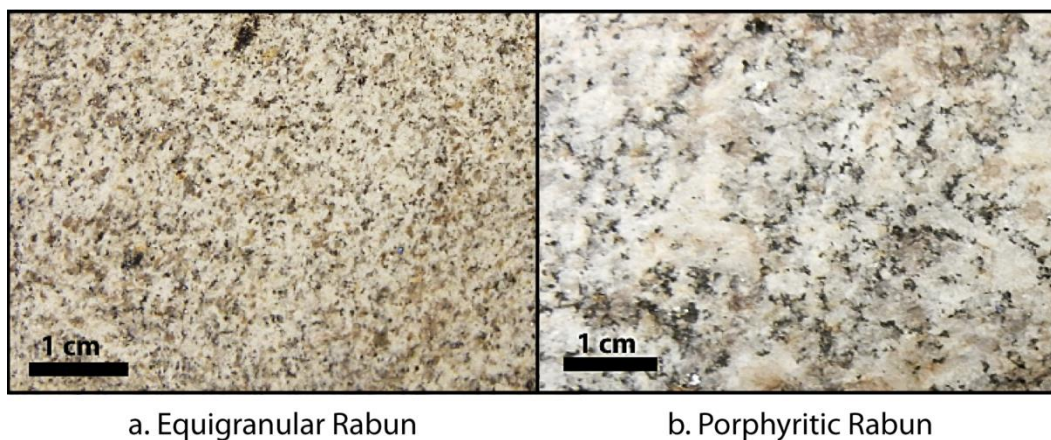


Figure 8. Textural phases of the Rabun pluton. The equigranular phase of the Rabun pluton is gray to tan, medium-grained, granodiorite to trondhjemite. The porphyritic to megacrystic phase is white- to tan-colored, medium- to coarse-grained granodiorite with potassic feldspar phenocrysts 1-2 cm long.

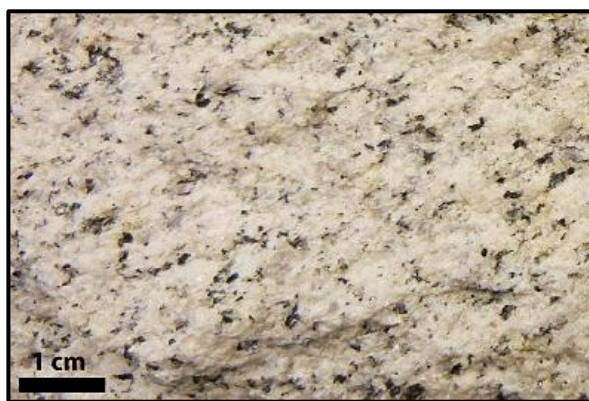


Figure 9. Stone Mountain granite. The Stone Mountain pluton is tan, medium- to coarse-grained equigranular granite.

Geochronology

Piedmont and Carolina Plutons

Ages of the Alleghanian Inner Piedmont and Carolina plutons are younger or synchronous with thrusting (Appendix I), ranging in age from 263 – 330 Ma; thrusting began ca. 330 Ma (Hatcher 2002). There is not a consistent distribution of ages across the terranes but plutons generally decrease in age and increase in frequency from west to east (Figure 2).

Suwannee Terrane Plutons

Granite discovered in boreholes of the coastal plain in southwestern Georgia and northern Florida revealed that some of the youngest Alleghanian-aged plutonism is located within accreted Gondwanan crust (294-296 Ma; Heatherington et al. 2010). Heatherington et al. (2010) interpreted these granites as the result of decompression melting associated with orogenic collapse. Consequently, orogenic collapse may be responsible for the late-stage Alleghanian plutonism present in the Carolina and Piedmont terranes.

Eastern Blue Ridge Plutons

EBR plutons are the oldest of the Alleghanian plutons (Miller et al. 2002) and predate the 330 Ma estimated collision of Laurentia and Gondwana (Hatcher 1989). High-precision, ID-TIMS U-Pb zircon analyses yielded Alleghanian ages for the Rabun pluton (335.1 ± 2.8 Ma), Stone Mountain pluton (335.6 ± 1.0 Ma), and the Mt. Airy pluton (334 ± 3 Ma; Miller et al. 2002). Stahr (2008) obtained identical SHRIMP ages for the Rabun pluton when he dated samples across the textural phases and concluded emplacement was rapid. Stahr (2008) also discovered an additional Alleghanian pluton in the EBR when he dated the Walnut Creek granodiorite adjacent to the Rabun pluton and obtained SHRIMP ages at 336.3 ± 1.6 Ma.

Geochemistry

Major Element Compositions

Geochemical trends among EBR, Piedmont, Carolina, and Suwannee plutons are somewhat obscured by the abundance and geographical spread of Piedmont/Carolina plutons. Variability within the Piedmont and Carolina plutons is to be expected because they were intruded into various terranes and span ~40 million years of orogenic activity (ca. 330-290 Ma). Distinctions are still evident when comparing SiO_2 , Al_2O_3 , and CaO content of each terrane (Figure 10). Average Al_2O_3 decreases from 16% in the EBR, to 14% in the Piedmont and Carolina terranes, and 13% in the Suwannee plutons (Figure 10). Average CaO decreases from the EBR (2.1%) to Piedmont/Carolina (1.5%) and into Suwannee terrane plutons (0.81%; Figure 10b). Figure 10c shows that average K_2O is lowest in the EBR (2.4%) and increases into the Piedmont/Carolina (4.7%) and the Suwannee plutons 4.9%. In unaltered rocks, potassium contents have a positive correlation with silica content. The absence of this trend indicates post-crystallization processes affected the original chemical compositions (Figure 10c; Hughes 1973). TiO_2 has a negative correlation with increasing silica content for each of the terranes (Figure 10d). The EBR plutons have Al_2O_3 and K_2O content distinct from the Piedmont and Carolina plutons with values comparable to the Tuolumne Intrusive Suite (TIS; Gray 2003) in the Sierra Nevada Mountains.

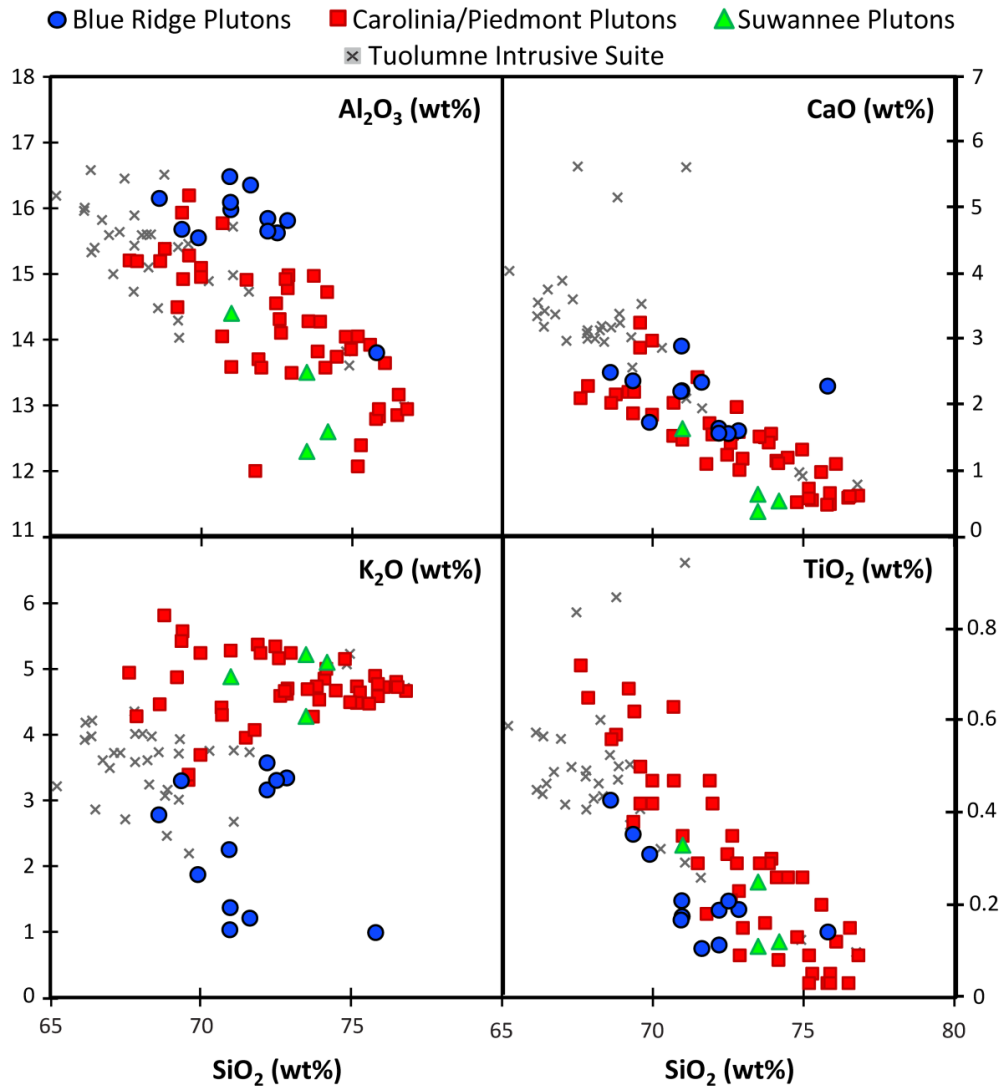


Figure 10. Major element silica variation diagrams for Alleghanian plutons. Data from Tuolumne intrusive suite (TIS), Sierra Nevada is shown for comparison to a known arc environment with gray X's (Gray 2003). Note how the EBR plutons have Al_2O_3 and K_2O contents comparable to the TIS. Mt. Airy and Stone Mountain pluton data are from this research, Walnut Creek and Rabun pluton data from Stahr 2008, Suwannee pluton data from Heatherington et al. 2010, and Piedmont/Carolina pluton data from Speer and Hoff 1997.

