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AGE AND ZIRCON INHERITANCE OF EASTERN BLUE RIDGE PLUTONS, SOUTHWESTERN NORTH CAROLINA AND NORTHEASTERN GEORGIA, WITH IMPLICATIONS FOR MAGMA HISTORY AND EVOLUTION OF THE SOUTHERN APPALACHIAN OROGEN

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ABSTRACT. High-resolution ion microprobe analysis of zircon has provided ages for previously undated plutons of the high-grade eastern Blue Ridge of northeastern Georgia and southwestern North Carolina. These data, together with backscattered electron imaging, reveal the presence of nearly ubiquitous inherited cores of highly variable age and magmatic rims that have experienced variable Pb loss, thus making interpretation of conventional U-Pb analyses very difficult. Ion probe rim analyses indicate that the plutons were emplaced during both the mid-Ordovician (Taconian orogeny; Whiteside pluton, 465 Ma; Persimmon Creek Gneiss, 480 Ma) and mid-Devonian (Acadian orogeny; Rabun pluton, 375 Ma; Pink Beds pluton, 390 Ma; Looking Glass pluton, 380 Ma). A large trondhjemite dike north of Asheville is less confidently assigned an age of 415 Ma. Zircons from all intrusions have predominantly 1.0 to 1.25 Ga cores (Grenvillian). In addition, both Devonian and Ordovician plutons have smaller populations of Late Proterozoic-early Paleozoic (0.5-0.75 Ga), Middle Proterozoic (1.4 Ga), and Late Archean (2.6-2.9 Ga) cores.

The ubiquitous, round cores and thick magmatic rims suggest significant resorption and then protracted growth within the melts. Zircon saturation temperatures based on whole-rock (~melt) Zr concentrations are lower than expected for magma generation (710°-760°C). Zirconium concentrations may not reflect saturation at maximum temperature, if melting was very rapid ($<\sim10^5$ yrs), or if zircon cores represent grains that were shielded from melt inside host grains for much of the magmatic history.

The Late Proterozoic-early Paleozoic and Grenvillian inheritance is similar to documented ages of basement exposed in the eastern Blue Ridge. No exposures of 1.4 Ga rocks are known in the southern Appalachians, but detrital and inherited zircons of this age have been reported, and 1.4 Ga granites are widespread in the craton to the northwest. However, the combination of absence of Early Proterozoic zircon and presence of Late Archean zircon is inconsistent with the known distribution of basement rocks in southeastern North America. No Archean rocks or inherited zircons have been reported from the southern and central Appalachians; the nearest Archean exposures are 1000 km north, across a dominantly Early Proterozoic terrane. This suggests either that the Laurentian configuration of Archean basement was very complex or that the crust that underlay the plutons at the time of their emplacement included a far-travelled terrane (emplaced during Grenvillian or early Paleozoic orogeny?).

Ages of magmatic and inherited zones of zircon from the plutons demonstrate that similar crust underlay the eastern Blue Ridge during both Taconian and Acadian orogenies, that there was no single episode of voluminous magmatism, and that metamorphism and deformation began before 470 Ma and continued after 370 Ma. These plutons do not constitute a significant convergence-related arc, though it is possible that they represent a displaced part of an arc that lies primarily to the east (in the Inner Piedmont?).

Previous geochemical studies have demonstrated that the eastern Blue Ridge intrusions include both a very primitive component, either mafic magma or relatively young mafic source rock, and a component derived from more mature

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felsic crust. The abundant inherited zircon cores verify contributions from similar crust to all the plutons, but they almost certainly magnify the real mass contribution from mature crust, especially in the more primitive rocks. There is no discernible distinction in petrogenesis between Taconian plutons and Acadian plutons.

INTRODUCTION

The southern Appalachian mountain chain records protracted continental orogeny related to multiple contractional events. These events have been attributed to a range of convergent tectonic mechanisms, including subduction, arc accretion, and continental collision. Both direct and oblique convergence mechanisms have been proposed, and subduction is interpreted to have been directed both toward and away from Laurentia, the core of North America that existed at the time (Hatcher, 1987). The eastern Blue Ridge Province was affected by all the major events that shaped the southern Appalachian orogen and is a key link in elucidating the assembly of the Appalachian portion of the North American continent. However, important aspects of the evolution of the eastern Blue Ridge remain obscure. In particular, the age and tectonic setting of plutonism remain uncertain. In this paper we present new data on the age and zircon inheritance of plutons in the eastern Blue Ridge of northeastern Georgia and southwestern North Carolina generated by high-resolution ion microprobe U-Pb analysis. Based on these data, we re-examine the genesis of the plutons and the nature of the crust that underlay them at the time of intrusion and address the implicit constraints on the tectonic history of this region.

BACKGROUND AND GEOLOGICAL SETTING

Regional Overview

The Blue Ridge province of the southern and central Appalachians includes low to high grade metamorphic rocks that have been thrust northwestward over the unmetamorphosed sedimentary rocks of the Valley and Ridge province. It is divided into eastern and western portions by the east-dipping Hayesville and related faults and bounded on the southeast by the Brevard fault (figs. 1, 2). The pre- to synmetamorphic Hayesville fault places the structurally complex eastern Blue Ridge assemblage of chemically immature clastic metasedimentary rocks, mafic to ultramafic bodies, variably deformed felsic intrusive rocks, and Grenvillian basement over the more mature metasedimentary rocks and basement of the western Blue Ridge (Rankin, 1975; Hatcher, 1978). The eastern Blue Ridge is generally similar lithologically to the adjacent Inner Piedmont. Together, the two belts comprise the Piedmont terrane (Williams and Hatcher, 1982, 1983; Piedmont zone of Hibbard and Samson, 1995). The Brevard fault, which separates the eastern Blue Ridge from the Inner Piedmont, is a major structure with a protracted, polyphase history of displacement (Hatcher, 1978), but it is equivocal whether or not it is a fundamental terrane boundary (Williams and Hatcher, 1983; Hatcher, 1987; Horton, Drake, and Rankin, 1989; Dennis and Wright, 1997).

The western Blue Ridge is demonstrably part of Laurentia, but the origin of the Piedmont terrane is controversial. The presence of (ophiolitic?) mafic-ultramafic complexes and very high pressure (subduction zone?) metamorphic assemblages has led some to suggest that the Piedmont terrane may be an exotic, far-travelled terrane that was accreted during Paleozoic orogeny, with the mafic rocks being remnants of the closed ocean basin (for example, Horton, Drake, and Rankin, 1989; Willard and Adams, 1994; compare Zen, 1981; Williams and Hatcher, 1983; Shaw and Wasserburg, 1984). The Piedmont terrane is alternatively interpreted to be a rifted fragment of Laurentia with remnants of the intervening basin, with the metasedimentary rocks representing distal sediment and the mafic rocks the oceanic crust of the small basin (Hatcher, 1978,

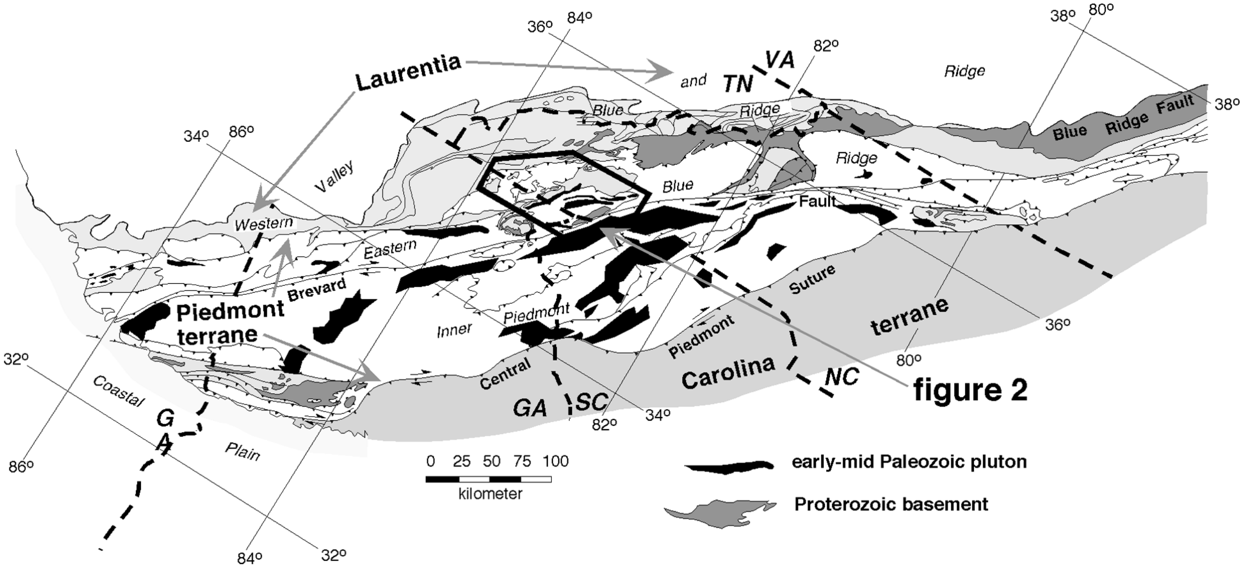

Fig. 1. Locator map showing study area (shown in more detail in fig. 2), southeastern edge of Laurentia (Valley and Ridge and western Blue Ridge), Piedmont terrane (eastern Blue Ridge, Inner Piedmont), and Carolina terrane.

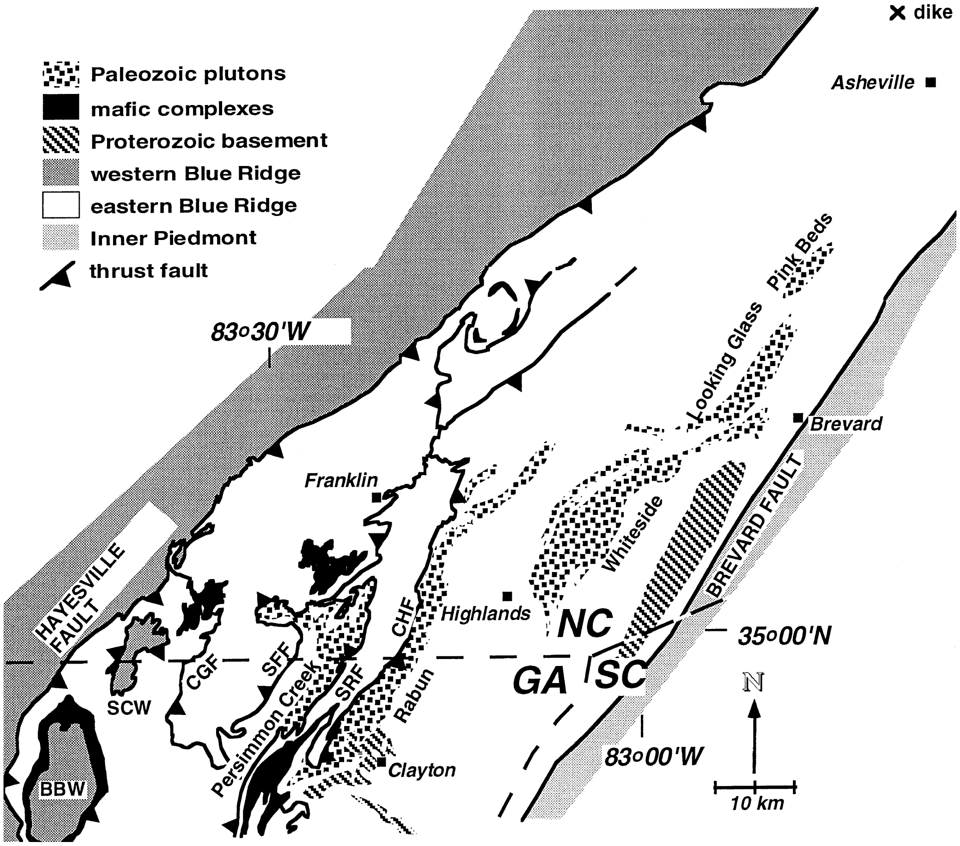

Fig. 2. Setting of eastern Blue Ridge plutons. BBW = Brasstown Bald window; SCW = Shooting Creek window; CGF = Chunky Gal fault; SFF = Shope Fork fault; SRF = Soque River fault; CHF = Chattahoochee fault.

