AN EXOTIC SOUTHERN AND CENTRAL APPPALACHIAN BASEMENT:

Pb AND Nd ISOTOPIC EVIDENCE

By

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To my parents, Ralph and JoAnn Fisher, and

my sister Jennifer Fisher,

For their constant love and support

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CHAPTER I

INTRODUCTION

Purpose

The eastern Laurentian craton comprises a sequence of Archean to Mesoproterozoic-age belts which get progressively younger from northwest to southeast (Figure 1). This observation has led to models of Grenvillian-age continental growth by (1) addition of juvenile material to the southeastern margin of Laurentia (Karlstrom et al., 1999, 2001) or (2) by reworking of pre-existing Laurentaian crust (Hatcher et al., 2004). Such models imply that the southern Appalachian basement should comprise either juvenile, mantle-derived crust or pre-existing Laurentian material as young as or younger than the eastern Mid-continent Granite Rhyolite Province (MCGRP) to the west. Either a mantle or reworked Laurentian crust model for the origin of the southern Appalachian basement would predict that (1) Sm/Nd-depleted mantle ages ($\mathbf{T_{DM}}$'s) would be the same as or less than the ~1.50-1.55 Ga ages observed in the eastern portion of Mid-continent Granite-Rhyolite province (EGRP), and (2) Pb isotopic signatures similar either to those in the MCGRP or to the more youthful crust that lies to the southeast, in the Adirondacks and Texas. However, recent work utilizing U-Pb zircon geochronology, and whole rock Sm-Nd and Pb isotopic data has cast doubt on this model for the origin of the southern Appalachian basement (Carrigan et al., 2003, Loewy et al., 2003, Ownby et al., 2004, Tohver et al., 2004).

Recent Work

An alternative model, based on whole rock Nd and Pb isotope data, has been proposed in which the southern and central Appalachian basement (SCAB) comprises exotic crust accreted to southeast Laurentia during Grenvillian orogenesis (Loewy et al., 2003; Tohver et al., 2004). The first large scale whole-rock Pb isotopic study for Proterozoic rocks in the eastern US was presented by Sinha et al. (1996) and Sinha and McLelland (1999). This work demonstrated that the source of Mesoproterozoic rocks of SCAB had a notably higher initial $^{207}Pb/^{204}Pb$ than that of Adirondacks, suggesting derivation of these units from different Pb isotopic reservoirs. High **T_{DM}'s** from the southern Appalachians substantiated this discrepancy (Carrigan et al., 2003; Ownby et al., 2004). Loewy et al. (2003) demonstrated the overlap of Pb isotopic data between juvenile Mesoproterozoic rocks found in the Adirondacks and Texas (west Texas and the Llano uplift). This trend showed little overlap with data from SCAB, which they demonstrated was strikingly similar to Pb data from Mesoproterozoic rocks of the southwest Amazonian craton. On these grounds, they suggested that SCAB was transferred to southeast Laurentia from Amazonia during the Grenville. Tohver et al. (2005; 2004; 2002) made a similar argument for an Amazonian origin for SCAB using existing Pb and Nd isotopic data, new thermochronology and a new paleomagnetic pole from ~1.2 Ga basalt from Rondonia that was consistent with an Amazonia collision near the Llano region of Texas at this time.

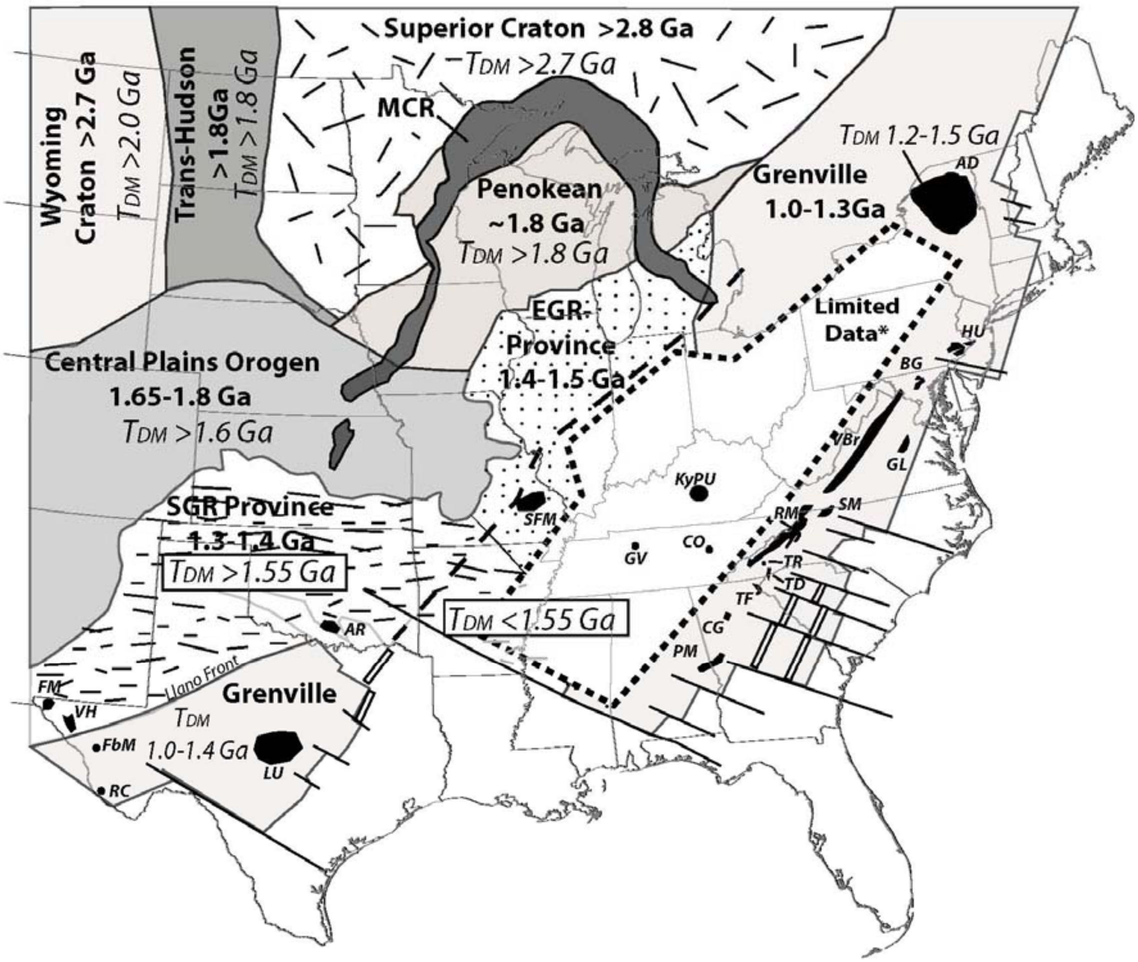


Figure 1. Generalized U/Pb zircon and T_{DM} (depleted mantle model age- age of crust formation based on Nd isotopic composition) distribution for Proterozoic and older igneous rocks of eastern North America. Thick dashed line separates T_{DM} ages >1.55Ga in the Midcontinent Granite-Rhyolite Province. Stippled pattern denotes the ~1470±30Ma Eastern Granite-Rhyolite Province (EGR), dashed pattern denotes ~1370±30Ma Southern Granite-Rhyolite Province (SGR). Modified from Van Schmus et al. 1996, Thomas et al. 2006, Sinha et al. 1996.
*Dashed box represents area where no isotopic data existed prior to this study except sample KyPU (U/Pb 1457 Ma; T_{DM} ~1.45) (Van Schmus et al. 1996).

AD-Adirondacks; AR-Arbuckle Mountains; BG-Baltimore Gneiss; CO-Crab Orchard(drill core); CG-Corbin Gneiss; FbM-Forbidden Mountain; FM-Franklin Mountains; GL-Goochland terrane; GV-Goodlettsville (drill core); HU-Honeybrook Uplands; LU-Llano Uplift; MCR-mid-continent rift; PM-Pine Mountain Windwow; RC-Rancheria Canyon; RM-Roan Mountain; SFM-St. Francis Mountains; SM-Sauratown Mountain Window; TD-Toxaway Dome; TF-Tallulah Falls Dome VBr-Virginia Blue Ridge, VH-Van Horn Mountains.

Testing Models of SCAB Origin

Evaluating and testing models of crustal origin with conventional methods of terrane correlation such as paleomagnetic and conventional geochronologic data often fall short in ancient, high-grade, polydeformed crust like SCAB. In these settings, modern U-Pb zircon geochronology combined with whole rock Pb and Nd isotopic data provide the most sensitive and robust recorders of crustal origin and growth. Therefore, in order to evaluate recent suggestions of a non-Laurentian SCAB origin, we present new whole rock Sm-Nd and Pb isotopic data for Mesoproterozoic igneous rocks from the southern Appalachian basement, the exposed MCGRP, and subsurface samples from between the southern Appalachians and the southeasternmost MCGRP. We also present a single new SHRIMP U-Pb zircon age from a subsurface sample. Combined with available geochronologic and isotopic studies, these data help characterize the isotopic signature of Proterozoic southeastern North America and provide the most complete set of isotopic constraints for the evaluation of the relationship of the SCAB to Laurentia**.**

Understanding the role of the southeast margin of Laurentia during the Grenville has important implications for Rodinian tectonics and paleogeography. Knowledge of the isotopic signature of individual crustal blocks currently juxtaposed within the Laurentian craton can provide a powerful test for comparing out-of-place Laurentian terranes with other cratons now far removed from Laurentia. Previous studies utilizing similar 'isotopic fingerprinting' has proven valuable for testing reconstructions of the Rodinian supercontinent (Wareham et al., 1998; Ruiz et al., 1999; Loewy et al, 2004; 2003; 2002,).

CHAPTER II

WHOLE ROCK ND AND PB ISOTOPES AS INDICATORS OF CRUSTAL ORIGIN

Sm-Nd isotopes

Samarium-neodymium $\mathbf{T_{DM}}$'s can provide an estimate for the time at which continental crust was extracted from a depleted mantle source. Therefore, $\mathbf{T_{DM}}$ ages may delineate crustal blocks of differing ages (Loewy et al., 2004; Bennett and DePaolo, 1987; DePaolo, 1981). Numerous estimates of the Nd isotopic evolution of the depleted mantle have been published with variations in resulting calculated $\mathbf{T_{DM}}$ age as much as 300 m.y. (Arndt and Goldstein, 1987). For consistency, all $\mathbf{T_{DM}}$ ages discussed in this study are calculated with the widely-used model of DePaolo (1981).

The assumptions and potential pitfalls of the use of $\mathbf{T_{DM}}$ -'crustal formation' ages have been discussed in some detail by Ardnt and Goldstein (1987). However, the most important consideration, that of the incorporation of pre-existing crustal material, will be discussed further. In order for a $\mathbf{T_{DM}}$ age to be a true 'crust formation' age, the sample must consist of material entirely derived from a depleted mantle source at the same time. Dating of samples using an independent isotopic system, preferably U-Pb zircon geochronology, permits testing of juvenile origin. If U-Pb zircon and $\mathbf{T_{DM}}$ ages are similar (within ~100 m.y.) then derivation from a predominantly depleted mantle source is likely, in which case $\mathbf{T_{DM}}$ ages provide the time of crust-mantle differentiation or the 'crustal-formation age'. Alternatively, if the $\mathbf{T_{DM}}$ age is significantly greater than U-Pb zircon age then at least partial derivation from pre-existing crust is likely. Therefore, although only providing an approximate average crustal residence time, $\mathbf{T_{DM}}$ ages can be used to detect incorporation of pre-existing crustal material (Arndt and Goldstein, 1997).

Pb isotopes

Previous studies have demonstrated coherent Pb isotopic signatures for Precambrian-age provinces (Wooden and Mueller, 1988; Wooden and Miller, 1990; Sinha and McLelland, 1996; Loewy et al. 2003, 2004;). Thus, Pb isotopes can be a valuable tool for both discriminating crust derived from different Pb isotopic sources as well as constraining the location of major terrane/crustal boundaries (Wooden et al. 1986; Liew et al., 1994**;** Sinha et al., 1999**).**

The identification of coherent Pb isotopic signatures for large crustal domains suggests that these regions had relatively uniform ratios at one time and that their compositions have subsequently diverged only as a consequence of variable U/Pb and Th/Pb ratios. Because both ^{206}Pb and ^{207}Pb are products of U decay (^{238}U and ^{235}U, respectively), and the two parents are inseparable by natural processes, the rates of change in the ratios of ^{206}Pb and ^{207}Pb to non-radiogenic ^{204}Pb are closely related and can be linked to the single parameter μ (^{238}U/^{204}Pb). Increase in thorogenic Pb, ^{208}Pb, is sensitive to natural fractionation of Th from U and therefore is only indirectly linked to evolution of ^{206}Pb and ^{207}Pb. The apparent Pb isotopic homogeneity of large tracts of crust at a point in the past suggests that either this crust was juvenile and derived from an isotopically distinct and uniform source, or that it was homogenized by a crustal-scale event. The anticipated variable μ values within this crustal domain lead to predictable subsequent evolution in uranogenic Pb leading to linear arrays in $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$, so long as there is no further fractionation of U from Pb (Figure 2a). The slope of this linear array ($\Delta^{207}Pb/\Delta^{206}Pb$) provides the age at which the domain was last ~homogenous in Pb isotopic composition, and the lower portion of the array, presumably occupied by samples with the lowest μ, provides an approximation of the initial Pb isotopic composition (Figure 2a).

Lead isotopic data from two similar age crustal provinces, each derived from a distinct Pb source, will produce two parallel arrays in uranogenic Pb space. Therefore, when comparing terranes it is convenient to define their Pb isotopic signature as either ESF (elevated seven-four) or LSF (low seven-four) (Figure 2b). Typically, regional Pb isotopic data sets do not fall along a single line in uranogenic Pb space, but rather define an array, reflecting sample heterogeneity resulting from modest variations in age and/or extent of isotopic homogenization (hence initial compositions) and subsequent histories among samples.