Trace Elements

Trace element concentrations can be used to determine the tectonic setting in which igneous rocks have formed (e.g. Pearce et al. 1984, Samson et al. 1995a). Igneous rocks that formed by partial melting of the crust are expected to have high concentrations of incompatible elements

(Pearce et al. 1984). Characteristic incompatible elements enriched in arc magmas include lanthanum, neodymium, niobium, strontium, uranium, yttrium and zirconium. Concentrations of these incompatible elements in the EBR, Piedmont, Carolina, and Suwannee plutons are illustrated with a multi-element plot (Figure 11).

The Alleghanian plutons have a generally decreasing trend across the multi-element plot - signifying a decreasing concentration with increasing compatibility; a pattern typical of crustal melts (Rudnick and Fountain 1995). EBR plutons have a relative depletion of incompatible elements Rb, U, Nb, La, Y and sometimes Nd and Zr in comparison to the Piedmont, Carolina, and Suwannee plutons (Figure 11). The concentration of incompatible elements in the EBR is comparable to the depletion observed in the TIS and may be the result of a continental arc. It could also be argued that this signature represents crustal melting of an arc terrane such as Carolina.

The EBR plutons have consistently higher strontium concentrations and lower rubidium concentrations than the plutons in the Piedmont, Carolina, and Suwannee terranes. This elevation can be explained by the increased compatibility of strontium in comparison to rubidium during partial melting; Sr enters the solid phase first, concentrating Rb in the melt (Rollinson 1993). Therefore, increased concentrations of Sr in EBR plutons may indicate a less evolved source. The lower concentrations of incompatible elements in the EBR plutons are also comparable to concentrations observed in arc settings such as the TIS (Figure 12).

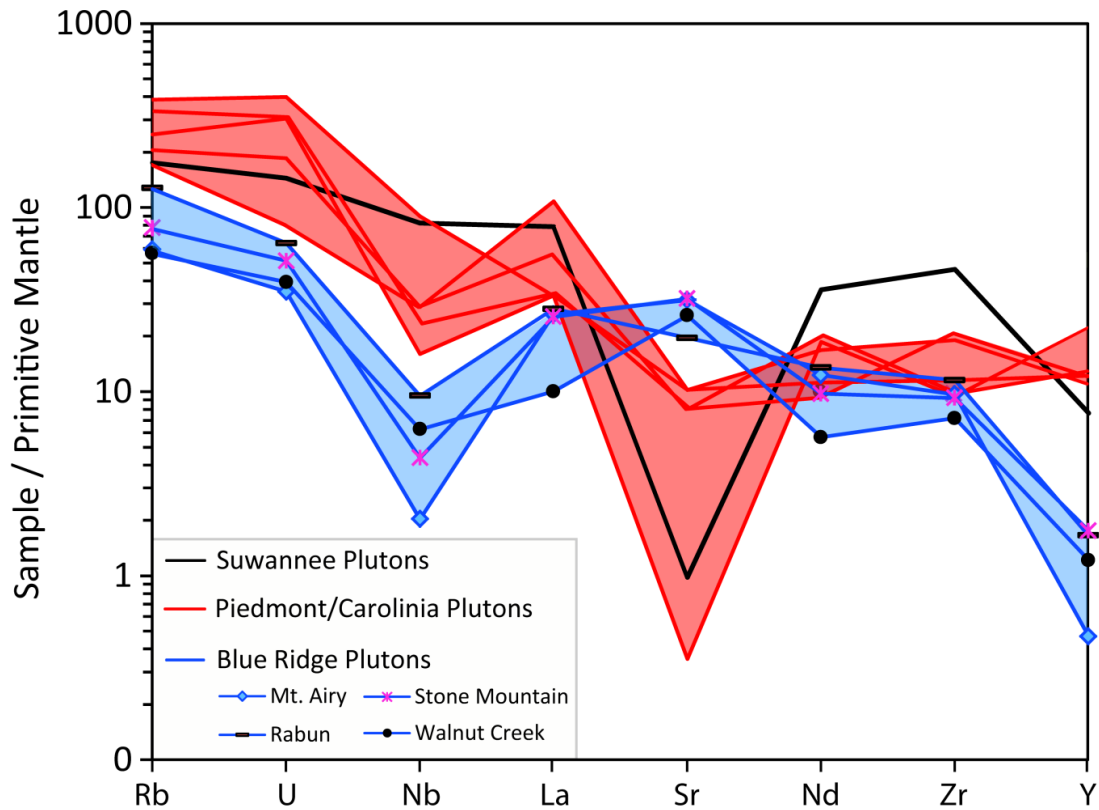


Figure 11. Multi-element plot of incompatible element concentrations. Elements increase in compatibility to the right (Rollinson 1993). Note the depletion of incompatible elements in the EBR plutons. Mt. Airy and Stone Mountain data from this research, Walnut Creek and Rabun from Stahr (2008), Suwannee data from Heatherington et al. (2010), and Piedmont/Carolina data from Speer and Hoff (1997). Piedmont/Carolina plutons include Castalia, Clouds Creek, Cuffytown Creek, Liberty Hill, and Portsmouth plutons.