1989; Hatcher and Goldberg, 1991). Uncertainty remains about the Grenvillian rocks exposed in the eastern Blue Ridge. Subsequent metamorphism and deformation have made their original contacts with the metasedimentary rocks difficult to decipher. At least some contacts appear to be depositional (Hopson, Hatcher, and Stieve, 1989), leading to the interpretation that these rocks represent Laurentian (Hatcher, 1989) or perhaps exotic basement of the eastern Blue Ridge. Alternatively, these exposures may mark structural windows through the Piedmont terrane into underlying Laurentia (Rankin and others, 1993). With the exception of a sliver of 1.2 Ga gneiss that overlies the Sauratown Mountains window (McConnell, ms, 1990), Grenvillian or older rocks have not been identified in the Inner Piedmont (eastern Piedmont terrane).

The tectonic history of the southern Appalachians is dominated by polyphase contraction interpreted to be responses to closing of ocean basins that are thought to have separated Laurentia from other landmasses. Contractional events are identified as the Potomac (500+ Ma), Taconian (~450-500 Ma), Acadian (~360-410 Ma), and Alleghanian (~265-325 Ma) orogenies (Hatcher, 1989; Hibbard and Samson, 1995; Goldberg and Dallmeyer, 1997). All these orogenies were accompanied by plutonism and thermal events. Peak metamorphism in the eastern Blue Ridge ranged from middle amphibolite to granulite facies. It is generally considered to have occurred during the Taconian orogeny when the Piedmont terrane was probably accreted (or reattached) to

Laurentia, but there is also abundant evidence for Acadian metamorphism (Kish, 1989; Goldberg and Dallmeyer, 1997; Miller and others, 1998).

Plutonism in the Piedmont terrane

Granitoid plutons of known or presumed Paleozoic age are widespread but relatively sparse in the eastern Blue Ridge, where they are mostly geochemically primitive (poor in K and incompatible elements and high field strength elements; Miller and others, 1997). The more abundant plutonic rocks of the Inner Piedmont are distinguished by more geochemically evolved compositions (Vinson, ms, 1999). Ages of Piedmont terrane intrusions are generally imprecisely defined because of resetting of the K-Ar and Rb-Sr systems during the protracted high temperature history of the region, low Rb/Sr ratios and initial isotopic heterogeneity, and discordance of conventional U-Pb ages. Based on available data, the ages of almost all Phanerozoic plutons appear to fall between ~350 and 520 Ma (Sinha, Hund, and Hogan, 1989). With rare exceptions (for example, Linville diabase, North Carolina, 415 Ma; Fetter and Goldberg, 1993), mafic rocks are poorly dated but considered to be older than the granitoids.

Eastern Blue Ridge plutons, southwestern North Carolina-northeast Georgia: Setting, nature, and age

This study deals with the Paleozoic intrusions located between Clayton, in northeastern Georgia, and Asheville, North Carolina (fig. 2). We investigated samples from the five major plutons in this area that were thought to be of possible Paleozoic age (Rabun, Persimmon Creek, Whiteside, Looking Glass, Pink Beds). These plutons are confined to the eastern portion of the eastern Blue Ridge. All but the Persimmon Creek are within the Chattahoochee thrust sheet, the easternmost structural unit of the Blue Ridge. The Persimmon Creek Gneiss is a metamorphosed pluton that lies 5 to 10 km northwest of the trend of the other plutons, in the Soque River sheet; it has been interpreted to be of either Middle Proterozoic (Grenvillian) or Paleozoic age (Hopson and others, 1989). In addition to the plutons, we studied a sample from a large dike 10 km north of Asheville that we consider to be representative of the common trondhjemite dikes of the North Carolina-Georgia Blue Ridge (Yurkovich and Butkovitch, 1982; Wood and Miller, 1984). These dikes are mostly located to the northwest of the plutons but within the eastern Blue Ridge.

Hatcher (1998) interprets the Chattahoochee thrust sheet to have originated in what is now the Inner Piedmont. By this interpretation, this is the westernmost Inner Piedmont thrust sheet and the westernmost Acadian sheet in the southern Appalachians; all other Inner Piedmont thrusts were decoupled from the Chattahoochee sheet as they were buttressed against the primordial Brevard fault and remained to the southeast. In contrast to the Hayesville fault, both the Chattahoochee and the Soque River faults postdate peak metamorphism, though both are ductile structures reflecting amphibolite facies conditions, and both were folded subsequently. The Soque River fault cuts the Persimmon Creek Gneiss, and the Chattahoochee fault cuts both the Rabun pluton and the Soque River fault.

Host rocks of the plutons and dikes are primarily metasedimentary schists and quartzofeldspathic paragneisses, along with varying amounts of interlayered amphibolite. All the intrusions postdate at least some regional fabric development and retain some magmatic texture, but all are overprinted by deformation and metamorphism. The Persimmon Creek, Whiteside, and Looking Glass plutons have the strongest metamorphic fabrics. The Rabun pluton has both a primary magmatic foliation and a tectonic fabric, and the dikes are weakly recrystallized.

The Blue Ridge intrusions are mineralogically and geochemically akin to the TTG association (tonalite-trondhjemite-granodiorite) that was an especially abundant constituent of the early crust (Barker, 1979). Abundant quartz and plagioclase (>20 and >40 modal percent, respectively) characterize all the intrusions except Persimmon Creek, which based on limited sampling appears to be poorer in quartz. Abundance of K-feldspar ranges from trace amounts to about 25 percent, and therefore rock type ranges from trondhjemite, quartz diorite, and tonalite, through granodiorite, and very rarely to granite. Biotite is ubiquitous, and muscovite is present in most rocks; the Persimmon Creek Gneiss locally contains hornblende. Epidote is common, occurring in most samples from all plutons; it is especially abundant in Persimmon Creek samples. Zircon, apatite, and opaque minerals are sparse but ubiquitous. Monazite is also widespread, whereas sphene, allanite, and rutile are restricted in occurrence. Garnet is present in some aplites and pegmatites and rarely in less felsic rocks. The mineral assemblages do not appear to be affected by metamorphism: the same minerals are present in both igneous- and metamorphic-textured samples. Based upon textural relations, we consider much of the muscovite and at least some of the epidote to be magmatic in origin. The intrusions are generally equigranular, except for the Rabun pluton, which is coarsely porphyritic with 1 to 2 cm K-feldspar phenocrysts, and the trondhjemite dikes, which are porphyries with plagioclase ± quartz, muscovite, and biotite phenocrysts set in a very fine grained groundmass. We found no evidence for major internal contacts between distinct units in the plutons–rather, compositions and textures appear to vary continuously. Mafic to intermediate rocks are very sparse to absent within the plutons except for Persimmon Creek, which based on only two analyses appears to have $<\sim60$ wt percent SiO_2 (table 1). Mafic complexes in the region are generally interpreted to be older than the plutons, but none is well-dated.

Geochemistry of all these intrusive rocks except for the Persimmon Creek Gneiss is discussed in detail by Miller and others (1997; see table 1). These rocks are peraluminous and have 66 to 74 wt percent SiO_2. They vary continuously between two roughly defined endmembers, one trondhjemitic and the other granodioritic. The trondhjemite endmember is distinguished by high Na_2O ($\sim$5 to 6 wt percent) and Sr ($\sim$700 to 1000 ppm) concentrations and ϵ_{Nd} ($\sim$+3 to +6); low $\delta^{18}O$ ($\sim$7 permil); low concentrations of large-ion lithophile elements (for example, K_2O $\sim$1 wt percent, Rb $\sim$25 ppm) and heavy rare earth elements (HREE) ($\sim$2 x chondrite); and low initial $^{87}Sr/^{86}Sr$ ratios ($\sim$0.7035 to 0.7045). The granodiorite endmember has elemental and isotopic compositions more typical of continent margin magmatism, though it also is unusually HREE poor (Na_2O $\sim$4 wt percent, Sr $\sim$400 to 500 ppm, K_2O $\sim$3 wt percent, Rb $\sim$100 ppm, HREE $\sim$4 x chondrite, $^{87}Sr/^{86}Sr$ $\sim$0.706, ϵ_{Nd} $\sim$-2 to -4, $\delta^{18}O$ $\sim$8.5 permil). Both endmembers are very poor in high field strength elements such as Ta. All intrusive units except for the Persimmon Creek Gneiss appear to include both endmembers; the dikes and Pink Beds and Whiteside plutons are mostly trondhjemitic, whereas the Rabun and Looking Glass plutons are mostly granodioritic. Two elemental analyses of the Persimmon Creek Gneiss suggest this pluton is quite distinct geochemically and is similar to a typical intermediate rock from a mature arc setting. In addition to being more mafic, it lacks the distinctive enrichment in Sr and Na and depletion in HREE and K_2O that characterize the other plutons.

Previously available radiometric data did not yield reliable ages for any of these intrusions. Whole rock Rb-Sr data for the Looking Glass pluton yield ages of 390±27 Ma (selected samples; Kish, ms, 1983) and 415±76 Ma (errorchron based on all data; Miller and others, 1997). Whole rock plus mineral Rb-Sr ages of 335 Ma for a trondhjemite dike (Kish and others, 1975; Kish, 1989) and $\sim$320 Ma for the Pink Beds pluton (Miller and others, 1997) are interpreted to be cooling ages. All conventionally analyzed zircon U-Pb fractions that have been analyzed are discordant. Two fractions each from the Whiteside and Pink Beds plutons have $^{206}Pb/^{238}U$ ages of 443 to 480 Ma and $^{207}Pb/^{206}Pb$ ages of 499 to 844 Ma (Miller and others, 1997; P.D. Fullagar, unpublished data). None of these data, taken as a whole or by pluton, yield chords with geologically reasonable intercepts. A

TABLE 1

Compositions of samples used for zircon studies

	Rabun (R22A)	**Persimmon Creek (P22)**	**Whiteside (CGG)**	**Looking Glass (LG1)**	**Pink Beds (PB1)**	**dike (T10F)**
SiO_2, wt%	66.8	57.9	69.0	71.5	70.9	67.9
TiO_2	0.37	0.82	0.26	0.20	0.15	0.27
Al_2O_3	15.1	18.1	17.5	14.5	15.7	17.5
Fe_2O_{3t}	2.73	6.36	1.81	1.81	1.52	1.60
MnO	0.03	0.07	0.03	0.02	0.01	0.02
MgO	0.84	3.19	0.85	0.59	0.45	0.84
CaO	2.58	5.94	3.80	1.60	2.88	2.99
Na_2O	4.49	3.32	5.47	4.80	5.57	6.29
K_2O	2.79	2.52	1.02	3.28	1.05	1.40
P_2O_5	0.12	0.23	0.12	0.06	0.04	0.08
LOI	0.70	0.50	0.10	0.47	0.54	0.47
total	98.65	98.95	99.96	98.83	98.91	99.36
Rb, ppm	77	83	44	100	41	28
Sr	431	441	760	347	405	1046
Ba	690	570	280	1030	460	340
Th	7.7	6.9	1.1	5.7	2.1	1.9
U	0.8	1.1	0.4	3.1	0.6	1.0
Zr	150	240	110	84	92	100
Ta	(0.4)	0.34	(0.2)	0.4	0.2	(0.04)
La	28	44.6	4.4	11.91	11	8
Ce	52	90.4	10	25.71	19	17
Nd	19	38	5	10.67	7	10
Sm	3.6	7.1	1.22	2.10	1.30	2.4
Eu	1.18	1.57	0.39	0.46	0.36	0.69
Tb	0.35	0.9	0.2	0.22	0.15	0.35
Dy	1.4	4.8	0.9	-	0.7	1.9
Yb	0.64	2.3	0.48	0.63	0.31	0.99
Lu	0.1	0.36	0.07	0.09	0.05	0.15
$^{87}Sr/^{86}Sr_i$	0.7059	-	0.7045	0.7053	0.7039	0.7040
εNd_i	-1.8	-	+3.2	-0.4	+4.9	+0.2
$^{206}Pb/^{204}Pb_{feld}$	18.49	-	-	18.47	18.17	-
$^{207}Pb/^{204}Pb_{feld}$	15.63	-	-	15.61	15.55	-
$^{208}Pb/^{204}Pb_{feld}$	38.35	-	-	38.25	37.84	-
$\delta^{18}O$	8.7‰	-	7.1‰	9.0‰	7.0‰	6.9‰
zircon sat T	755°C	762°C	731°C	714°C	720°C	720°C

Data from Miller and others (1997), except for P22 (new analysis by XRAL Laboratories) *sample locations:* R22A: Vulcan Materials quarry at Dillard, GA (Rabun Bald quad, 34°58′41″N, 83°21′28″W); P22: abandoned quarry on forest service road 83 (Prentiss quad, 35°01′51″N, 83°27′50″W); CGG: abandoned quarry on NC route 107, Cashiers (Cashiers quad, 35°07′02″N, 83°06′26″W); LG1: abandoned quarry on US Hwy 276 north of Pisgah Forest, NC (Shining Rock quad, 35°18′23″N,82°47′00″W); PB1: abandoned quarry on forest service road 1206 (Dunsmore Mtn. quad, 35°22′57″N, 82°44′25″W); T10F: abandoned quarry near intersection of NC route 191 and US Hwy 70 north of Asheville (Weaverville quad, 35°40′04″N, 82°36′24″W) single, small size fraction (<74 μm) from the Rabun pluton has a ^{206}Pb/^{238}U age of 333 and a ^{207}Pb/^{206}Pb age of 438 Ma (Miller and others, 1997). Taken together, the U-Pb data are consistent with field relations and Rb/Sr data that indicate early to mid Paleozoic magmatic ages, and they require a substantial Proterozoic inherited component and significant Pb loss. However, they do not permit quantitative assessment of any of these inferences. Initial zoning studies and ion microprobe work on the Whiteside and Rabun plutons summarized in Miller and others (1998) documented abundant inherited cores and variable Pb loss in zircons that accounted for the difficulty in interpretation of conventional U-Pb analyses and established Ordovician and Devonian ages for the Whiteside and Rabun plutons, respectively. In this paper, we present new data for the other intrusions and assess the significance of the entire data set.

