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Ion microprobe age and geochemistry of southern appalachian basement, with implications for Proterozoic and Paleozoic reconstructions

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Abstract

Ion microprobe U–Pb analyses of zircons from basement units in the southern Appalachians, combined with supporting isotopic compositions and major and trace element geochemistry, have delineated a granitic magmatic pulse ~1165–1150 Ma. The pulse is manifested by the Watauga River Gneiss (western Blue Ridge), Toxaway, Wiley, and Sutton Creek gneisses (eastern Blue Ridge), Pilot Mountain and Grassy Creek gneisses (Sauratown Mountains window), and possibly the Forbush gneiss (~1140 Ma, Inner Piedmont or Sauratown Mountains window) and Cranberry-Mine Layered Gneiss (~1190 Ma, western Blue Ridge). Additional samples analyzed include the Blowing Rock Gneiss (~1080 Ma, Grandfather Mountain window), and the Carvers Gap Granulite Gneiss (~1.8 Ga) and Cloudland Granulite Gneiss (detrital cores ~1.2–1.8 Ga) from the Mars Hill terrane. Age data were evaluated by calculating concordia ages and concordia probability plots using $^{206}Pb^{*}/^{238}U$ and $^{207}Pb^{*}/^{206}Pb^{*}$ data simultaneously. Rocks in the main magmatic pulse are granitic (63–72 wt.% SiO_2), but elevated in K and incompatible trace elements compared to typical subduction-related magmas, and initial Nd ratios cluster tightly near CHUR. Mars Hill terrane samples are distinct in age, geochemistry (poorer in K and incompatible elements), and isotopic compositions (ε_{Nd} −7.6 and −5 at 1.0 Ga). Zircons from almost all samples have metamorphic rims that yield ages ~1030 Ma, with the exception of the Blowing Rock Gneiss. Ages of Grenvillian magmatism and metamorphism are similar to reported ages from the northern Blue Ridge of Virginia, the Adirondack Highlands, the Central Metasedimentary Belt (Canadian Grenville Province), and the Llano uplift of Texas. This suggests the entire southeastern margin of Laurentia has a similar history ~1.2–1.0 Ga. Although consistent with known ages in Laurentia, the presence of ~1.8 Ga rocks and T_{DM} ages commonly >1.6 Ga is inconsistent with the inferred 1.6 Ga margin of Laurentia. This suggests either that the 1.4–1.5 Ga mid-continent terrane separates older portions of Laurentia, that this region was exotic, or that it was a

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rifted fragment of Laurentia reattached during Grenville orogeny. Surprisingly few Paleozoic metamorphic zircon rims have been identified, but the few analyses obtained from samples in the eastern Blue Ridge yield late Acadian ages (~350 Ma). The similarity of basement units across the southern Appalachians suggests a relationship between these provinces and that the Piedmont terrane is not exotic to Laurentia during the Appalachian orogenic cycle.

Keywords: Grenville; Zircon geochronology; Geochemistry; Southern appalachians; U–Pb absolute age

1. Introduction

In this paper we present new high-resolution ion microprobe (IMP) U–Pb data, together with supporting isotopic and elemental geochemistry, for eleven basement[1] units in the southern Appalachians of western North Carolina, northwestern South Carolina, and northeastern Georgia. Based upon these data, we address the nature, timing, and distribution of Proterozoic magmatism and metamorphism, the crustal affinities of these units, and the implications of these conclusions for the Proterozoic through Paleozoic tectonic history of this region.

The Grenville orogenic cycle was a worldwide event that spanned an interval from ~1.3 to 0.9 Ga. Fragments of Grenville age belts are found on all continents and are interpreted as remnants of the supercontinent Rodinia. Laurentia (proto-North America), with its central geographical location, plays a key role in the construction of Rodinia and its eventual breakup (Fig. 1, Hoffman, 1991; Moores, 1991; Rogers, 1996; Karlstrom et al., 1999; Weil et al., 1998). The Grenville cycle was originally defined based upon events pre- and post-dating deposition of the Flinton Group metasediments (Moore and Thompson, 1980), which are constrained to older than 1030 Ma metamorphism (Mezger et al., 1993; Corfu and Easton, 1997) and younger than 1150 detrital zircon ages (Sager-Kinsman and Parrish, 1993). Various workers have adopted different terminology for orogenic events during the Grenville cycle (cf. Rivers, 1997; Wasteneys et al., 1999; McLelland et al., 2001); we use the terms Elzevirian (~1220–1160 Ma) and Ottawan (~1080–1030 Ma) to refer to separate orogenic events that make up the larger Grenville cycle, and the general term Grenville to denote the overall tectonothermal events in the interval ~1.3–0.9 Ga. The Elzevirian orogeny is generally viewed as collision of an island arc terrane that developed ~1.3–1.2 Ga, while the Ottawan orogeny is regarded as a Himalayan-type continent–continent collision (Davidson, 1995; McLelland et al., 1996), perhaps with Amazonia (Hoffman, 1991). In contrast to the northeastern USA and Canada, Grenville history in the southern Appalachians is poorly known. This region, which is the focus of this paper, is critical for understanding the development of the southeastern margin of Laurentia during the Grenville.

Characterization of the Grenville and older basement of the southern Appalachians is important not only to understand the development of the southeastern margin of Laurentia during the Middle Proterozoic, but also to constrain reconstructions of the southern Appalachian orogen during the Paleozoic. Various tectonic interpretations have been proposed for the southern Appalachians. These interpretations generally begin with the close of the Grenville orogeny and proceed through subsequent continental rifting, ocean basin formation, convergence and subduction, and finally culminate in continent–continent and/or arc–continent collisions (Zen, 1981; Williams and Hatcher, 1983; Hatcher, 1987, 1989; Horton et al., 1989; Willard and Adams, 1994). Competing models for Appalachian tectonic evolution require accretion of a variety of terranes and propose different locations for the principal terrane boundaries. All models recognize the area southeast of the Carolina suture (i.e. Central

[1] The term 'basement' in this paper refers to Middle Proterozoic and older rocks. We exclude the Late Proterozoic metasedimentary rocks that postdate the Grenville and predate Appalachian orogeny.

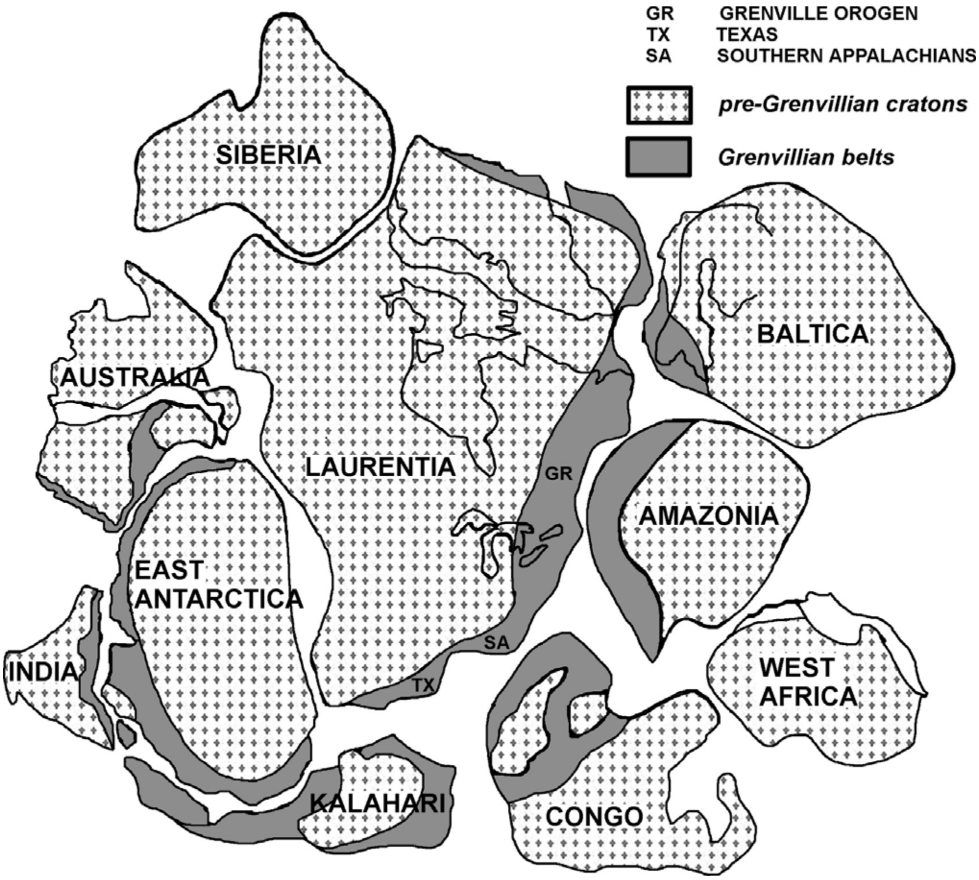

Fig. 1. One possible reconstruction of the late Mesoproterozoic supercontinent Rodinia. Archean cratons in light gray stipple, Grenvillian belts in dark gray. Modified from Hoffman (1991).

Piedmont suture) as a collage of exotic fragments where Grenville or older basement is very sparse or absent (Butler and Secor, 1991; Hibbard, 2000). The western Blue Ridge (WBR), which is generally agreed to have been part of Laurentia, contains abundant Grenvillian basement and metasedimentary cover (Fig. 2). Between the WBR and the Carolina suture are the eastern Blue Ridge (EBR) and Inner Piedmont (IP) provinces, whose tectonic histories and affinities remain controversial. They may both be exotic to Laurentia (Horton et al., 1989), only the IP may be exotic (Dennis and Wright, 1997), both may be Laurentian crust rifted during the Late Proterozoic and reattached during Appalachian orogeny (Hatcher, 1987, 1998; Bream et al., 2001b), or they may contain cryptic interior terrane boundaries not yet fully recognized or understood (Bream et al., 2001a). The nature of the sparse basement in this area can provide important evidence for the affinities of the enclosing terrane—if they are consistent with a reconstructed Laurentian margin, they support a native origin; if not, they suggest that the enclosing regions may be exotic.

Basement rocks are widely exposed in the WBR, sparser in the EBR, and presently unknown in the IP with the possible exception of the Forbush Gneiss adjacent to the Sauratown Mountains window (SMW) (McConnell, 1990). Almost all basement rocks in the southern Appalachians are believed to be Grenville age (1.0–1.25 Ga) based on Rb–Sr whole rock isochrons and conventional U–Pb dating methods (Stieve and Sinha, 1989; McConnell, 1990; McSween et al., 1991; Quinn

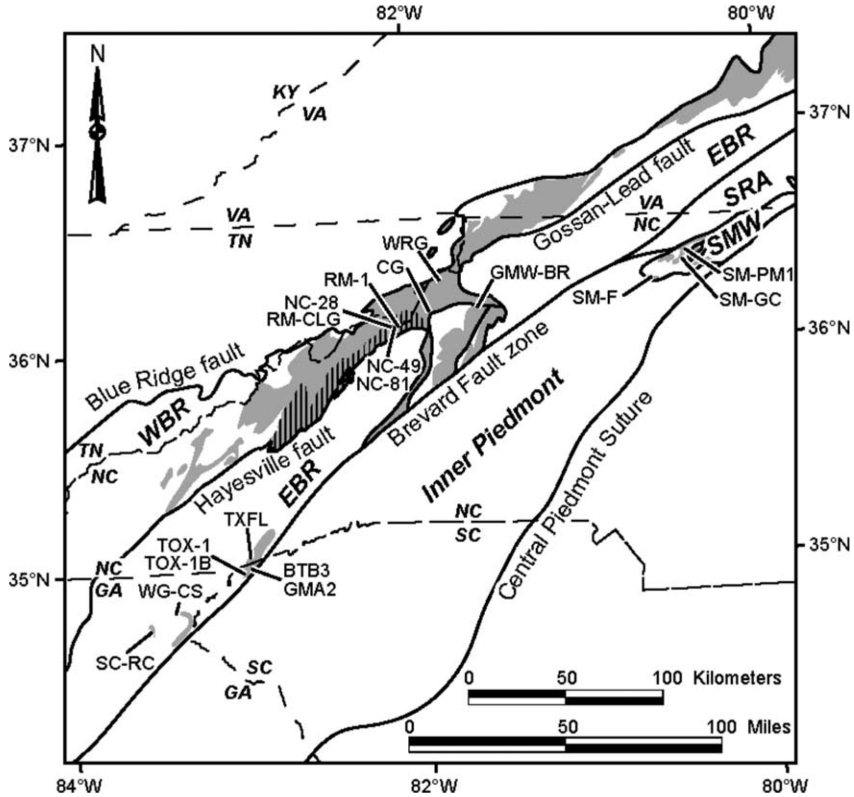

Fig. 2. General tectonic setting of the southern Appalachians with sample locations. Light gray shading indicates exposed basement rocks; Mars Hill terrane approximated by vertical line pattern. RM-1, RM-2, NC-81, NC-49—Carvers Gap Granulite Gneiss; RM-CLG, NC-28–Cloudland Granulite Gneiss; WRG, Watauga River Gneiss; CG, Cranberry-Mine Layered Gneiss; BMW-BR, Blowing Rock Gneiss; WG-CS, Wiley Gneiss; SC-RC, Sutton Creek gneiss; TOX-1, TOX-1B, TXFL, BTB-3, GMA-2–Toxaway Gneiss; SM-GC, Grassy Creek gneiss; SM-PM1–Pilot Mtn. gneiss; SM-PM-E, Enclave in Pilot Mtn. gneiss; SM-F, Forbush gneiss. WBR, western Blue Ridge; EBR, eastern Blue Ridge; SMW, Sauratown Mountains window; SMA, Smith River Allochthon. Modified from Drake et al. (1988) and Rankin et al. (1989); extent of Mars Hill terrane approximated from Brown et al. (1985).

and Wright, 1993; Su et al., 1994; Fullagar and Su, 1995; Fullagar et al., 1997). Rocks ranging from 1.4 to 1.5 Ga, well documented in the granite–rhyolite province that stretches across the continent (e.g. Van Schmus et al., 1996), are unknown in the southern Appalachians. No rocks older than Grenville have been identified, with the possible exception of the Carvers Gap Granulite Gneiss (1.8 Ga, Rb–Sr, Monrad and Gulley, 1983; ~1.4 and 1.8 Ga, U–Pb upper intercepts, Fullagar and Gulley, 1999).

Ages of southern Appalachian basement rocks are also documented in younger plutonic rocks and metasedimentary rocks as inherited or detrital zircon. Grenville age zircon is widespread as inherited cores in zircons from EBR Paleozoic plutons (much more sparsely as cores in IP plutons) and as detrital grains in metasedimentary rocks. These ages document contributions of basement to the pre- and syn-orogenic rocks of the region and verify the importance of Grenville age rock both in the deep crust and at the surface during the early Paleozoic (Mueller et al., 1994; Steltenpohl et al., 1996; Vinson et al., 1999; Miller et al., 1998, 2000b; Bream et al., submitted for publication). Pre-Grenville ages clustering around 1.4 Ga and 2.6–2.9 Ga are also documented in inherited cores from EBR plutons (Miller et al., 1998, 2000b), and rarely as 1.4 Ga and older detrital grains in sedimentary rocks and inherited cores in Neoproterozoic plutons (Mueller et al., 1994; Su et al., 1994; Steltenpohl et al., 1996; Bream et al., submitted for publication). Additional information on the nature of southern Appalachian basement rocks comes from Nd isotope data for basement and younger plutons, and suggests the presence of Meso and Paleoproterozoic basement in the Blue Ridge and possibly the IP as well (Fullagar et al., 1997; Fullagar, 2002). Some Pb isotope data also suggest the presence of ~1.7 Ga crust in the basement of the IP (Stuckless et al., 1986). These ancient inherited, detrital, and model ages, however, are not reflected in the known crystallization ages of exposed rocks.