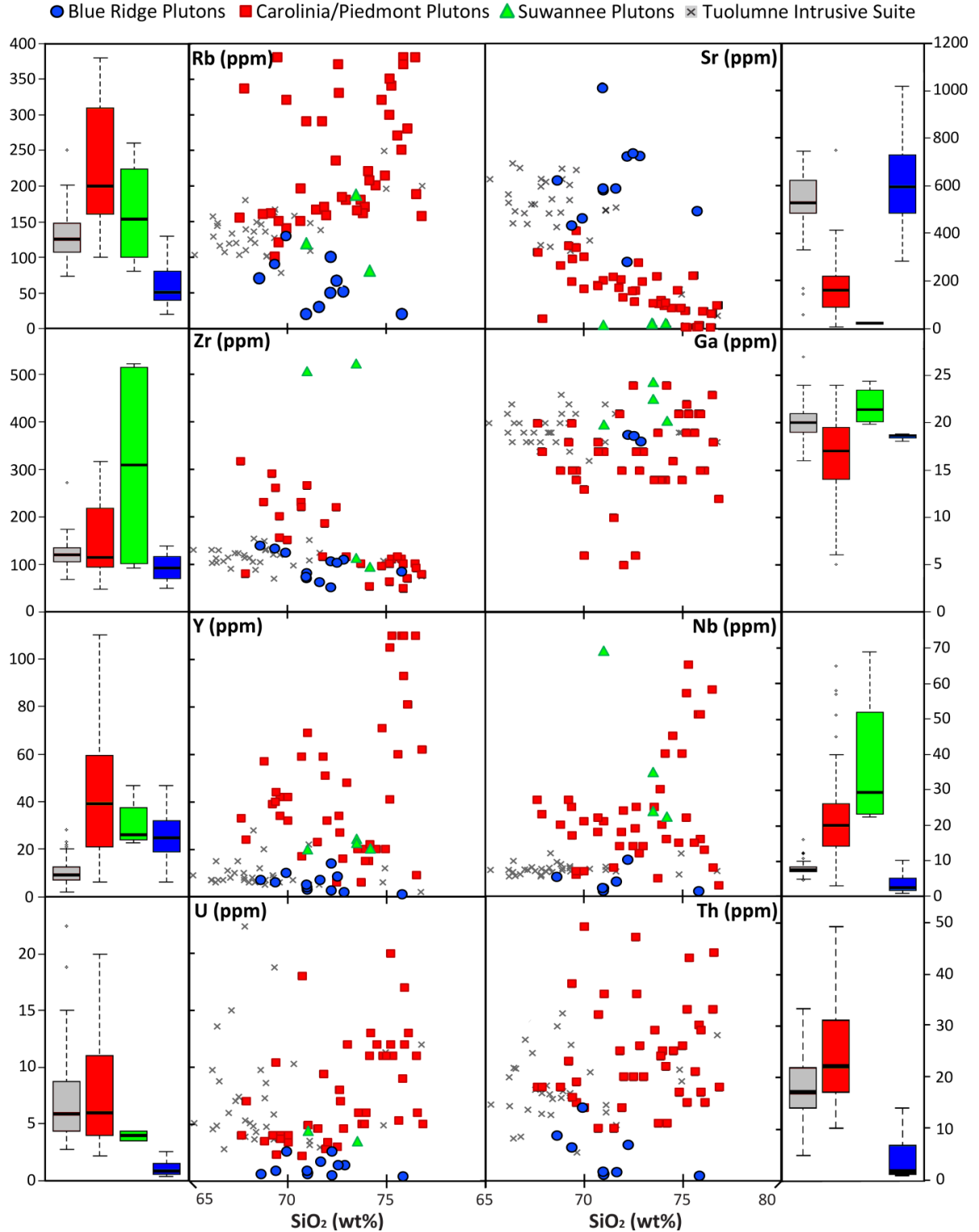


Figure 12. Alleghanian pluton trace element concentrations (ppm). Note the spread in Piedmont/Carolina plutons are distinct from concentrations in the EBR plutons. Mt. Airy and Stone Mountain data is from this research, Walnut Creek and Rabun from Stahr (2008), Suwannee data from Heatherington et al. (2010), and Piedmont/Carolina data from Speer and Hoff (1997).

Discrimination Diagram

Pearce et al. (1984) developed a tectonic discrimination diagram for granites based on the concentration of rubidium, yttrium, and niobium. The VAG field is characterized by known volcanic arc granites in the Aluetians (Perfit et al. 1980, Hill et al. 1981), the Andes (Saunders et al. 1980, Baldwin and Pearce 1982, Lopez-Escobar et al. 1979), Jamaica (Isaacs 1975), and Oman (Alabaster et al. 1982). A magma of anatectic origin would plot in the within plate granite field or the syn-collisional granite field. Previous researchers of the Piedmont and Carolina plutons frequently used tectonic discrimination diagrams but were unable to form unequivocal conclusions because plutons commonly plotted in different tectonic fields (e.g. Speer et al. 1994, Coler et al. 1994, Speer and Hoff 1997). The Blue Ridge plutons do not display the same scattering and instead all plot in the volcanic arc field (Figure 13).

Speer and Hoff (1997) argue that a pluton derived from crustal melting within a chemically evolved portion of the crust could also plot in the volcanic arc granite field. This may apply to the Piedmont, Carolina, and Suwannee plutons which plot near field boundaries but would not explain the distinct plotting of EBR plutons in the volcanic arc field.

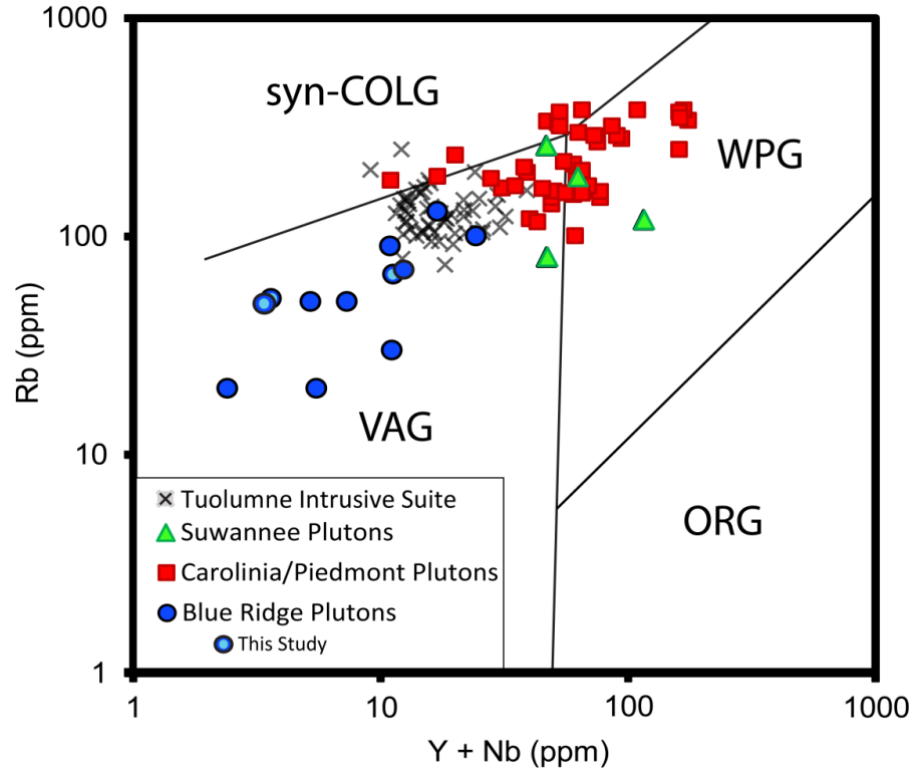


Figure 13. Alleghanian plutons plotted on a Pearce et al. (1984) tectonic discrimination diagram. VAG = Volcanic arc granites, Syn-COLG = syn-collisional granites, WPG = within plate granite, and ORG = ocean ridge granite. Note the distinct plotting of EBR plutons within the VAG field. Carolina/Piedmont and Suwannee plutons plot along field boundaries indicating variable source components. EBR pluton data is from this study and Stahr (2008). Suwannee pluton data is from Heatherington et al. (2010) and Piedmont/Carolina pluton data is from Speer and Hoff (1997).

Nd Isotopic Ratios

Magma derived from the melting of depleted mantle, upper crust, and lower crust each has distinct initial $^{143}\text{Nd}/^{144}\text{Nd}$. Samarium and neodymium are rare earth elements known for having a high compatibility allowing them to typically remain immobile during post-crystallization processes. Consequently, $^{143}\text{Nd}/^{144}\text{Nd}$ ratios are typically low in felsic rocks. Initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for the Carolina plutons range from 0.511920 to 0.512353 and 0.511843 to 0.512080 for the Piedmont plutons; all plutons have initial Nd values characteristic of a crustal source (<0.512628 ; Figure 14). Initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for the EBR plutons are higher and range between 0.511978 and 0.512252. Variations in Nd are more readily seen with epsilon neodymium; ϵ_{Nd} compares the $^{143}\text{Nd}/^{144}\text{Nd}$ in a sample to the estimation of $^{143}\text{Nd}/^{144}\text{Nd}$ for bulk earth (0.512638). The formula to calculate ϵ_{Nd} is shown below:

$$\epsilon_{\text{Nd}} = \frac{[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{sample}} - [^{143}\text{Nd}/^{144}\text{Nd}]_{\text{bulk earth}}}{[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{bulk earth}}} \times 10,000$$

EBR plutons have ϵ_{Nd} values between - 4.59 and + 0.76. Similarly, the initial ϵ_{Nd} values for plutons in the Carolina and Piedmont terranes range from -6.7 to +1.9 and -8.2 to -3.4, respectively (Samson et al. 1995a).

The composition of EBR basement is uncertain and limits the interpretation of isotopic signatures. Two distinct possibilities for EBR basement are Carolina and Grenville crust (Wagner et al. 2012). The Alleghanian plutons have ϵ_{Nd} values between the strong negative values of the Grenville basement and the positive values of the Carolina terrane and the depleted mantle (Figure 15). The spread of ϵ_{Nd} values suggest magma mixing between a juvenile

component with Grenville basement. It is debatable whether the juvenile component was a subducting oceanic slab or Carolina basement. Mantle model ages provide an additional indicator of juvenile source.