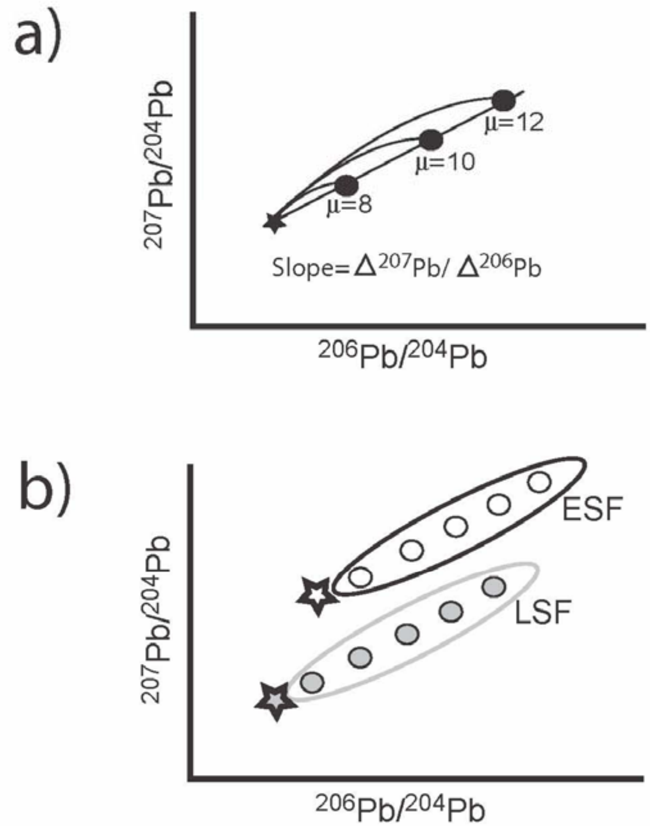


Figure 2. A) Pb isotopic compostion of a sample is dependent upon its u value, such that samples extracted from the same source at the same time will evolve in uranogenic Pb space along a curved line dictated by their respective u. The samples will define a line with a slope proportional to the age. The slope of this line gives the time of extraction. *If this age coincides with the average U/Pb zircon age of the terrane then subsequent reheating events did not reorganize Pb isotopic compostion.* B) Present day Pb isotopic compostion of samples from two different sources with different u (^{238}U/^{204}Pb). Stars denote the Pb compositions of the sources at the time of extraction, which is inherited by all crustal samples. Grey and black circles represent present day compositions of samples extracted from these sources at the same time in the past.

CHAPTER III

PROTEROZOIC ROCKS OF EASTERN NORTH AMERICA

Eastern North America comprises Archean to Proterozoic crustal provinces that are progressively younger toward the continental margin (Figure 1). Exposed basement closest to SCAB toward the interior of North America (to the NW) includes the Adirondacks to the north, the Llano uplift to the south in Texas, and the EGRP to the west. Previous isotopic data from these crustal provinces are discussed below.

Mid-continent Granite-Rhyolite Province (MCGRP)

The MCGRP comprises a large NE-SW trending belt of Mesoproterozoic felsic granitoids and associated rhyolites stretching from Ontario southwest to New Mexico (Figure 1). Exposures of the MCGRP are limited to the St. Francis Mountains, Missouri, and the Arbuckle Mountains, Oklahoma**;** the geochemical characteristics of the province are otherwise known only from drill core samples (Van Schmus et al., 1996; Lidiak et al., 1996). The MCGRP is divided on the basis of U/Pb ages into the Eastern Granite-Rhyolite Province (EGRP; ca. 1470 +/- 30 Ma) and the Southern Granite-Rhyolite Province (ca. 1370 +/- 30 Ma), as well as $\mathbf{T_{DM}}$ ages (Van Schmus et al., 1996**)**. The boundaries dividing the MCGRP based on U/Pb age and $\mathbf{T_{DM}}$ are not coincident and cut one another at a high angle. $\mathbf{T_{DM}}$ ages in the western portion of the mid-continent are uniformly >1.55 Ga (see thick dashed line in Figure 1, hereby referred to as the 1.55 Ga $\mathbf{T_{DM}}$ line) while those to the east are <1.55 Ga. The similarity between $\mathbf{T_{DM}}$ and U-Pb zircon age east of the 1.55 Ga $\mathbf{T_{DM}}$ line suggests a greater contribution from the depleted mantle than for samples west of the line (Van Schmus et al., 1996). Thus, Van Schmus et al. (1996) suggested that this boundary is a fundamental crustal feature marking the southeastern limit of Paleoproteozoic crust. Previous Pb isotopic data from the MCGRP comes only from two drill cores, in southeast Missouri and northwestern Illinois. Whole rock data from these cores were taken at various depths at both locations and define a strikingly coherent array with a secondary isochron age of ~1.45 Ga, plotting below the average crustal evolution curve of Stacey and Kramers (1975) (Doe et al., 1983).

Grenville-age Belts

Central and Southern Appalachians

Grenville-age **(0.9-1.3 Ga)** igneous or meta-igneous rocks are exposed throughout the SCAB, from Pennsylvania to Alabama (Figure 1). For ease of discussion we divide the Grenville age rocks within the Appalachian orogen into the southern Appalachian basement which includes massifs south of the North Carolina-Virginia border, and the central Appalachian basement which includes massifs north of the North Carolina-Virginia border**.**

Central Appalachians Grenville age rocks of the central Appalachian basement discussed here are limited to those with pre-existing Pb isotopic data (Sinha et al., 1996). These include the Honey Brook Uplands of Pennsylvania, the Baltimore Gneiss of Maryland, and numerous massifs in Virginia which are exposed in two roughly NE-SW trending belts, the Virgina Blue Ridge and the Goochland terrane (Figure 1).

Magmatic ages throughout the central Appalachian basement range from ~1.0-1.2 Ga (e.g., Aleinikoff et al. 2004; Owens and Sampson, 2004; Sinha et al., 1996). A relatively small range of $\mathbf{T_{DM}}$ ages (~1.3-1.5 Ga) is reported from the Virginia Blue Ridge and Goochland terrane (Owens and Sampson, 2004; Pettingill et al., 1984). With the exception of the Stage Road Layered Gneiss of Virginia, which defines a steeper slope, Pb isotopic data from the central Appalachians define a coherent array that overlaps and lies slightly above the Stacey and Kramers (1975) curve. This array yields an apparent $^{207}Pb/^{204}$ – $^{206}Pb/^{/204}Pb$ age of 1190 Ma (Sinha et al, 1996). The similarity between U-Pb zircon ages and the whole rock Pb-Pb age suggest that Paleozoic events did not affect regional Pb isotopic systematics (Sinha et al., 1996; Pettingill et al. 1984).

<u>Southern Appalachians</u> A majority of the basement in the southern Appalachians is exposed in a NE-SW trending belt along the Tennessee-North Carolina border (Hatcher et al., 20004). Smaller exposures are also found to the south and east including the Sauratown Mountain window, Trimont Ridge complex, Toxaway dome, Tallulah Falls dome, and the Pine Mountain window (Hatcher et al. 1984) (Figure 1).

The southern Appalachian basement is typically divided into the eastern and western Blue Ridge (EBR, WBR) (Figure 5) (Hatcher, 1978). The WBR as discussed here is the same as the Laurentian margin/western Blue Ridge terrane of Hatcher et al. (2004) and also includes the Corbin Gneiss, Georgia, and the Sauratown Mountains, thought to be a window into the WBR (McConnell, 1990). The EBR comprises the Cowrock, Cartooogechaye, Dahlonega Gold Belt, and Tugaloo terranes of Hatcher et al. (2004) as well as the Pine Mountain terrane, Georgia-Alabama. Additionally, we distinguish the Mars Hill Terrane, as it contains the most ancient crust thus far identified in the Appalachian orogen and is now considered to be exotic to Laurentia (fig SAB) (Hatcher et al., 2005; Ownby et al 2004; Carrigan et al. 2003).

Western Blue Ridge: The Grenville age basement of the WBR consists of orthogneisses of predominantly granitic composition (Carrigan et al. 2003). U-Pb zircon SHRIMP ages for the WBR define two major magmatic pulses at 1.02-1.08 and 1.13-1.18Ga as well as a single granitoid gneiss at 1.38 Ga (Berquist et al., 2005; Berquist 2005). Eight $\mathbf{T_{DM}}$ ages show no systematic variation with U-Pb age, and range from 1.34 to 1.75 Ga; two model ages are ≤ 1.55 Ga (1.34 and 1.46 Ga), and six are 1.59-1.75 Ga (Carrigan et al., 2003; Heatherington et al., 1996). Available Pb isotopic data are limited to the Corbin Gneiss and Sauratown Mountains and plot slightly below the Stacey and Kramers (1975) curve (Sinha et al., 1996). No Pb data have been published from the widespread exposures of Grenville-age basement along the Tennessee-North Carolina border, within the Watauga, Globe, and Elk River massifs of Bartholomew et al. (1984).

Eastern Blue Ridge: Exposures of the predominantly granitic basement rocks of the EBR are scarcer than those of the WBR and occur primarily in the Trimont Ridge complex, within the Toxaway and Tallulah Falls dome, and in the Pine Mountain terrane (Hatcher et al. 2004, Carrigan et al. 2003). U-Pb zircon ages from the EBR range from 1.14-1.17 Ga, and $\mathbf{T_{DM}}$ ages range from 1.50-1.69 Ga (Carrigan et al. 2003) (Heatherington et al., 2006, cite a range of 1.32-1.59 Ga for the Pine Mountain terrane, with xenoliths in granitic gneisses up to 1.97 Ga). Pb isotopic data from the Tallulah Falls dome and the Pine Mountain terrane overlap the Stacey and Kramers (1975) curve (Sinha et al., 1996).

Mars Hill Terrane: The Mars Hill Terrane has been distinguished from the surrounding EBR and WBR on the basis of (1) apparent older (1.8 Ga) age for some lithologies based U-Pb zircon and Rb-Sr isochron ages; (2) older $\mathbf{T_{DM}}$ ages (most >1.8 Ga); (3) well-preserved granulite-grade metamorphism of Mesoproterozoic age; (4) lithologic diversity – specifically, mafic rocks are abundant and interspersed with granitic gneisses on outcrop scale; (5) distinctive Pb isotopic compositions - $^{207}Pb/^{204}Pb$ ratios are higher than for other Appalachian rocks with similar $^{206}Pb/^{204}Pb$ ratios, and Pb data appear to define an unusually steep slope in $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ plots, suggesting greater antiquity (e.g., Merschat, 1977; Monrad and Gulley, 1983; Gulley, 1985; Raymond et al., 1989; Bartholomew and Lewis, 1988; Sinha et al., 1996; Ownby et al., 2004). However, recent investigations of the Mars Hill Terrane have demonstrated that the oldest magmatic and $\mathbf{T_{DM}}$ ages are confined to the Roan Mountain area, Tennessee-North Carolina border (Berquist 2005; Ownby et al., 2004). Based on the pre-Grenvillian history of Roan Mountain we discuss it separately from the adjacent Mars Hill terrane to the south, which has yielded two SHRIMP U-Pb zircon ages of 1.26 and 1.28 Ga, slightly older than the surrounding EBR and WBR (Ownby et al., 2004; Berquist 2005).

Roan Mountain: Investigations of the meta-igneous rocks exposed at Roan Mountain have demonstrated their distinctive age and isotopic characteristics (Ownby et al., 2004; Carrigan et al. 2003; Sinha et al., 1996; Monrad and Gulley, 1983). Monrad and Gulley (1983) determined a 1.8 Ga whole rock Rb/Sr isochron based on five meta-igneous samples**.** A magmatic age of 1.8 Ga was confirmed by U-Pb zircon dating by SHRIMP and LA-ICPMS, although recent studies have demonstrated that most magmatic ages are between 1.2 and 1.3 Ga (Fisher and Bream, unpublished data (see Appendix E and F); Ownby et al 2004; Carrigan et al. 2003). $\mathbf{T_{DM}}$ ages range from 1.65-2.32 Ga, the oldest known in the southeastern United States (Ownby et al. 2004; Carrigan et al., 2003). The unusual Pb isotopic characteristics cited above for the Mars Hill Terrane, which suggest an older age than the surrounding basement, were determined from samples collected on the flanks of Roan Mountain (Carvers Gap)(Sinha et al. 1996).

Adirondack Mountains

The Grenville-age rocks of the Adirondack Mountains comprise mainly granitic and anorthositic gneisses intruded into a predominantly carbonate sedimentary sequence (Daly and McLelland, 1991; Sinha and McLelland, 1999). U-Pb zircon ages range from ~1.35 Ga for tonalitic arc-related rock to 1.04 Ga for younger intrusions (McLelland et al., 1996). $\mathbf{T_{DM}}$ ages from the tonalites are ~1.37-1.40 Ga, within ~70 Ma of their U-Pb zircon ages, suggesting a juvenile mantle derivation. Younger lithologies typically have $\mathbf{T_{DM}}$ ages similar to the tonalites (1.5-1.3 Ga), suggesting derivation by melting of the magmatic arc crust (McLelland et al. 1993; Daly and McLelland, 1991). The Pb isotopic data from the Adirondacks form a coherent array plotting below the Stacey and Kramers (1975) curve (Sinha and McLelland, 1999).

Texas

Grenville-age basement is exposed in Texas in both the Llano Uplift and in the Franklin and Van Horn Mountains (west Texas) as well as within xenoliths hosted in Tertiary volcanic rocks at Rancherias Canyon and the Forbidden Mountains (fig 1) (Bickford et al., 2000; Smith et al., 1997; Cameron and Ward, 1998). Surface exposures in Llano and west Texas both contain younger (~1.07-1.12 Ga) granitic rocks intruded into predominantly sedimentary-volcanic sequences (Bickford et al., 2000; Smith et al., 1997). Both the granitic and older igneous units, as well as the xenoliths, have $\mathbf{T_{DM}}$ ages ~1.0-1.4 Ga (Roller 2004; Smith et al., 1997; Cameron and Ward, 1998). Pb isotopic data from these units form a coherent array plotting below the Stacey and Kramers (1975) curve (Roller 2004; R.C. Roback, personal communication; Cameron and Ward, 1998).

Summary of previous whole-rock Pb isotopic data

Whole rock Pb isotopic data for igneous rocks discussed above define three coherent arrays in Pb space (Figure 3):

(1) The Roan Mountain samples (excluding a single sample thought to be metasedimentary) and the Stage Road Layered Gneiss define an array with the steepest slope, suggesting either an older age for these rocks or mixing between distinct Pb isotopic sources. If the array is a result of mixing, an ancient source component is still needed to explain the elevated $^{207}Pb/^{204}Pb$ of one end member (Sinha et al., 1996). While a secondary isochron age of ~3.0 Ga (Sinha et al., 1996) is likely too old, some Roan Mountain samples have 1.8 Ga magmatic ages, abundant detrital and inherited zircon ages are >1.6 Ga, and $\mathbf{T_{DM}}$ ages approach 2 Ga (Ownby et al., 2004; Carrigan et al., 2003; Sinha et al., 1996).