2. Rock units sampled

We have examined basement units from the WBR, the Mars Hill terrane, the Grandfather Mountain window, the EBR, and the Sauratown Mountain window and adjacent IP (Fig. 2). Although the majority of basement is found in the WBR, we have intentionally emphasized sampling in the scattered exposures to the east-southeast to address the possible relationships between adjacent provinces and the reconstruction of the Grenville orogen as represented by these exposures. Metasedimentary rocks appear to be very sparse among the basement, with the exception of the Cloudland Gneiss in the Mars Hill terrane. Published ages are dominantly Grenvillian, with the single exception of the Carvers Gap Granulite Gneiss of the Mars Hill terrane. Sample lithologies, locations, and previous geochronological data are summarized in Table 1. Basement in the WBR occurs in four massifs: the Elk River and Watauga massifs, the Globe massif in the Grandfather Mountain window (a window into the WBR), and the enigmatic Mars Hill terrane (Bartholomew and Lewis, 1984, 1988, 1992). Samples from the Elk River massif, the Watauga massif, and the Globe massif include the Cranberry Mine Layered Gneiss, Watauga River Gneiss, and the Blowing Rock Gneiss, respectively. Samples from the Mars Hill terrane include the Carvers Gap Granulite Gneiss and the Cloudland Granulite Gneiss. Bartholomew and Lewis (1984) postulated that the Grenville age rocks of the Globe massif and its cover rocks within the Grandfather Mountain window originated in a geographic position between the Watauga and Elk River massifs prior to thrusting, and that the Watauga massif was juxtaposed against the Elk River massif during Paleozoic thrusting. The lithologically distinctive Mars Hill terrane lies structurally between rocks of the overlying EBR and the underlying Elk River massif (Bartholomew and Lewis, 1992; Raymond and Johnson, 1994), and may have a far more complex and different history than surrounding basement terranes. Basement in the EBR is mostly exposed in two internal massifs (Hatcher, 1984): the Toxaway dome (represented by samples of the Toxaway Gneiss) and the Tallulah Falls dome (represented by samples of the Wiley Gneiss and the Sutton Creek Gneiss), although other localities have been reported (e.g. Quinn and Wright, 1993). The SMW is believed to be a window through the IP into the WBR. The Grassy Creek and Pilot Mountain Gneisses are located inside this window in the Pinnacle thrust sheet and are thought to be correlative. The Forbush Gneiss has been interpreted to lie outside the window in the IP and as such would be the only basement unit so far identified in the IP (McConnell, 1990), but it may occur in windows exposing rocks of the SMW.

3. Methods

3.1. Data collection

We collected fresh, representative samples (~5 kg) of rock units from roadcuts, quarries, and outcrops (Fig. 2). Standard mineral separation techniques were used to concentrate zircon grains from 14 of these samples. Zircons from an additional five samples previously collected and separated by Fullagar and students at UNC-Chapel Hill (Monrad and Gulley, 1983) were also studied (NC-28, -49, -81; BTB3; GMA2). Approximately

Table 1
Rock units sampled

Province	Rock unit (Sample identification)	Lithology	Location (7.5-min. quad. long. and lat.)	Previous geochronology (isotopic system)	References
Western Blue Ridge (including Mars Hill terrane)					
Mars Hill terrane	Carvers Gap Granulite Gneiss (RM-1[a]RM-2[b])	Felsic to mafic, weakly foliated, hornblende-garnet-biotite granulite	Carvers gap (NC) 36 06.2N, 82 06.7W	1815±31 Ma (Rb–Sr whole-rock) ~1.8 and ~1.4 Ga (U/Pb upper intercepts)	Monrad and Gulley (1983), Bartholomew and Lewis (1984), Fullagar and Gulley (1999)
	Carvers Gap Granulite Gneiss (NC-49[a])	Massive, granoblastic, mainly felsic, granulite facies metamorphism	Carvers gap (NC) 36 06.1N, 82 07.5W		
	Carvers Gap Granulite Gneiss (NC-81[a])	Layered mafic-to-felsic, granulite facies metamorphism	Bakersville (NC) 36 06.3N, 82 07.6W		
	Cloudland Granulite Gneiss (RM-CLG[a])	Felsic, weakly banded, garnet-rich paragneiss	Bakersville (NC) 36 06.2N, 82 08.0W	807±26 Ma (Rb–Sr whole-rock)	Monrad and Gulley (1983)
	Cloudland Granulite Gneiss (NC-28[a])	Granulite facies, weakly banded paragneiss; sparse kyanite, abundant garnet	Bakersville (NC) 36 06.2N, 82 08.0W		
Elk Park massif	Cranberry–Mine Layered Gneiss (CG[a])	Massive to layered quartzofeldspathic gneiss	Elk Park (NC) 36 10.7N, 81 55.4W	1018±19 Ma (Rb–Sr whole-rock)	Fullagar and Bartholomew (1983), Bartholomew and Lewis (1984)
Watauga massif	Watauga River Gneiss (WRG[a])	Massive, coarse-grained, medium-gray to greenish-gray granodioritic gneiss	Sherwood (NC) 36 18.8N, 81 51.1W	1177±29 Ma (Rb–Sr whole-rock)	Fullagar and Bartholomew (1983), Bartholomew and Lewis (1984)
Grandfather Mountain window-Globe massif	Blowing Rock Gneiss (GMW-BR[a])	Well-foliated biotite augen gneiss containing large k-spar porphyroclasts	Boone (NC) 36 11.1N, 81 39.3W	1005±33 Ma (Rb–Sr whole-rock)	Fullagar and Odom (1973)
Eastern Blue Ridge					
Tallulah Falls dome	Wiley Gneiss (WG-CS[a])	Quartzo-feldspathic biotite bearing augen gneiss	Tiger (GA) 34 48.2N, 83 25.3W	1179±15 Ma (Rb–Sr whole-rock)	Hatcher (1984), Stieve and Sinha (1989)
	Sutton Creek gneiss (SC-RC[a])	Fine grained, equigranular, foliated, granitoid gneiss	Clarkesville NE (GA) 34 44.2N, 83 34.5W	1114 Ma (Rb–Sr whole-rock)	Hatcher (1984), Stieve and Sinha (1989)
Toxaway dome	Toxaway Gneiss (TOX-[a], TOX-1B[a], TOX-1C[c], TOX-2[c], TOX-5[c]);	Medium grained, well-foliated quartzo-feldspathic banded gneiss	Cashiers (SC) 35.0026N, 83.0429W	1197±56 Ma (Rb–Sr whole-rock)	Fullagar and Odom (1973), Hatcher (1987)
	Toxaway Gneiss (GMA2[a])	Banded granitic gneiss	Reid (SC) 35 00.4N, 82 59.6W		

Table 1 (*Continued*)

Province	Rock unit (Sample identification)	Lithology	Location (7.5-min. quad. long. and lat.)	Previous geochronology (isotopic system)	References
	Toxaway Gneiss (BTB3[a])	Banded augen gneiss	Reid (SC) 35 00.4N, 82 59.6W		
	(TXFL[a], TXFL 3[c], TXFL 4[c])	Medium grained quartzo-feldspathic augen gneiss	Reid (NC) 35 07.2N, 82 55.5W		
Sauratown Mountains window and adjacent Inner Piedmont					
	Grassy Creek gneiss (SM-GC[a])	Microcline porphyro-clasts, biotite augen gneiss	Pinnacle (NC) 36 20.9N, 80 27.2W	1173 ± 33 Ma (Rb–Sr whole-rock)	McConnell (1990)
	Pilot Mountain gneiss (SM-PM1[a], SM-PM2[c], SM-PM-E[a])	Medium grained, biotite quartzofeldspathic augen gneiss; E sample is a biotite-plag enclave cut from surrounding granite	Pilot Mountain (NC) 36 23.0N, 80 26.4W	1172 Ma ($^{207}Pb^{*}/^{206}Pb^{*}$) 1173 ± 33 Ma (Rb–Sr whole-rock)	
	Forbush gneiss (SM-F[a])	Microcline porphyro-clasts, biotite augen gneiss	Copeland (NC) 36 15.5N, 80 38.0W	1230 ± 6 Ma (U–Pb zircon upper intercept)	

[a] Chemical analysis and geochonology.
[b] Chemical analysis.
[c] Thin section only.

60 large zircon grains (~ 80–300 m) were hand picked and mounted in epoxy with fragments of a zircon standard (AS3, 1099.1 ± 0.5 Ma, Paces and Miller, 1993). Mounts were polished to the approximate centers of the grains. Our sampling was biased in favor of large grains both because of the mineral separation process, which eliminates most small grains, and because we prefer large grains that are likely to provide clearer evidence for overall history of the source, magmatic growth, and metamorphic growth. Individual zircons were imaged for internal zoning using backscattered electron detection (BSE) and cathodoluminescence (CL) (Cameca SX52 electron microprobe at the University of Tennessee, Knoxville; Hitachi S-4200 scanning electron microscope at Vanderbilt University). Mount maps and zoning images were used as guides for U–Pb analyses using the Cameca IMS 1270 high-resolution IMP at the University of California, Los Angeles. IMP techniques follow those described in Quidelleur et al. (1997). The primary beam was focused to a ~ 10–20 micron ellipse or circle. The smaller beam was used when emphasis was placed on analysis of thinner zones that were considered important for interpretation; otherwise, the larger beam was preferred because it yielded higher count rates and better analytical precision.

Whole-rock powders were used for geochemical analyses (major and trace elements and Nd and Sr isotopes) of the 14 newly collected samples, plus one additional sample from which zircons were not separated (RM-2). Several thin slabs were cut from each fresh sample (parallel to lineation and perpendicular to foliation where applicable) and powdered in an alumina ceramic shatterbox. Major and trace elements were analyzed by XRAL Activation Services, Inc. and Activation Laboratories, Inc., using X-ray fluorescence, inductively coupled plasma mass spectrometry, instrumental neutron activation analysis, and direct coupled plasma spectroscopy. Nd and Sr isotopic analyses were performed at the University of North Carolina at Chapel Hill on a multi-collector Micromass Sector 54 mass spectrometer. We include partial elemental analyses of samples NC-28, -49, and -81, from Gulley (1982) for comparison.

3.2. Data reduction

Ages were interpreted in light of zoning patterns. Concentric, euhedral, oscillatory zones without discontinuities were interpreted as representing a single stage of magmatic growth (Paterson et al., 1989; Vavra, 1990; Hanchar and Miller, 1993; Miller et al., 1992, 2000b; Roberts and Finger, 1997; Pidgeon et al., 1998). Assuming that the outermost continuous magmatic zoning sequence in zircons from a single sample were correlative and did not span a measurable interval (cf. Reid et al., 1997; Reid and Coath, 2000), we pooled analyses for all points within these zones to estimate magmatic age. Homogeneous outer zones that encircle interior magmatic cores are interpreted as metamorphic growth. Although the exact mechanism by which such zones grow remains uncertain, they undoubtedly reflect high-grade metamorphism (Hanchar and Miller, 1993; Ayers et al., 1996; Fraser et al., 1997; Roberts and Finger, 1997; Nemchin et al., 2001). As with magmatic ages, we pooled analyses from metamorphic rims. In almost all cases (see discussions of ambiguous data in the following section), pooled data were consistent with magmatic or metamorphic growth and variable subsequent Pb loss. Ages tend to cluster at an upper limit and spread downward to varying extents toward younger ages. The presence of noticeable discontinuities between ages of inherited cores, magmatic growth, and exterior metamorphic overgrowth is consistent with their treatment as separate growth events.

The majority of analyses were corrected for common lead using a ^{204}Pb correction that was very minor in most cases (92% of ^{204}Pb corrected analyses have ⩾98% radiogenic ^{206}Pb). For analyses with low ^{208}Pb/^{204}Pb and Th/U ratios, we prefer a ^{208}Pb correction, which tended to produce smaller analytical errors and less reverse discordance. However, the ^{208}Pb correction assumes concordance between the U and Th systems, and in a few cases the ^{208}Pb correction produced questionable results (e.g. grossly discordant), possibly indicating discordance between the two systems. In these cases, we deferred back to the ^{204}Pb correction.

Like all U–Pb data sets, each analysis results in three different ages ($^{206}Pb^*/^{238}U$, $^{207}Pb^*/^{235}U$, and $^{207}Pb^*/^{206}Pb^*$). The $^{207}Pb^*/^{235}U$ age we consider to be the least reliable because of the high dependence upon both common Pb correction and U–Pb calibration, and because $^{207}Pb^*/^{235}U$ ages are always intermediate between $^{206}Pb^*/^{238}U$ and $^{207}Pb^*/^{206}Pb^*$ ages. Therefore, we emphasize the $^{206}Pb^*/^{238}U$ age (high precision but calibration dependent) and $^{207}Pb^*/^{206}Pb^*$ age (generally somewhat lower precision but calibration independent) in our interpretation of ages. We evaluated the data in several ways: (1) we plotted the data on Tera-Wasserburg (T-W) concordia diagrams and computed a concordia age using ISOPLOT (Ludwig, 1991, 1998). Younger outlier analyses (presumably representing Pb loss) were removed and the age recalculated until a reasonable MSWD ($<$ 2.0) and probability of concordance (>0.25) were attained. In a few cases, reversely discordant analyses resulted in a very low calculated probability of concordance and were removed from the age regressions, although in most of these cases the $^{206}Pb^*/^{238}U$ age of the reversely discordant point was very similar to the concordia age. (2) If a satisfactory concordia age could not be attained in the manner described above due to a slight tendency toward discordance in the data, a $^{207}Pb^*/^{206}Pb^*$ weighted mean age and an MSWD were calculated. If MSWD was high (>2.0), younger outlier analyses were removed to bring the recalculated MSWD down. In one case (sample RM-1), Pb loss clearly occurred in the geologic past, and a discordia regression line was calculated using ISOPLOT. We interpret the upper intercept as the true magmatic age. (3) We analyzed the data for probability of concordance by plotting the data on concordia probability plots (CPP), which are a slight variation of standard probability plots that we have developed for use with U–Pb data (Fig. 3). We are unaware of any previous use of probability plots in this manner in the literature. Standard probability plots (summed probabilities for all analyses broken down into million year intervals, assuming Gaussian distributions of uncertainties; Deino and Potts, 1992), which use a single age (e.g. $^{206}Pb^*/^{238}U$), can produce geologically meaningless peaks when plotting discordant or reversely discordant U–Pb data. Additionally, plotting the probability of a single U–Pb age gives no preference to more concordant analyses that are more likely to represent the true age. Therefore, to calculate a probability plot using multiple age information simultaneously (e.g. $^{206}Pb^*/^{238}U$ and $^{207}Pb^*/^{206}Pb^*$), we used a bivariate normal distribution joint density function to calculate the density of each analysis at million year intervals along concordia, and summed these values for all analyses of a given sample. As with standard probability plots, we assumed that the upper limit of strong probability, usually marked by a distinct peak, represents the likely true age, with younger ages representing Pb loss. Although all individual analyses have a total volume of one under the curve of the joint density function, individual analyses do not all have the same area on the cross section produced by the intersection of this volume with concordia. Therefore, analyses with smaller analytical errors *and a higher degree of concordance* are more influential on the position of the peak of the summed curve. This method provides an advantage for U–Pb data over standard probability plots in that it considers multiple age information, and thereby degree of concordance, simultaneously. It must, however, be used with caution when evaluating data that are not concordant, and in cases of strong discordance a standard $^{207}Pb^*/^{206}Pb^*$ probability plot will likely yield more reliable information.