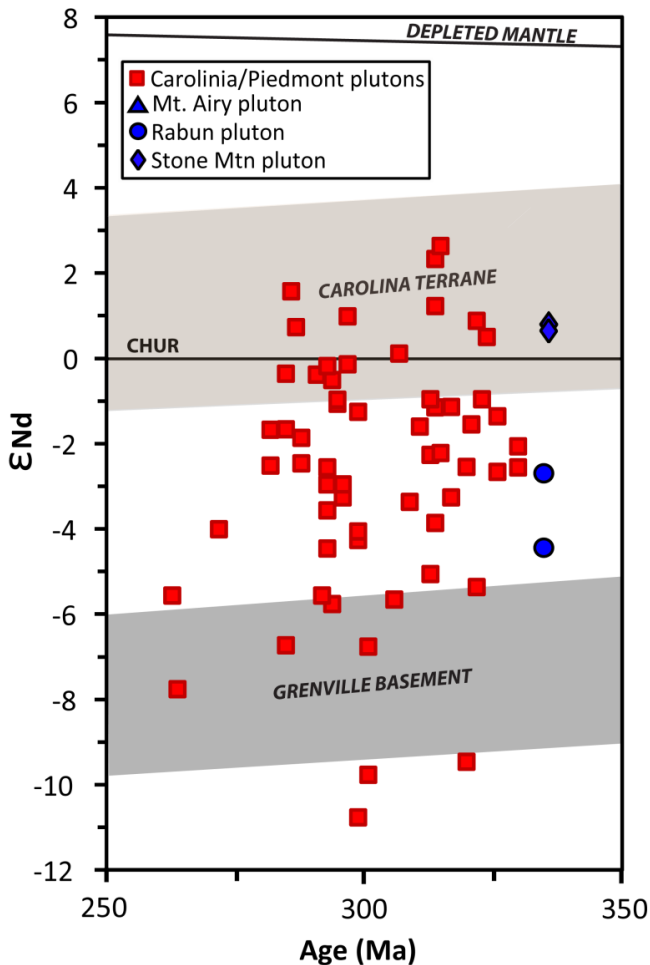


Figure 14. ϵ_{Nd} vs. age of Alleghanian plutons. The EBR and Piedmont/Carolina plutons have overlapping ϵ_{Nd} values ranging from low positive (+3) to strongly negative (-11). Note how most of the plutons plot between Grenville basement and Carolina terrane or depleted mantle. Data for EBR plutons is from this study, data for Carolina and Piedmont plutons is from Samson et al. (1995a), Samson et al. (1995b), and Coler et al. (1997). Field for Grenville basement and Carolina terrane is from Samson et al. (1995a), Samson et al. (1995b), Coler et al. (1997). Depleted mantle evolution curve is from DePaolo (1981).

Alleghanian plutons in the EBR, Piedmont, and Carolina terranes have mantle model ages beginning in the Mesoproterozoic and continuing into the middle Neoproterozoic. The Mesoproterozoic ages are coeval with Grenville orogenesis and the Neoproterozoic ages are coeval with either the rifting of Rodinia (Hatcher 2005) or early volcanic arc magmatism in Carolina beginning at ca. 630 Ma (Hibbard et al. 2002).

Of the three EBR plutons analyzed, the Rabun pluton was the only one with mantle model ages coeval with Grenville basement crystallization (1.3-1.0 Ga; Li et al. 2008; Table 1, Figure 16). Numerous xenocrystic zircons from the Rabun pluton were also dated within the Mesoproterozoic (Miller et al. 2006, Stahr 2008; Figure 16). The other two plutons, Mt. Airy and Stone Mountain, have mantle model ages in the middle Neoproterozoic between 752 Ma and 832 Ma. Although the mantle model ages from the Mt. Airy pluton are Neoproterozoic, a xenocrystic zircon within the pluton was dated at ca. 1084 indicating at least partial assimilation of Grenville crust (Miller et al. 2006, Stahr 2008; Figure 16).

Pluton	Age (Ma)	Inherited Zircon Age (Ma)	Sample	ϵ_{Nd}	τ_{DM} (Ma)
Mt. Airy	334 +/- 3	1084	MA1	-0.6	832
			MA2	-0.36	815
Rabun	335.1 +/- 2.8	1115	RB1	-4.52	1299
			RB2	-2.72	987
Stone Mountain	335.6 +/- 1	-	SM1	0.76	768
			SM2	0.63	752
Reference	Miller et al. 2006		This study		

Table 1. EBR pluton ID-TIMS ages and Nd isotopic data. Note how the Rabun pluton has mantle model ages and xenocrystic zircons dated within the Mesoproterozoic (Miller et al. 2006, Stahr 2008). Mt. Airy and Stone Mountain have mantle model ages in the middle Neoproterozoic. Although the mantle model ages from the Mt. Airy pluton are Neoproterozoic, a xenocrystic zircon within the pluton was dated as late Mesoproterozoic (Miller et al. 2006, Stahr 2008; Figure 16). Mantle model ages are from this study, ages from Miller et al. (2006), and xenocrystic zircon ages from Miller et al. (2006) and Stahr (2008).

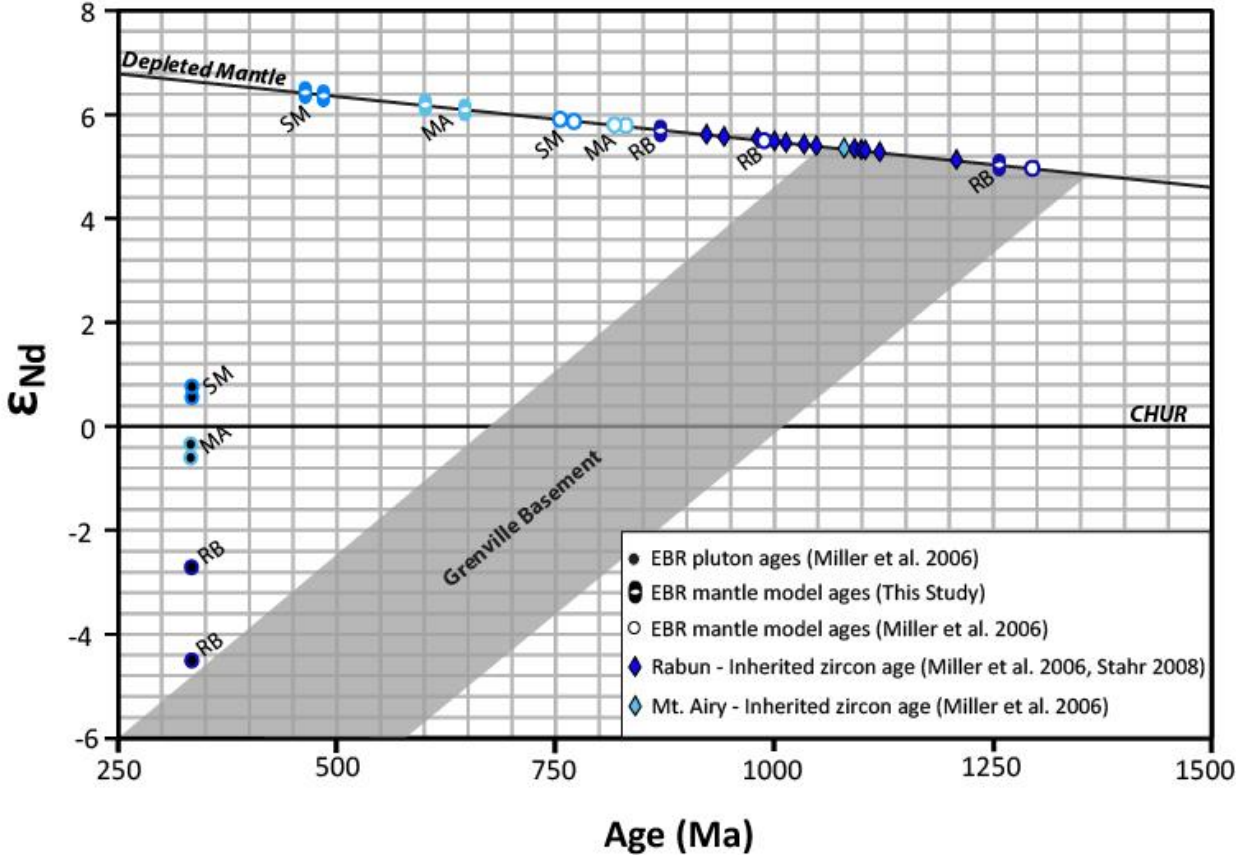


Figure 15. Nd evolution in the EBR plutons. The mantle model ages (white circles) represent the time when the pluton originally derived from its source which was potentially the depleted mantle. Black circles represent ϵ_{Nd} values at crystallization. Xenocrystic zircons are shown with diamonds (Miller et al. 2006, Stahr 2008). A field showing the Nd evolution of Grenville basement is shown in gray (Samson et al. 1995a, Samson et al. 1995b, Coler et al. 1997, Nance et al. 2002, Daly and McLelland 1991, McLelland et al. 1993). Depleted mantle curve is from DePaolo (1981). Note the overlap in mantle model age and xenocrystic zircons for the Rabun pluton with Grenville basement. The overlap indicates partial derivation from Grenville crust. Mt. Airy and Stone Mountain have mantle model ages coeval with the rifting of Rodinia but a xenocrystic zircon coeval with Grenville basement. The disagreement of mantle model ages with the xenocrystic zircon age in the Mt. Airy pluton indicates magma mixing or assimilation. Therefore, mantle model ages within the Mt. Airy pluton, and the proximal Stone Mountain pluton, may be insignificant. The elevation in ϵ_{Nd} values out of the Grenville field indicates mixing with a juvenile component.