METHODS

We collected very fresh 20 to 50 kg samples from quarries in each of the intrusions (fig. 2;table 1). Standard mineral separation techniques culminating in hand picking were used to select zircon grains for investigation. About 50 to 70 large grains (~80 to 300 μm) were selected from each of the samples. 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 magma and its source. Zircons were mounted in epoxy with fragments of a zircon standard, polished, and then "mapped" by backscattered electron (BSE) imaging (primarily using the JEOL 733 Superprobe at Rensselaer Polytechnic Institute; some with the ETEC Omniscan scanning electron microscope at Vanderbilt University). Variations in BSE brightness, which correlates with mean atomic number, reveal micron-scale compositional variation. We believe that Hf concentration is the principal control of BSE brightness (Hanchar and Miller, 1993), but we have also noted a good correlation between brightness and apparent U concentration indicated by ion probe analysis. Grains were viewed on the Cameca ims 1270 high-resolution ion microprobe at the University of California-Los Angeles by reflected light, so it was necessary to match the shape and crack geometry of zircons with the BSE images to locate points for analysis. Ion microprobe techniques follow those described in Quidelleur and others (1997). For our initial analyses (Whiteside and Rabun samples, performed in 1996), the ion beam was focused to a ~15 x 20 μm ellipse. Most subsequent analyses of the remainder of the samples (performed in 1997) employed a 10 x 10 μm, nearly circular beam. In some cases, ^{206}Pb/^{238}U and ^{207}Pb/^{235}U ages showed apparent reverse discordance. We are uncertain of the cause of this discordance but suspect that it is connected with imperfect centering on the much smaller ^{207}Pb peak. Where there is a reverse-sense discrepancy, we consider the ^{206}Pb/^{238}U age to be more reliable. Zircon AS3 (1099.1+0.5 Ma , Paces and Miller, 1993) was used as a standard. Almost all measured total ^{206}Pb/^{204}Pb ratios were greater than 2000 (greater than 99 percent radiogenic ^{206}Pb); a single analysis had ^{206}Pb/^{204}Pb = 74, and three others had values <1000 (table 2). Uranium concentrations were estimated semiquantitatively by comparing the peak ratio UO^{+}/ZrO$_2$ in unknowns to that in standard AS3, which has a mean concentration of 374 ppm.

We assumed that concentric, euhedral, oscillatory rim zones without discontinuities grew at the same time (within analytical uncertainty) for all zircons in a given sample. Such zones almost certainly represent magmatic growth (Paterson, Stephens, and Herd, 1989; Vavra, 1990; Miller and others, 1992; Hanchar and Miller, 1993; Roberts and Finger, 1997; Pidgeon, Nemchin, and Hitchen, 1998), and it is highly unlikely that growth of rims from a single sample spanned a measurable interval. We expect a noticeable discontinuity between inherited zircon in the interior and magmatic overgrowth, because some resorption is likely and conditions (T, melt composition) are

Table 2

Zircon Pb/U data for analyzed spots

analysis[1]	^{206}Pb*/^{238}U	2 σ	^{207}Pb*/^{235}U	2 σ	age, Ma ^{206}Pb*/^{238}U	2 σ	age, Ma ^{207}Pb*/^{235}U	2 σ	age, Ma ^{207}Pb*/^{206}Pb	2 σ	% radiogenic ^{206}Pb[2]	U conc. (ppm)
LG1-A10-sp1	0.0576	0.0010	0.419	0.012	361	6	355	10	317	54	100.0	928
LG1-A10-sp2	0.1744	0.0054	1.781	0.068	1036	30	1039	26	1043	46	100.0	117
LG1-A11-sp1	0.0524	0.0008	0.387	0.014	329	6	332	10	350	82	99.9	654
LG1-A11-sp2	0.1931	0.0080	2.047	0.096	1138	44	1131	32	1118	66	99.9	127
LG1-A14-sp1	0.0608	0.0006	0.447	0.008	381	4	375	6	341	34	99.9	2094
LG1-A14-sp2	0.0607	0.0014	0.430	0.066	380	8	363	48	259	334	94.1	1069
LG1-A14-sp3	0.1622	0.0040	1.647	0.052	969	22	989	20	1033	38	99.9	309
LG1-A14-sp4	0.0546	0.0008	0.398	0.008	343	6	341	6	324	54	99.9	1573
LG1-A18-sp1	0.1814	0.0046	1.933	0.074	1075	26	1093	26	1129	54	99.9	176
LG1-A22-sp1	0.1535	0.0040	1.570	0.134	921	22	959	54	1047	158	95.8	317
LG1-A22-sp2	0.0608	0.0010	0.453	0.012	381	6	380	8	374	46	100.0	1117
LG1-A23-sp1	0.3734	0.0302	8.287	0.706	2045	142	2263	78	2466	70	99.8	17
LG1-A23-sp2	0.4620	0.0392	12.900	1.102	2448	172	2673	80	2847	82	99.2	17
LG1-A23-sp3	0.0599	0.0016	0.460	0.082	375	10	384	58	440	372	97.2	297
LG1-B4-sp1	0.0585	0.0008	0.425	0.010	366	4	360	8	316	48	99.9	1413
LG1-B5-sp1	0.2180	0.0088	2.702	0.128	1271	46	1329	36	1423	72	99.8	49
LG1-B6-sp1	0.0566	0.0010	0.374	0.068	355	6	322	50	94	406	92.0	993
LG1-B10-sp1	0.1887	0.0044	2.046	0.042	1115	24	1131	14	1162	34	100.0	277
P22-D1-sp1	0.1426	0.0028	1.455	0.038	859	16	912	16	1042	46	99.8	367
P22-D1-sp2	0.0793	0.0014	0.621	0.018	492	8	490	12	482	66	99.9	415
P22-D7-sp1	0.2289	0.0170	2.731	0.310	1329	88	1337	84	1350	164	99.6	20
P22-D7-sp2	0.0732	0.0012	0.569	0.012	455	8	457	8	468	50	99.9	446
P22-D17-sp1	0.2045	0.0140	2.353	0.210	1200	76	1228	64	1279	118	99.8	25
P22-D17-sp2	0.0749	0.0012	0.571	0.022	466	8	458	14	422	76	99.2	993
P22-D17-sp3	0.0751	0.0020	0.588	0.026	467	12	469	16	481	88	99.9	250
P22-D20-sp1	0.1812	0.0062	1.854	0.104	1073	34	1065	36	1048	84	99.9	79
P22-D20-sp2	0.0767	0.0012	0.605	0.016	477	8	481	10	500	40	99.9	766
P22-D9-sp1	0.0766	0.0012	0.593	0.016	476	8	473	10	460	50	99.9	460
P22-E6-sp1	0.0755	0.0052	0.745	0.538	469	32	565	314	973	1386	75.5	122
P22-D23-sp1	0.0751	0.0030	0.566	0.038	467	18	455	26	397	148	99.8	92
PB-A4-sp1	0.0610	0.0028	0.440	0.030	382	18	370	22	296	148	99.7	99
PB-A4-sp2	0.0585	0.0016	0.409	0.026	366	10	348	18	228	120	99.8	125
PB-A4-sp3	0.0627	0.0018	0.412	0.020	392	10	351	14	84	106	99.9	182
PB-A8-sp1	0.1769	0.0098	1.702	0.136	1050	54	1009	52	922	124	99.7	34
PB-A8-sp2	0.0633	0.0018	0.429	0.018	396	12	363	12	157	82	99.9	217
PB-A9-sp1	0.1748	0.0058	1.719	0.088	1038	32	1016	32	967	66	99.9	89
PB-A11-sp1	0.1938	0.0124	2.201	0.200	1142	66	1181	64	1254	134	99.4	23
PB-A13-sp1	0.1056	0.0026	0.901	0.038	647	14	652	20	670	80	99.6	207

PB-A13-sp2	0.1181	0.0070	1.024	0.110	720	40	716	56	704	164	99.8	131
PB-A16-sp1	0.1530	0.0124	1.535	0.132	918	70	945	52	1007	130	100.0	23
PB-A16-sp2	0.0612	0.0014	0.458	0.028	383	8	383	20	385	126	98.8	345
PB-B2-sp1	0.1714	0.0084	1.766	0.100	1020	46	1033	36	1061	82	99.9	44
PB-B7-sp1	0.0597	0.0030	0.419	0.068	374	18	355	48	237	326	99.0	55
PB-B7-sp2	0.0570	0.0032	0.412	0.062	357	20	351	46	305	324	99.3	51
PB-B12-sp1	0.2056	0.0064	2.284	0.084	1206	34	1207	26	1210	38	100.0	187
PB-B16-sp1	0.0745	0.0034	0.567	0.048	463	20	456	32	418	172	99.6	89
PB-B16-sp2	0.1373	0.0038	1.282	0.058	830	22	838	26	860	76	99.7	128
PB-B27-sp1	0.0634	0.0018	0.476	0.016	396	10	395	10	388	68	100.0	412
PB-C7-sp1	0.1480	0.0166	1.425	0.272	890	94	900	114	924	324	99.0	12
PB-C21-sp1	0.1734	0.0104	1.774	0.124	1031	56	1036	46	1048	88	99.8	42
TR10-D2-sp1	0.1679	0.0100	1.607	0.150	1001	56	973	58	911	132	99.7	27
TR10-D4-sp1	0.0659	0.0052	0.352	0.178	412	32	306	134	-1	0	97.3	18
TR10-D9-sp1	0.0643	0.0034	0.535	0.062	402	20	435	42	616	234	99.7	26
TR10-D9-sp2	0.1666	0.0060	1.701	0.086	994	34	1009	32	1042	72	99.8	107
TR10-D9sp2@1	0.1861	0.0144	1.942	0.184	1100	78	1096	64	1086	114	99.9	46
TR10-D17-sp1	0.1936	0.0112	2.108	0.188	1141	60	1151	62	1172	130	99.6	22
TR10-E1-sp1	0.1615	0.0052	1.623	0.060	965	28	979	24	1011	44	99.9	195
TR10-E1-sp2	0.1898	0.0124	1.888	0.136	1120	68	1077	48	991	64	99.9	129
TR10-E1-sp3	0.1807	0.0056	1.955	0.066	1071	30	1100	22	1159	38	99.8	167
TR10-E2-sp1	0.0789	0.0046	0.599	0.046	490	28	477	30	414	124	99.9	117
TR10-E2-sp2	0.1032	0.0052	0.779	0.044	633	30	585	26	401	50	100.0	429
TR10-E2-sp3	0.1936	0.0120	2.030	0.160	1141	64	1126	54	1096	112	99.6	27
TR10-E2-sp4	0.0723	0.0044	0.612	0.058	450	26	485	36	653	150	100.0	32
TR10-E2-sp5	0.1756	0.0118	1.737	0.174	1043	64	1022	64	979	160	99.7	23
TR10-E10-sp1	0.1558	0.0054	1.667	0.078	933	30	996	30	1137	76	99.5	84
TR10-E10-sp2	0.1788	0.0052	1.923	0.064	1060	28	1089	22	1146	34	99.9	132
TR10-E10-sp3	0.0723	0.0030	0.521	0.056	450	18	426	38	295	244	99.6	66
TR10-E14-sp1	0.1257	0.0038	1.161	0.044	763	22	782	22	838	62	99.7	258
TR10-E14-sp2	0.1961	0.0110	2.134	0.164	1154	60	1160	52	1170	92	99.8	49
TR10-E14-sp3	0.0665	0.0026	0.501	0.050	415	16	412	34	397	202	98.9	166
TR10-F18-sp1	0.1585	0.0080	1.598	0.082	948	44	969	32	1017	72	99.9	132
TR10-F1-sp1	0.0688	0.0024	0.510	0.030	429	14	419	20	365	112	99.7	141
TR10-F13-sp1	0.0657	0.0042	0.441	0.082	410	26	371	58	132	396	99.0	37