Reported uncertainties in text, tables, and figures are $\pm 2\sigma$ a priori (including only data point errors), but the scatter of the data in a few samples (where noted) requires reporting them at the 95% confidence level (including scatter about the mean). All calculated concordia ages include decay constant errors.

4. Results

4.1. Geochronology

Zircon zoning and U–Pb data are strikingly consistent for most of our samples. Almost all of the zircons from the samples that we investigated have magmatic interiors marked by oscillatory

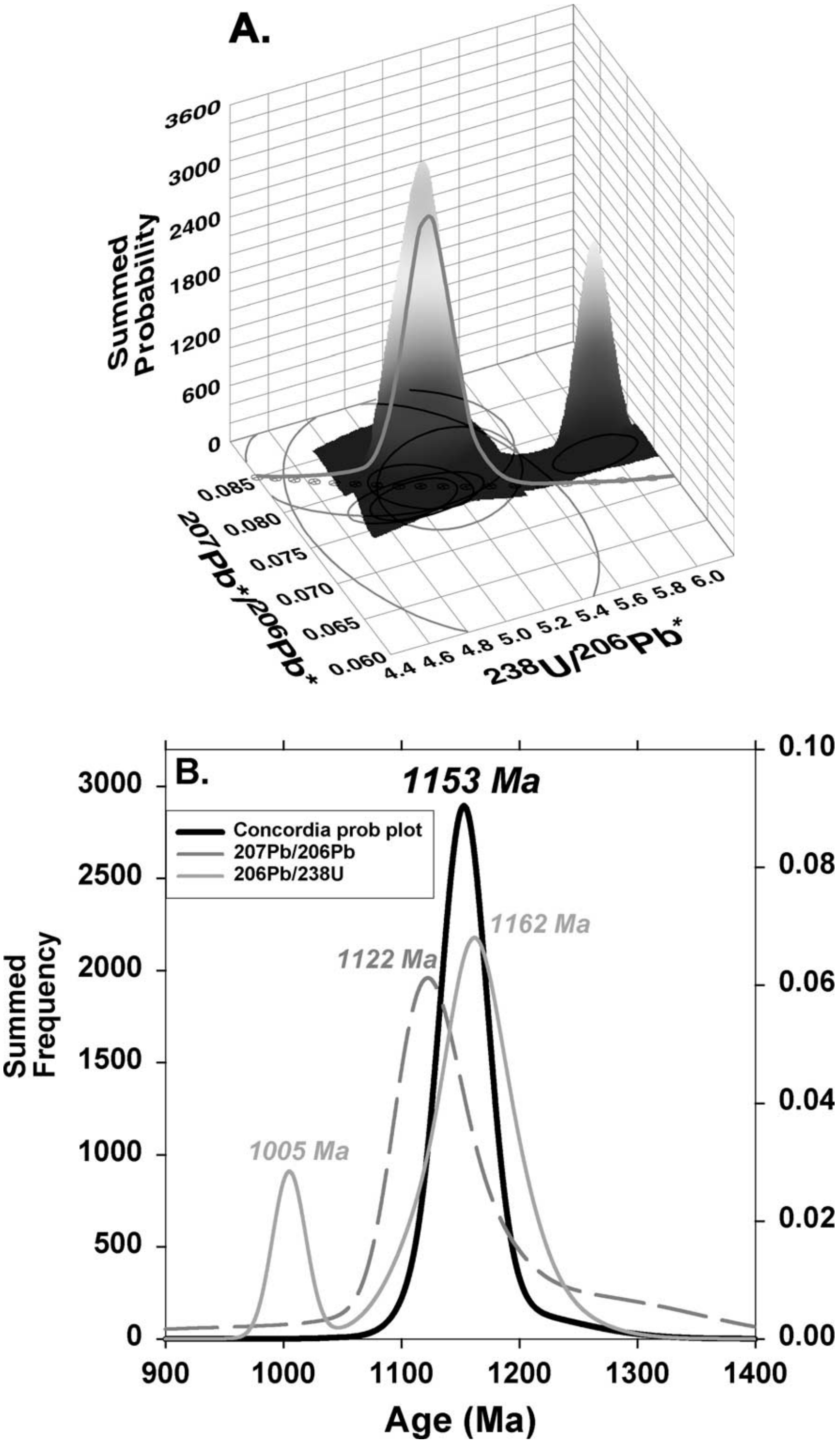
A.
Summed Probability
3600
3000
2400
1800
1200
600
0
0.085
0.080
0.075
0.070
0.065
0.060
207Pb*/206Pb*
4.4 4.6 4.8 5.0 5.2 5.4 5.6 5.8 6.0
238U/206Pb*
B.
1153 Ma
Concordia prob plot
207Pb/206Pb
206Pb/238U
1162 Ma
1122 Ma
1005 Ma
Summed Frequency
3000
2500
2000
1500
1000
500
0
0.10
0.08
0.06
0.04
0.02
0.00
900 1000 1100 1200 1300 1400
Age (Ma)

Fig. 3

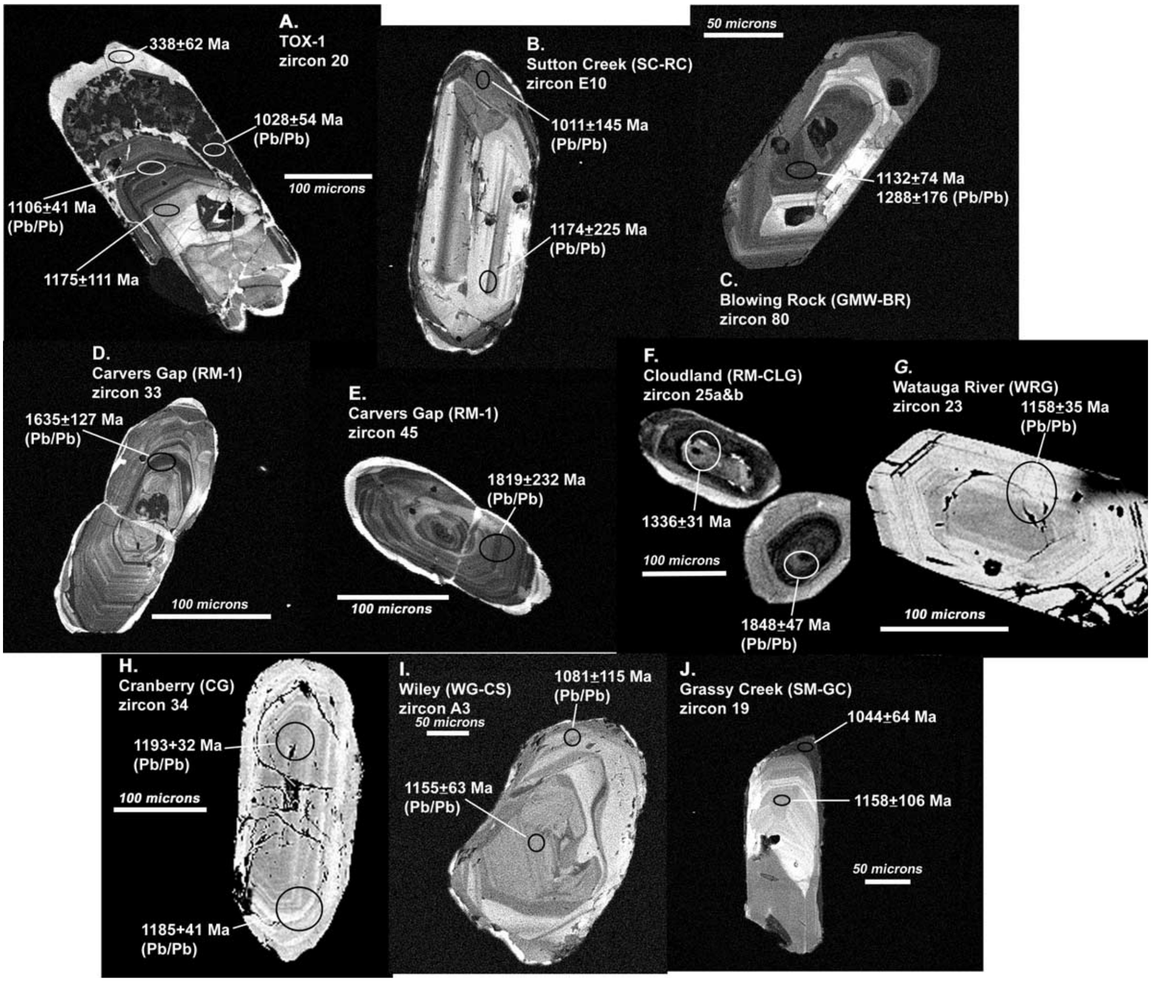

Fig. 4. Back-scattered electron and cathodoluminescence images of selected representative zircon grains, showing compositional zoning and locations of analytical spots. Ages are $^{206}Pb^*/^{238}U$ unless noted as Pb/Pb ($^{207}Pb^*/^{206}Pb^*$); errors are ± 2 sigma. Zircons typically display interior magmatic zones surrounded by secondary metamorphic rims. Zircons from some samples show an additional metamorphic rim of Paleozoic age (~ 350 Ma, see A). Inherited cores are generally absent, with the exception of the Blowing Rock Gneiss (C).

euhedral zoning, one or more identifiable homogeneous unzoned metamorphic rims, and lack inherited cores (Fig. 4). Zircon grains were typically subhedral with some rounding of the corners and edges. Exceptions to these generalizations include the Blowing Rock Gneiss and the metasedimentary Cloudland Granulite Gneiss. Zircons from the Blowing Rock Gneiss had no visible

Fig. 3. (A) Three-dimensional view of summed Gaussian density surface for 7 selected analyses of TOX-1. A single discordant point plots separately from the remaining analyses. The peak of the main curve is slightly reversely discordant at (~ 5.06, 0.0775). The intersection of the summed curve with concordia gives the CPP shown as the thick black line (also as gray line in 4B). The CPP yields the most probable peak along concordia, and is most strongly influenced by analyses that are more precise and more concordant. See text for discussion. (B) Probability plots for $^{206}Pb^*/^{238}U$ (light gray line) and $^{207}Pb^*/^{206}Pb^*$ (dashed gray line) data (vertical scale on right) and CPP (black line, vertical scale on left) for data in 4A.

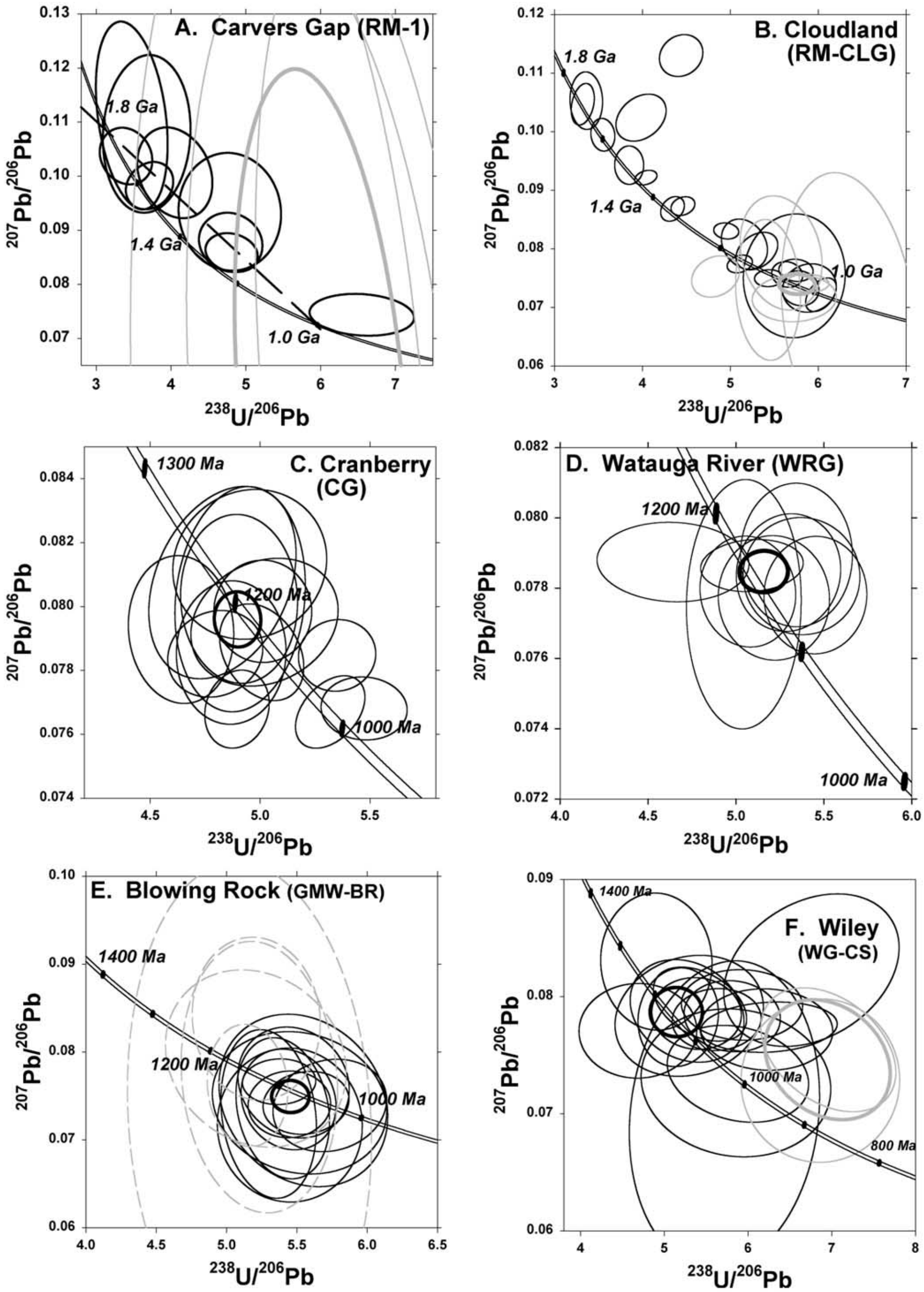

Fig. 5. Common Pb corrected analyses of selected samples plotted on Tera-Wasserburg concordia diagrams. Magmatic interiors (or detrital cores) are thin black ellipses; metamorphic rims are thin gray; inherited cores are dashed light gray. Thick black and gray lines represent calculated concordia ages. See text for discussion of preferred ages. Concordia diagrams for samples not shown are available from author(s).