Isotopes Summary

The coeval Mesoproterozoic inherited zircon ages and mantle model ages from the Rabun pluton suggest at least partial derivation from Grenville basement. If derivation was solely from Grenville basement, ϵ_{Nd} values would be expected to plot within the Grenville field. Instead, ϵ_{Nd}

values from the Rabun plot above the Grenville field and below the depleted mantle evolution line (Figures 15 and 16). This suggests magmatism involved mixing of Grenville basement with a juvenile, mafic, component.

There are two possible interpretations of the Mt. Airy and Stone Mountain mantle model ages: 1) the plutons originated from the melting of Neoproterozoic crust created during the rifting of Rodinia (ca. 760-610 Ma; Li et al. 2008), or 2) mixing of a crustal and mantle source occurred during emplacement. Similar to the Rabun pluton, the Mt. Airy pluton has an inherited zircon coeval with the Grenvillian orogeny but ϵ_{Nd} values higher than the Grenville crust. The disagreement in the age of xenocrystic zircons, mantle model ages, and ϵ_{Nd} values in the Mt. Airy pluton indicates mantle mixing is the probable scenario. Although the Stone Mountain pluton does not have a dated inherited zircon age linking it to Grenville crust, a similar conclusion is plausible for it because of its spatial, temporal, and chemical similarity to the Mt. Airy pluton.

Alleghanian Tectonic Modeling

Current tectonic models for the Alleghanian orogeny do not explain ca. 335 Ma plutonism in the eastern Blue Ridge (e.g. Hatcher 1987, Miller et al. 2006). As described above, the EBR plutons record mixing of juvenile and crustal magmas in the late Mississippian. The proposed tectonic model explains the EBR intrusions with melting above a west-dipping subduction zone (Figure 17a). Plutons in the Piedmont and Carolina terranes intruded later, after the collision of Gondwana with Laurentia (Figure 17b). These Alleghanian plutons in the Piedmont and Carolina terranes record magma mixing of crustal components. It is possible that several heating mechanisms attributed to crustal melting in the Piedmont and Carolina terranes. Thus, a specific

mechanism is not illustrated in the model. Anatectic plutonism continued into the late Pennsylvanian simultaneously with large-scale crustal shortening (Figure 17c). As thrusting advanced, the terranes were transported a minimum of 250 km northwestward (Figure 17; Hatcher 2005 and Barineau et al. 2006).

Wedging of Carolina into Laurentian basement is a conceivable, but unlikely, source for the arc signature observed in the EBR plutons; Carolina is composed of amalgamated Neoproterozoic to Early Paleozoic peri-Gondwanan volcanic arcs (Hibbard et al. 2002). However, if Carolina basement dominates the signature of the EBR plutons, the same pattern would be expected in the Carolina plutons which reside completely in the volcanic arc terranes. Instead, the Carolina plutons have an evolved crustal signature, evidence for crustal mixing isotopically.

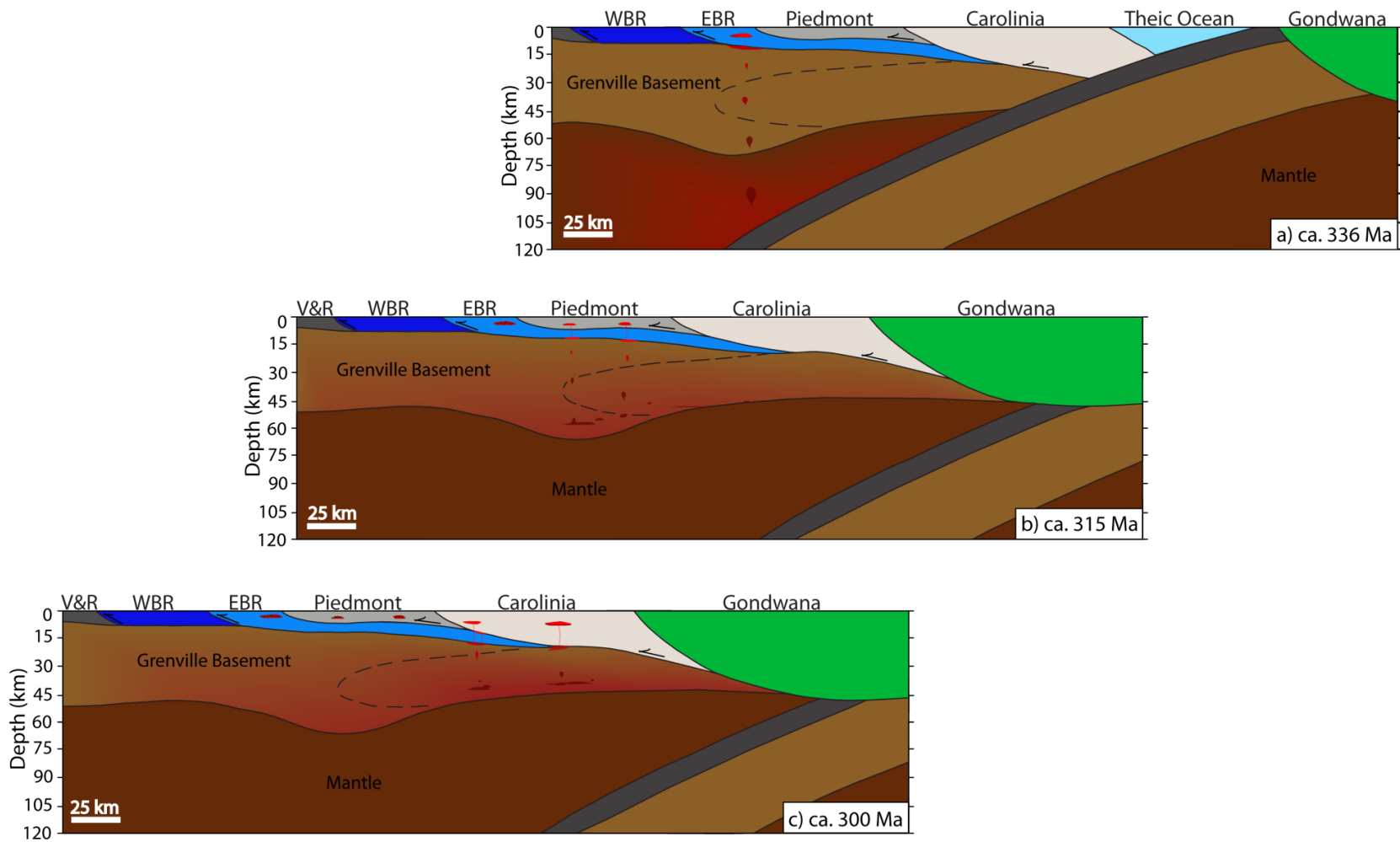


Figure 16. Proposed tectonic model for the Alleghanian orogeny showing the progression of plutonism and shortening westward. Figure 16A shows EBR pluton generation at ca. 335 Ma during west-dipping subduction. Post-collisional plutonism is shown in Figures 16B (ca. 315 Ma) and 16C (ca. 300 Ma). Anatectic plutonism progressed eastward from B to C. Figures are stacked off-center to show the progression of crustal shortening westward. Dashed line represents the proposed wedging of Carolina into Grenville basement (Wagner et al. 2012). Terrane thicknesses modeled from Cook and Vasudevan (2003). Plutons are highly schematic and do not attempt to explain emplacement mechanisms.

Discussion

Orthogneiss in the Killingworth dome, south-central Connecticut dated at ~335 Ma was interpreted to have intruded above an east-dipping subduction zone during the final accretion of the Avalon terrane (Aleinikoff et al. 2003, Wintsch et al. 2007). The coincidence of early Alleghanian ages in New England and in the EBR may indicate a thermo-tectonic event was occurring along the entire length of the Laurentian margin significantly earlier than previously recognized. It is also interesting to note recently recognized early Alleghanian plutons in the southern Appalachians. The Wedowee, Almond, and Blakes Ferry plutons in the southern Appalachian Mountains yielded ages between 330 and 350 Ma with geochemical characteristics suggestive of deep-crustal partial melting (Schwartz et al. 2011). Schwartz et al. (2011) proposed that the early Alleghanian plutonism reflects thickening of the EBR during Neocadian deformation.