(2) Mesoproterozoic rocks of the Adirondacks, Llano Uplift, West Texas, and samples from drill cores in northwest Illinois and southeast Missouri all define a coherent LSF array below curve of Stacey and Kramers (1975), suggesting a common Pb isotopic source (Figure 3).

(3) A third ESF array defined by the Grenville age SCAB plots with and slightly above the crustal Pb evolution curve of Stacey and Kramers (1975) (Figure 3). All units discussed above, with the exception of Roan Mountain and Stage Road Layered Gneiss, have secondary isochron ages consistent with available U-Pb zircon ages (~1.0-1.25 Ga), demonstrating that subsequent magmatic and metamorphic events did reorganize Pb systematics (Sinha et al., 1996). It should be noted that almost no overlap exists between the ESF and LSF data sets for $^{206}Pb/^{204}Pb < \sim 18.5$.

Summary of Previous Whole-rock Sm/Nd Isotopic Data

Roan Mountain samples have the oldest $\mathbf{T_{DM}}$ ages (1.65-2.32 Ga) in the Appalachian orogen, coinciding with the steepest slope in Pb space. The LSF basement rocks discussed above have $\mathbf{T_{DM}}$ ages ranging from ~1.55 Ga in the EGRP to ~1.0 Ga in the Llano Uplift. These samples typically have $\mathbf{T_{DM}}$ ages within ~100 my of their respective U-Pb zircon ages, attesting to the juvenile nature of these provinces. Lithologies with an ESF signature can be subdivided into two groups based on $\mathbf{T_{DM}}$ ages. The central Appalachian basement typically has $\mathbf{T_{DM}}$ ages between 1.3 and 1.5 Ga and U-Pb zircon ages of 1.0-1.2 Ga. The southern Appalachian basement has $\mathbf{T_{DM}}$ ages which range from 1.3-2.3 Ga with 14 of 18 samples > 1.55 Ga, including those from Roan Mountain.

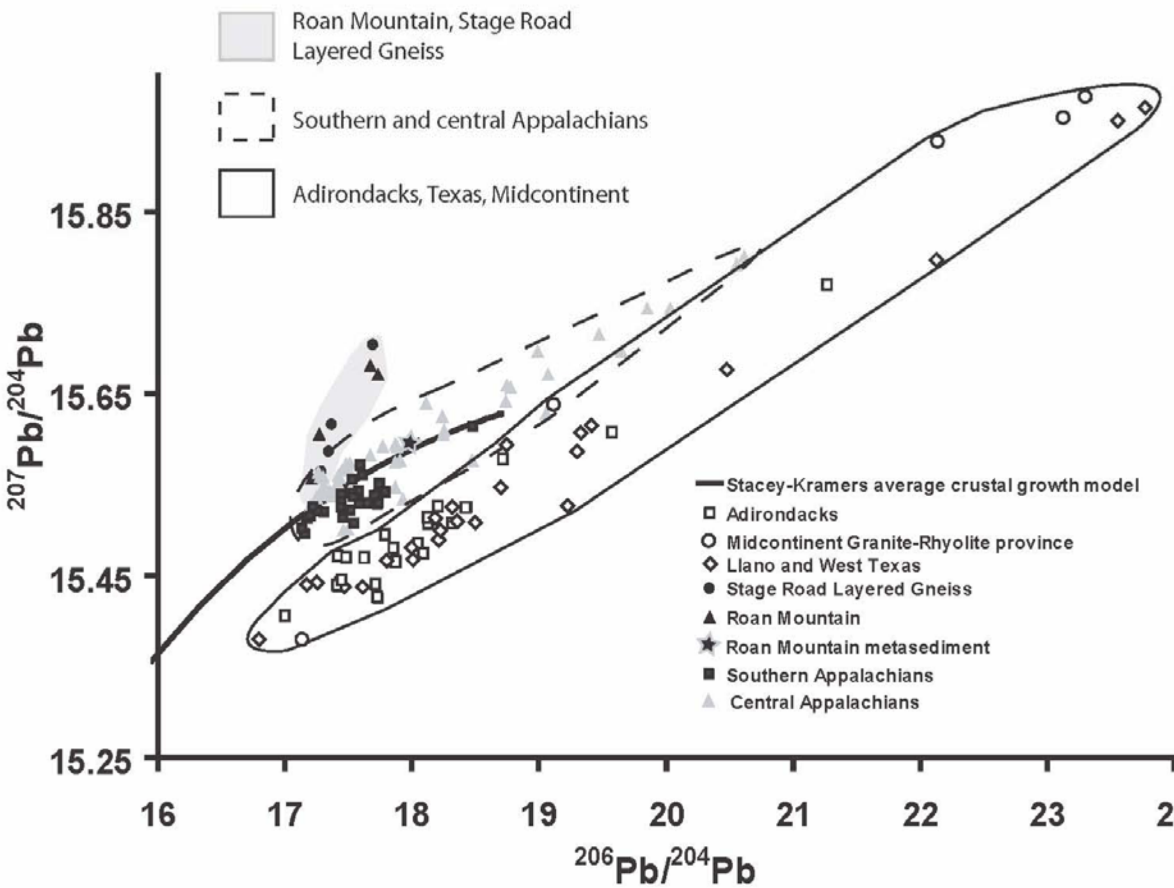
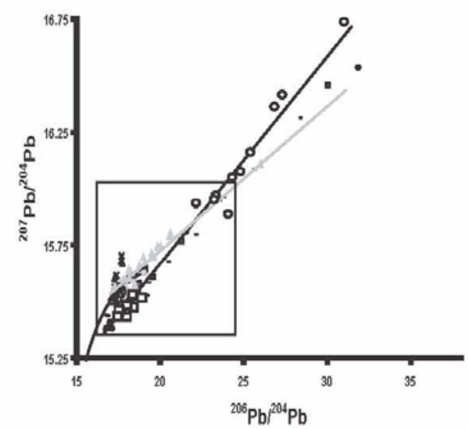


Figure 3. Present day uranogenic ($^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$) Pb isotopic compostions from previous studies of Proterozoic igneous rocks of eastern North America. Adirondacks (Sinha and McLelland, 1999); Midcontinent granite-rhyolite province (Doe et al., 1983); Llano and West Texas (Roller 2004; Roback, personal communication; Smith et al. 1997); southern and central Appalachian basement (Sinha et al., 1996).



CHAPTER IV

RESULTS: NEW DATA

Whole rock Nd and Pb isotopic data were obtained from surface and drill core samples of Proterozoic igneous and meta-igneous basement of the southern Appalachian basement and MCGRP in order to better constrain the origin of Grenville-age basement in the southern and central Appalachians. Previous Pb isotopic comparisons of Proterozoic eastern North America did not include the extensive MCGRP, suggested to be the protolith of Appalachian basement massifs (Hatcher et al., 2004), or the WBR basement of the southern Appalachians, thought to have formed at the Laurentian margin during the Grenville (Bartholomew and Lewis, 1986, 1992; Hatcher et al., 2005, 2004). New Nd isotopic data from the southern Appalachian basement were collected to better characterize the Nd isotopic signature of the WBR, EBR, and Mars Hill terrane. In addition, a single drill core sample from central Tennessee was dated using SHRIMP U-Pb zircon geochronology. These data, combined with previous Pb, Nd, and U-Pb isotopic data, elucidate the relationships among units of SCAB (WBR, EBR, Mars Hill terrane) and adjacent portions of Proterozoic Laurentia. *Note: major and trace-element geochemistry for samples CO-DC, GV-DC, and RMHB is in Appendix C.*

U-Pb Zircon Data

Zircon from a granitic drill core sample from central Tennessee (GV-DC; see Figure 1) was dated using SHRIMP U-Pb zircon geochronology. Analyses displayed a wide range of discordance and produced a poorly constrained lower intercept age (Figure 4), perhaps due to a regional Pb loss episode at ~260 Ma (Doe et al., 1983), in general agreement with the. The upper-intercept age of 1381±27 Ma is interpreted to represent the crystallization age. Together with previous zircon U-Pb data from a Kentucky drill core sample (KyPU, 1457±10 Ma; Van Schmus et al., 1996), these data confirm the eastern extension of ~1400 Ma MCGRP granites into central Tennessee and Kentucky (Figure

1).

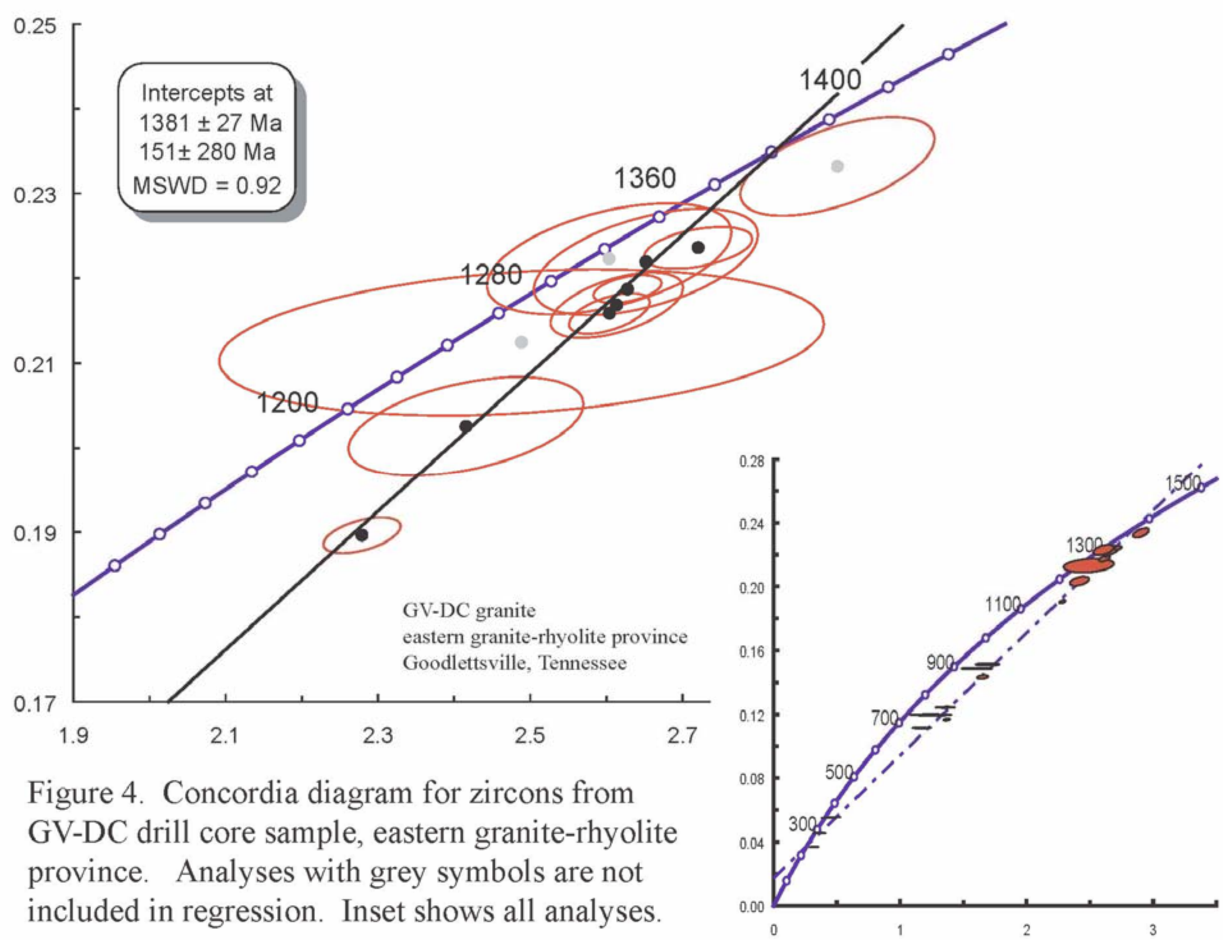


Figure 4. Concordia diagram for zircons from GV-DC drill core sample, eastern granite-rhyolite province. Analyses with grey symbols are not included in regression. Inset shows all analyses.

Whole-rock Pb Isotope Data

Whole rock Pb isotopic analyses were performed for 23 southern Appalachians basement samples, including the WBR (Figure 5) and 14 samples from the MCGRP, both east and west of 1.55 Ga $\mathbf{T_{DM}}$ line of (Van Schmus et al. 1996) (Figure 6), and (Table 1). All of the MCGRT samples, including GV-DC and a troctolite drill core from eastern Tennessee (CO-DC; see Figure 1), plot below Stacey and Kramers' (1975) crustal evolution curve (Figure 7a). These data fall within the LSF array defined by data previously reported from the Adirondacks, Texas, and two drill holes in northwest Illinois and southeast Missouri. There does not appear to be a relationship between $\mathbf{T_{DM}}$ age and whole rock Pb-Pb age, i.e. samples with older $\mathbf{T_{DM}}$ do not yield older Pb-Pb ages. All whole-rock Pb isotopic data for the MCGRT define a coherent array with a secondary isochron age of ~1.45 Ga, suggesting either a major crustal homogenization event at this time, or derivation from a relatively homogenous reservoir in the upper mantle.

Newly analyzed EBR samples provide the first Pb data for Trimont Ridge, the Toxaway dome, and two unnamed basement exposures in the Dahlonega Gold Belt and Tugaloo terrane in North Carolina (as defined by Hatcher et al., 2004) which previously lacked Pb isotopic data. These samples and two others from the Tallulah Falls dome all plot within the ESF array defined by Sinha et al. (1996) for the southern and central Appalachian basement (Figure 7b). Similarly, 8 samples from the WBR and 2 samples from the Mars Hill terrane (outside of the Roan Mountain area) plot within or slightly above the SCAB ESF array defined by Sinha et al. (1996) (Figure 7b).

Five samples from Roan Mountain, including a single metasedimentary sample (RMCLG), confirm the steeper slope (older age?) of this unit (Figure 7c). All Roan Mountain samples plot within the field identified by Sinha et al. (Carvers Gap; 1996), and most have a higher $^{207}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ than the surrounding basement. It should be noted that the other two Mars Hill terrane samples also fall within the array defined by Roan Mountain/Carvers Gap data, at its lower end where it overlaps with the dominant ESF field.