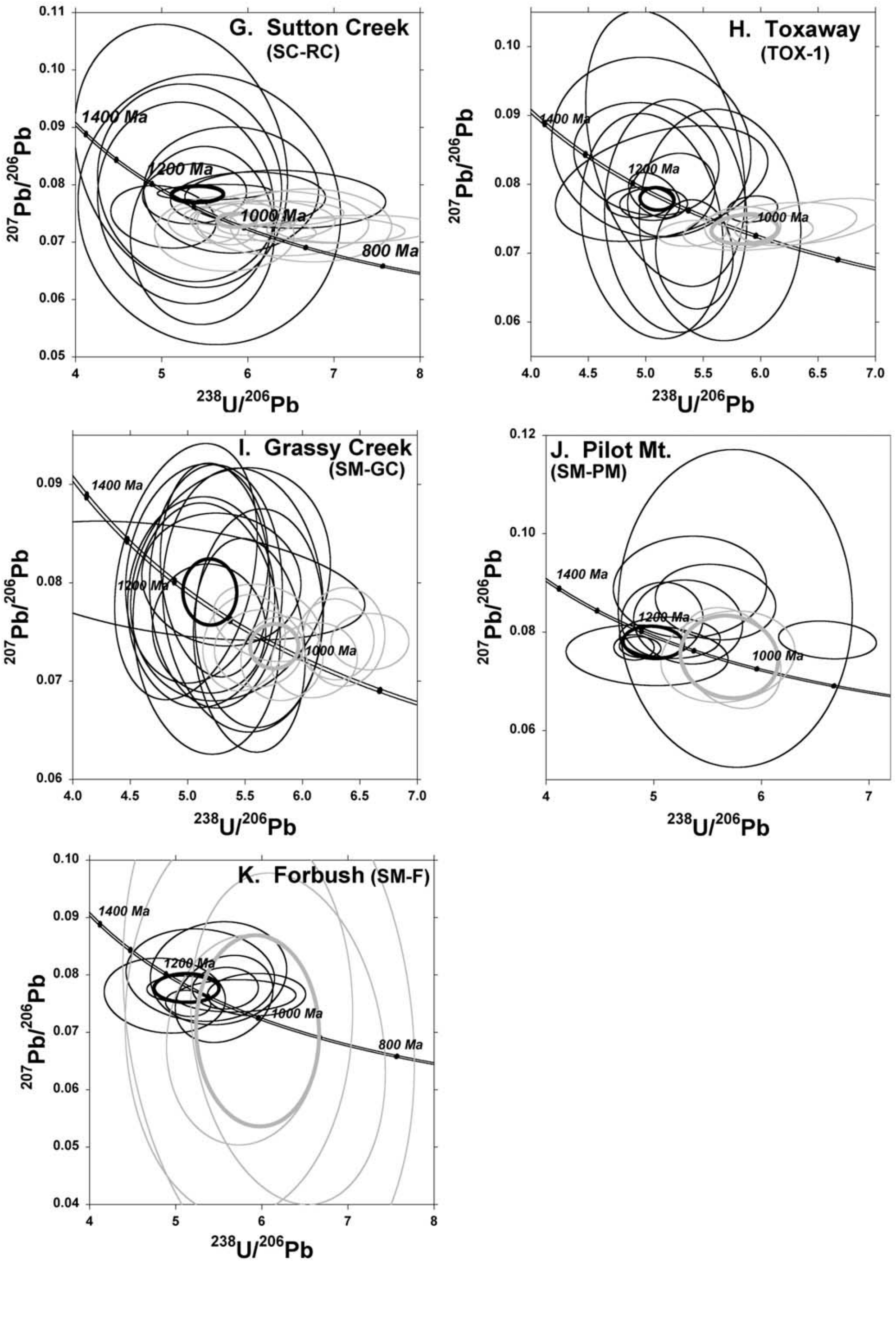

Fig. 5 *(Continued)*

Table 2
Summary of geochronological results

Sample	Preferred magmatic ages	Preferred metamorphic ages
Carvers Gap (RM-1)	1765 ± 140	1007 ± 150
Carvers Gap (NC-49)	1209 ± 22 (?)	966 ± 51 (Pb loss?)
Carvers Gap (NC-81)	> 1.6 Ga	1022 ± 40
Cloudland (RM-CLG)	Detrital cores 1.0–1.8 Ga	1035 ± 19
Cloudland (NC-28)	Detrital cores 1.0–1.3 Ga	963 ± 64 (Pb loss?)
Cranberry (CG)	1192 ± 11	N/A
Watauga River (WRG)	1158 ± 9	N/A
Blowing Rock (GMW-BR)	1081 ± 14	N/A
Wiley (WG-CS)	1158 ± 19	1056 ± 93
Sutton Creek (SC-RC)	1156 ± 23	1030 ± 19
Toxaway (TOX-1)	1151 ± 17	1027 ± 23
Toxaway (G-MA-2)	1157 ± 36	1039 ± 82
Toxaway (TXFL)	1149 ± 32	1028 ± 14
Toxaway (TOX-1B)	1039 ± 11 or 1149 ± 56 (?)	1037 ± 94
Toxaway (B-TB-3)	1141 ± 148	921 ± 45 (Pb loss?)
Grassy Creek (SM-GC)	1165 ± 54	1032 ± 20
Pilot Mt. (SM-PM1)	1165 ± 33	1043 ± 49
Pilot Mt. enclave (SM-PM-E)	1159 ± 13 (reset inherited grains?)	N/A
Forbush (SM-F)	1143 ± 33	998 ± 72

metamorphic overgrowths, were more elongate and euhedral, and contain a few apparently inherited cores. Zircons from the Cloudland Granulite Gneiss are typically highly rounded, and contain detrital cores (ultimately of magmatic origin based upon oscillatory zoning) with thick, homogeneous rims.

New U–Pb data for analyzed points are available in the journal data repository[2], and selected samples in Fig. 5 (T-W concordia diagrams) and 6 (CPPs). Age results are summarized in Table 2. Concordia and probability diagrams not shown are available from the author(s). With the exception of the Carvers Gap Granulite Gneiss, ages of magmatic interiors are Grenville age (1.0–1.2 Ga), with preferred pooled ages ranging from ~1080 to ~1190 Ma. Zoning and rim-and-core ages of individual units are discussed below.

[2] Journal data repository can be found on journal website, http:/www.elsevier.com/locate/precamres

4.1.1. Western Blue Ridge—Mars Hill terrane

Samples in the Mars Hill terrane (Carvers Gap Granulite Gneiss and Cloudland Granulite Gneiss) record the only pre-Grenville history among our samples. Among them, they show evidence for both early to mid-Proterozoic detrital cores and magmatic cores up to 1.8 Ga. All have thick, well-developed metamorphic rims.

4.1.1.1. Carvers Gap Granulite Gneiss (RM-1). Most analyses of magmatic cores in RM-1 are discordant, showing various degrees of Pb loss from minor to extreme. Eight of 9 analyses (excluding the analysis showing the largest amount of Pb loss) form a discordia line with an upper intercept of 1765 ± 140 Ma, and a lower intercept of 1007 ± 150 Ma (MSWD = 0.98, probability of fit = 0.44; (Fig. 5A). The analysis that shows the largest amount of Pb loss probably was affected in both late Ottawan time and in a subsequent event, possibly in the Paleozoic (Taconic orogeny?, Monrad and Gulley, 1983) or in Mesozoic to recent time. We interpret the upper intercept as the age of magmatic growth, and the lower intercept as the time of significant Pb loss in the zircon cores. While the errors are large, the data confirm that the Rb–Sr whole-rock age of 1815 ± 31 Ma (Monrad and Gulley, 1983) reflects the age of igneous crystallization, and not a metamorphic or mixed age. The lower intercept of the discordia formed by the magmatic cores is indistinguishable from the concordia age of the metamorphic rim analyses (998 ± 120, MSWD = 0.59, probability = 0.44). The CPP of the rim analyses reveals a peak at 983 Ma (Fig. 6A). The similarity in the ages of metamorphic rim growth and of the lower intercept of the magmatic cores suggests that around ~1.0 Ga the Carvers Gap Granulite Gneiss underwent Pb loss in the zircon cores while rim growth was occurring during metamorphism.

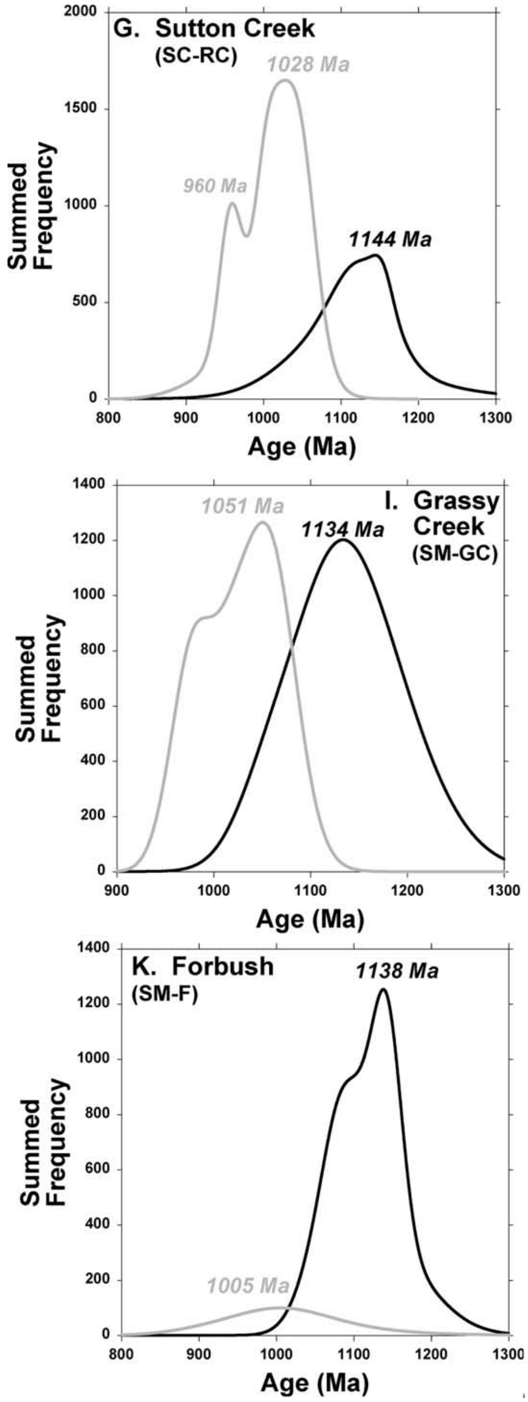

Fig. 6. Selected CPPs calculated using $^{238}U/^{206}Pb^*$ and $^{207}Pb^*/^{206}Pb^*$ data simultaneously. Gaussian probability densities (calculated using $^{238}U/^{206}Pb^*$ ratio and standard error, $^{207}Pb^*/^{206}Pb^*$ ratio and error, and the error correlation coefficient) for all analyses are summed along the concordia curve at million year intervals and plotted against age. Black curves for magmatic zones; gray for metamorphic rims. A and F use two vertical scales—left scale is for metamorphic rims and right is for magmatic interiors. See text for discussion; plots not shown are available from author(s). Samples as in Fig. 5.

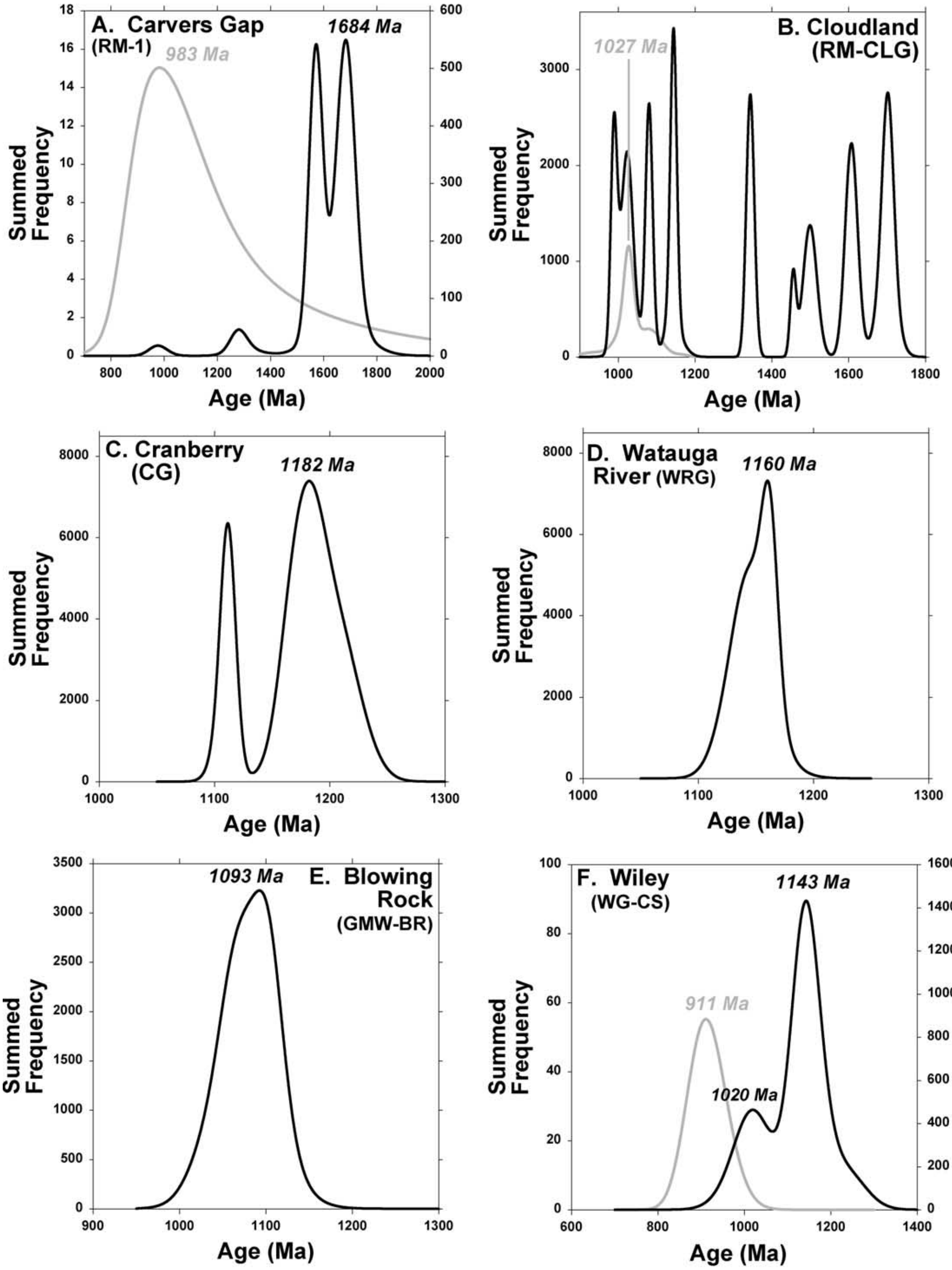
A. Carvers Gap
(RM-1)
983 Ma
1684 Ma
B. Cloudland
(RM-CLG)
1027 Ma
C. Cranberry
(CG)
1182 Ma
D. Watauga
River (WRG)
1160 Ma
E. Blowing
Rock
(GMW-BR)
1093 Ma
F. Wiley
(WG-CS)
911 Ma
1020 Ma
1143 Ma
Summed
Frequency
Age (Ma)

Fig. 6

4.1.1.2. Carvers Gap Granulite Gneiss (NC-49). Analyses of magmatic interiors yield a spread of age, but three of seven yield a concordia age of 1209 ± 22 Ma (MSWD = 1.6, probability = 0.21). The CPP yields a peak at 1225 Ma. This age is different from our other samples of the Carvers Gap Granulite Gneiss, and may indicate either a separate, later magmatic episode or extensive Pb loss. Alternatively, it could suggest that these zircons are detrital and that this sample actually represents metasedimentary rock of the Cloudland Granulite Gneiss. Three analyses of metamorphic rims are all late Ottawan age, one being slightly younger than the other two. The two older points yield a concordia age of 966 ± 51 Ma (MSWD = 0.083, probability = 0.77), similar to ages obtained in other samples. The CPP yields a peak at a younger age of 903 Ma, but is strongly influenced by the younger, more precise data point.