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*radiogenic Pb, corrected for common Pb

[1] each analysis represents a single spot on a zircon; label represents sample number-zircon number-spot number; "@ 1" indicates second analysis at same spot; sample numbers: R = R22A, Rabun pluton, C = CGG, Whiteside pluton, LG1 = Looking Glass pluton, P22 = Persimmon Creek Gneiss, PB = PB1, Pink Beds pluton, TGR10 = trondhjemite dike;

[2] % radiogenic ^{206}Pb calcualted from uncorrected ^{206}Pb/^{204}Pb ratios (% radiogenic ^{207}Pb, calculated similarly, is not shown); common Pb ratios used in correction: ^{206}Pb/^{204}Pb = 18, ^{207}Pb/^{204}Pb = 15.5.

inevitably different for different episodes of zircon growth. Following this reasoning, we analyzed points in what we interpreted to be magmatic overgrowths and pooled them for each sample. In almost all cases (see discussions of ambiguous data in following section), the pooled data were consistent with magmatic growth and variable subsequent Pb loss. Analytical points tend to cluster at an upper limit and spread downward to varying extents toward younger ages. We evaluated the ages in two ways: (1) We checked which analyses appeared to come from the same, potentially true-age, magmatic population (that is, no Pb loss within analytical uncertainty) by calculating pooled mean $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ and MSWD. If MSWD was high (>3), younger outlier analyses were excluded to bring the recalculated MSWD down. With two possible exceptions discussed in the following section, *all* outliers from the dominant rim populations were analyses that were displaced toward lower $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$, presumably reflecting Pb loss. For those samples that appeared to register Pb loss, we accepted the data that clustered at the old end of the array with a reasonable MSWD and used it as an estimate of the age of rim growth. We considered $^{206}Pb/^{238}U$ data to be more reliable than $^{207}Pb/^{235}U$ data, and so we focused on coherence of $^{206}Pb/^{238}U$ in selecting analyses to be used in the pooled weighted mean, which we accept as the best estimate of true age. (2) We plotted the rim $^{206}Pb/^{238}U$ data on probability plots–sums of probabilities for all analyses broken down into million year intervals, assuming Gaussian distributions of uncertainties (Deino and Potts, 1992). Our assumption was that the upper limit of strong probability (usually marked by a distinct peak) represented the likely true age, with younger ages representing Pb loss.

Because there was no reason to assume that any identifiable group of cores would be of the same age, we did not pool core data for statistical purposes. In discussions below we use the $^{206}Pb/^{238}U$ for core analyses that are concordant within 2σ uncertainty. For discordant analyses, we use the $^{207}Pb/^{206}Pb$ age as our best estimate (recognizing that it is in fact a lower limit on true age).

All reported uncertainties in text, tables, and figures are $\pm 2\sigma$.

RESULTS

More than 95 percent of the zircon grains we investigated have cores and magmatic rims that were identifiable in BSE. Grains from the pluton samples have thick rims (~30 to 100 µm parallel to c-axis; 0 to 30 µm perpendicular to c-axis) marked by delicate, oscillatory, euhedral zoning. Cores are commonly fairly large (~50 to 150 µm) and ovoid. The large ovoid cores and euhedral rims generally result in a stubby but euhedral, doubly terminated morphology (aspect ratio ~2 or less). Many cores are dark and unzoned in BSE; others have truncated oscillatory zones. Cores older than 1.3 Ga are invariably dark and lack oscillatory zoning. Cracks, which are probably related to radiation damage, are concentrated in bright zones, most commonly in rims, and vary greatly in abundance from grain to grain and sample to sample. As discussed below, zircons from the dike have thin, discontinuous rims surrounding very large, often angular cores, commonly resulting in stubby anhedral morphology. Examples of zoning are illustrated in figure 3.

New U-Pb data for analyzed points are presented in table 2 and figures 4 through 6; data for the Whiteside and Rabun plutons are available from the Geological Society of America (GSA Data Repository item 9851) or from the first author. All rim ages are well within the constraints on intrusion ages discussed previously, with preferred pooled ages ranging from 374 to 472 Ma. They are concordant or very nearly so within 2σ uncertainty. Apparent core ages range from approximately the age of the oldest plutons (460 Ma) to 2.9 Ga. Zoning and rim and core ages of individual intrusions are discussed below.

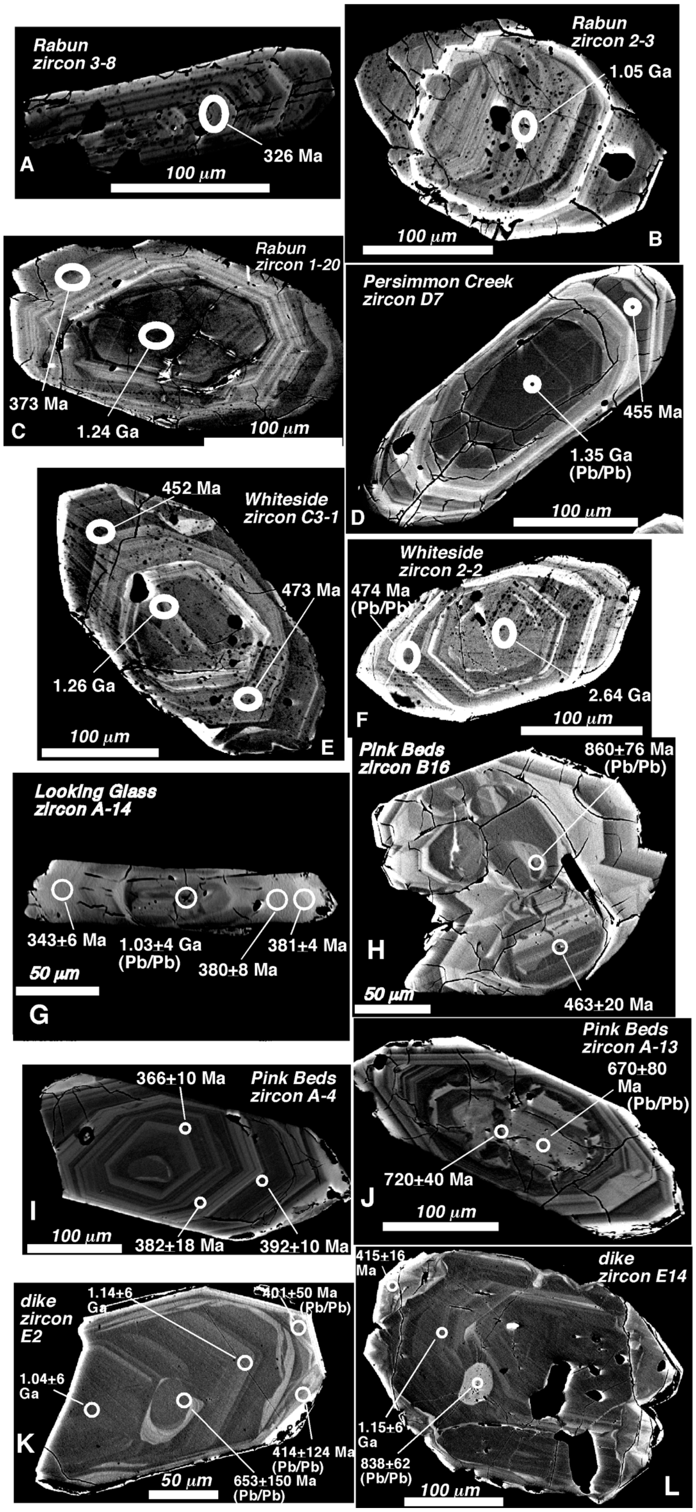

Fig. 3. Backscattered electron images of representative zircons, showing compositional zonation and locations of analyzed spots. Ages are ^{206}Pb/^{238}Pb unless noted otherwise; uncertainties are +2 σ (values for uncertainties are for final significant figures–for example, for 2.85+8 Ga, the uncertainty is 0.08 Ga). See Miller and others (1998) for other images of Rabun and Whiteside zircons.

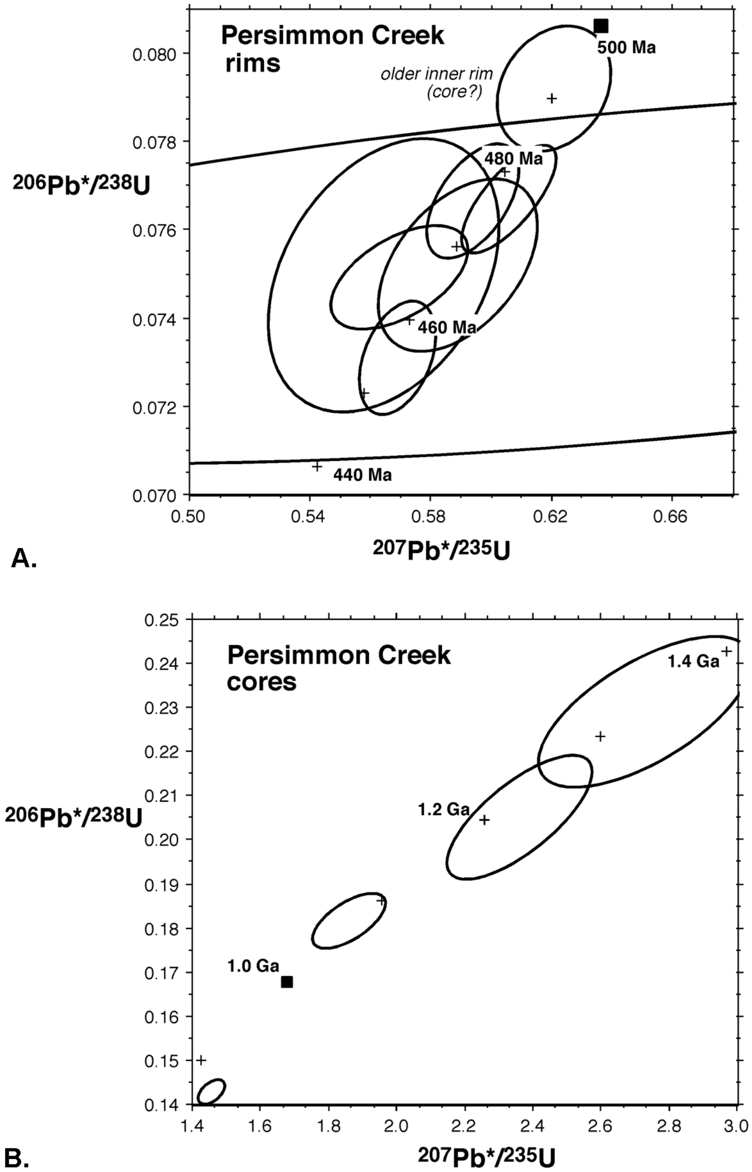

Fig. 4. Analyses of zircons plotted on concordia; uncertainty ellipses are ±2 σ (see Miller and others, 1998, for Rabun and Whiteside concordia). (A) Persimmon Creek rims; (B) Persimmon Creek cores.

Rabun pluton.–The Rabun sample includes the largest number of zircon grains that lack cores. Acicular core-free grains with aspect ratios of about 5 constitute 15 to 20 percent of the population (fig. 3A). The remainder are mostly typical of the zircons from the pluton samples, with large ovoid cores and euhedral rims. Some have thin, bright BSE zones surrounding strongly oscillatory zoned cores and inside the magmatic rims (fig. 3B). Cracks are common, especially in the rims.