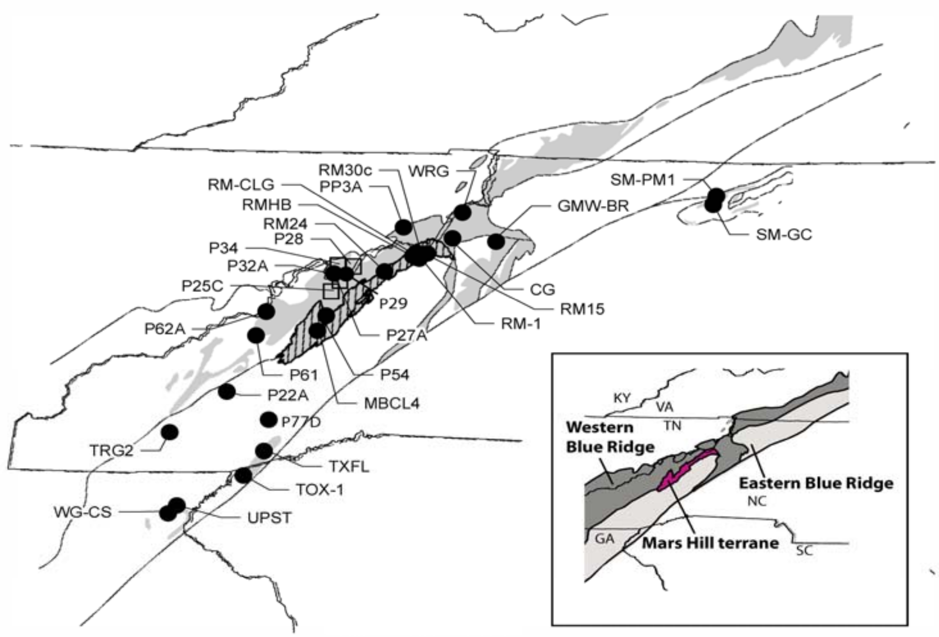


Figure 5. Generalized tectonic map of southern Appalachians showing sample locations with Pb and/or Nd isotopic data. Grey patterns denote exposures of Grenville-age basement. Filled circles represent samples with both Pb and Nd isotopic data (this study; Ownby et al., 2004; Carrigan et al., 2003) Open squares represent samples with only Nd isotopic data (this study). Modified from Carrigan et al., 2003.
Note: Nd data is not available for RMHB.

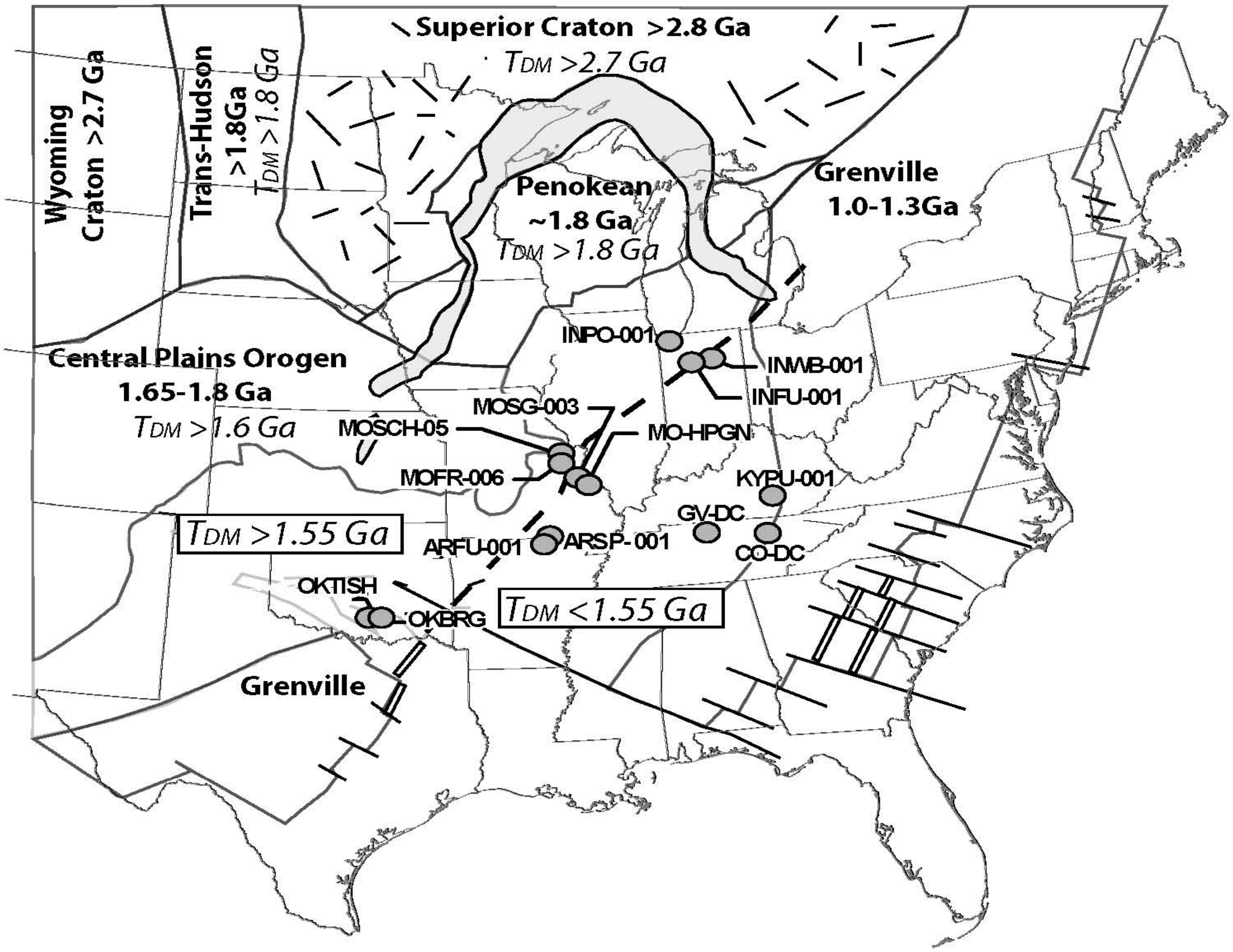


Figure 6. Sample locations for Midcontinent Granite-Rhyolite province Pb isotopic data presented here. Thick dashed line separates TDM ages >1.55Ga (to the west) from those < 1.55 Ga.

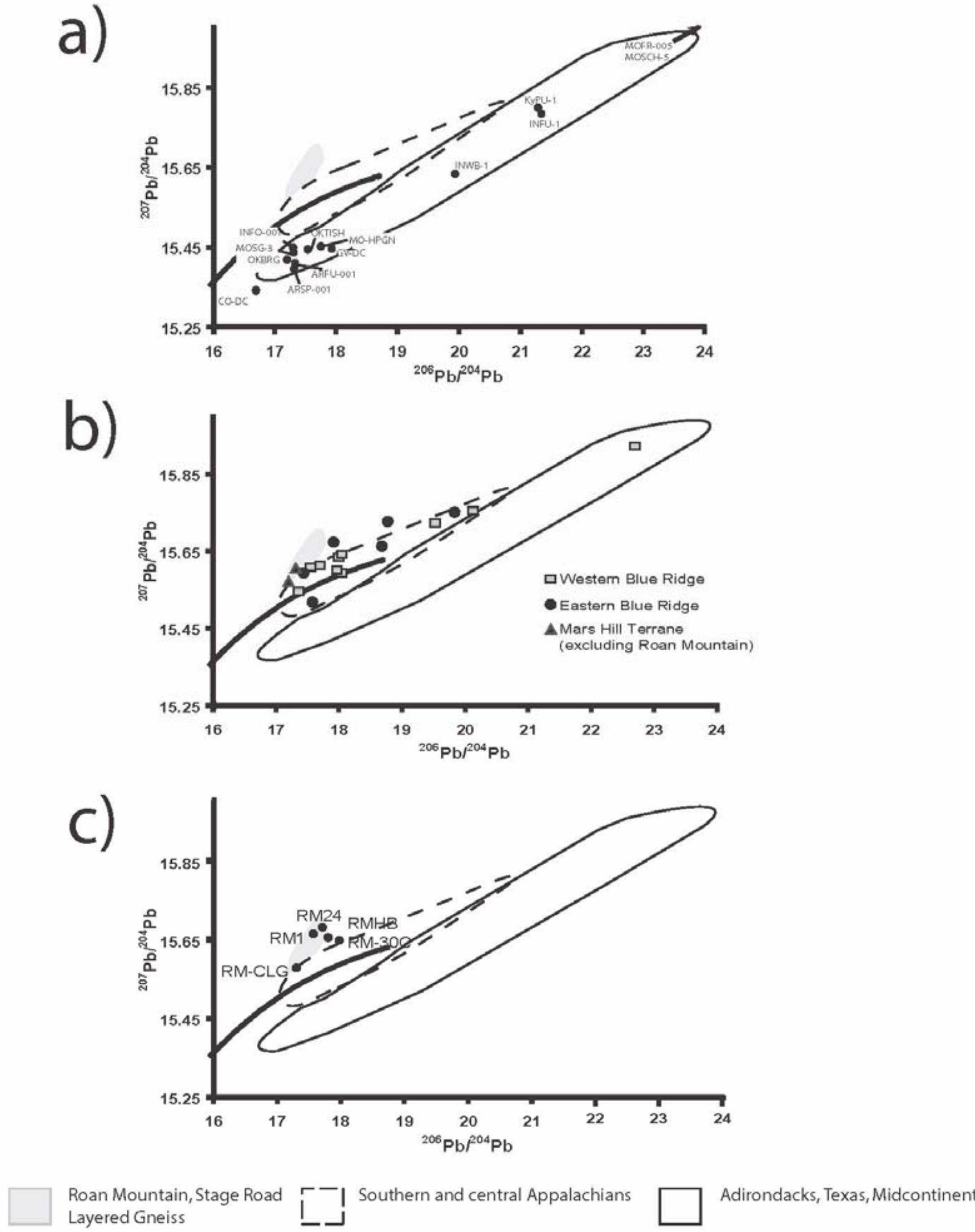


Figure 7. Present day uranogenic Pb isotopic data from this study plotted within previously defined arrays of Mesoproterozoic eastern North America(see Figure 4 for references). (a) Midcontinent granite-rhyolite province, (b) southern Appalachian basement (c) Roan Mountain

Table 1. Pb isotopic data.

Sample	Lithology	magmatic age (Ma)	$^{206}Pb/^{204}Pb$ Ratio	$^{206}Pb/^{204}Pb$ 2σ	$^{207}Pb/^{204}Pb$ Ratio	$^{207}Pb/^{204}Pb$ 2σ	$^{208}Pb/^{204}Pb$ Ratio	$^{208}Pb/^{204}Pb$ 2σ	T_{DM}	latitude	longitude
Western Blue Ridge											
CG[c]	granitic gneiss	1192	20.17	0.004	15.76	0.005	42.38	0.005	1.61	-81.918	36.169
GMW-BR[c]	augen gneiss	1081	19.54	0.022	15.73	0.027	39.25	0.034	1.34	-81.850	36.184
WRG[c]	granitic gneiss	1158	22.74	0.003	15.93	0.004	41.30	0.004	1.71	-81.850	36.302
P32A[b]	granitic gneiss	1375	17.57	0.004	15.61	0.005	38.14	0.005	1.69	-82.543	35.986
P61[b]	granulite	1159	17.35	0.009	15.55	0.010	36.82	0.011	1.66	-82.983	35.680
P62A[b]	granite	1019	18.02	0.004	15.64	0.004	38.29	0.004	1.49	-82.929	35.797
PP3A[b]	leucocratic granite	1073	17.71	0.004	15.61	0.004	37.15	0.005	1.43	-82.175	36.226
Sauratown Mt. Window											
SM-GC[c]	augen gneiss	1165	18.02	0.005	15.60	0.005	37.37	0.006	1.67	-80.451	36.336
SM-PM1[c]	augen gneiss	1165	18.00	0.007	15.64	0.007	37.47	0.008	1.75	-80.434	-36.383
SM-PME[c]	augen gneiss	1165	17.97	0.006	15.60	0.007	37.38	0.008	1.75	-80.434	-36.383
Mars Hill terrane (excluding Roan Mountain											
MB-CL4[a]	mafic granulite	1257	17.34	0.004	15.60	0.004	42.03	0.005	1.53	-82.641	35.728
P54[b]	felsic granulite	1278	17.19	0.007	15.57	0.002	36.85	0.008	1.65	-82.614	35.766
Roan Mountain											
RM1[c]	leucocratic granulite gneiss	1765	17.55	0.006	15.66	0					
RM24[a]	banded granulite gneiss	N.A.	17.69	0.006	15.68	0.006	38.56	0.006	1.94	-82.278	36.005
RM-30C[a]	mafic gneiss	1209	17.95	0.004	15.65	0.004	38.87	0.005	2.32	-82.094	36.127
RMHB[f]	mafic granulite	~1250	17.78	0.003	15.65	0.004	38.95	0.003	N.A.	-82.145	36.093
RM-CLG[c]	paragneiss	detrital	17.28	0.004	15.58	0.004	37.68	0.004	1.82	-82.133	36.101
Eastern Blue Ridge											
P22A[b]	felsic/amphibolitic migmatite	1268	18.77	0.007							
P77D[b]	granitic gneiss	1261	19.85	0.003	15.76	0.004	39.74	0.004	1.88	-82.840	35.322
Trimont Ridge											
TRG2[e]	quartzofelspathic gneiss	1103	28.53	0.010	16.30	0.010	47.98	0.012	1.57	-83.444	35.191
Tallulah Falls Dome											
WG-CS[c]	granitic augen gneiss	1158	17.46	0.004	15.60	0.004	38.82	0.004	1.59	-83.418	34.801
UStC[e]	tonalitic gneiss	1129	18.68	0.007	15.67	0.008	38.49	0.009	1.69	-83.410	34.833
Toxaway Dome											
TOX 1[c]	quartzofelspathic banded gneiss	1149									
TXFL[c]	granitic augen gneiss	1149	17.58	0.004	15.52	0.021	38.08	0.005	1.52	-82.931	35.117