Other researchers have noticed a bimodal age distribution among the plutons, with an early phase at ca. 335 (Foster et al. 2012). Two granitoids (Stone Mountain, GA and Tyrone) within the Piedmont revealed ca. 335 Ma ages, and the younger phase of magmatism, between 293-302 Ma, was defined by six plutons intruding the Piedmont, Carolina, Pine Mountain, and Suwannee terranes. This gap in magmatism may mark a transition from two melting mechanisms and support the distinctions observed in this research between EBR and Carolina/Piedmont plutons.

Conclusions

The Alleghanian plutons in the EBR have a strong continental-arc trace element and isotopic signature. EBR plutons were emplaced prior to the collision of Gondwana with Laurentia at ca. 330 (Hatcher 1987). The EBR plutons could not have formed from anatexis. The mechanisms for heating in the crust include; crustal thickening, delamination, and crustal arching. Even if these heat sources were generated early in the collision of Gondwana with Laurentia, it would require that they first penetrated the EBR and then progressed eastward toward the collision zone, opposite of the expected progression.

Instead, trace element concentrations and Nd isotopic evidence support the production of EBR Alleghanian plutons in a continental-arc setting; the EBR plutons have trace element signatures comparable to known arc environments such as the TIS and the Andes (Figure 13) and isotopic values consistent with crustal and mantle mixing (Figures 15 and 16). Their crystallization at ca. 335 coincides with the westward subduction of the Theic oceanic lithosphere beneath Laurentia (Hatcher 1987).

Alternatively, the Piedmont, Carolina, and Suwannee plutons have high concentrations of incompatible elements characteristic of a crustal source (Figure 12). Depleted mantle model ages for these plutons are between 1426 Ma and 657 Ma (Samson and Speer 1993). Their geochemical and isotopic variations suggest magma mixing or assimilation. Plutons likely formed during syn-collisional crustal melting and involved assimilation of Grenville and Carolina crusts. Although an unequivocal source for anatexis remains to be identified, previous research suggests it was either due to crustal arching or crustal thickening (Speer et al. 1994).

In summary, Alleghanian tectonothermal activity deserves a more complicated interpretation. EBR magmatism is distinct temporally, spatially, isotopically and chemically from Piedmont and Carolinian plutonism suggesting that there were two phases of magmatism during the Alleghanian orogeny. The first phase occurred during the final subduction of the Theic oceanic lithosphere and produced continental-arc plutons in the EBR. The second phase occurred during large-scale crustal shortening and produced anatectic plutons in the Piedmont, Carolina, and Suwannee terranes.

Appendix I. Geochronology Resources

Part A. U-Pb zircon ages

Reference	Rock analyzed	Age (Ma)	Type	Uncertainty
Dallmeyer et al. (1986)	Edgefield	317±4	*	*
Grauert (1973)	Gunpowder Granite	330	Chord	*
Pavlidis et al. (1979)**	Falmouth Intrusive Suite	300-340	Concordant Zircons	*
Ross & Bickford (1980)	Elberton Granite	320±20	Chord	1σ
Wright et al. (1985)	Petersburg Granite	330±8	Chord	2σ

Part B. Rb-Sr ages

Reference	Rock analyzed	Age (Ma)	Type	Uncertainty
Dvoracek ¹	Danburg	313±4	whole rock	1σ
Deuser & Herzog (1962)	Rockingham, VA peg.	321±17	muscovite	*
	Stokes, NC peg.	276±15	muscovite	*
Farrar et al. (1981)	Butterwood Creek pluton	292±30	whole rock	2σ
	Raleigh block	238-296	biotite/whole rock	*
Fullagar (1971)	Liberty Hill	299±31	whole rock	*
	Winnsboro	301±9	whole rock	*
Fullagar (1981)	Harbison	309±6	whole rock/ mineral	*
Fullagar & Butler (1979)	Catawba pluton	323±28	whole rock	1σ
	Columbia	285±14	whole rock	1σ
	Clouds creek	313±4	whole rock/ mineral	1σ
	Cuffytown creek	294±1.2	whole rock	1σ
	Lexington pluton	292±17	whole rock	1σ
	Landis	292±58	whole rock	1σ
	Lilesville	326±54	whole rock	1σ
	Pageland	296±10	whole rock	1σ
	Peedee	326±54	whole rock	1σ
	York	322±12	whole rock	1σ
Fullagar & Kish (1981)	Clover	306±8	whole rock/ mineral	1σ
Jones and Walker (1971)	Siloam	264±6	whole rock	*
Julian (1972)	Castalia	313±27	whole rock	*
Russel et al. (1985)	Portsmouth	263±25	whole rock	*
Snoke et al. (1980)	Augen gneiss	291±4	whole rock	1σ
	Lineated gneiss	284±17	whole rock	1σ
	Edgefield pluton	254±11	whole rock	1σ
	Lake Murray gneiss	313±25	whole rock	1σ
Wedemeyer (1981)	Sims	288±13	whole rock	*

* denotes information not provided. ¹ denotes personal communication to Samson (1995a)

Appendix II. Field Work Locations

Pluton	Sample	Location (DMS)	Purpose
Mt. Airy	MA-10-11-1	36° 30' 24.5" N	Sr/Nd Ratios, Geochemistry
		80° 35' 17.9" W	
	MA-10-11-2	36° 30' 27.4" N	
		80° 34' 49.4" W	
Rabun Pluton	RB-01-12-1	35° 09' 10.8" N	Sr/Nd Ratios
		83° 12' 21.6" W	
	RB-01-12-2	35° 14' 30.0" N	
		83° 05' 24.0" W	
Stone Mountain	SM-10-11-1	36° 23' 20.7" N	Sr/Nd Ratios, Geochemistry
		81° 03' 31.9" W	
	SM-01-12-2	36° 23' 30.5" N	Sr/Nd Ratios
		81° 02' 38.0" W	

Appendix III. Neodymium Data

Mount Airy Pluton					
<i>Sample: MA-1</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512378	0.000008	-5.06	0.15
T(initial)	330.00 Ma	0.512181	0.000026	-0.62	0.50
T(DM)	833.23 Ma	0.511880	---	6.17	---
T(ChUR)	375.93 Ma	0.512154	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.0911	$\pm 2\sigma$	0.0007		
<i>Sample: MA-2</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512390	0.000007	-4.84	0.13
T(initial)	330.00 Ma	0.512194	0.000026	-0.38	0.50
T(DM)	816.52 Ma	0.511904	---	6.22	---
T(ChUR)	357.98 Ma	0.512177	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.0907	$\pm 2\sigma$	0.0006		
Rabun Pluton					
<i>Sample: Rb-A</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512236	0.000009	-7.83	0.17
T(initial)	330.00 Ma	0.511978	0.000025	-4.59	0.49
T(DM)	1306.14 Ma	0.511209	---	5.01	---
T(ChUR)	797.71 Ma	0.511610	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.1197	$\pm 2\sigma$	0.0009		
<i>Sample: Rb-B</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512279	0.000011	-7.00	0.21
T(initial)	330.00 Ma	0.512073	0.000025	-2.73	0.50
T(DM)	986.94 Ma	0.511662	---	5.78	---
T(ChUR)	541.16 Ma	0.511941	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.0953	$\pm 2\sigma$	0.0007		
Stone Mountain Pluton					
<i>Sample: Sm-1</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512459	0.000018	-3.49	0.35
T(initial)	330.00 Ma	0.512252	0.000026	0.76	0.50
T(DM)	764.89 Ma	0.511978	---	6.35	---
T(ChUR)	271.38 Ma	0.512289	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.0960	$\pm 2\sigma$	0.0007		
<i>Sample: Sm-2</i>	T(Ma)	$^{143}\text{Nd}/^{144}\text{Nd}$	$\pm 2\sigma$	ϵNd	$\pm 2\sigma$
T(Now)	0.00 Ma	0.512441	0.000007	-3.85	0.13
T(initial)	330.00 Ma	0.512246	0.000026	0.63	0.50
T(DM)	752.68 Ma	0.511995	---	6.38	---
T(ChUR)	283.57 Ma	0.512273	---	0.00	---
$^{147}\text{Sm}/^{144}\text{Nd}$	0.0903	$\pm 2\sigma$	0.0006		