We interpret eight out of twelve rim analyses to reflect Pb loss (up to 30 percent). The remaining four cluster tightly, yielding a $^{206}Pb/^{238}U$ age of 374±4 Ma (MSWD =

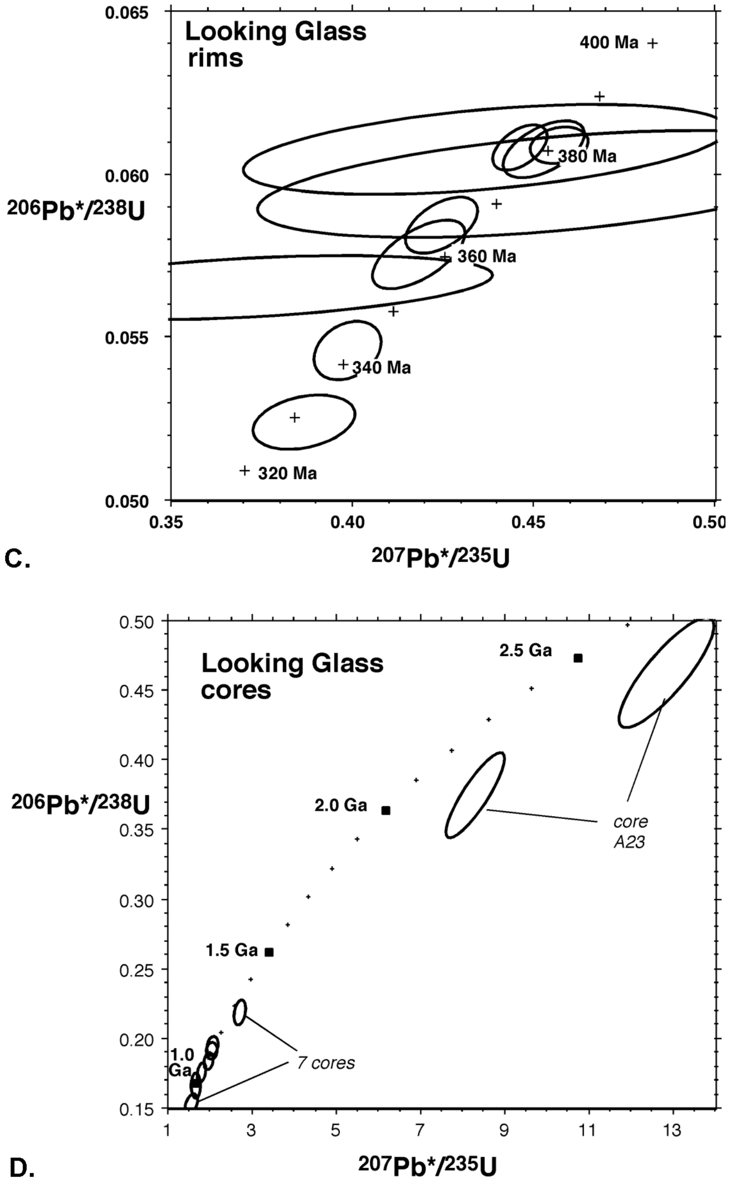

Fig. 4(C) Looking Glass rims; (D) Looking Glass cores.

1.3)(^{207}Pb/^{235}U age is 363±8 Ma, MSWD 0.04). The probability plot (fig. 5A) reveals a distinct shoulder at ~375 Ma and a peak at 355 Ma. Because the analyzed zones that yield ages around 370 to 375 Ma appear to represent the final stage of magmatic growth, our preferred interpretation is that this is the age of the pluton and that modest Pb loss is very common. Alternatively, it is possible (though less likely) that the age is ~355 Ma and that the older ages are inherited from a very young plutonic source.

Most measured core ages are between 1.0 and 1.2 Ga, but one core is 1.41 Ga, and two discordant points from another core both yield ^{207}Pb/^{206}Pb ages of 2.6 of 2.7 Ga (fig. 3B,C).

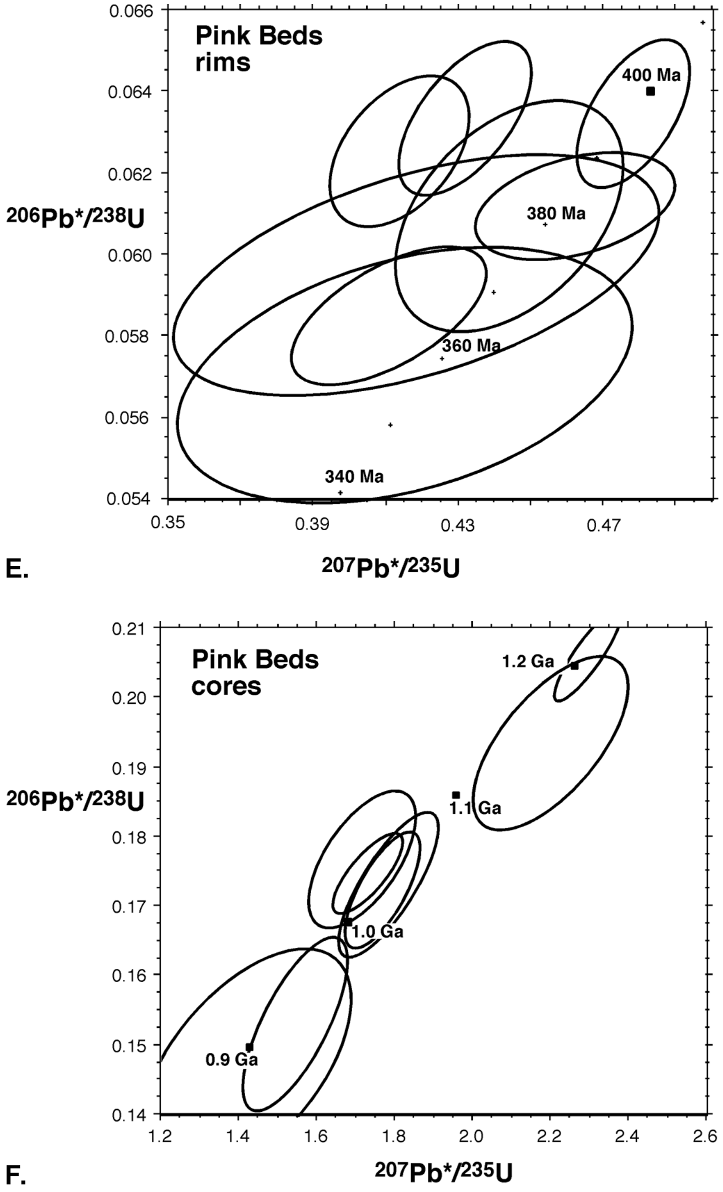

Fig. 4(E) Pink Beds rims; (F) Pink Beds cores.

Persimmon Creek Gneiss.–Zoning in both rims and cores of zircons from the Persimmon Creek Gneiss is especially well developed. All grains have readily identifiable cores, most with truncated oscillatory zoning. Cracks are only modestly developed.

One of seven rim analyses appears to reflect minor Pb loss (455±8 Ma ^{206}Pb/^{238}U; $>2\sigma$ younger than any other rim analysis). Another analysis, concordant at 492±8 Ma (^{206}Pb/^{238}U) and 490±11 (^{207}Pb/^{235}U), differs significantly from the weighted mean of the remaining five analyses (^{206}Pb/^{238}U 472±4 Ma, MSWD = 1.6; ^{207}Pb/^{235}U 472±6 Ma, MSWD = 2.1)(fig. 4A,I). This apparently older, relatively precise age may (A) be the best

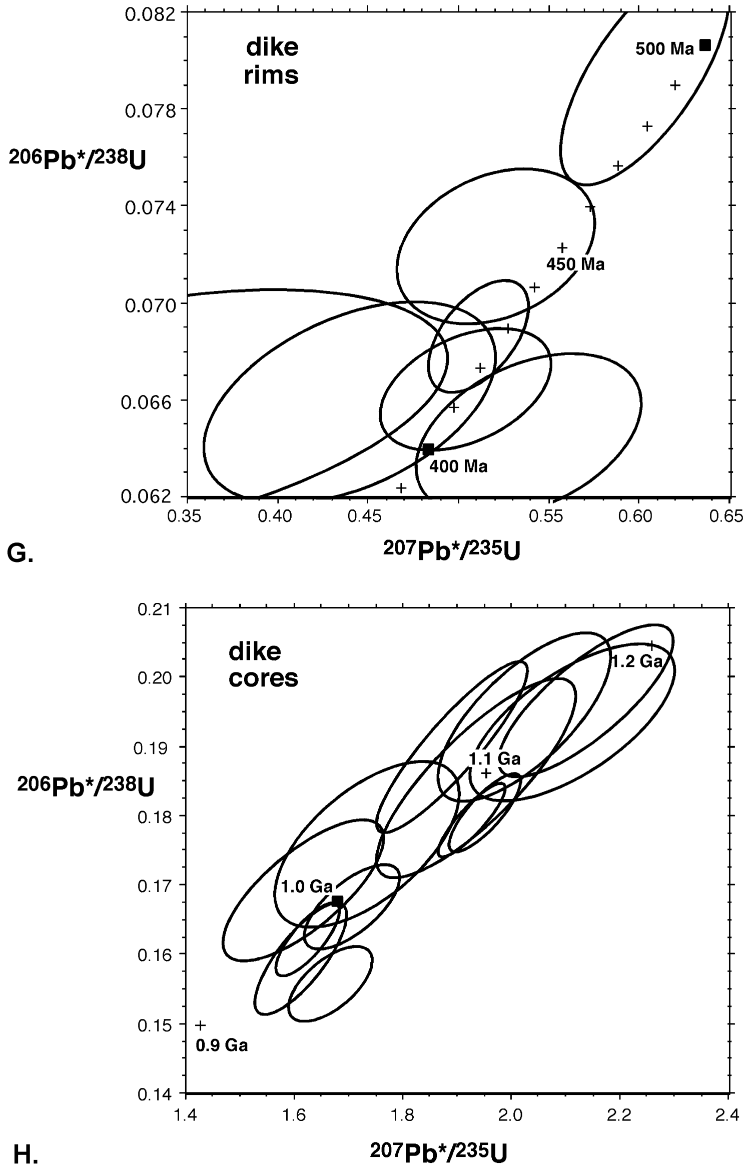

Fig. 4(G) dike rims; (H) dike cores.

estimate of true age, with all other analyses reflecting Pb loss; (B) be an inheritance age from a slightly older pluton in the source region; or (C) simply be an analytical artifact. Based on its location within the zoning pattern, it does not appear to be inherited. The probability plot (fig. 5B) shows twin, closely spaced peaks at 475 and 467 Ma. The data strongly indicate an age of ~480±15 Ma; we cannot confidently distinguish between the possible older age of ~492 Ma and the dominant age of ~470 to 475 Ma.

Most analyzed cores of Persimmon Creek zircons are 1.0 to 1.25 Ga; a single core is ~1.4 Ga (figs. 4B, 3D).

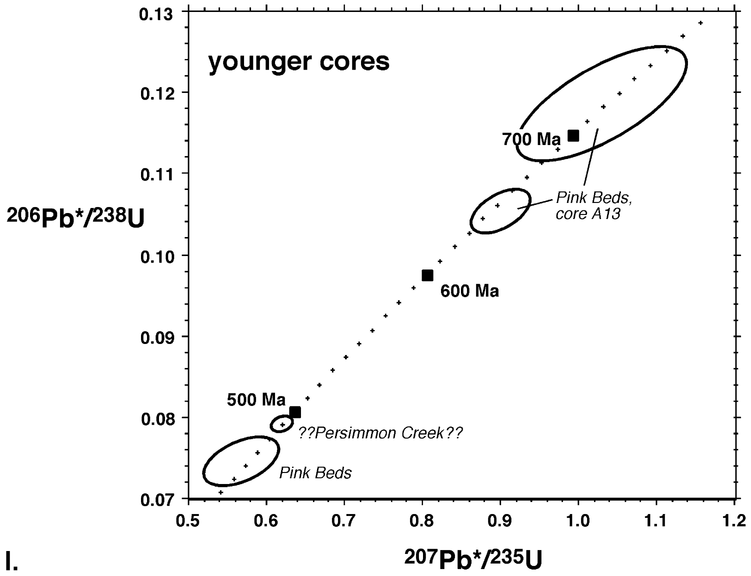

Fig. 4(I) younger cores (<0.8 Ga) from Pink Beds pluton and a questionable core from Persimmon Creek.