Midcontinent											
CO-DC[f]	troctolite	N.A.	16.69	0.004	15.34	0.004	36.24	0.004		-84.855	35.917
GV-DC[f]	granite	1381	17.92	0.004	15.44	0.004	37.54	0.004		-86.703	36.340
ARFU-001[d]	granite	1347	17.32	0.005	15.41	0.005	36.86	0.006	1.50	-91.69	36.30
ARSP-001[d]	diorite	1376	17.31	0.003	15.39	0.003	36.82	0.003	1.49	-91.40	36.48
INFU-1[d]	granite	1475	21.35	0.003	15.78	0.003	39.65	0.003	1.74	-86.47	40.92
INPO-001[d]	granite	1446	17.29	0.008	15.45	0.010	36.87	0.008	1.78	-87.12	41.62
INWB-1[d]	granite	1270	19.94	0.003	15.63	0.004	38.78	0.004	1.50	-85.80	40.93
KYPU-1[d]	granite	1457	21.29	0.003	15.80	0.004	40.11	0.004	1.45	-84.50	37.12
OKTISH[d]	granite	1363	17.53	0.004	15.44	0.003	37.47	0.003	1.49	-96.65	34.34
OKBRG[d]	granitic gneis	1389	17.20	0.005	15.42	0.005	38.47	0.005	1.48	-96.55	34.35
MOSG-3[d]	granite	1328	17.31	0.008	15.44	0.008	37.17	0.007	1.49	-90.45	38.03
MOFR-006[d]	granite	1458	24.04	0.007	16.02	0.008	41.65	0.008	1.60	-90.92	38.43
MOSCH-5[d]	rhyolite	1472	35.88	0.011	16.99	0.014	48.68	0.018	1.52	-90.73	38.61
MO-HPGN[d]	granodiorite	1478	17.75	0.002	15.45	0.002	36.62	0.003	1.53	-90.20	37.78

Sources of samples and T_{DM} ages:

a=Ownby et al. 2004
b=Berquist 2005
c=Carrigan et al. 2003
d=Van Schmus et al. 1996
e=Hatcher et al. 2004
f=this study

Whole-rock Sm-Nd isotopic data

Whole rock Sm/Nd analyses were performed for 8 WBR, 3 EBR and 2 Mars Hill terrane (non-Roan Mountain) samples collected along a NW-SE transect of the Blue Ridge (Table 2). Combined with previous southern Appalachian Sm/Nd isotopic data (Ownby et al., 2004; Carrigan et al. 2003) the EBR, WBR, and Mars Hill terrane show significant overlap in ε_{Nd} vs. time plots (Figure 8). One of the new EBR samples extends the range of $\mathbf{T_{DM}}$ ages to 1.88 Ga (total range now 1.50-1.88 Ga), and one WBR analysis extends the upper limit to1.82 Ga (1.34-1.82 Ga). Previously, the only samples analyzed from the Mars Hill terrane came from the Roan Mountain area; our 2 new analyses, all south of Roan Mountain, yielded $\mathbf{T_{DM}}$ ages 1.53 and 1.65 Ga. As noted previously, $\mathbf{T_{DM}}$ ages of Roan Mountain samples range from 1.65-2.32 Ga (Ownby et al., 2004; Carrigan et al. 2003)

$\mathbf{T_{DM}}$ ages for samples from the southern Appalachian basement are 200-600 Ma greater that their U/Pb magmatic ages, indicative of derivation from either older crust or a juvenile mantle magma contaminated by older crust. Available data from the ~1.0-1.2

Ga central Appalachians have younger of $\mathbf{T_{DM}}$ ages (~1.3-1.5 Ga) that are closer to their U/Pb ages, suggesting a greater juvenile mantle contribution or incorporation of younger pre-existing crust than in the southern Appalachians.

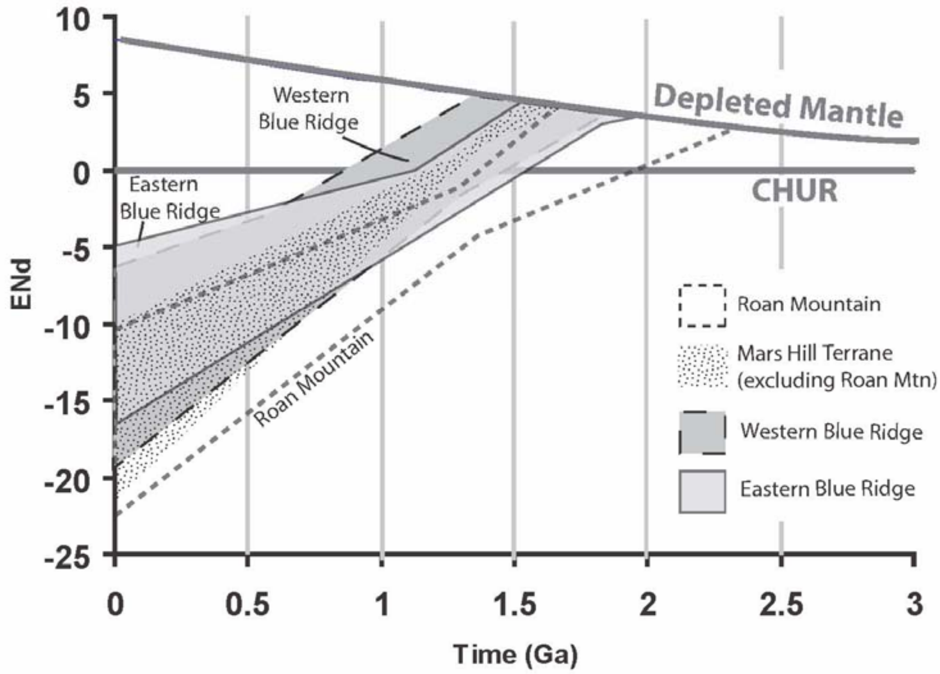


Figure 8. Nd isotopic fields for southern Appalachian terranes discussed in text, including new data from this study. Previous data are from Ownby et al. (2004) and Carrigan et al. (2003).

Table 2. Sm-Nd isotope Geochemistry

Sample	Age (Ma)	Sm(ppm)	Nd(ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	μNd $_0$	μNd at Mag age	T_{DM} (Ga)
Western Blue Ridge								
P27A	1100†	9.115	46.838	0.12045	0.511926	-13.9	-3.2	1.82
P25 C	1056*	4.906	35.317	0.086	0.511661	-19.1	-4.1	1.65
P28	1171*	8.335	46.567	0.11078	0.511958	-13.3	-0.4	1.60
P29	1100†	0.744	6.066	0.07591	0.511690	-18.5	-1.5	1.50
P32A	1375*	4.793	30.154	0.09839	0.511764	-17.0	0.3	1.69
P34	1130*	5.462	38.894	0.08691	0.511790	-16.5	-0.7	1.50
P61	1159*	8.405	45.753	0.1137	0.511951	-13.4	-1.1	1.66
P62A	1019*	14.265	82.700	0.10676	0.511997	-12.5	-0.8	1.49
PP3A	1073*	0.961	6.322	0.09413	0.511922	-14.0	0.1	1.43
Eastern Blue Ridge								
PP22A	1268*	15.655	86.455	0.11207	0.511815	-16.1	-2.3	1.84
P22B	1268*	2.858	8.458	0.20918	0.512787	2.9	0.9	11.18‡
P77D	1261*	17.359	66.133	0.16246	0.512409	-4.5	1.1	1.88
Mar Hill terrane (excluding Roan Mountain)								
MBCL-4	1250**	2.334	22.388	0.06454	0.511543	-21.4	-0.2	1.53
P54	1278*	4.579	21.849	0.12973	0.512130	-9.9	1.1	1.65

Preferred magmatic ages of zircon geochronology from this study;
* age from Berquist (2005), age from Ownby et al (2004) ** , † reference age.
‡ **T_{DM} age**-meaningless (mafic sample)

CHAPTER V

DISCUSSION

Isotopic Domains in Proterozoic Basement of Southeastern North America

The three coherent, but distinct, Pb isotopic arrays defined by Proterozoic rocks of eastern North America suggest differences in the crustal histories for rocks of each array:

Roan Mountain and the Stage Road Layered Gneiss of the Virginia Blue Ridge define the steepest array in $^{207}Pb/^{204}Pb$-$^{206}Pb/^{204}Pb$ space, possibly indicating an older age for these units. Only a single $\mathbf{T_{DM}}$ age of 1.59 Ga is available from the Stage Road layered gneiss, but isotopic data from Roan Mountain confirm antiquity for this area, with $\mathbf{T_{DM}}$ ages up to 2.32 Ga, and 1.8 Ga Rb/Sr and U-Pb magmatic ages (Fisher and Bream, unpublished data (see Appendix E and F); Ownby et al., 2004; Carrigan et al., 2003; Monrad and Gulley, 1983; Pettingill et al., 1984). $\mathbf{T_{DM}}$ ages > 1.9 Ga and evidence for a >1.4 Ga magmatic event have not been identified elsewhere in the SCAB, including the remainder of the Mars Hill Terrane. The nearest known Laurentian rocks that could produce the $\mathbf{T_{DM}}$ ages observed at Roan Mountain lie ~1000 km to the NW in the Central Plains (Van Schmus et al, 1996) and Penokean Orogens (Van Wyck and Johnson, 1997) (Figure 1).

Two coherent subparallel arrays are defined by the remainder of the Pb isotope data. Juvenile crust of the Adirondacks, Llano Uplift, West Texas and MCGRP all have overlapping Pb isotopic compositions that define a distinct LSF array, suggesting a common source. An ESF array is defined by Mesoproterozoic basement in both the southern and central Appalachians, suggesting a Pb source for these units distinct from that of the nearby juvenile, LSF crust of the Adirondacks, Texas, and MCGRP.

A plot of ^{208}Pb/^{204}Pb vs ^{206}Pb/^{204}Pb for all Proterozoic eastern North American samples is shown in Figure 8. There is no clear distinction between the ESF domain (grey and black data symbols) and LSF domain (open data symbols) defined by the uranogenic Pb data. Most samples from the MCGRP plot along or below the crustal growth curve of Stacey and Kramers (1975), indicating average or slightly lower Th/U values (Th/U </~4). The Adirondacks, Texas and central Appalachian data are scattered above and below the curve of Stacey and Kramers (1975). Data for the southern Appalachians typically have a higher ^{208}Pb/^{204}Pb for a given ^{206}Pb/^{204}Pb than the other domains and a smaller range of ^{206}Pb/^{204}Pb, including the central Appalachians. Roan Mountain samples are especially distinct in their high ^{208}Pb/^{204}Pb and low ^{206}Pb/^{204}Pb, indicating very high Th/U (evident in whole rock data: Appendix D; Ownby et al., 2004).

Present day elevated ^{208}Pb/^{204}Pb ratios (relative to ^{206}Pb/^{204}Pb), such as those observed in the southern Appalachian basement, are the result of an increase in Th/U in the past, and have been associated with preferential U loss during metamorphism (Wooden et al., 1986). In addition, most southern Appalachian basement samples show a narrower range of ^{206}Pb/^{204}Pb (17-18) than is observed in the central Appalachian and other domains. These characteristics may reflect Grenville high-grade metamorphism in the deep crust that resulted in U loss and hence increase in Th/U and decrease in U/Pb. As a consequence, thorogenic ^{208}Pb has continued to rise at near-normal rates while growth of uranogenic ^{206}Pb (and ^{207}Pb) has been limited. Plausibly, the southern

Appalachian isotopic signature may reflect greater involvement of older, deep, high-grade crust, represented by Roan Mountain gneisses, than occurred elsewhere in the Appalachians.

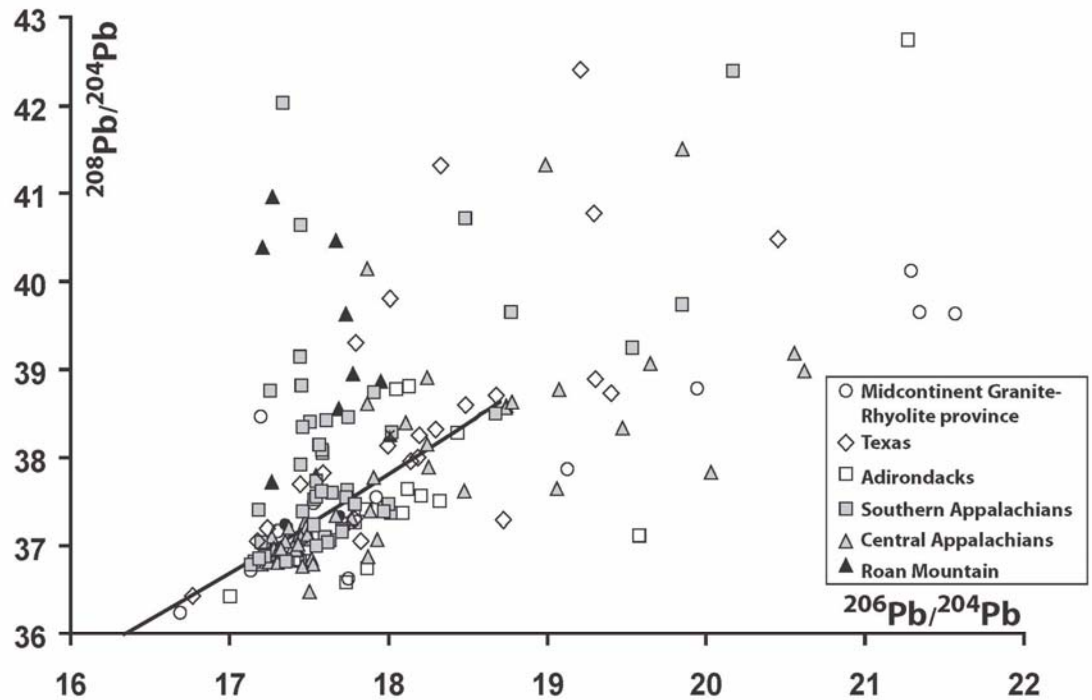


Figure 9. Thorano-uranogenic Pb isotopic compositions of Mesproterozoic eastern North America. Black line is crustal growth curve of Stacey and Kramers (1975). Data from this study and references in Figure 3.