4.1.1.3. Carvers Gap Granulite Gneiss (NC-81). Analyses of magmatic interiors yield 4 approximately concordant ages of 1.1–1.2 Ga, two discordant points with $^{207}Pb/^{206}Pb$ ages near 1.4 Ga, and a single nearly concordant point at 1.6 Ga. These data may indicate a magmatic age ⩾1.6 Ga with variable Pb loss, or that these are detrital zircons of variable age in a metasedimentary gneiss (such as Cloudland). Three of 6 analyses of metamorphic rims yield a concordia age of 1022 ± 40 Ma (MSWD = 1.06, probability = 0.30).

4.1.1.4. Cloudland Granulite Gneiss. The Cloudland Granulite Gneiss is the only metasedimentary unit investigated. Zircons are typically very round with oscillatory-zoned cores and thick homogeneous rims. The cores in RM-CLG range in apparent age from ~1.0–1.8 Ga, with over half Grenville (~1.0–1.2 Ga; Fig. 5B). Nine analyses yield $^{207}Pb^*/^{206}Pb^*$ ages between ~1.35 Ga and 1.85 Ga. Several of these are strongly discordant, suggesting that Pb loss may skew the apparent ages, but 5 concordant analyses span most of this range and likely indicate great diversity in true detrital ages. Five of 6 analyses of metamorphic rims yield a concordia age of 1035 ± 19 Ma (MSWD = 0.19, probability = 0.66), identical to the age obtained in most of our samples. The CPP peak is similar at 1027 Ma (Fig. 6B). The high metamorphic grade of the rocks in this thrust sheet and the universal presence of large rims in the zircons indicates that the zircons recrystallized in-situ and the age of the zircon rims represents a minimum age of deposition. This age is considerably older than the Rb–Sr age of 807 ± 26 Ma (Monrad and Gulley, 1983). The youngest detrital cores represent an upper limit of deposition, but this age is uncertain due to the abundant Pb loss. Abundant Grenville age cores may indicate that the Cloudland Granulite Gneiss was deposited shortly before metamorphism at ~1.0 Ga. However, these ages may indicate near total Pb loss from these cores, and the true upper limit on deposition may fall within the older concordant ages (~1.4 Ga?).

4.1.1.5. Cloudland Granulite Gneiss (NC-28). Analyses of detrital cores yield variable $^{206}Pb^*/^{238}U$ ages, all with large uncertainties, ranging in age from ~0.8 to 1.4 Ga. The CPP yields peaks at 1283 and 944 Ma. The ages younger than 1.0 Ga almost certainly represent Pb loss. We are uncertain whether the other apparent ages are real, or whether these analyses represent older zircon also affected by Pb loss that is so prevalent in all samples from the Roan Mountain area. Three analyses of metamorphic rims yield a concordia age of 963 ± 64 (MSWD = 0.00069, probability = 0.98), similar to the 960 Ma peak on the CPP. The age is younger than the age of metamorphism obtained much more precisely in our other samples, but the errors are large and overlap the preferred metamorphic age.

4.1.2. Western Blue Ridge—Elk River massif

4.1.2.1. Cranberry-Mine Layered Gneiss. Nine of 15 analyses of magmatic zones yield a concordia age of 1192 ± 11 Ma (MSWD = 0.97, probability = 0.33; (Fig. 5C). Four analyses are significantly younger and document Pb loss. Two analyses are reversely discordant and were not used in the age regression, but have $^{206}Pb^*/^{238}U$ ages similar to the concordia age. The CPP yields a slightly younger peak at 1182, but the curve is asymmetric toward older ages (Fig. 6C). No metamorphic rims (observed as very thin overgrowths in BSE and CL images) were analyzed.

4.1.3. *Western Blue Ridge—Watauga massif*

4.1.3.1. Watauga River Gneiss. Analyses of Watauga River Gneiss magmatic zones range from concordant to slightly discordant with one analysis showing negative U/Pb ratios and ages, but a $^{206}Pb^{*}/^{207}Pb^{*}$ age that is consistent with other values for this sample. All 10 analyses yield a $^{207}Pb^{*}/^{206}Pb^{*}$ pooled age of 1158 ± 9 (MSWD = 0.5; Fig. 5D) that we regard as the best estimate of true age, and the data yield a sharp, distinct peak on the CPP at 1160 Ma (Fig. 6D). No metamorphic rims (observed as very thin overgrowths in BSE and CL images) were analyzed.

4.1.4. *Grandfather Mountain Window—Globe massif*

4.1.4.1. Blowing Rock Gneiss. The Blowing Rock Gneiss is the only sample that shows evidence for inherited zircon cores. The cores are rounded, with oscillatory zoning indicative of magmatic growth (Fig. 5E). The 5 core age analyses overlap the analyses of magmatic zones, but their means are older at ~1140 Ma, similar to the ages of many of our other samples. The 11 analyses of magmatic zones yield a concordia age of 1081 ± 14 Ma (MSWD = 1.06, probability = 0.30). The CPP yields an older peak at 1093 Ma, but the curve is asymmetric toward younger ages (Fig. 6E), and the midpoint halfway up the curve yields an age of 1082 Ma, identical to the concordia age. If the cores are included in the age regression, the concordia age is 1092 ± 13 (MSWD = 1.5, probability = 0.22). Metamorphic overgrowths appear to be absent in CL and BSE images.

4.1.5. *Eastern Blue Ridge—Tallulah Falls dome*

4.1.5.1. Wiley Gneiss. Nine of 16 analyses of magmatic zones yield a concordia age of 1141 ± 27 (at 95% confidence level), but with a very low probability of 0.003 (Fig. 5F) due to overall general discordance in the data. The CPP yields a very similar peak at 1143 Ma (Fig. 6F), and is likely influenced by analyses that represent Pb loss. However, six of 16 analyses yield a concordia age of 1156 ± 27 Ma with a reasonable probability (MSWD = 0.47, probability = 0.49) and 13 of 16 analyses yield an indistinguishable $^{207}Pb^{*}/^{206}Pb^{*}$ age of 1158 ± 19 Ma (MSWD = 0.85). We regard this age as the best estimate of true crystallization age. The two metamorphic rims analyzed are both relatively discordant, but their $^{207}Pb^{*}/^{206}Pb^{*}$ ages (1056 ± 93 Ma, MSWD = 0.54) are in general agreement with the ages of Ottawan metamorphic rims determined much more precisely in other samples.

4.1.5.2. Sutton Creek Gneiss. Eleven of 12 analyses of magmatic zones yield a concordia age of 1136 ± 20 with a very low probability of concordance (0.005) due to general discordance in the data (Fig. 5G). The CPP yields a peak at 1144 Ma (Fig. 6G), likely younger than the true age due to the discordance of the data. All 12 analyses yield a $^{207}Pb^{*}/^{206}Pb^{*}$ age of 1156 ± 23 Ma (MSWD = 0.48), which we regard as the best estimate of true age. Twelve analyses of metamorphic rims also display a range of discordance, but $^{207}Pb^{*}/^{206}Pb^{*}$ ages are consistent. Ten of 12 analyses yield a pooled age of 1030 ± 19 Ma (MSWD = 1.3), and the CPP yields a peak with a similar age of 1028 Ma.

4.1.6. *Eastern Blue Ridge—Toxaway dome*

Five samples representing variations in lithology from the Toxaway Gneiss have been analyzed. All are granitic gneisses; TOX-1 and GMA2 are strongly banded, TXFL is a weakly banded augen gneiss, TOX-1B is a more biotite-rich banded gneiss, and BTB3 is a banded augen gneiss.

4.1.6.1. TOX-1. Eleven of 13 analyses of magmatic zones yield a concordia age of 1151 ± 17 Ma (MSWD = 0.44, probability = 0.51; Fig. 5H). The sharp, distinct peak at 1153 Ma on the CPP agrees well with the concordia age (Fig. 6H). The 6 analyses of Ottawan metamorphic rims range from concordant to slightly discordant and yield a $^{207}Pb^{*}/^{206}Pb^{*}$ age of 1027 ± 23 Ma (MSWD =

0.3). The CPP shows a slightly younger peak at 1012 Ma.

4.1.6.2. GMA2. Analyses of magmatic zones of GMA2 vary in $^{206}Pb^*/^{238}U$ ages, and older analyses are somewhat reversely discordant. Three of 7 analyses yield a concordia age of 1157 ± 36 (at 95% conf., MSWD = 4.6, probability = 0.033); the high MSWD and low probability of concordance are due to the reversely discordant nature of the data. The CPP yields a sharp, distinct peak at 1152 Ma, consistent with other samples of the Toxaway Gneiss. Three analyses of metamorphic rims also range in $^{206}Pb^*/^{238}U$ ages, but yield a $^{207}Pb^*/^{206}Pb^*$ age of 1039 ± 82 (MSWD = 0.45), similar to metamorphic ages found in other samples. A single reversely discordant point yields a peak at 1068 Ma on the CPP, but in all likelihood this age is meaningless.

4.1.6.3. TXFL. Nine of 16 analyses of magmatic zones yield a concordia age of 1142 ± 28 Ma (MSWD = 0.94, probability = 0.33), but 11 of the 16 analyses yield a slightly older pooled $^{207}Pb^*/^{206}Pb^*$ age of 1149 ± 32 Ma (MSWD = 0.72). The CPP yields a younger peak at 1135 Ma. The older age (1149) is more in agreement with the age obtained on other samples of the Toxaway Gneiss, and we prefer it as the best approximation of the true age. Grenville metamorphic rims show variable Pb loss similar to the TOX-1 sample and are mostly discordant. Eleven of 12 analyses yield a pooled $^{207}Pb^*/^{206}Pb^*$ age of 1028 ± 14 Ma (MSWD = 1.86), identical to the Ottawan metamorphic age recorded in other samples. The CPP yields a much younger peak at 929 Ma due almost entirely to a single younger, but more concordant, analysis. In this case of strong discordance, a standard probability plot using $^{207}Pb^*/^{206}Pb^*$ data would yield a peak closer to the true age.

4.1.6.4. TOX-1B. The analyses of the more biotite rich sample of the Toxaway Gneiss are the most difficult to interpret. Magmatic interiors range in age from younger, normally discordant points to older, reversely discordant points. There is considerable spread in the $^{206}Pb^*/^{238}U$ data, but the $^{207}Pb^*/^{206}Pb^*$ data cluster tightly and yield a pooled age of 1039 ± 11 (MSWD = 1.66). This age is significantly younger (120 myr) than the other samples of Toxaway Gneiss, but is strikingly similar to the age of Ottawan metamorphism found in nearly all of our samples. It is possible that this sample represents a later dike, but it is geochemically and petrographically similar (see following sections) to other samples of the Toxaway Gneiss, and field evidence seems more consistent with a cogenetic origin. The oldest $^{206}Pb^*/^{238}U$ analysis is 1149 ± 56, similar to the preferred ages of the other samples. We cannot rule out the possibility that the true age of this sample is identical to the other two from the Toxaway Gneiss, and that the data represent error in ^{207}Pb and U calibration, and variable Pb loss. The CPP yields three peaks at 1021, 1045, and 1079 Ma; we do not consider any of these reliable. Alternatively, the 1039 Ma $^{207}Pb^*/^{206}Pb^*$ age may represent resetting during Ottawan time. Metamorphic rims of TOX-1B display large errors and significant spread in the $^{206}Pb^*/^{238}U$ ages. The 5 analyses yield a $^{207}Pb^*/^{206}Pb^*$ age of 1037 ± 94 Ma (MSWD = 1.17). The errors are large, but the age is consistent with metamorphic ages obtained in other samples. The similarity of the $^{207}Pb^*/^{206}Pb^*$ ages between magmatic interiors and metamorphic rims suggests that both ages may reflect metamorphic overprinting. The CPP yields two peaks at 905 and 1038 Ma, the older of which may be a reasonable estimate of the age of metamorphism.

4.1.6.5. BTB3. Analyses of magmatic zones of BTB3 show a large spread in $^{206}Pb^*/^{238}U$. A single analysis yields a $^{206}Pb^*/^{238}U$ age of 1196 ± 28 and a $^{207}Pb^*/^{206}Pb^*$ age of 1141 ± 148 Ma. The CPP yields distinct peak at 1195 Ma. The age, especially $^{207}Pb^*/^{206}Pb^*$, is similar to other pooled ages obtained on other samples of the Toxaway Gneiss. Two analyses of metamorphic rims have large errors and yield a concordia age of 921 ± 45 Ma (MSWD = 0.87, probability = 0.35). The CPP also yields a peak at 921 Ma. This age is younger than the age of Ottawan metamorphism recorded much more precisely in our other samples, but most likely represents Pb loss.

4.1.6.6. Paleozoic metamorphic ages. The Toxaway Gneiss zircons show two distinct rims in CL and BSE images. The outermost rims are typically very thin and low in U concentration, making them difficult to date precisely. Four analyses have been obtained with $^{206}Pb^*/^{238}U$ ages ~350 Ma (late Acadian), but the errors are large. Another 4 discordant analyses appear to fall upon a line between the Paleozoic and Grenville ages of rim growth, and are in all likelihood mixed ages resulting from spots that overlap zones.

4.1.7. Sauratown mountains window and adjacent Inner Piedmont

4.1.7.1. Grassy Creek gneiss. Eleven of 13 analyses of magmatic interiors yield a concordia age of 1143 ± 28 (MSWD = 1.5, probability = 0.23; Fig. 5I), and the CPP yields a peak at 1134 Ma (Fig. 6I). However, the ages show a slight degree of discordance and the $^{207}Pb^*/^{206}Pb^*$ data of all 13 points yield an age of 1165 ± 54 Ma (MSWD = 0.42). Though the error is much larger, this age is essentially identical to that obtained on the Pilot Mountain Gneiss (see below), thought to be correlative with the Grassy Creek gneiss. Metamorphic rim analyses vary from concordant or nearly so to normally discordant. Five of 8 analyses yield a concordia age of 1032 ± 20 Ma (MSWD = 0.025, probability = 0.87), and all 8 analyses yield a pooled $^{207}Pb^*/^{206}Pb^*$ age of 1037 ± 31 Ma (MSWD = 0.56), similar to other samples. The CPP exhibits a slightly older peak at 1051 Ma.

4.1.7.2. Pilot Mountain Gneiss. Seven of 10 analyses of magmatic interiors of Pilot Mountain gneiss zircons yield a concordia age of 1165 ± 33 (at 95% confidence level, MSWD = 2.3, probability = 0.13; Fig. 5J). The high degree of scatter in the data is due largely to two relatively precise, reversely discordant analyses (obtained on the same grain), one of which was removed for the concordia age calculation. The CPP yields a distinct peak at 1158 Ma (Fig. 6J). The 2 analyses of metamorphic rims are concordant and yield a concordia age of 1043 ± 49 Ma (MSWD = 0.105, probability = 0.75), and the CPP yields a peak at 1043 Ma. The ~1040 Ma age is slightly older than, but still consistent with, ages of Ottawan metamorphism recorded in other samples.

4.1.7.3. Pilot Mountain Gneiss enclave. Although all are interpreted as inherited grains, 3 of 7 analyses yield a concordia age of 1159 ± 13 Ma (MSWD = 0.047, probability = 0.83). This age is slightly younger but more precise than the age of the host rock (SM-PM). None of the analyses of these inherited grains yielded older pre-Grenville ages, and were likely reset during magmatism.