Whiteside pluton.–Whiteside zircons range from very stubby to acicular (aspect ratios ~1 to 4). About 10 to 15 percent lack visible cores. Relative proportions of core and rim are highly variable from grain to grain. Most cores are dark, but a few have truncated oscillatory zoning, and several grains have multiple cores. Cracks are sparse.

None of the seven Whiteside rim analyses exhibits clear evidence for Pb loss. Six of the seven yield a concordant pooled age (^{206}Pb/^{238}U 466±10 Ma, MSWD 1.6; ^{207}Pb/^{235}U 459±12 Ma, MSWD 3.3). The seventh analysis is very strongly reversely discordant but yields a ^{207}Pb/^{206}Pb age (474±32 Ma) essentially identical to the weighted mean age of the other six; we suspect an error in U concentration. The probability plot (fig. 5C) shows a smooth, symmetrical broad distribution with a Gaussian shape and a well defined peak at 466 Ma.

Most cores are 1.20 to 1.28 Ga. A single core is concordant at ~2.6 Ga (fig. 3E).

Looking Glass pluton.–All zircons investigated from the Looking Glass pluton have distinct cores. Most cores are ovoid and dark and either lack zoning or have large, simple zones bounded by curved surfaces; some are oscillatory zoned, rounded fragments. A few grains have multiple cores. Rims are fairly heavily cracked.

Five of nine rim analyses reflect Pb loss (fig. 4C). The remaining four analyses yield ages of 380±3 Ma (^{206}Pb/^{238}U; MSWD = 0.4) and 377±4 (^{207}Pb/^{235}U; MSWD = 0.4), consistent with Kish's (ms, 1983) Rb-Sr age of 390±27 Ma. The probability plot (fig. 5D) reveals a very large, sharp peak at 380 Ma, confirming the age of the pluton.

The dominant core population is 1.0 to 1.2 Ga (figs. 3G, 4D). One core yields a ^{207}Pb/^{206}Pb age of 1.42 Ga. Two discordant analyses from another yield a maximum ^{207}Pb/^{206}Pb age of 2.85 Ga (figs. 3G, 4D). The chord connecting these two points gives an upper intercept of 3.2 Ga, which we take to be the maximum age of this zircon, and a lower intercept of 1.7 Ga.

Pink Beds pluton.–Zircons from the Pink Beds pluton are quite variable. All have identifiable cores, but they range from very small to dominating the grain, and some grains have well-defined multiple cores (fig. 3H). Grains with small cores commonly have very large, delicately zoned rims (fig. 3I). Some cores are raggedly zoned (fig. 3J),

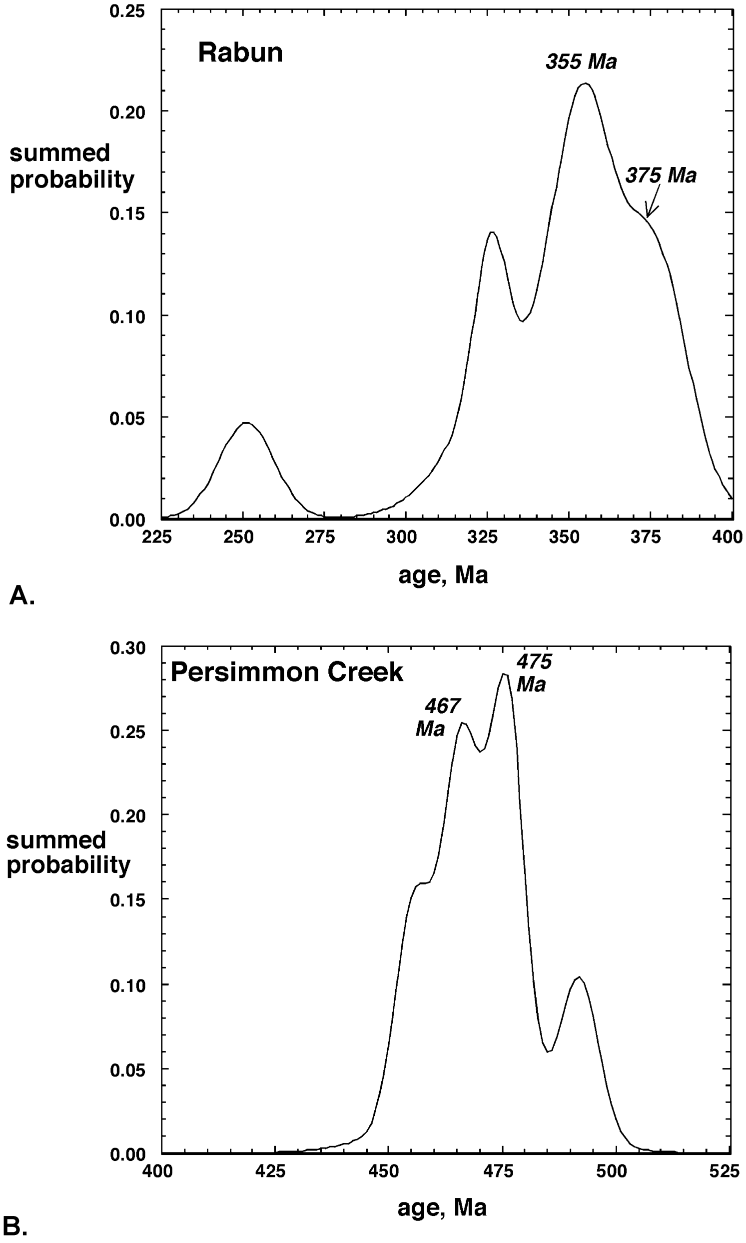

Fig. 5. Probability plots of $^{206}Pb/^{238}U$ ages of zircon rims. Gaussian probability distributions of individual analyses are summed for each sample in million year intervals (Deino and Potts, 1992). (A) Rabun pluton; (B) Persimmon Creek Gneiss.

whereas others appear to represent small fragments of large, oscillatory zoned crystals. Intensity of cracking is highly variable.

Lead loss is evident in two of eight rim analyses (fig. 4E). Two of the remaining six are distinctly reversely discordant, leading to pooled ages that are also reversely discordant. The weighted mean ages are 388±5 ($^{206}Pb/^{238}U$; MSWD = 1.9) and 374±6

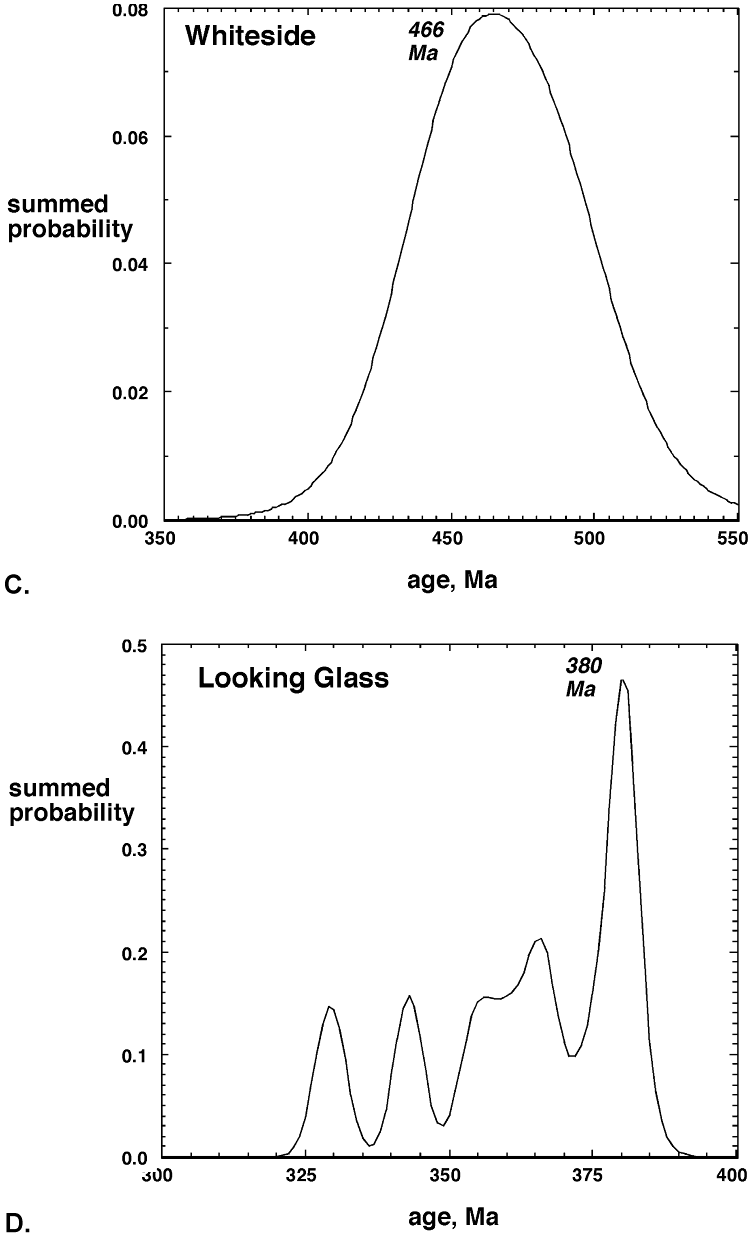

Fig. 5(C) Whiteside pluton; (D) Looking Glass pluton.

Ma ($^{207}Pb/^{235}U$; MSWD = 6.0). The probability plot (fig. 5E) shows closely spaced but distinct peaks at 393.5 and 384.5 Ma. We suspect that the older age is more reliable. There is no correlation between rim ages and distance from rim, and the rims appear to represent continuous growth, so it is unlikely that there was more than one distinguishable episode of growth represented by rim zones.

Most cores are 1.0 to 1.25 Ga, but two yield relatively young ages (fig. 4F,I). One is concordant at ~460 Ma (fig. 3H); two analyses from the other are also roughly

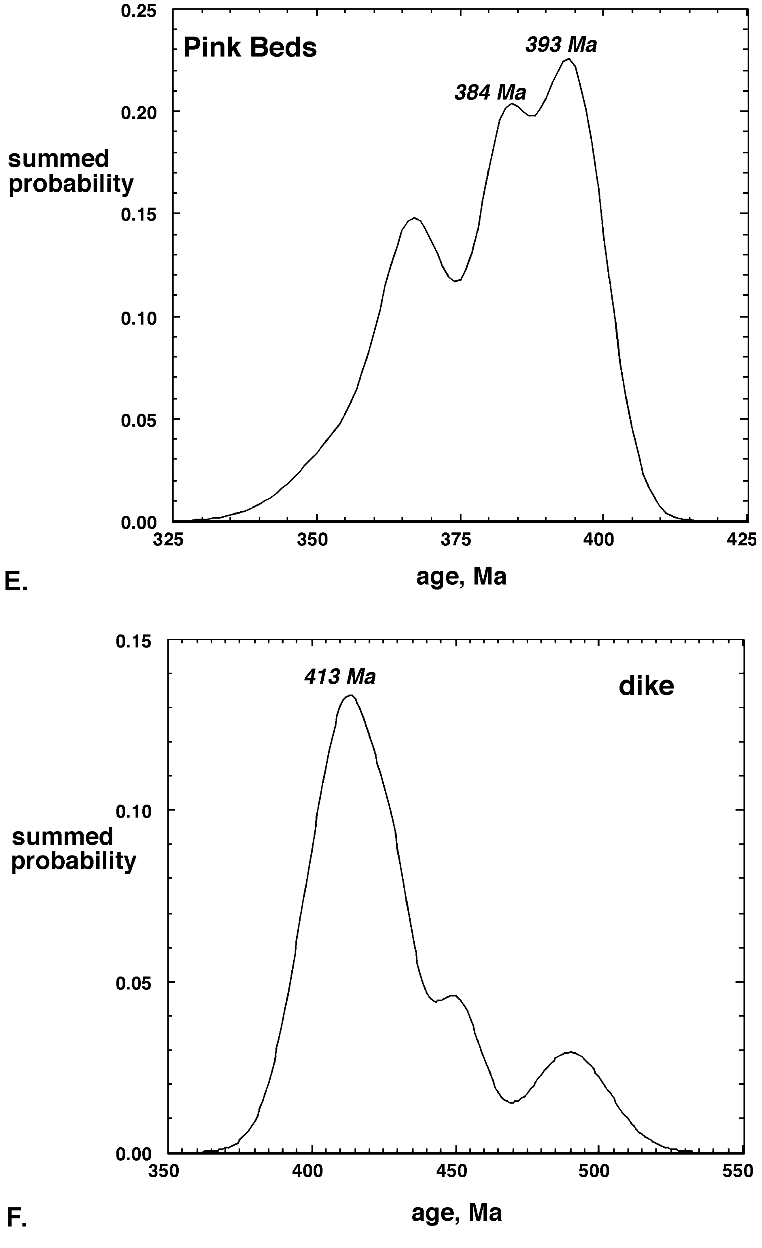

Fig. 5(E) Pink Beds pluton; (F) dike.

concordant within uncertainty at 650 and 720 Ma (fig. 4I). We interpret 720 Ma to be close to the true age and the younger age to reflect modest Pb loss.