References

- Alabaster, T., Pearce, J. A., Malpas, J., 1982, The Volcanic Stratigraphy and Petrogenesis of the Oman Ophiolite Complex, *Contributions to Mineralogy and Petrology*, 81:168-183.
- Aleinikoff, John N., Wintsch, Robert P., Scott, Robert B., Walsh, Gregory J., Yacob, Ezra Y., 2003, New SHRIMP U-Pb ages for late Proterozoic and Paleozoic igneous rocks in the Avalon and Bronson Hill Terranes of south-central Connecticut; confirmations and surprises. Abstracts with programs - Geological Society of America, 35:3:24.
- Bailey, Christopher M., 2004, Significant southwestward transport of the Goochland Terrane along the Spotsylvania high-strain zone, Virginia Piedmont. Abstracts with programs - Geological Society of America, 36:2:106.
- Baldwin, A. J., Pearce, J. A., 1982, Discrimination of Productive and Non-Productive Porphyritic Intrusions in the Chilean Andes, *Economic Geology*, 77:664-674.
- Barker, F., 1979, Trondhjemite: Definition, environment and hypothesis of origin, in Barker, F., ed., *Trondhjemites, dacites, and related rocks*: Amsterdam, Elsevier, p. 1-12.
- Barineau, C. I., Tull, J. F., & Mueller, P. A., 2006, Accretion of a Volcanic Complex along the Paleozoic Laurentian Margin; Potential Links between the Hillabee Greenstone, Eastern Blue Ridge of Alabama, and Paleozoic Events in the Foreland, Geological Society of America – Abstracts with Programs, 38:3:6-6.
- Butler, J.R., and Ragland, P.C., 1969. A petrochemical survey of plutonic intrusions in the Piedmont, southeastern Appalachians, U.S.A.: *Contributions to Mineralogy and Petrology*, 24: 164-190.
- Butler, J.R., 1972. Age of Paleozoic Regional Metamorphism in the Carolinas, Georgia, and Tennessee Southern Appalachians, *American Journal of Science*, 272: 319-333.
- Chowns, T.M., and Williams, C.T., 1983, Pre-Cretaceous rocks beneath the Georgia Coastal Plain-Regional implications, in Gohn, G.S., ed., *Studies Related to the Charleston, South Carolina, Earthquake of 1886-Tectonics and Seismicity*: U.S. Geological Survey Professional Paper 1313-L:42.
- Coler, D., Samson, S.D., and Speer, J., 1994, Detailed Sm-Nd isotopic study of the Rolesville batholith, N.C.: Evidence for variable source compositions of an Alleghanian granite: Geological Society of America Abstracts with Programs, 26:4:8.
- Coler, D., 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*, 134: 257-275.
- Cook, Frederick A., Vasudevan, Kris, 2006, Reprocessing and Enhanced Interpretation of the Initial COCORP Southern Appalachians Traverse, *Tectonophysics*, 420:161-176.
- Daly, J. S., McLelland, J. M., 1991, Juvenile Middle Proterozoic crust in the Adirondack Highlands, Grenville province, northeastern North America, *Geology*, 19:119–122.

- Dallmeyer, R.D., Wright, J.E., Secor, D.T., Snoke, A.W., 1986, Character of the Alleghanian orogeny in the southern Appalachians: Part II. Geochronological constraints on the tectonothermal evolution of the eastern Piedmont in South Carolina, *Geological Society of America Bulletin*, 97: 1329-1344.
- DePaolo, D.J., 1981, Neodymium isotopes in the Colorado Front range and crust-mantle evolution in the Proterozoic, *Nature(London)*, 291: 193-196.
- Deuser, W.G., Herzog, L.F., 1962, Rubidium-strontium age determination of muscovite and biotites from pegmatite of the Blue Ridge and Piedmont, *Journal of Geophysical Research*, 67: 1997-2004.
- Farrar, S.S., Russell, G.S., Russell, C.W., Glover, L. III, 1981, Alleghanian deformation and metamorphism in the eastern Piedmont of North Carolina: new evidence from Rb-Sr whole-rock and biotite ages, *Geological Society of America Abstracts with Programs*, 13: 449-450.
- Foster, David A., Mueller, P. A., Heatherington, A., Wooden, J. L., Daitch, P., Ma, C., 2012, Alleghanian magmatism in the southern Appalachians: Implications for Pangean tectonic models, *Abstracts with Programs – Geological Society of America*, 44:4:23.
- Fullagar, P.D., 1971, Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians. *Geological Society of America Bulletin*, 82: 2845-2862.
- Fullagar, P.D., 1971, Age and origin of plutonic intrusions in the Piedmont of the southeastern Appalachians, *Geological Society of America Bulletin*, 82: 2845-2862.
- Fullagar, P.D., and Butler, J.R., 1979, 325 to 265 M.Y. old granitic plutons in the Piedmont of the southern Appalachians, *American Journal of Science*, 279: 161-185.
- Fullagar, P.D., 1981, Summary of Rb-Sr whole rock ages for South Carolina, *SC Geology*, 25: 29-32.
- Fullagar, P.D., and Kish, S.A., 1981, Mineral age traverse across the Piedmont of South Carolina and North Carolina, in: *Geological Investigations of the Kings Mountain Belt and Adjacent Areas in the Carolinas*, J.W. Horton, Jr., J.R. Butler and D.M. Milton. Carolina Geological Society Field Trip Guidebook, eds., p. 155-165.
- Glover, L. III, Speer, J. A., Russel, G. S., and Farrar, S. S., 1983, Ages of regional metamorphism and ductile deformation in the central and southern Appalachians: *Lithos*, 16: 223-245.
- Gray, Walt, 2003, Chemical and Thermal Evolution of the Late Cretaceous Tuolumne Intrusive Suite, Yosemite National Park, California, doctoral dissertation, University of North Carolina at Chapel Hill.
- Harris, N. B. W., Pearce, J. A., and Tindle, A. G., 1986, Geochemical characteristics of collision-zone magmatism, in Coward, M. P., and Reis, A. C., eds., *Collision Tectonics: Geological Society Special Publication 19*, p. 67-81.
- Hatcher, R. D., Jr., 1987, Tectonics of the southern and central Appalachian internides: *Annual Rev. Earth and Planetary Sciences*, 15:337-362.
- Hatcher, R.D., Jr., 1989, Tectonic synthesis of the U.S. Appalachians. In: R.D. Hatcher, Jr. W.A. Thomas and G.W. Viele (Editors), *The Appalachian – Ouachita orogen in the United States*. In: *Geology of North America*, Geological Society of America, Boulder, Colorado, F-2:511-536.

- Hatcher, R.D., Jr., 2002, The Alleghanian (Appalachian) orogeny, a product of zipper tectonics: Rotational transpressive continent-continent collision and closing of ancient oceans along irregular margins, in Martinez Catalan, J.R., Hatcher, Jr., Arenas, R., and Garcia, F.D., eds., *Variscan-Appalachian Dynamics: The Building of the Late Paleozoic Basement*: Geological Society of America Special Paper 394:199-208.
- Hatcher, R.D., Jr., 2005, Blue Ridge geology geotraverse east of the Great Smoky Mountains National Park, western North Carolina. Carolina Geological Survey annual field trip, p. 1-12.
- Hill, M., Morris, J., Whelan, J., 1981, Hybrid Granodiorites Intruding the Accretionary Prism, Kodiak, Shumagin and Sanak Islands, S.W. Alaska, *Ibid*, 86:10:69-90.
- Heatherington, A.L., Mueller, P.A., and Wooden, J.L., 2010, Alleghanian plutonism in the Suwannee terrane, USA: Implications for late Paleozoic tectonic models, in Tollo, R.P. Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea; The Lithotectonic Record of the Appalachian Region*: Geological Society of America Memoir 206: 607-620.
- Hibbard, J.P., Stoddard, E.F., Secor, D.T., Dennis, A.J., 2002, The Carolina Zone: overview of Neoproterozoic to Early Paleozoic peri-Gondwanan terranes along the eastern Flank of the southern Appalachians, *Earth-Science Reviews*, 57:299-339.
- Hibbard, J.P., Van Staal, C.R., Rankin, D.W., Williams, H., 2006, Lithotectonic map of the Appalachian Orogen, Canada-United States of America, Geological Survey of Canada, Map 2096A, scale 1:1,500,000.
- Horton, J.W., Jr., Sutter, J.F., Stern, T.W., and Milton D.J., 1987, Alleghanian deformation, metamorphism, and granite emplacement in the central Piedmont of the southern Appalachians: *American Journal of Science*, 287:635-660.
- Hughes, C. J. (1973). Spilites, keratophyres, and the igneous spectrum. *Geological Magazine*, 109:6:513-527.
- Isaacs, M. C., 1975, Comparative Geochemistry of Selected Jamaican Intrusive Rocks, Master's Thesis, Leeds University.
- Jones, L.M., and Walker, R.L., 1973, Rb-Sr whole rock age of the Siloam granite, Georgia: A Permian intrusive in the southern Appalachians, *Geological Society of America Bulletin*, 84: 3653-3658.
- Julian, E., 1972 (unpublished), The Castalia Adamellite in Franklin and Nash counties, North Carolina, and the petrogenesis of some associate aplites and pegmatites, thesis, 61 pp., North Carolina State University, Raleigh, NC.
- Li, Z. X., Bogdanova, S. V., Collins, A. S., Davidson, A., De Waele, B., Ernst, R. E., Vernikovsky, V., 2008, Assembly, configuration, and breakup history of rodinia; a synthesis. *Precambrian Research*, 160:1-2:179-210.
- Lopez-Escobar, L., Frey, F. A., Oyarzun, J., 1979, Geochemical Characteristics of Central Chile (33° – 34° S) Granitoids, *Contributions to Mineralogy and Petrology*, 70:439-450.
- Lux, D. R., and Guidotti, C. V., 1985, Evidence for extensive Hercynian metamorphism in western Maine: *Geology*, 13:10:696-700.