4.1.7.4. Forbush Gneiss. Eight of 9 analyses yield a concordia age of 1114 ± 19 Ma (MSWD = 0.27, probability = 0.60; Fig. 5K). The CPP, on the other hand, yields a distinct peak at 1138 Ma, with a younger "shoulder" near ~1094 Ma (Fig. 6K). The main peak is heavily controlled by a single older concordant analysis, which may be a better representation of the true age than younger, less concordant analyses. The 4 oldest analyses yield a concordia age of 1143 ± 33 (MSWD = 0.084, probability = 0.77), similar to the peak on the CPP. We prefer the older age, but cannot rule out the younger as implausible. Analyses of metamorphic rims have large errors and yield a concordia age of 998 ± 72 Ma (MSWD = 0.17, probability = 0.68). The CPP yields a low, broad curve, as expected from the large analytical errors, with a peak at 1005 Ma. This age is ~30 myr younger than the ages obtained for metamorphism from the other samples from the EBR and SMW, but still likely represents the same metamorphic event given the size of the errors.

4.2. Major and trace element geochemistry

The granitic basement samples we investigated range in SiO_2 content from 59 to 76 wt.% (Table 3). The Grenville age samples, with the exception of the Blowing Rock Gneiss (59 wt.%), range from 63–72 wt.%. They are strongly but variably enriched in LIL and rare earth elements (REE; Fig. 7) and, except for the Grassy Creek gneiss sample, have negative Eu anomalies. One sample from the Toxaway Gneiss (TOX-1B, biotite-rich gneiss) is strongly depleted in heavy REE, though

Table 3
Major and Trace Element Geochemistry

	Carvers Gap (RM-1)	(RM-2)	(NC-49)[a]	(NC-81)[a]	Cloudland (RM-CLG)	(NC-28b)[a]	Cranberry (CG)	Watauga River (WRG)	Blowing Rock (GMW-BR)
SiO_2, wt%	75.79	47.40	72.76	65.94	68.48	61.86	70.40	64.45	59.39
Al_2O_3	12.82	14.89	13.64	15.29	14.76	17.08	14.42	16.88	14.95
Fe_2O_3[b]	2.81	15.12	2.78	9.21	6.05	12.76	3.04	3.97	7.28
MgO	0.61	6.85	0.7	3.38	1.73	1.94	0.86	0.62	1.80
CaO	2.85	9.69	2.39	5.44	3.13	1.45	1.78	2.03	3.99
Na_2O	2.96	2.73	3.21	3.11	2.91	2.36	3.87	4.67	3.38
K_2O	2.15	0.91	4.5	0.72	0.61	6.55	4.17	3.92	3.71
TiO_2	0.266	2.494	0.26	0.57	0.804	0.7	0.399	0.583	1.501
MnO	0.059	0.201	0.03	0.1	0.111	0.1	0.050	0.039	0.104
P_2O_5	0.06	0.25	0.11	0.14	0.03	0.05	0.14	0.22	0.55
LOI	0.12	−0.09	–	–	0.10	–	1.02	2.96	2.03
total	100.49	100.44	99.13	98.84	98.72	98.15	100.15	100.35	98.67
Rb, ppm	40	14	90	17	8	177	176	156	124
Sr	255	309	380	394	242	477	229	217	456
Ba	849	234	–	–	185	–	889	651	1807
Th	0.44	1.61	–	–	4.44	–	49.1	29.1	17.1
U	0.10	0.43	–	–	0.43	–	6.79	6.87	4.19
Zr	106	146	201	112	746	410	177	289	791
Hf	2.6	3.8	–	–	21.7	–	5.1	7.8	17.4
Ta	ND[c]	0.92	–	–	0.56	–	0.90	6.82	1.6
Y	10	30	13	17	90	106	18	101	51
Nb	3.6	8.3	–	–	12.7	–	16.3	28.9	20.0
La	30.4	13.9	–	–	73.7	–	80.9	49.0	114
Ce	53.1	32.5	–	–	140	–	163	97.4	238
Pr	5.56	4.36	–	–	14.4	–	18.0	11.7	29.5
Nd	20.0	20.6	–	–	51.4	–	67.7	47.4	119
Sm	3.16	5.01	–	–	8.41	–	10.3	12.0	20.8
Eu	0.913	1.71	–	–	2.08	–	1.16	1.87	3.96
Gd	2.57	5.36	–	–	10.6	–	6.98	14.6	16.5
Tb	0.31	0.92	–	–	2.08	–	0.71	2.71	2.07
Dy	1.70	5.58	–	–	13.4	–	3.44	14.9	10.2
Ho	0.34	1.08	–	–	2.96	–	0.58	3.36	1.82
Er	1.06	2.94	–	–	8.80	–	1.34	10.4	5.01
Tm	0.170	0.437	–	–	1.39	–	0.201	1.80	0.672
Yb	1.09	2.66	–	–	8.52	–	1.16	11.9	3.99
Lu	0.174	0.397	–	–	1.33	–	0.142	1.85	0.505

Table 3 *(Continued)*

	Wiley	Sutton Creek	Toxaway			Grassy Creek	Pilot Mt.		Forbush
	(WG-CS)	(SC-RC)	(TOX-1)	(TXFL)	(TOX-1B)	(SM-GC)	(SM-PM)	(SM-PM-E)	(SM-F)
SiO_2, wt%	70.1	68.6	72.3	70.3	71.92	65.66	63.39	49.95	66.15
Al_2O_3	13.6	14.9	13.8	14.3	14.20	15.76	16.41	19.26	15.79
Fe_2O_3[b]	3.4	3.41	2.82	2.85	2.58	5.19	5.58	9.69	4.74
MgO	0.74	0.75	0.45	0.5	0.50	0.28	1.44	2.83	1.24
CaO	1.71	1.55	1.6	2.57	1.68	2.26	3.48	5.39	2.89
Na_2O	2.27	3.12	3.16	3.63	3.17	3.75	4.31	4.63	4.09
K_2O	5.73	5.03	5.1	3.99	5.26	5.62	3.60	3.67	3.31
TiO_2	0.453	0.598	0.379	0.344	0.339	0.508	0.794	1.252	0.669
MnO	0.04	0.04	0.05	0.05	0.033	0.098	0.095	0.154	0.074
P_2O_5	0.15	0.19	0.09	0.09	0.10	0.11	0.31	0.48	0.24
LOI	0.9	1.8	0.25	1.35	0.44	0.38	0.81	1.42	0.60
total	99.4	100.3	100.2	100.2	100.22	99.62	100.23	98.73	99.78
Rb, ppm	141	240	242	130	205	89	95	135	52
Sr	119	206	172	218	195	197	382	512	362
Ba	1250	1420	1180	999	901	1825	1474	763	1450
Th	22.2	62	14.5	9	96.13	2.62	0.88	2.07	0.36
U	2.1	2	1.7	0.9	2.06	0.91	0.83	0.87	0.42
Zr	297	534	295	232	329	902	391	308	338
Hf	7	14	8	7	10.1	20.1	9.5	7.0	8.0
Ta	0.7	1.6	0.7	1	0.19	0.9	0.6	1.4	0.3
Y	81	32	40	26	15	49	40	116	24
Nb	6	27	14	9	9.1	15.4	12.4	26.4	8.9
La	49	170	59.9	40.8	165.12	33.8	36.6	62.2	35.8
Ce	109	317	133	86.1	325.98	76.6	80.3	163	70.1
Pr	12.2	34	14.2	9.3	34.54	10.7	10.6	23.1	8.81
Nd	56.4	140	63.5	42.4	116.04	50.4	46.7	104	38.2
Sm	11.4	20.2	11.8	7.8	17.55	11.8	10.0	22.9	7.74
Eu	1.49	2.22	1.94	1.6	1.749	4.17	2.31	2.97	2.10
Gd	12	15	10.3	7	9.66	10.8	9.07	20.4	6.95
Tb	1.6	1.2	1.2	0.8	0.95	1.71	1.41	3.29	0.94
Dy	13.9	7.7	7.9	5.5	4.06	9.55	7.55	18.5	4.78
Ho	2.64	1.09	1.32	0.9	0.52	1.92	1.47	3.83	0.92
Er	9.4	3.5	4.4	3	0.95	5.53	4.14	10.7	2.39
Tm	1.1	0.4	0.5	0.4	0.110	0.791	0.571	1.62	0.315
Yb	8.2	2.7	3.9	2.9	0.50	5.17	3.48	9.62	1.81
Lu	1.02	0.34	0.48	0.39	0.049	0.819	0.474	1.27	0.224

[a] From Gulley (1981).
[b] Total Fe as Fe_2O_3.
[c] ND, not detected at limit of 0.1 ppm.

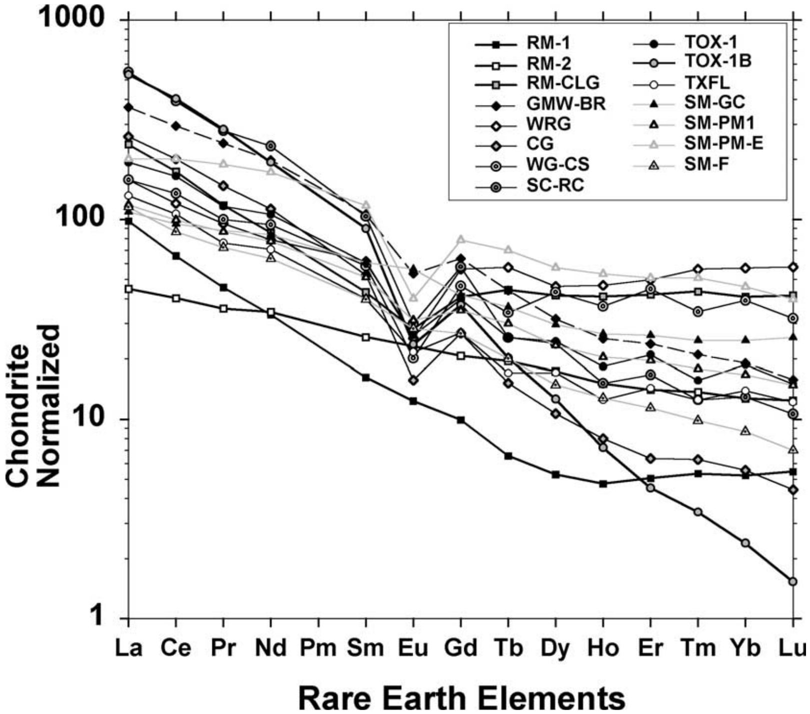

Fig. 7. Chondrite normalized REEs.

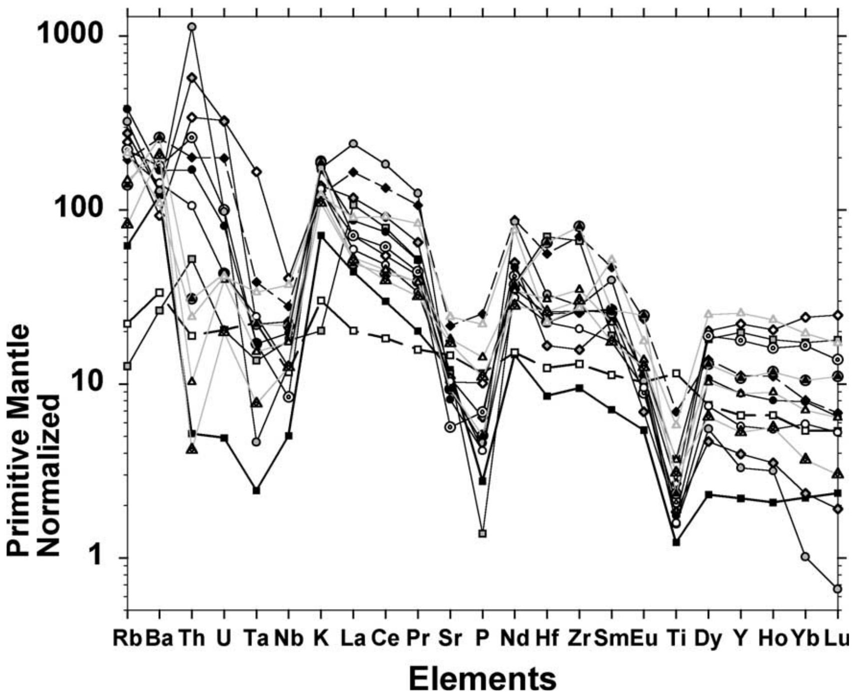

Fig. 8. Selected primitive mantle-normalized elements after Sun and McDonough (1989). Symbols as in Fig. 7.

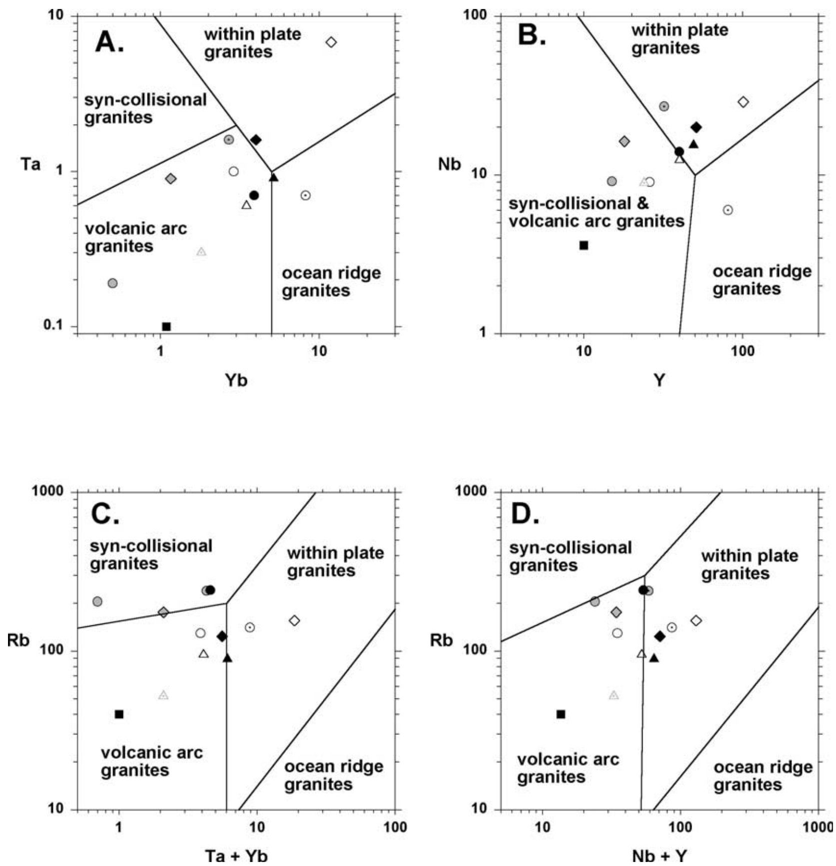

Fig. 9. Tectonic discrimination diagrams after Pearce et al. (1984). Samples plot largely as volcanic arc granites, but straddle the fields of within plate and syn-orogenic granites. (A) Ta vs. Yb; (B) Nb vs. Y; (C) Rb vs. Yb+Ta; (D) Rb vs. Nb+Y. Symbols as in Fig. 7.

it displays a pattern similar to the other samples in the light to middle REE. All samples show relative depletion in high field strength elements compared to LIL on primitive mantle-normalized plots (Fig. 8; Sun and McDonough, 1989), and plot on tectonic discrimination diagrams (Fig. 9; Pearce et al., 1984) in a range that straddles the boundaries between volcanic-arc granites, within plate granites, and syn-collisional granites, though most fall within the volcanic-arc granites field. The ~ 1.8 Ga Carvers Gap Granulite Gneiss (RM-1) differs from the Grenville-age samples in being more siliceous (76 wt.%) but much poorer in K_2O, REE, and LIL trace elements, and lacking an Eu anomaly. An additional sample of Carvers Gap Granulite Gneiss (RM-2) was thought to be a more mafic variety of RM-1 and was not dated. Geochemistry and isotopic ratios (see following section), however, clearly show this sample to be a distinct lithology. In addition to its much lower silica content (47 wt.%), it is less enriched in LREE but more enriched in middle to heavy REE than sample RM-1. The sample of Cloudland Granulite Gneiss (RM-CLG) is moderately siliceous (68 wt.%), strongly peraluminous, poor in K_2O, and very rich in Zr, presumably reflecting a "dirty" sandstone protolith.