Trondhjemite dike.–The zircons from the dike are very distinct from those from all other samples. They are almost entirely core, with thin, discontinuous rims ranging from 0 to 30 µm thick (fig. 3M,K,L). Almost all are stubby and anhedral with aspect ratios less than 2. The cores themselves are variably zoned. Some are dark and lack evident zoning,

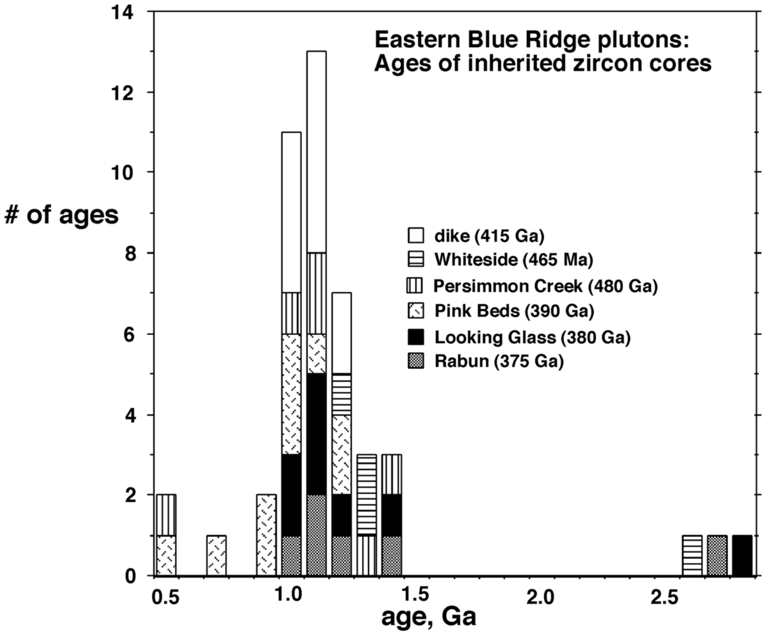

Fig. 6. Distribution of zircon core ages from eastern Blue Ridge plutons. $^{206}Pb/^{238}U$ ages are used for concordant data, $^{207}Pb/^{206}Pb$ ages for discordant data. (The three Archean cores were each analyzed twice; only the more concordant of the two data points is shown for each core).

others have oscillatory zoning, yet others are clearly composite, and still others have overgrowths that predate the magmatic rims. These grains have relatively few cracks.

Analyses of rims of the dike zircons present problems that are not encountered with the zircons from the plutons. Their small size makes it more difficult to avoid adjacent core with the ion beam and requires placement at the very margin of the grain, which commonly has a less regular surface than the remainder of the grain (poorer polish, cracks, downward slope at the edge toward epoxy matrix). Although Pb loss is more likely at the edge, we could not identify evidence for it in any of the seven rim analyses. Two strongly reversely discordant analyses from thin rims at the very edges of grains (see fig. 3K) have older $^{206}Pb/^{238}U$ ages (490, 450 Ma) than the rest and were excluded from the mean. The remaining five yielded a $^{206}Pb/^{238}U$ age of 417 ± 9 Ma (MSWD = 1.3) and a $^{207}Pb/^{235}U$ age of 414 ± 17 Ma (MSWD = 0.9)(fig. 9A). The probability plot (fig. 5F) reveals a major peak at 413 Ma and small humps based on single ages at 450 and 490 Ma. We suspect that the age is in fact about 410 to 420 Ma and that the discordant older ages are artifacts of the difficulty of analysis of high-relief grain edges.

All cores of dike zircons appear to be 1.0 to 1.15 Ga (fig. 4H). Two points within 1.1 Ga cores yielded substantially younger, discordant ages, apparently as a result of Pb loss (fig. 3K,L).

DISCUSSION

Interpretation of Zircon Growth and Degradation History

The nearly ubiquitous cores mark the initial growth of the zircon grains. Perhaps 50 percent of the cores are marked by fine-scale oscillatory zoning that we interpret to indicate growth from a magma (Hanchar and Miller, 1993). Zoning patterns indicate that these cores are fragments of much larger broken grains. The remainder of the cores are either dark and lack apparent zoning or have larger zones with anhedral, commonly rounded, boundaries. We are not sure how to interpret these cores – they may represent metamorphic growth, or their original magmatic zoning may have been obscured by metamictization and homogenization. No grains older than 1.3 Ga have oscillatory zonation. Almost all cores are rounded, probably by resorption in melt. The exceptions are those in zircons from the dike, which are subangular and appear to have undergone little resorption. Although typical cores are only about 50 to 100 μm in diameter, the original grains from which they were derived may have been considerably larger. As noted above, many cores are clearly fragments, and we interpret resorption to have led to more equant, spherical shapes.

The cores are the nuclei upon which growth in the Paleozoic magmas occurred. Cores tend to be subequant or only slightly elongated; aspect ratios of zircon grains $\geq\sim2$ are a result of much faster growth in the melt parallel to the c-axis, hence rims are many times thicker in the c-direction. Watson's (1996) models of dissolution and growth of zircon grains indicate that it should generally take a minimum of many thousands of years for tens of μm of rim growth. Rim thicknesses that, excluding the dike, average about 50 μm thus suggest very long magma residence times for the Blue Ridge zircons. Thus, these are not late, accidentally included grains, and the magma did not crystallize rapidly. Thin rims on its zircons suggest that the dike is an exception in that it probably crystallized rapidly, as also suggested by its fine-grained groundmass.

Retention of inherited cores suggests that melts were zircon-saturated. Assuming that this is so and that the approximate Zr concentration in the melts can be established, the magma temperature can be estimated (Watson and Harrison, 1983). Igneous rocks do not perfectly reflect melt compositions, because they were formed as mixtures of melt and crystals, but their compositions do generally constrain melt Zr well enough for application of the zircon thermometer. It is reasonable to assume that almost all Zr in these rocks is now held in zircon, which was partly dissolved (now rim material) and partly restitic (cores). The cores (undissolved zircon), though prominent, make up only ~10 to 20 percent of the masses of the observed zircon grains and therefore have minimal effect on the calculated saturation temperature. Cumulate material in the rocks presumably includes both zircon and other crystals, so it also will not greatly influence estimates of Zr concentration in melt. An average Zr concentration for a pluton probably gives a reasonable estimate of Zr concentration in the initial melt (±25 percent uncertainty in Zr concentration results in uncertainty of only ~20°C in temperature estimate). Typical compositions of these intrusions (~75 to 150 ppm Zr) yield saturation temperatures near 700° to 760°C (table 1; the Persimmon Creek sample, with a more mafic composition and therefore higher zircon solubility, also yields a saturation T of 760° despite its higher Zr concentration of 240 ppm).

The abundance of zircons with cores suggests that crystal fractionation prior to emplacement of these intrusions was not very effective in removing zircon and reducing Zr and therefore that these Zr concentrations and the implied temperatures may be reasonable approximations of the temperature of magma generation. However, although the zircon saturation thermometer is very robust in terms of tolerating imprecision in estimates of melt compositions, it *does* assume saturation, a condition that must be met for the thermometer to work but that *may* not apply. According to Watson's (1996) calculations, zircons with radii of ~100 to 200 μm may survive (as partially dissolved cores) for many thousands, though not hundreds of thousands, of years during thermal events that reach temperatures as much as 100°C or more above the apparent saturation temperature. Melt immediately adjacent to the dissolving grain is saturated, but the melt as a whole remains undersaturated during the high-T excursion. The implication is that if the melting events that produced these magmas were of long duration ($>10^5$-10^6 yrs), the zircon saturation temperatures are good estimates of the temperature of these magmas and of melting. If they were brief events or if some zircons were prevented from contacting melt, they may be poor estimates, at least of maximum temperature – but if thermal history can be constrained, zircon survival may provide a useful indicator of duration of the thermal event. The thick rims suggest that growth occurred over a protracted interval and that melt and zircon equilibrated, and therefore that saturation temperatures are reasonable estimates for the bulk of the solidification interval. This does not, however, require a long, low temperature melting interval (see discussion of petrogenesis below).

Ages of Magmatism and Constraints on Tectonism

All the plutons fit into two age groups. The Pink Beds, Looking Glass, and Rabun plutons are all ~370 to 395 Ma (mid-Devonian) and thus were emplaced during the Acadian orogeny. The Persimmon Creek Gneiss and Whiteside pluton at ~465 to 480 Ma (Middle Ordovician) crystallized during the Taconian orogeny. The dike appears to represent a distinct age of about 415 Ma, shortly before or at the beginning of the Acadian orogeny. Because of difficulty of analysis of the thin, irregular magmatic rims, the age of the dike is somewhat less certain, but we nonetheless regard it as likely that its age does lie between those of the two groups of plutons. The fabrics of the intrusions are grossly consistent with these ages: the older intrusions are relatively strongly recrystallized, whereas all the post-Taconian intrusions except the Looking Glass pluton retain distinctly magmatic textures. There is no obvious spatial correlation with age or chemical composition. The Pink Beds and Looking Glass plutons are very close spatially and in age but are geochemically distinct. The Ordovician Whiteside pluton, which is geochemically rather similar to the Pink Beds but quite different from the nearby Looking Glass pluton, lies between these two Devonian intrusions and the Devonian Rabun pluton (which is geochemically akin to the Looking Glass pluton). The Whiteside pluton and the Persimmon Creek Gneiss are similar in age, but they are in separate thrust sheets and probably were not initially close and differ geochemically. The nearly identical inheritance of Ordovician (Taconian) and Devonian (Acadian) plutons limits transport of this region with respect to underlying crust that contributed to the magmas. Presumably, transport during this 100 my interval must have been less than the scale of the terrane defined by this inheritance pattern. At present, we do not know this scale (see following section).

Existing models generally appeal to closure of an ocean basin by subduction and accretion of the associated arc terrane (~Piedmont terrane) to Laurentia during the Potomac (or Penobscottian) and Taconian orogenies (Hatcher, 1987, 1989; Sinha, Hund, and Hogan, 1989; Hibbard and Samson, 1995; Stewart, Adams, and Trupe, 1997). The study area has the largest concentration of Paleozoic intrusions in the Blue Ridge of Georgia and North Carolina, but even here the intrusion fraction is rather small, and the Ordovician plutons that might be postulated as part of a subduction-related arc are far less voluminous than would be expected if they represented an arc terrane. Furthermore, although compositions of the plutons are consistent with their having been part of a subduction-related magmatic arc (Miller and others, 1997; table 1), the associated mafic to intermediate rocks that are invariably part of arc assemblages are not well represented. It is conceivable that remnants of an arc of which the older Blue Ridge intrusions were a part are primarily located in the Inner Piedmont to the southeast, and that the thrust sheets that carry the Ordovician plutons of the eastern Blue Ridge have been tectonically displaced from Inner Piedmont roots. Plutons are considerably more abundant in the Inner Piedmont, but they too appear to lack mafic to intermediate associates, and their high-K, incompatible element-enriched compositions differ strikingly from the those of Blue Ridge plutons (Vinson, ms, 1999).

The modest to strong amphibolite facies recrystallization of the mid-Devonian plutons verifies Acadian (or younger) metamorphism (Goldberg and Dallmeyer, 1997).

The Chattahoochee fault crosscuts the Rabun pluton, demonstrating that faulting postdates ~375 Ma. The Soque River fault postdates the ~480 Ma Persimmon Creek Gneiss and predates the Chattahoochee fault. Taken together, these data and observations suggest formation of major thrust sheets at moderate to high temperature in the eastern Blue Ridge during the Acadian as well as the Taconian orogeny. Acadian deformation apparently did not juxtapose contrasting terranes in this region, however, as did Taconian structures (for example, the Hayesville fault), and metamorphism did not reach as high grade as it did during the Taconian. The Taconian peak predated the ~470 Ma Ordovician plutons, which intruded metamorphic rocks that were already at high grade. This observation is consistent with the 494±13 Ma metamorphic zircon rims from granulite facies metamorphic rocks west of the Persimmon Creek Gneiss at Winding Stair Gap (Miller and others, 1998), though Goldberg and Dallmeyer (1997) suggested a slightly later peak (~460 Ma) for rocks in northwestern North Carolina based on garnet Sm-Nd ages.