- Massey, M.A., Moecher, D.P., 2005, Deformation and metamorphic history of the western Blue Ridge terrane boundary, southern Appalachian orogen, *Tectonics*, 24:5:18.
- McLelland, J.M., Daly, J.S., Chiarenzelli, J., 1993, Sm–Nd and U–Pb isotopic evidence of juvenile crust in the Adirondack lowlands and implications for the evolution of the Adirondack Mountains. *Journal of Geology*, 101:97–105.
- McSween, H.Y., Jr., Speer, J.A., and Fullagar, P.D., 1991, A survey of the plutonic rocks of the Carolinas, in Horton, J.W., Jr., and Zullo, V.A., eds., *The geology of the Carolinas: Carolina Geological Society Golden Anniversary Volume*, p.109-126.
- Miller, B.V., Stewart, Kevin, 2002, Pluton ages in the eastern Blue Ridge Province, North Carolina: constraints on timing of tectonics and metamorphism in deep levels of an Ordovician accretionary wedge complex. *Geological Society of America Abstracts with Programs*.
- Miller, B.V., Fetter, Allen H., Stewart, Kevin, 2006, Plutonism in three orogenic pulses, Eastern Blue Ridge Province, southern Appalachians, *Geological Society of America Bulletin*, 118:1:171-184.
- Miller, B.V., Stewart, K.G., and Whitney, D.L., 2010, Three tectonothermal pulses recorded in eclogite and amphibolite of the Eastern Blue Ridge, Southern Appalachians, in Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir* 206:701–724.
- Nance, R. D., Murphy, J. B., Keppie, J. D., 2002, A Cordilleran model for the evolution of Avalonia. *Tectonophysics*, 352:11-2:11-31.
- Pearce, J.A., Harris, N.B. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. *Journal of Petrology*, 25:956-983.
- Perfit, M. R., Brueckner, H., Lawrence, J. R., Kay, R. W., 1980, Trace element and Isotopic Variations in a zoned pluton and associated volcanic rocks, Unalaska Island: Alaska: a model for fractionation in the Aleutian calc-alkaline suite. *Contributions to Mineralogy and Petrology*, 73:69-87.
- Price, V. Jr., 1969, Distribution of trace elements in plutonic rocks of the southeastern Piedmont, Ph.D. dissertation, University of North Carolina at Chapel Hill.
- Raymond, L. A., McCarter, R. L., Love, A. B., and Broman, B., 2003, The case for an Acadian arc in the eastern Blue Ridge belt (Toe terrane), southern Appalachian orogen, USA: *Geological Society of America Abstracts with Programs*, 35:6:345.
- Rollinson, H.R., 1993, *Using Geochemical Data: Evaluation, Presentation, Interpretation*, Longman, UK. 352 pp.
- Ross, C.R., and Bickford, M.E., The U-Pb age of zircons in the Elberton granite, Piedmont of Georgia, in: *Geological, Geochemical, and Geophysical Studies of the Elberton Batholith, Eastern Georgia*, J.C. Storer and J.A. Whitney. *GSA Geological Society Guidebook* 19: 52-62.
- Rudnick, R. L., Fountain, D. M., 1995, Nature and composition of the continental crust; a lower crustal perspective. *Reviews of Geophysics*, 33(3), 267-309. doi:10.1029/95RG01302.

- Russel, G. S., Russel, C. W., and Farrar, S. S., 1985, Alleghanian deformation and metamorphism in the eastern North Carolina Piedmont: *Geological Society of America Bulletin*, 96: 381-387.
- Russel, G.S., Speer, J.A., Russel, C.W., 1985, The Portsmouth granite, a 263 Ma post metamorphic biotite granite beneath the Atlantic coastal plain, Suffolk, Virginia. *Southeast Geology*, 26: 81-93.
- Samson, S.D., and Speer, J.A., 1993, Nd isotope geochemistry of Alleghanian granitoid plutons in the southern Appalachians. *EOS (Transactions, American Geophysical Union)*, 74:335.
- Samson, S.D., Coler, D.G., and Speer, J.A., 1995a, Geochemical and Nd-Sr-Pb isotopic composition of Alleghanian granites in the southern Appalachians: origin, tectonic setting and source characterization. *Earth Planetary Science Letter*, 134: 359-376.
- Samson, S.D., Hibbard, J.P., and Wortman, G.L., 1995b, Nd isotopic evidence for juvenile crust in the Carolina terrane, southern Appalachians. *Contributions to Mineralogy and Petrology*, 121: 171-184.
- Saunders, A. D., Tarney, J., Stern, C. R., Dalziel, I. W. D., 1979, Geochemistry of Mesozoic marginal basin floor igneous rocks from southern Chile. *Geological Society of America Bulletin*, 90:237-258.
- Schwartz, Joshua J., Johnson, K., Ingram, S. III, 2011, U-Pb zircon geochronology of Neocadian and Early Alleghanian plutonic rocks in the Alabama eastern Blue Ridge, southern Appalachian Mountains, *Geological Society of America – Abstracts with programs*, 43:1:62.
- Sinha, A. K. and Zietz, I., 1982, Geophysical and geochemical evidence for a Hercynian magmatic arc, Maryland to Georgia: *Geology*, 10: 593-596.
- Speer, J.A., McSween, H.Y., Jr., and Gates, A.E., 1994, Generation, segregation, ascent, and emplacement of Alleghanian plutons in the southern Appalachians: *Journal of Geology*, 102:249-267.
- Speer, J.A., Hoff, Kevin, 1997, Elemental composition of the Alleghanian granitoid plutons of the southern Appalachians, in Sinha, A.K., Whalen, J.B., and Hogan, J.P., eds., *The Nature of Magmatism in the Appalachian Orogen*: Boulder, Colorado, Geological Society of America Memoir 191.
- Stahr III, D.W., Hatcher Jr., R.D., 2004, Emplacement of the Devonian Rabun granodiorite, northeast Georgia and North Carolina Blue Ridge; detailed geologic mapping, and structural, and petrologic analysis. *Geological Society of America – Abstracts with programs*, 36:5:406.
- Stahr III, D.W., Miller, Calvin, Hatcher, Robert D. Jr., Wooden, Joe, Fisher, Christopher M., 2005, Evidence for high-temperature ductile Alleghanian deformation in the eastern Blue Ridge: implications of new structural, petrologic, and geochronologic data from southwestern North Carolina, *Geological Society of America Abstracts with Programs*, 37:7:72.
- Stahr, Donald W., 2008, Tectonometamorphic evolution of the eastern Blue Ridge: Differentiating multiple Paleozoic orogenic pulses in the Glenville and Big Ridge Quadrangles, Southwestern North Carolina. Master's Thesis, University of Tennessee.

- Trupe, Charles H., Stewart, Kevin G., Adams, Mark G., Foudy, John P., 2004, Extent and significance of Alleghanian faulting near the Grandfather Mountain Window, northwestern North Carolina. Geological Society of America Abstracts with Programs, 36:2:139.
- Wagner, L. S., Stewart, K., & Metcalf, K., 2012, Crustal-scale shortening structures beneath the Blue Ridge Mountains, North Carolina, USA. Lithosphere, Pre-Issue Publication, www.search.proquest.com.
- Wedemeyer, R.C., 1981, Geochemistry and geochronology of the Sims Granite, Eastern Carolina Slate Belt, North Carolina, Thesis, 63 pp., East Carolina University, Greenville, NC.
- Wetmore, Paul H., Schmidt, K. L., Paterson, S. R., Herzig, C., 2002, Tectonic implications for the along strike variation of the Peninsular Ranges batholith, southern and Baja California. Geology, 30:3:247-250.
- Whitney, J.A., Jones, L.M., Walker, R.L., Age and origin of the Stone Mountain granite, Lithonia district, Georgia, Geological Society of America Bulletin, 87: 1067-1077.
- Wintsch, Robert P., Aleinikoff, John N., Tollo, Richard P., Unruh, Daniel M., 2007, Age and origin of the Killingworth Dome, south-central Connecticut; implications for the late Paleozoic tectonic evolution of southern New England. Abstracts with programs - Geological Society of America, 39:80.