Despite similarities in uranogenic Pb isotopic data, the Nd isotopic signature of the southern Appalachian basement is notably older (1.34-1.88 Ga) than the more uniform $\mathbf{T_{DM}}$ ages (1.35-1.50 Ga) found in the central Appalachians. A Laurentian origin for SCAB predicts $\mathbf{T_{DM}}$ ages to be the same or less than the $\leq$1.55 Ga EGRP, which bounds SCAB to the west. Although Sm/Nd isotopic data from the central Appalachians are consistent with this model, less than 30% of southern Appalachian samples have $\mathbf{T_{DM}}$ ages <1.55 Ga, and thus the data are at odds with a Laurentian derivation (Berquist et al., 2005; Ownby et al., 2004; Carrigan et al., 2003). This is illustrated in a probability plot of $\mathbf{T_{DM}}$ ages available for Proterozoic rocks from the EGRP, and Grenville age rocks in Texas, the Adirondacks and SCAB (Figure 10).

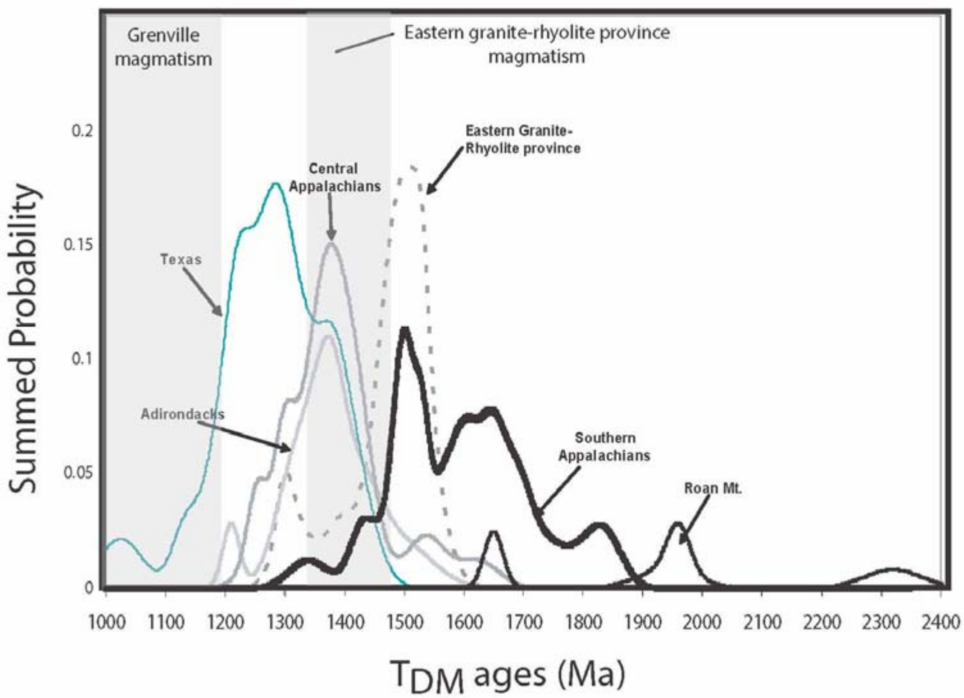


Figure 10. Summed probability plot of TDM ages for Proterozoic rocks of eastern North America. Adirondacks (Daly and McLelland, 1991; McLelland et al. 1993); Midcontinent granite-rhyolite province (Van Schmus et al., 1996); West Texas and Llano (Roller 2004; Cameron and Ward 1998; Smith et al., 1997; Whitefield 1997; Patchett and Ruiz, 1989); central Appalachian basement (Owens and Sampson, 2004; Pettingill et al. 1986); southern Appalachian basement (Hatcher et al., 2004; Ownby et al., 2004; Carrigan et al., 2003; Heatherington et al., 1996). *Uncertainties for individual TDM ages are calulated based on $^{147}Sm/^{144}Nd$ (see Appendix A for explanation).*

Recent work has suggested that Roan Mountain-type crust may represent an exposed lower crustal fragment similar to that which underlies the younger, Grenville-age rocks of the southern Appalachians (Ownby et al., 2004; Fullagar 2002). Similar, ~Paleoproterozoic and older crust has also been suggested to underlie the Pine Mountain terrane (Heatherington et al., 2006). Thus, it is plausible that both the southern and central Appalachian basement may have come from a similar, ESF Pb isotopic source, with either variable lower crustal ages, the older of which must underlie the southern Appalachians, or a larger juvenile component in the central Appalachian Grenvillian rocks.

Implications of Lead Isotopic Domains for Architecture of Southeastern North America

The utility of mapping distinct Precambrian isotopic domains, even in areas where Precambrian rocks are not exposed at the surface, has been established in previous studies (Kistler and Peterman, 1973; Wooden et al., 1986; Wooden and Miller, 1990). Similar mapping of the ESF and LSF uranogenic Pb isotope arrays of Proterozoic eastern North America provides a striking map pattern showing no geographic overlap of the arrays (Figure 11). All samples plotting within the ESF array form a NW-SE trending belt outboard of all LSF signature samples and parallel to the proposed SE Laurentian margin of Bartholomew and Lewis (1986; 1992).

If the SCAB indeed represents an exotic terrane accreted to the SE Laurentian margin, then the boundary between ESF and LSF signatures may indicate potential suture locations. Although such a suture is likely buried beneath Paleozoic thrust sheets, regional geophysical data define a major subsurface crustal boundary beneath Paleozoic

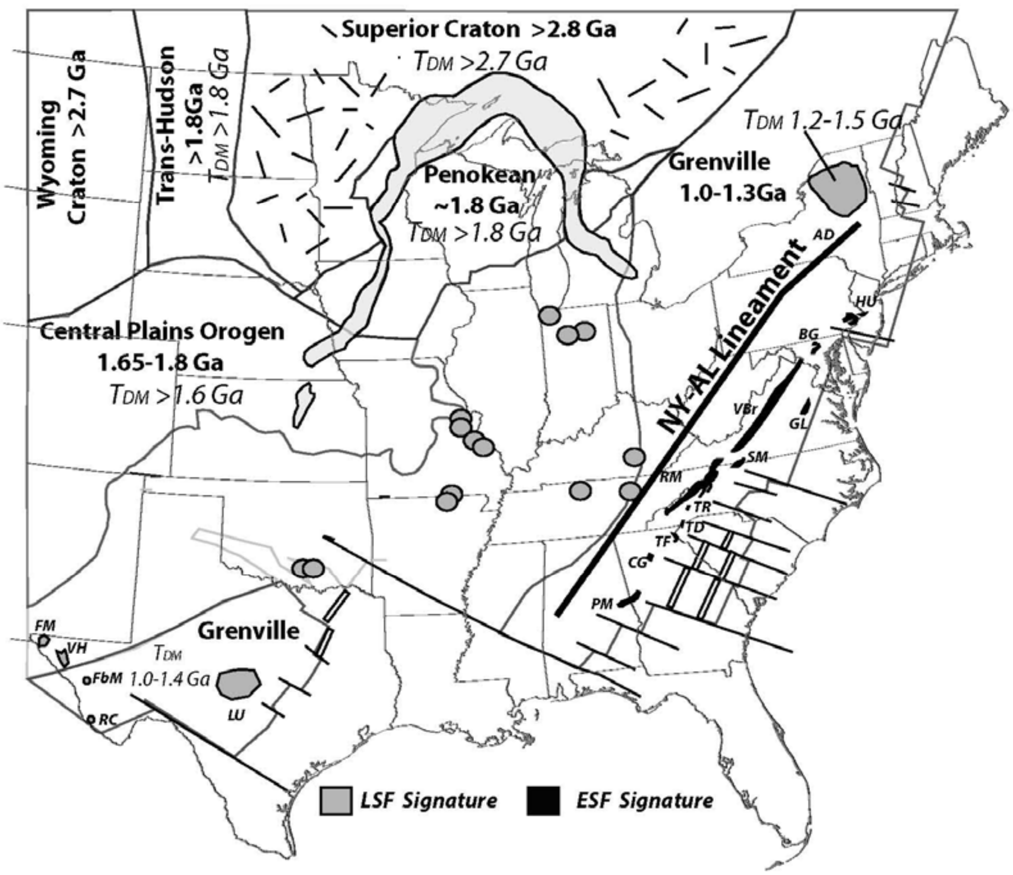


Figure 11. Distribution of Proterozoic LSF and ESF Pb signatures compared with the location of the NY-AL lineament.

cover, termed the New York-Alabama (NY-AL) lineament (King and Zietz, 1978), which could mark its location. Defined by both magnetic and density gradients,

the NY-AL lineament stretches from New York to Alabama, eastern USA, parallel to but west of the proposed SE Laurentian margin during the Grenville (Bartholomew 1986; 1992) (King and Zietz, 1978). Shown in Figure 11, it separates the rocks of LSF signature west of the lineament with those of ESF signature to the east (Fisher et al., 2005, 2006). The division of the data is especially compelling given new Pb data from samples collected close to the lineament on either side, i.e. WBR exposures and EGRP drill core. The relatively narrow gap between currently exposed LSF and ESF basement also includes the frontal faults of the Appalachians. All ESF are in the NW-directed upper plate, allochthonous with respect to the deep crust. Thus, the original location of the suture in autochthonous crust could lie as much as hundreds of km to the southeast, beneath overthrust Appalachians (Hatcher 1984; Bartholomew and Lewis, 1992).

Possible Origin of Southern Appalachian Basement in Rodinia

Recent Rodinian reconstructions have placed either the Amazonian or Kalahari craton in a near conjugate margin position relative to southeastern Laurentia during the Grenville orogeny and suggest the possibility that fragments of these cratons remain within North America (Hoffman, 1991; Daziel et al., 2000; Loewy et al., 2003; Tohver et al., 2004). Data from the MCGRP and the southern Appalachian basement presented here strengthen arguments for an exotic SCAB that was accreted as a fragment during the construction of Rodinia.

Limited Pb isotopic data from Kalahari (Wareham et al., 1998) appear to overlap the LSF signature of juvenile Laurentian rocks and therefore could not have produced the

ESF signature observed in SCAB samples. In contrast, the Sunsas orogen, within Amazonia, experienced 1.3 to 1.0 Ga magmatism and has >1.6 Ga T_{DM} ages and ESF Pb isotopic signatures similar to SCAB (Figure 12) (Geraldes et al. 2001; Loewy et al., 2003; Tohver et al., 2004).

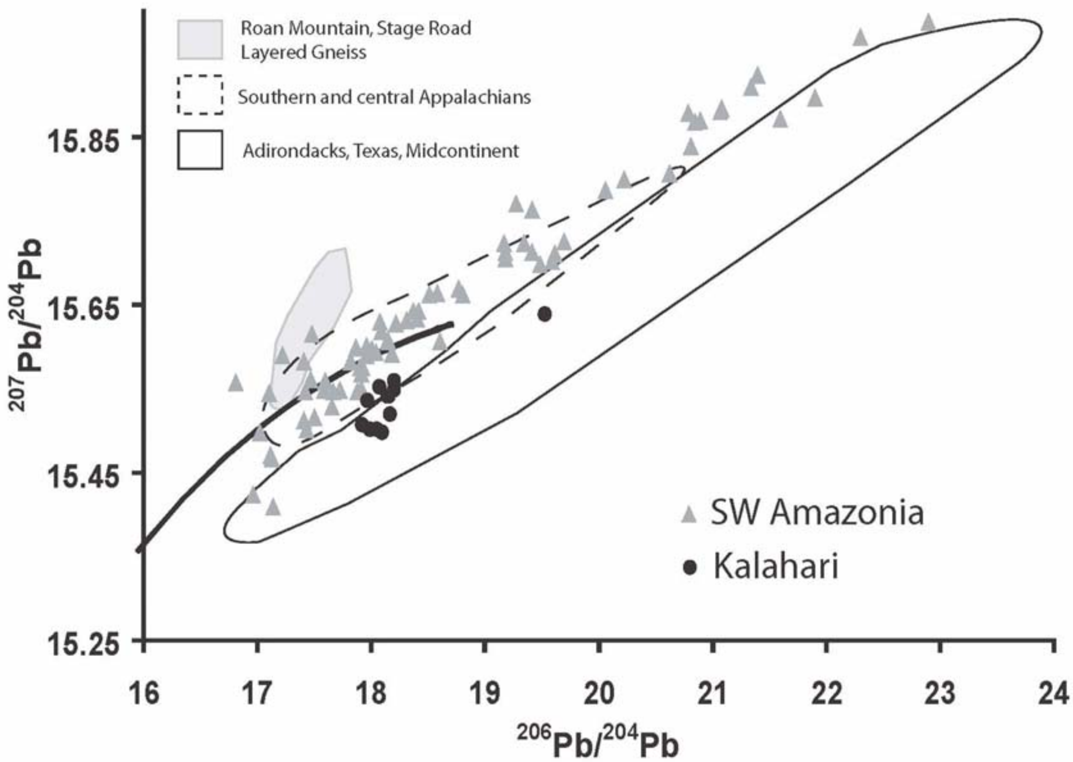


Figure 12. Present day uranogenic ($^{207}Pb/^{206}Pb$ vs. $^{206}Pb/^{204}Pb$) isotopic compostions from the Grenville-age Natal-Namaqua belt of Kalahari (Wareham et al., 1998) and southwest Amazonia (Geraldes et al., 2001; Tohver et al., 2004) plotted with data from Mesoproterozoic eastern North America (see this study and Figure 4 for data references).

Based on paleomagnetic and structural data, Tohver et al. (2004; 2005) suggest a collision between SW Amazonia and the Llano segment of Laurentia followed by sinistral displacement of Amazonia along the Laurentian margin. A possible best fit for the geophysical data from the NY-AL lineament suggests sinistral movement along its strike, which agrees with the oblique collisionsal and/or roational (?) model of Tohver et al. (2004; 2005) and is compatible with the distribution of ESF and LSF samples presented here.

Conclusions

1. New whole-rock Pb isotopic data from Mid-continent Granite-Rhyolite province and Western Blue Ridge basement samples provide a more complete characterization of the Pb isotopic signatures of Mesoproterozoic age rocks in the eastern USA. These data indicate that WBR basement has a very similar heritage to most Proterozoic Appalachians rocks and demonstrate that the MCGRP crust is similar to that of adjacent juvenile North American Proterozoic crust (Adirondacks, Texas). Furthermore, these data confirm that Appalachian crust is distinct from that of adjacent North America, and that rocks from a small area in the vicinity of Roan Mountain, NC-TN, is isotopically even more extreme and distinctive than those in the remainder of the Appalachians.

2. The Pb isotope data, together with Sm-Nd $\mathbf{T_{DM}}$ ages, strongly support recent suggestions of an exotic origin for Proterozoic Appalachian crust (Loewy et al 2003; Ownby et al., 2004; Tohver et al 2004).