4.3. Isotopic geochemistry

Initial ε_{Nd} values calculated for the granitoids are surprisingly similar, ranging from −0.7 to

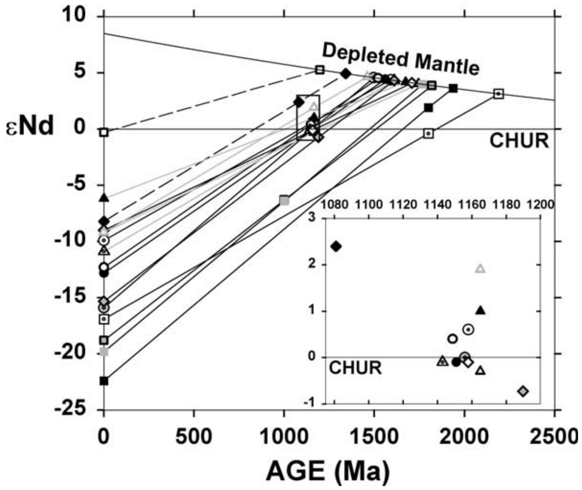

Fig. 10. ε_{Nd} vs. Time. Samples plotted at modern, initial, and T_{DM} values. Inset shows Grenville age samples. Depleted mantle curve after DePaolo (1981). Symbols as in Fig. 7.

+1.0, with the exceptions of the older Carvers Gap Granulite Gneiss (+1.9 at 1.8 Ga) and younger Blowing Rock Gneiss (+2.4 at 1081 Ma; Fig. 10Table 4). Depleted mantle model ages (T_{DM}, DePaolo, 1981) range from ~1.2 to 2.1 Ga, with most granites in the range ~1.5–1.7. The Mars Hill terrane rocks had much lower ε_{Nd} values during the Grenville (−7.6 and −5) than the Grenville age samples, and older T_{DM} ages (~1.8–2.2). The mafic sample (RM-2) from Carvers Gap (not dated by U–Pb) is again clearly a separate lithology from sample RM-1, with a much higher ε_{Nd} value during the Grenville (+4.4) and a T_{DM} age of 1198 Ma.

Calculated initial $^{87}Sr/^{86}Sr$ ratios of Toxaway dome and Tallulah Falls dome samples range from 0.698 to 0.710 (Table 4), indicating some open-system behavior after initial crystallization. The wide range of initial ratios probably has little meaning but is consistent with previously reported younger Rb–Sr whole-rock ages and rather poor isochrons that suggest disturbance of the Rb/Sr isotopic system (Fullagar and Odom, 1973; Fullagar and Bartholomew, 1983; Stieve and Sinha, 1989; additional Toxaway Gneiss data, Fullagar, unpublished data). The mean initial ratio for these samples of ~0.703 may be a rough approximation of the true value for the EBR basement gneisses. Likewise, the calculated initial $^{87}Sr/^{86}Sr$ ratio for the Watauga River Gneiss (0.690) indicates open system behavior. The Blowing Rock and SMW gneisses have much lower Rb/Sr ratios and yield initial $^{87}Sr/^{86}Sr$ ratios that are reasonable: 0.7017 for Blowing Rock Gneiss and 0.7039–0.7042 for the Grassy Creek, Pilot Mountain, and Forbush gneisses.

5. Interpretations and discussion

5.1. Nature, timing, and distribution of magmatism

The considerable similarity in age and geochemistry among the samples we have investigated suggests that the majority represent the same general magmatic episode during Elzevirian time. Samples from the SMW, EBR, and WBR Watauga massif range in mean age from 1150–1165 Ma. They range in SiO_2 from 63–72 wt.%, have similar elemental compositions enriched in K, LIL, and REE, and are relatively depleted in HFSE. Their initial ε_{Nd} values are essentially identical (−0.7 to +1.0). The Forbush gneiss we regard as similar in age to the majority of our samples, but it could be distinctly younger (~1115 Ma). In all other ways (geochemistry, isotopic compositions, metamorphic rim age), it is essentially identical to the bulk of our samples. The Cranberry Mine Gneiss in the WBR Elk River massif is also similar to the bulk of our samples, but slightly older (~1190 Ma), consistent with field interpretations that it makes up part of the country rock into which younger Grenville-age granitoids intruded (Bartholomew and Lewis, 1984).

Available data from the literature on southern Appalachian basement support our interpretation that these samples and others are part of the same general magmatic episode. The Corbin Gneiss, located in the southern Blue Ridge of Georgia (Fig. 11), is geochemically and isotopically similar to the majority of our samples, and Heatherington et al. (1996) reported a $^{206}Pb^{*}/^{238}U$ minimum crystallization age of 1106±13. Quinn and Wright (1993) reported an upper intercept age

Table 4
Sm–Nd and Rb–Sr isotopic data

Sample	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ ($\pm 2\sigma$)[a]	ε_{Nd}	ε_{Nd_i}[b]	TDM (Ma)[c]	Sr (ppm)	Rb (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ ($\pm 2\sigma$)[a]	$^{87}Sr/^{86}Sr_I$[b]
Carvers gap (RM-1)	2.830	19.132	0.0916	0.511490 (04)	−22.4	1.9	1937	39.06	253.6	0.4460	0.718556 (10)	0.707009
Carvers gap (RM-2)	5.01	19.28	0.1607	0.512625 (04)	−0.3	4.4	1198	12.3	310.1	0.114	0.704732 (11)	0.703099
Carvers gap (NC-81)	4.951	24.48	0.1252	0.511773 (07)	−16.9	−0.4	2189	–	–	–	–	–
Cloudland (RM-CLG)	7.69	48.04	0.0990	0.511673 (08)	−18.8	−6.3	1819	7.8	249.6	0.091	0.715261 (11)	0.713965
Cloudland (NC-28/68)	2.963	20.09	0.0913	0.511621 (06)	−19.8	−6.4	1767	–	–	–	–	–
Cranberry (CG-1970)[d]	4.41	27.04	0.10096	0.511853 (07)	−15.3	−0.7	1610	–	–	–	–	–
Watauga (WRG)	15.87	71.81	0.1368	0.512178 (03)	−9.0	−0.1	1709	210.6	236.9	2.579	0.733552 (11)	0.690793
Blowing rock (GMW-BR)	14.04	72.34	0.1201	0.512217 (08)	−8.2	2.4	1341	129.4	417.9	0.8966	0.715559 (08)	0.701690
Wiley (WG-CS)	9.123	44.8	0.1260	0.512129 (04)	−9.9	0.6	1591	125.9	152.1	2.4052	0.749799 (07)	0.709922
Sutton creek (SC-RC)	16.99	117.4	0.0896	0.511823 (05)	−15.9	0.0	1496	261.9	235.1	3.2376	0.751664 (11)	0.698080
Toxaway (TOX-1)	7.395	41.58	0.1101	0.511980 (05)	−12.8	−0.1	1560	236.4	191.8	3.5830	0.758325 (10)	0.699283
Toxaway (TXFL)	6.186	34.80	0.1100	0.512005 (08)	−12.3	0.4	1522	123.0	230.1	1.5500	0.731778 (28)	0.706281
Grassy creek (SM-GC)	9.719	40.61	0.1482	0.512320 (06)	−6.2	1.0	1674	93.45	199.5	1.3575	0.726917 (10)	0.704273
Pilot Mt. (SM-PM1)	10.70	48.24	0.1373	0.512166 (07)	−9.2	−0.3	1745	90.40	361.2	0.7247	0.716030 (10)	0.703942
Pilot Mt. Enclave (SM-PM-E)	18.79	94.91	0.1225	0.512167 (05)	−9.2	1.9	1461	117.5	634.9	0.536	0.715431 (11)	0.706492
Forbush (SM-F)	7.205	36.44	0.1224	0.512077 (07)	−10.9	−0.1	1610	55.82	340.3	0.4748	0.711656 (08)	0.703887

[a] 2σ errors on $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ ratios reported as last two significant digits.
[b] Initial values calculated using preferred crystallization ages from Table 3, except RM-2 and Cloudland samples (assumed age 1.0 Ga).
[c] T_{DM} ages calculated as in DePaolo (1981), using $^{147}Sm/^{144}Nd = 0.1967$ and $^{143}Nd/^{144}Nd = 0.512638$ for CHUR present day values.
[d] Data for Cranberry from Fullagar et al., 1997, sample 1970. Initial values recalculated using new U–Pb age from Table 3.

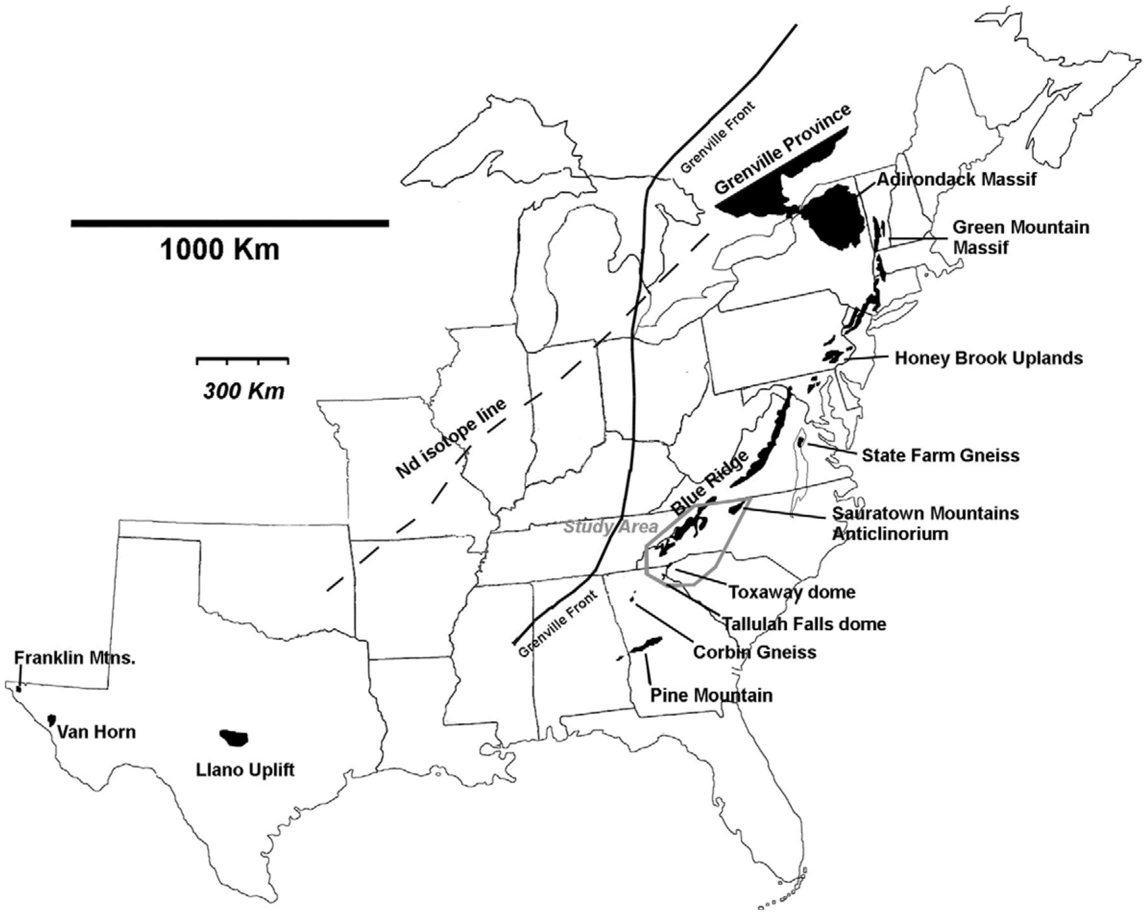

Fig. 11. Exposures of Mesoproterozoic basement in the eastern United States. Nd isotope line separates basement rocks with Nd model ages > 1.55 Ga to northwest and < 1.55 Ga to southeast for the mid-continent region, and is interpreted to represent the 1.6 Ga margin of Laurentia. Modified from Van Schmus et al., 1996 and Aleinikoff et al., 2000.

of 1147 ± 8 Ma for a biotite + hornblende orthogneiss collected near Sylva, NC, in the EBR. It is possible that these two samples are part of the same magmatic pulse that we have identified. Additionally, whole-rock Pb isotope studies suggest that the basement units from the Sauratown Mountains, Tallulah Falls dome, and Corbin Gneiss are part of the same isotopic reservoir (Sinha et al., 1996). These findings are consistent with ours, and indicate relative uniformity among the majority of basement rocks across the southeast.

We cannot unequivocally identify the tectonic setting into which these magmas were emplaced, but field evidence and geochemistry provide constraints. Although our samples have a broadly arc-like trace-element signature, they are unusually potassic and rich in incompatible elements for an arc assemblage. Basement exposures lack evidence for the mafic to intermediate component that accompanies modern continental and island arc subduction zone magmatism. Data on tectonic discrimination diagrams scatter across several fields, and are not definitive. Nd data indicate that these magmas were neither primitive melts from depleted asthenosphere nor products of anatexis of Mars Hill-like crust. Rather, they were likely derived from mixing of older crustal material (Early Proterozoic?) and more primitive melts, or possibly from melting of 1.4–1.5 Ga juvenile material that makes up much of the mid-continent. Thus, these rocks do not definitively record juvenile subduction-related arc magmas that would have accreted onto Laurentia. The triggering mechanism cannot be well established with our current data.

The Blowing Rock Gneiss is unique among our samples in age and geochemistry. It is distinctly younger than the other samples at ~1080 Ma, and records inherited zircon that is similar in age to the other Grenville age samples (~1150 Ma). Additionally, it is the most mafic of our dated samples, and its initial ε_{Nd} value of +2.4 is distinctly higher and initial $^{87}Sr/^{86}Sr$ ratio of 0.7017 is lower than other samples, reflecting a more primitive component.

The data for sample RM-1 (Carvers Gap Granulite Gneiss) show that some zircon grains have lost a large amount of lead from their interiors in late Grenville time, experienced an additional growth stage during Ottawan metamorphism, and have probably also lost some lead in recent time causing difficulties for dating by conventional methods. Nonetheless, the data presented here strongly support 1.8 Ga as the magmatic age. This sample and others from the Carvers Gap area are also very distinct from the remaining samples in elemental and isotopic compositions. A more in-depth analysis of Mars Hill terrane rocks by Ownby et al. (submitted for publication) also indicates a larger diversity of ages and rock types. These data support the notion that the Mars Hill terrane records a more complex history than other basement exposures in the region (cf. Gulley, 1985; Bartholomew and Lewis, 1992; Raymond and Johnson, 1994; Sinha et al., 1996).