3. Comparison of Pb isotopic data from the southern and central Appalachians with terranes suggested to have been in the vicinity of SE Laurentia during Rodinian construction favors an Amazonian connection. Thus, the NY-AL lineament could represent the boundary between Laurentian crust to the NW and accreted Amazonian crust to the SE.

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APPENDIX A. TDM age analytical uncertainty calculation

Potential sources of error in calculating **TDM** age include extrapolation beyond the crystallization age (which assumes no change in Sm/Nd), uncertainty in the composition of mantle sources in space and time, and analytical uncertainty. Analytical uncertainty of **TDM** ages is the result of the uncertainty of $^{147}Sm/^{144}Nd$ and $^{144}Nd/^{143}Nd$ measurements that are used to calculate **TDM** age (illustrated by the sub-horizontal bands in Figure A). The uncertainty in **TDM** age is further increased as the extrapolation line intersects the depleted mantle model curve (Figure 13a). Samples with higher $^{147}Sm/^{144}Nd$ intersect the depleted mantle model curve at low angle resulting a larger uncertainty in **TDM** ages. An approximation of this uncertainty is presented here for $^{147}Sm/^{144}Nd$ between 0.14 and 0.07, typical of continental/crustal materials. This approximation assumes an uncertainty of ±0.000005 for measured $^{144}Nd/^{143}Nd$, and a 0.4% uncertainty in $^{147}Sm/^{144}Nd$ (Patchett and Kouvo, 1986). Figure (13b) shows the calculated uncertainty for Sm/Nd from 0.14-0.07, the ratios considered in this study.

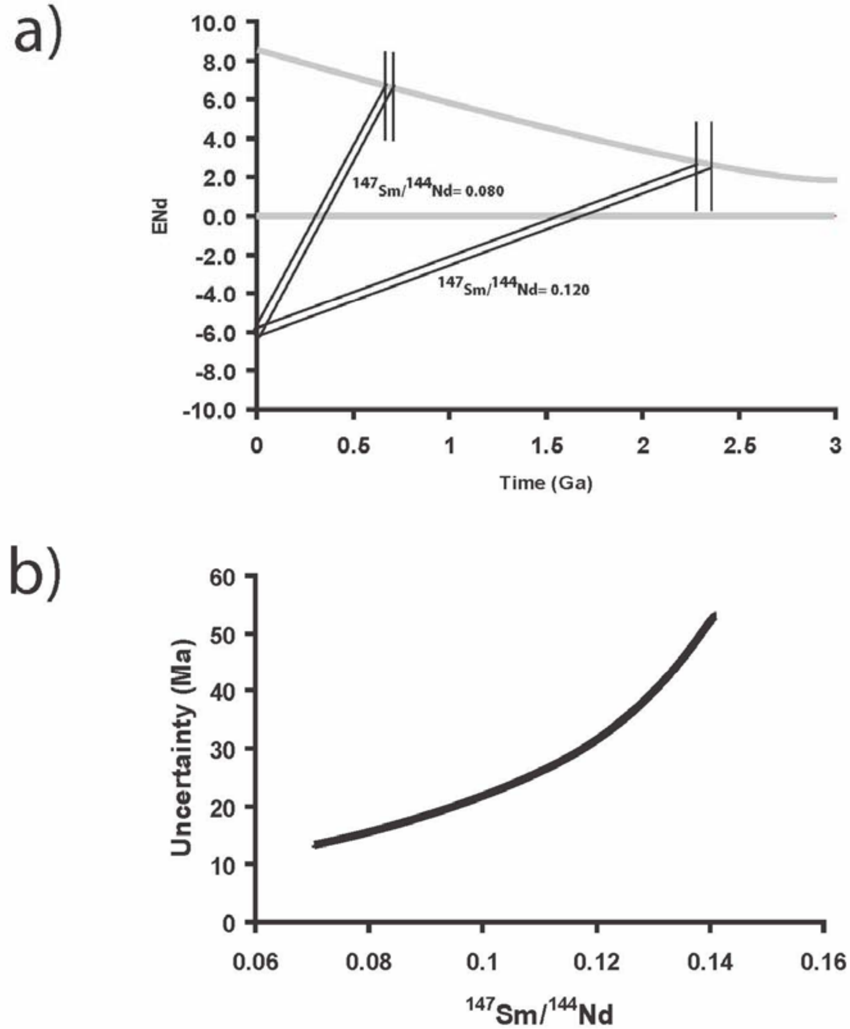

Figure 13. a) ENd vs. time diagram showing the effect of uncertainties in $^{147}Sm/^{144}Nd$ and $^{144}Nd/^{134}Nd$ on $\mathbf{T_{DM}}$ age. b) Diagram showing $\mathbf{T_{DM}}$ age uncertainty as a function of $^{147}Sm/^{144}Nd$ and $^{144}Nd/^{134}Nd$.

APPENDIX B. Methods

Whole-rock Elemental and Isotopic data

Fresh, representative 1-5 kg samples for whole rock geochemistry and isotope analysis as well as U/Pb zircon analysis were collected from roadcuts, outcrops, and quarries. In the case of drill cores, the freshest possible portions were used. Thin slabs were cut from each sample (parallel to lineation and perpendicular to foliation, where applicable) and powdered in an alumina ceramic shatterbox. Drill core samples were cut into smaller slabs, or consisted of cuttings and were pulverized in an alumina ceramic mortar and pestle.

Both whole rock Sm/Nd and Pb isotopic analyses were performed at the University of North Carolina-Chapel Hill on a Micromass Sector 54 mass spectrometer. For Pb analysis, 300 mg aliquots of the pulverized powder were washed in 1N HNO3 for 30 minutes on a warm hotplate before dissolution in Teflon™ dissolution bombs. Samples were dissolved in two stages using HF/HNO3 and 6N HCl. Pb was isolated using an HBr anion exchange technique, loaded onto standard Re filaments with a mixture of silica gel and phosphoric acid, and analyzed with a VG Sector 54 TM thermal ionization mass spectrometer. Twenty analyses of NBS981 indicate fractionation of 0.12% per amu with measured isotopic ratios within 0.05%. For Sm/Nd analyses, 300 mg aliquots of pulverized powder were spiked with ^{147}Sm/^{150}Nd mixed spike and dissolved in the same manner as the Pb samples, except the powders were not washed in HNO3. Rare earth elements (REE) were isolated using REE-SPECTM column chemistry. Sm and Nd were subsequently isolated using LN-spec columns. Analyses were normalized to

$^{146}Nd/^{144}Nd$ = 0.7219. Twenty-seven analyses of JNdi yielded an average $^{143}Nd/^{144}Nd$ of 0.5121080 +/- 0.0006% std error. TDM ages are calculated using the theoretical isotopic decay constant (6.54*10-12/yr) of Lugmair and Marti (1978) and the depleted mantle model of DePaolo (1981; ENd=0.25T2-3T+8.5).

Zircon U/Pb geochronology

Zircons from sample GV-DC were separated from ~100 g of core material at Vanderbilt University. The sample was crushed in an alumina ceramic shatter box to sieve size of <500 microns. Zircons were separated using heavy liquids and a Frantz Isodynamic magnet separator, then handpicked from non-magnetic fractions and mounted in epoxy with zircon standard R-33 and VP-10. Mounts were then polished to reveal the approximate center of the grain and imaged by cathodoluminescience (CL) to reveal internal morphology. Points on zircons (~30μm in diameter) were analyzed according to the Stanford/U.S. Geological Survey (USGS) Sensitive High-Resolution Ion Microprobe, Reverse Geometry (SHRIMP-RG) Facility procedure (Bacon et al., 2000) Data reduction used the SQUID software package of Ludwig (Ludwig 2002a, 2002b).

Appendix C. Major- and trace- element geochemistry (drill cores and RM-HB)

Element/Oxide:	CO-DC	GV-DC	RMHB
SiO_2	49.89	72.31	55.34
Al_2O_3	22.55	13.4	11.73
Fe_2O_3(T)	6.54	1.82	8.77
MnO	0.082	0.04	0.211
MgO	5.79	0.43	11.26
CaO	9.74	0.89	8.2
Na_2O	3.67	3.8	2.26
K2O	0.53	4.99	1.36
TiO_2	0.408	0.209	0.437
P_2O_5	0.25	0.06	0.09
LOI	0.99	0.97	0.52
Total	100.4	98.92	100.2
Rb	<10	170	61
Sr	982	109	234
Ba	338	636	584
Y	4	33	30
Zr	10	178	71
Hf	<0.2	6.6	2.1
Nb	0.7	28.2	3.9
Ta	<0.3	1.5	0.3
Zn	39	25	83
Cu	49	3	69
V	66	14	145
Ni	179	2	326
Cr	401	11.1	298
Co	53.8	2.3	53.8
Sc	9.39	4.14	36.6
La	4.87	48.1	22.3
Ce	10.6	94.1	51.4
Pr	1.45	10.2	6.69
Nd	6.65	34.5	26.7
Sm	1.48	6.07	5.83
Eu	0.89	0.99	1.27
Gd	1.48	5.05	5.1
Tb	0.2	1.4	0.88
Dy	1.04	4.47	4.91
Ho	0.19	0.99	0.99
Er	0.49	3.48	2.95
Tm	0.07	0.63	0.456
Yb	0.56	4.61	2.94
Lu	0.08	0.7	0.429
U	0.01	6.21	0.21
Th	0.11	19.5	2.77

Note: oxide value in wt. %, trace element value in ppm. LOI-loss on ignition.

APPENDIX D. Major- and trace- element geochemistry for Roan Mountain

Element/Oxide:	CLG1	CLG2	CLG3	CLG4	CLG5
SiO_2	62.45	66.7	71.49	73.6	65.29
Al_2O_3	21.17	19.01	14.35	13.74	19.34
Fe_2O_3(T)	9.19	7.49	1.34	2.97	5.76
MnO	0.029	0.024	0.017	0.052	0.066
MgO	0.87	0.68	0.42	0.67	1.04
CaO	1.35	0.95	0.83	1.59	2.1
Na_2O	1.51	1.09	1.86	2.53	2.88
K2O	2.21	2.27	7.95	4.14	2.62
TiO_2	0.669	0.592	0.13	0.406	0.813
P_2O_5	0.04	0.02	0.07	0.04	0.04
LOI	0.06	0.02	0.33	0.19	0.21
Total	99.54	98.84	98.78	99.9	100.2
Rb	46	52	178	104	60
Sr	224	176	270	216	313
Ba	851	885	2633	1322	1045
Y	56	49	25	56	61
Zr	299	327	38	363	275
Hf	9	9.6	1.1	10.4	7.3
Nb	6.7	6.8	3.2	12.2	11.5
Ta	0.2	0.2	0.2	0.5	0.4
Zn	143	119	< 1.0	94	80
Cu	3	4	2	49	7
V	61	40	9	18	46
Ni	23	42	< 1	8	14
Cr	84.7	81.1	18	50.2	89.3
Co	12.6	10.7	3.5	3.9	10.9
Sc	9.68	8.8	4.69	6.8	14.3
La	136	80.7	125	74.3	85.3
Ce	283	161	231	154	171
Pr	34.2	17.7	25.2	17.9	20.2
Nd	125	61.9	84.6	64.1	70.5
Sm	21.7	10.5	12.3	12.2	12.4
Eu	4.11	2.76	4.91	2.74	3.58
Gd	16.9	10	7.85	10.7	11.5
Tb	2.09	1.56	0.83	1.68	1.86
Dy	10.6	8.79	4.03	9.48	10.6
Ho	1.97	1.77	0.74	1.87	2.06
Er	5.57	5.06	2.08	5.54	6.05
Tm	0.771	0.663	0.307	0.793	0.854
Yb	4.69	3.65	1.84	4.93	5.39
Lu	0.661	0.488	0.244	0.702	0.769
U	0.72	0.43	0.68	2.77	0.38
Th	26.2	12.6	18.5	18.9	9.9

Note: oxide value in wt. %, trace element value in ppm. LOI-loss on ignition.

APPENDIX E. Concordia plot for CLG-4 (Figure 14)

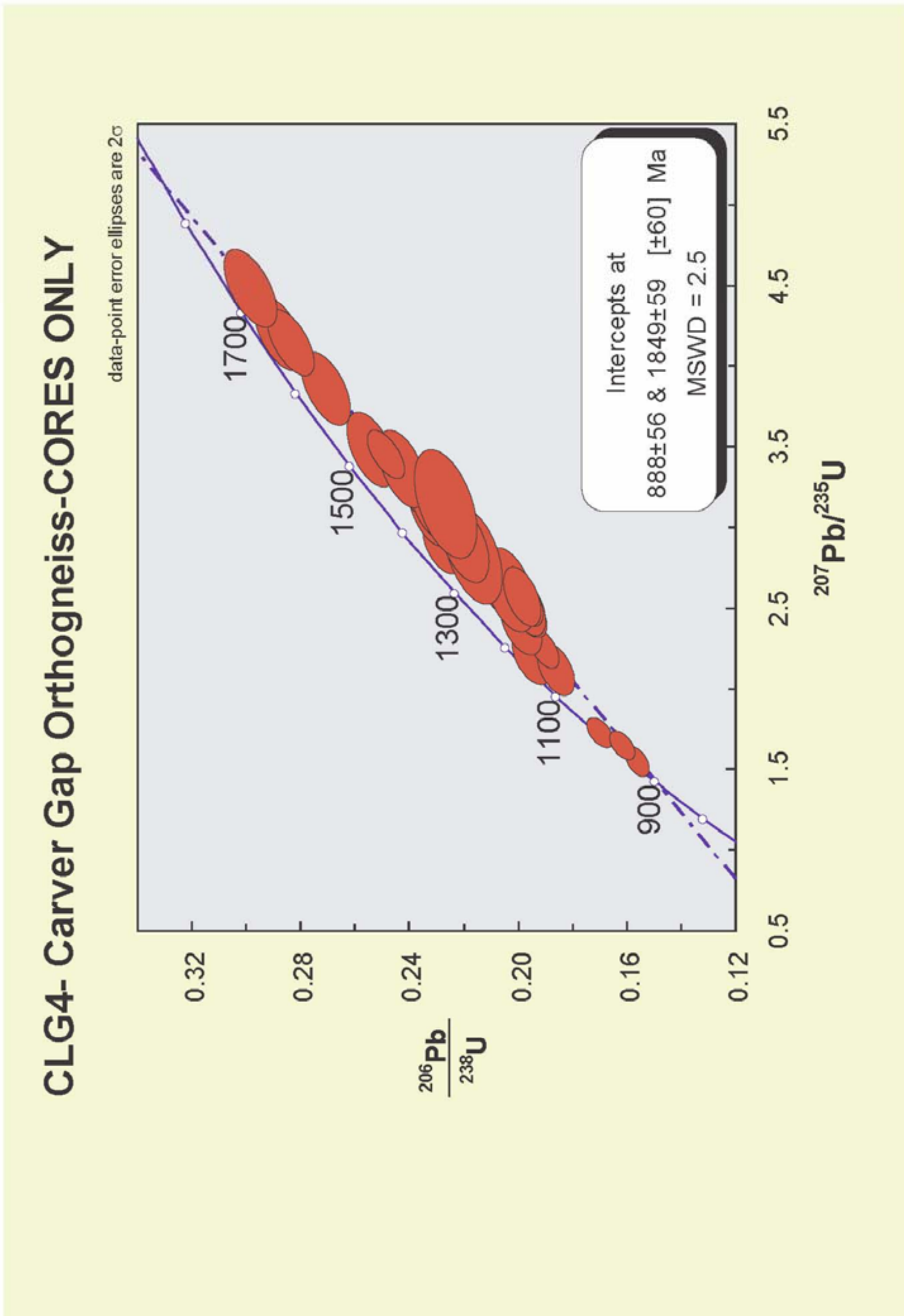

Figure 14. Concordia diagram for zircons cores from sample CLG-4, Roan Mountain (Carver's Gap) orthogneiss. Analyses performed using LA-ICPMS