5.2. Timing and distribution of Grenvillian metamorphism

Zircons from all of the samples that we have investigated, with the exception of the Blowing Rock Gneiss, have metamorphic rims; the vast majority of these rims yield ages ~1.0 Ga. We interpret these rims as representing the same high-grade metamorphic growth event. Seventy-two of 79 analyses yield a $^{207}Pb^{*}/^{206}Pb^{*}$ age of 1028 ± 9 Ma (MSWD = 0.87). We regard this age as our best estimate of the timing of Ottawan metamorphism in the southern Appalachians. This event is broadly distributed geographically and may have a relation to the timing of tectonic plate collision.

The Blowing Rock Gneiss, located in the Globe massif, does not record the Ottawan metamorphic event so ubiquitous in our samples from the EBR, IP, SMW, and the Mars Hill terrane. Zircons from the Watauga River Gneiss and Cranberry Mine Layered Gneiss also did not yield direct evidence for Ottawan metamorphism, although their very thin metamorphic rims may reflect a less intense event. Absence or near absence of the Ottawan metamorphic overprint in these samples is consistent with previous interpretations that they were located to the NW (cratonward) of the Mars Hill terrane, the SMW, and the EBR massifs during Grenville time (Bartholomew and Lewis, 1988), perhaps beyond the zone of high-grade metamorphism. Alternatively, these massifs could have been at a higher level in the crust relative to the other samples during the Ottawan orogeny and not have experienced a high enough grade of metamorphism to intensely recrystallize zircon.

5.3. Comparison with other Grenvillian ages in eastern North America

In the Adirondack Highlands, the earliest phase of magmatism (~1360–1300 Ma) was dominated by arc-like tonalites with positive initial Nd isotopic ratios near those of contemporaneous MORB and T_{DM} ages within 70 Ma of crystallization ages (Daly and McLelland, 1991). Similar rocks are also found in the Adirondack Lowlands (McLelland et al., 1993). Likewise, in the Elzevir terrane of the Canadian Grenville province, igneous rocks of calc-alkaline arc-like affinity also formed in the interval ~1300–1230 Ma (Marcantonio et al., 1990). Similarly, the Green Mountain massif of Vermont records tonalitic and trondhjemitic magmatism ~1350–1310 Ma (Aleinikoff et al., 1990; Ratcliffe et al., 1991), and ~1326–1300 Ma tonalitic gneisses form the oldest rocks of the Llano uplift complex in Texas (Mosher, 1998). These rocks are generally interpreted as primitive island arcs that accreted to Laurentia during stages of the Grenville orogenic cycle. These rock types and ages, however, have so far not been found in the southern Appalachians, nor are they reported in rocks from the northern Blue Ridge of Virginia (Aleinikoff et al., 2000). Although most plate tectonic models require arc magmatism prior to continental collision and orogenesis, so far we have not found clear and definitive evidence for arc magmas prior to the onset of the Elzevirian orogeny in the southern Appalachians, unlike other areas of North America. Based upon our data, the oldest Grenvillian magmatism in the southeast is the Cranberry Mine Layered Gneiss (~ 1190 Ma), an age that is currently not recognized in the northern Blue Ridge, but may be correlative to Elzevirian magmas in the Grenville province.

Three major Grenvillian magmatic pulses have been identified in the Adirondack Highlands at 1160–1130, 1110–1090, and 1060–1045 Ma (McLelland et al., 1996, 2001; Fig. 11). Magmatic ages from the northern Blue Ridge of Virginia and Massachusetts show similar distributions, ranging from 1150–1140, 1110, and 1075–1055 Ma (Aleinikoff et al., 2000). Granitoids in the Frontenac terrane (Grenville province) occur in two intervals, 1180–1150 and 1090–1065 Ma (van Breamen and Davidson, 1988; Corriveau et al., 1990; Marcantonio et al., 1990). The ages presented here (1165–1150 Ma) clearly extend the older pulse into the southeast, but rocks with similar ages are unknown in the Llano uplift of Texas (Mosher, 1998). Rocks of this age in the northern Blue Ridge are granitic to monzonite gneisses, while similar age rocks in the Adirondacks are anorthosite–mangerite–charnockite–granite suite rocks. Although our samples do not include anorthosite, mangerite, charnockite, or monzonitic rocks, the chemistry of our granitoids is similar in several respects to the granitoids of the Adirondack Highlands and the Frontenac Terrane (high in K_2O and FeO, high in incompatible elements, similar REE patterns; compare with Carl et al., 1990; Marcantonio et al., 1990; McLelland et al., 1991). These granitoids in the Adirondack Highlands and the Frontenac terrane have both been interpreted as anorogenic melts derived from a mixture of crustal and mantle sources after the peak of the Elzevirian orogeny (Marcantonio et al., 1990; Chiarenzelli and McLelland, 1991; McLelland et al., 1996). The data for our samples are consistent with this interpretation, but the limited exposures and data for these rocks in the southeast require caution in their interpretation. The two younger pulses of magma are not as well represented in our data set, but the Blowing Rock Gneiss (~ 1080 Ma) is similar to the youngest, or perhaps the middle, pulse of magma along the eastern margin of North America. It is also similar in age to rocks of the latest period of magmatism in Texas (~ 1119–1070 Ma; Mosher, 1998). If truly correlative, these observations suggest a similar magmatic, and possibly tectonic, history for a large portion of the southeastern margin of Laurentia extending from Canada to Texas during both Elzevirian and Ottawan time.

The Goochland terrane of Virginia includes the easternmost exposure of Grenvillian rocks in the southern and central Appalachians. The crustal affinity of the Goochland terrane is unknown, but it has been largely interpreted as Laurentian crust. The State Farm Gneiss, exposed in the core of an antiformal dome, has yielded an age of 1048 ± 6 Ma (Owens and Tucker, 1999). Similarly, Aleinikoff et al. (1996) reported crystallization and metamorphic ages for the Montpelier Anorthosite, exposed at the northern end of the dome, of 1045 ± 10 and 1011 ± 2 Ma, respectively. They proposed that the similarities in age and composition between the Montpelier Anorthosite and the Roseland anorthosite, located in the Blue Ridge of Virginia, indicate a common history between these terranes. However, these magmatic ages are not recorded in any of our samples and are younger than the youngest pulse of granitic magma in the Blue Ridge of Virginia (1075–1055 Ma). It is unknown whether these rocks constitute the basement of the Goochland terrane, or if they intruded into associated amphibolites (Aleinikoff et al., 1996). The age of the oldest rocks in the Goochland terrane is therefore unknown, but no pre-Ottawan history has yet been reported. This complete lack of Elzevirian age magmas is in stark contrast with the remainder of the Blue Ridge. This discrepancy may be explained by the location of the Goochland terrane (east of other terranes), but is also consistent with an exotic origin prior to the onset of the Ottawan orogeny.

As with magmatic ages, the age of late Grenville metamorphism recorded in our samples is also similar to metamorphic ages reported from basement rock in the northern Blue Ridge, the Adirondack Highlands, and portions of the Grenville province. SHRIMP analyses of zircon metamorphic rims from Virginia yield an age of 1043 ± 11 Ma, and monazites yielded multiple ages younger than magmatic crystallization ages, the youngest of which is ~1030 Ma (Aleinikoff et al., 2000). SHRIMP II dating of metamorphic zircons from charnockites in the Adirondacks yields ages ~1050–1040 Ma (McLelland and Hamilton, 2001). Regional metamorphism in the Grenville province occurred principally in two stages ~1190–1150 Ma and ~1080–1020 Ma (Mezger et al., 1993; Corfu and Easton, 1997; Wasteneys et al., 1999; McLelland et al., 2001), the latter corresponding to the metamorphic ages presented here. We have so far found no evidence for an Elzevirian age metamorphic event, but Ottawan metamorphism clearly affected not only the Grenville province but also rocks along the entire southeastern margin of Laurentia, including the outlying Goochland terrane (as mentioned previously).

5.4. Laurentian mid-continent connection

The ages for Grenville basement rocks presented in this work (1190–1150 Ma, 1080 Ma, 1030 Ma) are similar to ages along the entire eastern margin of North America, as discussed above. Similarly, the Mars Hill terrane, although distinct in the southern Appalachians and perhaps the entire Blue Ridge, also yields ages commonly found in the North American mid-continent and granite–rhyolite terrane (1.8 Ga; detrital cores 1.8, 1.5–1.4, 1.2 Ga). The data therefore suggest, but do not require, a Laurentian heritage for the basement rocks of the region. However, Van Schmus et al., 1996 defined a line through the mid-continent that separates T_{DM} model ages > 1.55 to the northwest from T_{DM} model ages < 1.55 to the southeast (Fig. 11). This line is interpreted as the eastern limit of pre-1600 Ma continental crust; to the east of the line, sparse exposures and drill cores indicate that largely juvenile 1.4–1.5 Ga plutonic and volcanic rocks comprise the basement. In the southern Appalachians, T_{DM} model ages are generally > 1.5 Ga, and most are ~1.6–1.8 Ga (Fullagar et al., 1997; this study). Also, 1.4–1.5 Ga rocks are unknown, and detrital or inherited zircon of this age is very sparse. Additionally, Sinha et al. (1996) interpreted elevated $^{207}Pb/^{206}Pb$ whole-rock isotopes of the Carvers Gap Granulite Gneiss as indicating a distinct Archean component, and Stuckless et al. (1986) reported Pb isotopic evidence suggesting ~1.7 Ga crust in the basement of the IP. Data from detrital and inherited zircons in the EBR and IP further document a pre-1.5 Ga crustal component (e.g. Heatherington and Mueller, 1997; Miller et al., 2000b; Steltenpohl et al., 2001; Bream et al., submitted for publication). All of these data, especially the Paleoproterozoic age (~1.8 Ga) of the Carvers Gap Granulite Gneiss, are inconsistent with the inferred ~1.6 Ga eastern margin of Laurentia through the mid-continent. Instead, they suggest either that basement in the southern Appalachians is a far traveled terrane or alternatively that the 1.4–1.5 Ga terrane separates older, rifted portions of Laurentia and does not define a true continental boundary at ~1.6 Ga (cf. Gower and Tucker, 1994). If this region was far traveled, it may have accreted to Laurentia during the Grenville orogeny. As noted by Ownby et al. (submitted for publication), the closest crust of similar age is near the Great Lakes. Several terranes in the Grenville province are considered allochthonous, but older rocks (~1.75–1.45 Ga) reworked during the Grenville cycle are typically found in the parautochthonous belt (Davidson, 1995). Alternatively, the basement rocks, especially the Mars Hill terrane, may be of exotic origin and accreted to southeastern Laurentia from another continent during the Grenville orogeny. Speculation on the origin of the Mars Hill terrane is unwarranted with only the preliminary data presented here.

5.5. Constraints on paleozoic tectonics

Geochronology and geochemistry, especially Nd isotopic data and metamorphic ages, are entirely consistent with an EBR–WBR connection, especially the Watauga massif, Toxaway and Tallulah Falls domes, and the SMW. The relationship between other massifs in the WBR (Elk River and Globe) and these samples is plausible, but less compelling. This suggests that the enclosing terranes are not exotic with respect to one another during Paleozoic orogenies, and that the Piedmont terrane is native Laurentia crust with regard to Appalachian orogenesis. Internal basement massifs of the EBR have been previously interpreted as rifted fragments of Laurentia reattached during Paleozoic tectonic events (Hatcher, 1984; Hatcher et al., submitted for publication), and the data presented here are consistent with this interpretation.

Evidence for Paleozoic metamorphism from zircons is surprisingly limited in our samples, given the multiphase overprinting that occurred in these rocks. Although some workers have regarded the Taconic as the most important Paleozoic metamorphic event in the southern Appalachians (e.g. Dallmeyer, 1975; Butler, 1991), no Taconic metamorphic ages have been found in this study. Taconic ages from metamorphic zircon by IMP have been reported in the southern Appalachians (~470–460 Ma; Bakersville eclogite, Miller et al., 2000a; Winding Stair Gap metapelites, Moecher and Miller, 2000; Mars Hill terrane garnet amphibolite, Ownby et al., submitted for publication), but are located westward of the younger ages obtained here from samples of the Toxaway Gneiss. The Paleozoic analyses reported here have very large errors, but appear to be late Acadian (~350 Ma) in age (Fig. 4A). An analysis of metamorphic zircon rims from a variety of rock types in the area suggests a regionally extensive period of zircon growth at this time (Carrigan et al., 2001; Bream et al., 2001b), but more data are needed to determine this age precisely and evaluate its geological significance.

6. Conclusions

(1) IMP U/Pb zircon ages, Nd isotopic compositions, and whole-rock major and trace element geochemical data define a granitic (SiO_2 63–72 wt.%) magmatic pulse ~1165–1150 Ma, characterized by high K and other incompatible elements, ε_{Nd} near CHUR, and a subduction zone trace element ‘signature’. Zircons from these rocks lack older inherited cores. The Cranberry-Mine and Forbush gneisses are similar to this pulse in all aspects, but the former is slightly older (~1190 Ma), and the latter slightly younger (~1140 Ma). The Blowing Rock Gneiss is distinctly younger (~1080 Ma), is the most geochemically primitive of the granitoids investigated, and represents a separate pulse of magmatism from the rest of the samples.

(2) Samples from the Mars Hill terrane are distinct in age, isotopic compositions, and geochemistry, and highly variable compared to the rest of the relatively homogeneous basement. Zircons from the Carvers Gap Granulite Gneiss confirm the previously determined ~1.8 Ga age as the crystallization age. The metasedimentary Cloudland Granulite Gneiss contains detrital cores with apparent U–Pb ages ranging from ~1.2–1.8 Ga. Isotopic and elemental geochemistry shows that the Grenville age magmas could not have been derived exclusively from Mars Hill terrane-type crust, but could have resulted from a mixture of Carvers Gap-like crust and juvenile material.

(3) Almost all samples record late Grenville metamorphism, with a combined age of 1028±9 Ma. WBR massifs that reflect a less intense event, or none at all, may have been beyond the zone of high-grade metamorphism or shallower in the crust during the Ottawan orogeny. Although the ages and geochemistry of the Mars Hill terrane and the rest of the basement samples are very different, both were intensely metamorphosed at the close of the Grenville, and they were in all likelihood in proximity by ~1030 Ma. Both Elzevirian and Ottawan ages in the southern Appalachians are similar to reported ages in the northern Blue Ridge, Adirondacks, the Canadian Grenville province, and the Llano uplift of Texas. This suggests that the southeastern margin of

Laurentia from Ontario to Texas has a similar tectonic history during the interval ~1.2–1.0 Ga.

(4) Although magmatic, metamorphic, and detrital ages in the southern Blue Ridge are similar to other Laurentian ages (1.8, 1.5–1.4, 1.19–1.14, 1.08, 1.03 Ga), the presence of 1.8 Ga rocks and Nd model ages commonly greater than 1.55 Ga is inconsistent with the inferred 1.6 Ga margin of Laurentia. This suggests that the 1.4–1.5 Ga granite–rhyolite terrane in the mid-continent may separate older, rifted portions of Laurentia, perhaps reattached during Grenville orogeny, or alternatively that these rocks were exotic to Laurentia during the Grenville.

(5) The similarity of basement rocks across the WBR–EBR contact suggests that the Piedmont terrane is not exotic with respect to Laurentia, but rather supports the interpretation that it represents a rifted fragment, separated in the Neoproterozoic and reattached during Appalachian orogeny. The complete lack of Taconic ages among the samples we have investigated is surprising, given the strong indications that the Taconic orogeny played a key role in shaping the southern Appalachian orogen. Paleozoic metamorphic zircon rims appear to be late Acadian in age, although more data on the timing of peak high-grade metamorphism are needed to evaluate the significance of various thermal events.

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