APPENDIX F. U/Pb isotopic data for CLG-4

Sample	$^{207}Pb/^{206}Pb$	1σ	% error	$^{207}Pb/^{235}U$	1σ	% error	$^{206}Pb/^{238}U$	1σ	% error	error correlation	$^{207}Pb/^{206}Pb$ age	1σ	$^{207}Pb/^{235}U$ age	1σ	$^{206}Pb/^{238}U$ age	1σ
CORES																
11_clg4_c	0.09845	0.00334	3.393	3.19731	0.12875	4.0268	0.23452	0.00883	3.7651	0.93501446	1595	62.13	1358.2	46.09	1456.5	31.15
13_clg4_c	0.09299	0.00305	3.28	2.72047	0.10693	3.9306	0.21126	0.0079	3.7395	0.95138038	1487.6	60.83	1235.5	42.06	1334.1	29.18
14_clg4_c	0.10737	0.00396	3.688	3.85566	0.16444	4.2649	0.2593	0.00992	3.8257	0.89701647	1755.3	65.97	1486.3	50.79	1604.5	34.39
15_clg4_c	0.10858	0.00403	3.712	3.53758	0.15147	4.2817	0.23526	0.009	3.8256	0.89345783	1775.6	66.31	1362	46.98	1535.7	33.89
16_clg4_c	0.07873	0.00292	3.709	1.95456	0.08363	4.2787	0.17925	0.00679	3.788	0.88531438	1165.5	71.78	1062.9	37.12	1100	28.74
26_clg4_c	0.08721	0.00326	3.738	2.37323	0.10202	4.2988	0.19647	0.00748	3.8072	0.88564538	1365.1	70.13	1156.3	40.28	1234.6	30.71
27_clg4_c	0.09363	0.00303	3.236	2.91163	0.11352	3.8988	0.22451	0.00839	3.737	0.95849549	1500.6	59.94	1305.6	44.18	1384.9	29.47
28_clg4_c	0.10131	0.0032	3.159	3.67314	0.14095	3.8373	0.26173	0.00976	3.729	0.97178169	1648.3	57.37	1498.7	49.88	1565.5	30.63
32_clg4_c	0.09642	0.00301	3.122	3.31552	0.12651	3.8157	0.24822	0.00925	3.7265	0.97663382	1556	57.55	1429.3	47.75	1484.7	29.77
34_clg4_c	0.09739	0.00339	3.481	3.43758	0.14085	4.0974	0.25477	0.00964	3.7838	0.92347408	1574.8	63.75	1463.1	49.52	1513	32.23
35_clg4_c	0.10662	0.00357	3.348	4.49551	0.17979	3.9993	0.30435	0.01148	3.772	0.94315271	1742.4	60.19	1712.9	56.73	1730.1	33.22
44_clg4_c	0.09094	0.00292	3.211	2.53113	0.09836	3.886	0.20088	0.00751	3.7386	0.96205338	1445.2	60.16	1180	40.3	1281	28.28
45_clg4_c	0.07929	0.00247	3.115	2.17879	0.083	3.8095	0.19831	0.00738	3.7214	0.97689757	1179.4	60.42	1166.3	39.71	1174.3	26.51
47_clg4_c	0.09179	0.00301	3.279	2.98054	0.11737	3.9379	0.23434	0.00879	3.751	0.95253359	1462.9	61.17	1357.2	45.88	1402.7	29.94
48_clg4_c	0.08066	0.00285	3.533	2.21324	0.09161	4.1392	0.19802	0.00748	3.7774	0.91259518	1213.2	67.78	1164.7	40.22	1185.2	28.95
49_clg4_c	0.10595	0.00348	3.285	4.42181	0.17432	3.9423	0.30118	0.01133	3.7619	0.95423785	1730.8	58.97	1697.2	56.11	1716.4	32.65
51_clg4_c	0.08456	0.00283	3.347	2.31816	0.09243	3.9872	0.19783	0.00742	3.7507	0.94068065	1305.4	63.65	1163.6	39.96	1217.9	28.28
60_clg4_c	0.0999	0.00402	4.024	3.18397	0.14465	4.5431	0.22996	0.00893	3.8833	0.85477082	1622.2	72.98	1334.3	46.79	1453.3	35.1
61_clg4_c	0.09479	0.00326	3.439	2.66167	0.10827	4.0677	0.2026	0.00765	3.7759	0.92825665	1523.9	63.54	1189.3	40.99	1317.9	30.02
62_clg4_c	0.09209	0.00311	3.377	2.58095	0.10355	4.0121	0.2022	0.00761	3.7636	0.93806513	1469.2	62.83	1187.1	40.8	1295.3	29.36
64_clg4_c	0.09177	0.0031	3.378	2.53636	0.10177	4.0124	0.19941	0.0075	3.7611	0.93735791	1462.4	62.89	1172.2	40.34	1282.5	29.22
66_clg4_c	0.09777	0.00339	3.467	3.10125	0.12671	4.0858	0.22884	0.00866	3.7843	0.92621506	1582	63.4	1328.4	45.42	1433	31.37
74_clg4_cc	0.07181	0.00239	3.328	1.59734	0.0635	3.9754	0.16046	0.00601	3.7455	0.94217446	980.5	66.28	959.3	33.4	969.2	24.83
76_clg4_cc	0.07297	0.00242	3.316	1.77675	0.07052	3.969	0.17565	0.00658	3.7461	0.94382562	1013	65.76	1043.1	36.09	1037	25.79
77_clg4_c	0.09697	0.00362	3.733	2.98444	0.12856	4.3077	0.22199	0.0085	3.829	0.88887871	1566.7	68.42	1292.4	44.86	1403.7	32.76
78_clg4_c	0.09327	0.00307	3.292	2.58352	0.10208	3.9512	0.19979	0.0075	3.7539	0.95007673	1493.4	61.07	1174.2	40.31	1296	28.92
79_clg4_c	0.1046	0.00333	3.184	4.32411	0.16731	3.8692	0.29817	0.01118	3.7495	0.96906452	1707.3	57.48	1682.2	55.5	1698	31.91
80_clg4_c	0.09503	0.00327	3.441	3.10808	0.12657	4.0723	0.23589	0.00892	3.7814	0.92857446	1528.7	63.48	1365.3	46.54	1434.7	31.28
81_clg4_c	0.08989	0.00286	3.182	2.62785	0.10151	3.8629	0.21085	0.00789	3.742	0.96871303	1423.1	59.51	1233.4	41.98	1308.5	28.41
83_clg4_c	0.10348	0.00349	3.373	3.90916	0.157	4.0162	0.27246	0.0103	3.7804	0.94127878	1687.5	60.9	1553.3	52.17	1615.6	32.47
88_clg4_c	0.09162	0.00541	5.905	2.50665	0.15523	6.1927	0.1973	0.00831	4.2119	0.68013007	1459.5	108.37	1160.8	44.72	1274	44.95
89_clg4_c	0.09157	0.0043	4.696	2.37785	0.12157	5.1126	0.18727	0.00745	3.9782	0.77811914	1458.4	86.8	1106.6	40.46	1236	36.55
90_clg4_c	0.09218	0.00575	6.238	2.8146	0.18299	6.5015	0.22018	0.00953	4.3283	0.66573955	1471.1	114.06	1282.8	50.33	1359.4	48.71
91_clg4_c	0.09001	0.00393	4.366	2.88147	0.13962	4.8454	0.23084	0.00909	3.9378	0.81267947	1425.7	81.27	1338.9	47.58	1377.1	36.53
92_clg4_c	0.09277	0.00525	5.659	2.55074	0.15214	5.9645	0.19827	0.00828	4.1761	0.70015809	1483.2	103.64	1166	44.57	1286.6	43.51
93_clg4_c	0.10103	0.00526	5.206	2.89412	0.16105	5.5647	0.20657	0.0085	4.1148	0.73944773	1643.1	93.65	1210.5	45.43	1380.4	41.99
94_clg4_c	0.08287	0.00755	9.111	2.0594	0.18875	9.1653	0.1792	0.00868	4.8438	0.52848841	1266.1	168.11	1062.6	47.43	1135.4	62.64
95_clg4_c	0.09422	0.00356	3.778	2.72797	0.11842	4.341	0.20878	0.00801	3.8366	0.88380846	1512.5	69.6	1222.3	42.69	1336.1	32.25
97_clg4_c	0.09379	0.00551	5.875	3.23625	0.20039	6.192	0.2488	0.01062	4.2685	0.6893506	1503.9	107.17	1432.3	54.8	1465.9	48.03

Sample	$^{207}Pb/^{206}Pb$	1σ	% error	$^{207}Pb/^{235}U$	1σ	% error	$^{206}Pb/^{238}U$	1σ	% error	error correlation	$^{207}Pb/^{206}Pb$ age	1σ	$^{207}Pb/^{235}U$ age	1σ	$^{206}Pb/^{238}U$ age	1σ
CLG-4																
RIMS																
09_clg4_r	0.07482	0.00243	3.25	1.8456	0.07203	3.90	0.17814	0.00664	3.73	0.955	1063.6	63.88	1056.8	36.33	1061.9	25.7
10_clg4_r	0.07286	0.00241	3.31	1.73519	0.06864	3.96	0.17197	0.00642	3.73	0.944	1010.2	65.68	1023	35.32	1021.7	25.48
12_clg4_r	0.07369	0.00243	3.30	1.69883	0.06701	3.94	0.16647	0.00621	3.73	0.946	1033	65.19	992.6	34.34	1008.1	25.21
17_clg4_r	0.07308	0.00248	3.39	1.74036	0.07007	4.03	0.17195	0.00644	3.75	0.930	1016.2	67.32	1022.8	35.42	1023.6	25.96
18_clg4_r	0.07482	0.00248	3.31	1.78509	0.07075	3.96	0.17226	0.00644	3.74	0.943	1063.8	65.33	1024.5	35.4	1040	25.79
19_clg4_r	0.07615	0.00246	3.23	1.85275	0.07221	3.90	0.17568	0.00655	3.73	0.957	1098.9	63.39	1043.3	35.92	1064.4	25.7
29_clg4_r	0.07336	0.00238	3.24	1.61473	0.06308	3.91	0.15891	0.00593	3.73	0.955	1023.8	64.3	950.7	32.97	975.9	24.5
30_clg4_r	0.07604	0.00245	3.22	1.89438	0.07374	3.89	0.17984	0.00671	3.73	0.959	1096.2	63.25	1066.1	36.65	1079.1	25.87
31_clg4_r	0.07377	0.00251	3.40	1.62896	0.06562	4.03	0.1594	0.00597	3.75	0.930	1035.2	67.16	953.4	33.21	981.5	25.34
33_clg4_r	0.07105	0.00241	3.39	1.65809	0.06682	4.03	0.16845	0.00631	3.75	0.930	959	67.94	1003.6	34.82	992.6	25.53
42_clg4_r	0.07408	0.00237	3.20	1.89935	0.07348	3.87	0.18506	0.0069	3.73	0.964	1043.5	63.11	1094.5	37.53	1080.9	25.73
43_clg4_r	0.07821	0.00252	3.22	1.99724	0.07773	3.89	0.18431	0.00688	3.73	0.959	1152.1	62.68	1090.5	37.45	1114.6	26.33
46_clg4_r_	0.07436	0.00252	3.39	1.85541	0.07475	4.03	0.18008	0.00676	3.75	0.932	1051.2	66.93	1067.4	36.91	1065.4	26.58
50_clg4_r	0.08197	0.0027	3.29	2.13812	0.08433	3.94	0.18823	0.00705	3.75	0.950	1244.9	62.99	1111.8	38.23	1161.2	27.29
58_clg4_r	0.07629	0.00467	6.12	1.81407	0.116	6.39	0.17156	0.00712	4.15	0.649	1102.8	117.76	1020.7	39.16	1050.5	41.85
63_clg4_r	0.07585	0.00255	3.36	1.73399	0.06944	4.00	0.16494	0.00619	3.75	0.937	1091	65.94	984.2	34.24	1021.2	25.79
65_clg4_r	0.07091	0.00239	3.37	1.28233	0.05142	4.01	0.13046	0.00489	3.75	0.935	954.9	67.45	790.5	27.88	837.9	22.88
67_clg4_r	0.07057	0.00283	4.01	1.27897	0.05792	4.53	0.13075	0.00499	3.82	0.843	944.9	79.99	792.2	28.46	836.4	25.8
75_clg4_rd	0.07362	0.00243	3.30	1.69083	0.06691	3.96	0.16567	0.00621	3.75	0.947	1031	65.32	988.2	34.32	1005.1	25.25
82_clg4_r	0.07554	0.00255	3.38	1.82518	0.07327	4.01	0.17426	0.00655	3.76	0.936	1083	66.18	1035.5	35.94	1054.5	26.33

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