Implications of Inheritance

Our population of inherited cores is rather limited (55 analyses, 41 cores), but it is sufficient to identify a distinctive pattern (fig. 6). By far the dominant population among the cores of zircons from all the eastern Blue Ridge intrusions is of Middle Proterozoic age (Grenville). Much smaller populations are ~0.5 to 0.7 Ga, 1.4 Ga, and 2.6 to 2.9 Ga. Both the older (Ordovician) and younger (Devonian) plutons contain all the older populations; the youngest population is represented in the Ordovician plutons only by a single questionable "inner rim" analysis (see below). The dike zircons appear to contain only Middle Proterozoic cores.

The Middle Proterozoic ages of cores are not surprising regionally (though their abundance is surprising petrogenetically – see following section). Grenville basement of this age is well known in this area (Stieve, Sinha, and Hatcher, 1988; McConnell, ms, 1990; Quinn and Wright, 1993; Fullagar and Su, 1995; Fullagar, Goldberg, and Butler, 1997). Ubiquitous Middle Proterozoic zircons demonstrate that broadly similar basement or sediment derived from it underlay all the intrusions at the time of their emplacement.

The few young cores appear to represent both early Paleozoic (~460 Ma in the Devonian Pink Beds pluton; 490 Ma "inner rim" [outer core?] from the Ordovician Persimmon Creek Gneiss) and Late Proterozoic magmatism (~720 Ma, Pink Beds pluton). Both these ages are consistent with those of known rock units from the region that are plausible components of the deep crust beneath these plutons at the times of their emplacement. We have shown above that plutons near 470 Ma are present within tens of kilometers of the Pink Beds pluton, and very high grade zircon-forming metamorphism also occurred here at about this time (Miller and others, 1998). Furthermore, Cambrian and Ordovician plutons are exposed sporadically from Alabama to Delaware in the Piedmont terrane (Sinha, Hund, and Hogan, 1989). Bimodal intrusive and extrusive rocks exposed in the western (Laurentian) Blue Ridge of North Carolina, Tennessee, and Virginia are about 700 to 760 Ma (Su , Golberg, and Fullagar, 1994; Tollo and Aleinikoff, 1996; Aleinikoff and others, 1995; Goldberg, Butler, and Fullagar, 1986). These rocks are interpreted to be related to initial rifting of Laurentia and are likely to have been underthrust, along with sediment derived from them, beneath the Piedmont terrane well before generation of the Pink Beds pluton.

The ~1.4 Ga cores are somewhat less expectable than the ~1.1 Ga and Late Proterozoic-early Paleozoic cores. No rocks of this age have been dated in the southern Appalachians, but the 1.4 to 1.5 Ga granite-rhyolite terrane that stretches across the continent may impinge upon the eastern Laurentian basement or have contributed to sediments deposited upon it. Zircons of this age have been detected from the western Blue Ridge as inherited grains in 750 Ma granite from Tennessee (Su, Goldberg, and

Fullagar, 1994) and as detrital grains in Cambrian quartzite from Alabama (Steltenpohl and others, 1996).

The most puzzling cores are those from the Ordovician Whiteside pluton and the Devonian Rabun and Looking Glass plutons that yield Late Archean ages. The nearest known exposure of Archean rocks is 1000 km away in the Superior Province adjacent to the Great Lakes. No inherited or detrital zircons of this age have been reported from the southern or central Appalachians. The presence of these cores suggests one of the following: (1) that there is a previously unknown Archean component in Laurentian basement of the southern Appalachians; (2) that there are detrital Superior Province zircons in metasedimentary rocks of the southern Appalachians; or (3) that the eastern Blue Ridge is either part of an exotic terrane with Archean basement or contains detrital zircons shed from an unrecognized terrane.

Possibility (1) is difficult to refute, but it would require a complex configuration for Laurentian basement provinces. Based upon Pb isotope data, Sinha (1997) suggests that there may have been an Archean component in the source of the Carvers Gap Gneiss of northwestern North Carolina (western Blue Ridge). The long distance sedimentary transport implied by possibility (2) is not a major obstacle, but the apparent absence of Early Proterozoic zircon is. Although the southern Appalachians are separated from known Archean rocks by 1000 km of Early Proterozoic (1.6-2.0 Ga) terrane, we have not identified a single core in that age range. It is difficult to envision a sedimentary transport mechanism that would bring large zircons from a 1000+ km distant source but none from the intervening terrane.

The exotic continental terrane suggested as possibility (3) is highly speculative but intriguing. Any plausible source for an exotic terrane should have the potential to provide the observed pattern of older zircon inheritance: abundant grains with 1.0 to 1.25 Ga ages, some with 1.4 Ga and Late Archean ages, and relatively few (or none) with Early Proterozoic ages (the Late Proterozoic-early Paleozoic grains presumably reflect post-accretion geography). Possible sources might include northeastern Canada and the Gondwanan continents. Accretion of fragments of these terranes to southern Laurentia could have occurred during the Grenville orogeny. Sinha (1999) has suggested Grenvillian juxtaposition of contrasting terranes in what is now the Appalachians, and Dalziel, Mosher, and Gahagan (1998) propose that the Kalahari craton collided with the south-central Laurentian margin about 1.1 Ga. Alternatively, Late Proterozoic-early Paleozoic oblique transport and/or ocean basin closure might have resulted in accretion of a far-travelled terrane in or beneath the Blue Ridge. It is noteworthy that all reported occurrences of Archean (2.5-3.0 Ga) zircon in and to the east of the Appalachians are detrital or inherited grains from terranes thought to be Gondwanan or peri-Gondwanan, accreted during Appalachian orogeny (Bevier, White, and Barr, 1990; David, Gariepy, and Phillipe, 1991; Karabinos and Gromet, 1993 [northern Appalachians]; Mueller and others, 1994 [Florida]). The reported occurrences appear to differ from that described here, however, in that in each case Early Proterozoic zircon is also present.

Zircon Preservation and the Generation and History of the Eastern Blue Ridge Magmas

Possible sources of the Blue Ridge magmas, excluding Persimmon Creek Gneiss, are evaluated in Miller and others (1997) based upon petrochemical constraints. In that paper, we attempted to constrain separately the genesis of more primitive trondhjemitic and less primitive granodioritic endmembers and then to reconcile the two in a comprehensive model. Briefly, we suggested the following constraints for the trondhjemitic endmember: (1) Initial $^{87}Sr/^{86}Sr$ ratios and ϵ_{Nd} values that are depleted relative to bulk Earth require dominantly juvenile input, though the isotopic compositions are less extreme than Paleozoic depleted mantle and suggest a crustal component as well; oxygen isotope ratios are also closer to those of juvenile than of crustal rocks; (2) high Sr and absence of a negative Eu anomaly (commonly presence of a positive anomaly) suggest that feldspar was not abundant in the residue of melting; (3) low large-ion lithophile element (LIL) concentrations indicate a relatively LIL-poor (primitive, depleted) source; and (4) Very low HREE concentrations indicate a HREE-concentrating mineral in the residue, almost certainly garnet (±hornblende). Constraints on the origin of the granodiorite endmember include: (1) Less primitive isotopic compositions require a very substantial contribution from ancient crust (also consistent with moderate LIL concentrations); and (2) slightly elevated Sr, minimal Eu anomalies, and low HREE suggest a mineral in the residue (probably garnet) that would concentrate HREE and counterbalance the effect of a modest amount of feldspar on the Eu anomaly. We suggested two models, each assuming that magma compositions were acquired through open-system processes in the deep crust where garnet stability is enhanced and plagioclase diminished: (A) Arc-like mafic magmas interacted with the crust via melting-assimilation-storage-hybridization (MASH) processes (Hildreth and Moorbath, 1988); trondhjemites were highly fractionated but only slightly contaminated, whereas granodiorite was crust-rich melt with a smaller juvenile MASH component; or (B) the lower crust during the early Paleozoic included both rocks of evolved composition (felsic igneous and/or metasedimentary) and primitive rocks (arc-like mafic rocks emplaced magmatically or tectonically); as a consequence of tectonic thickening, this heterogeneous crust eventually warmed and produced melts that included variable proportions of the mafic and felsic components.

Although we still cannot discriminate confidently between these two models, our new data on zircons permit us to evaluate further the processes involved in generating these magmas (including Persimmon Creek). Two conclusions are especially obvious. First, all samples are rich in inherited zircon, verifying that ancient crustal material must have played a significant role in even the most primitive samples. Second, the plutons range over almost 100 my in age; it is therefore not required that the tectonic setting or mechanism of generation be uniform (although there seem to be no systematic distinctions in geochemistry, mineralogy, or emplacement history that indicate differences). We address below the implications of the zircon data for the histories of these magmas.

We suspect that most or all of the inherited zircon cores – at least those of Grenvillian and older age – were derived from the relatively felsic material(s) that contributed to the eastern Blue Ridge magmas. The primitive, mafic source component was probably not old (even mafic crust >1 Ga would probably have been less primitive in Nd isotopic composition than the trondhjemitic endmember), and it is unlikely to have carried older, inherited zircon. The ubiquity of inherited zircon thus suggests that relatively felsic material contributed to all the magmas. A high percentage of felsic-derived zircon cores does not, however, require a major felsic mass contribution. The small fraction (~10 to 20 percent) of zircon mass residing in cores from our separates is certainly an overestimate of the total inherited zircon fraction because we deliberately selected large grains. Furthermore, the more felsic contributors to the magmas were probably richer in zircon than the mafic contributors and provided a disproportionate share of the zircon endowment. We suspect that felsic contributions as low as 10 percent, entirely consistent with the most primitive observed isotopic compositions, could account for the amount of inheritance that we see.

The abundance of inherited cores has implications for the nature of the melting events. As noted above, preservation of cores suggests but does not prove zircon saturation in the melt (Watson and Harrison, 1983; Watson, 1996). Either temperatures of the parental melts were <750°C, or, if temperatures rose much higher (>~800 to 850°C), the high temperature interval (>750°C) was geologically brief (no more than ~10^5 yrs); or another factor (such as shielding of zircon from melt inside surviving host grains) preserved some zircon in spite of protracted high temperature. Generating appreciable magma fractions at temperatures of 750°C or below requires abundant water, either from an external source or from muscovite breakdown (Gardien and others, 1995). It is difficult to refute the possibility that water from an external source induced near-H_2O saturated melting. However, there is neither a strong reason to suspect that a fluid source was available nor any evidence that these magmas were especially water-rich – pegmatite is not unusually abundant, and there is no evidence for fluid-related alteration at contacts. Dehydration of muscovite may well have contributed to melt generation (see below), but only pelites contain enough muscovite to yield very much low-temperature melt (Gardien and others, 1995). The geochemistry of the eastern Blue Ridge intrusive rocks precludes derivation primarily from pelites (Miller and others, 1997; compare Miller, 1985) and hence it is unlikely that muscovite breakdown led to extensive low-temperature melting. An alternative to melting at ~750° or less is melting at higher temperature with preservation of metastable zircon.

At present, the most widely accepted mechanisms for large-scale melting of the crust – whether mafic or felsic – involve breakdown of hydrous minerals (biotite or hornblende) and/or introduction of heat from mafic magma and require temperatures of 800° to 900°C or more (Vielzeuf and Montel, 1994; Patiño Douce, 1995; Gardien and others, 1995; Wolf and Wyllie, 1995; Rapp, Watson, and Miller, 1991; McCarthy and Patiño Douce, 1997). If melting did occur at these temperatures, a melting mechanism is required that either would be rapid so that the zircon would not be in contact with melt for long enough to dissolve or would leave some zircon shielded from melt within a host phase. Heating associated with crustal thickening is generally considered to be a very slow process (tens of millions of years; Zen, 1988; Patiño Douce , Humphreys, and Johnston, 1990) and seems to imply protracted melting events and therefore equilibrium dissolution of zircon. It is conceivable that rapid ($<\sim10^5$ yrs) melting, melt extraction, and ascent to a cooler (<750°C) environment, where crystallization could be completed under zircon-saturated conditions, might occur as a consequence of rapid emplacement of closely spaced dikes or sills of basaltic magma (Huppert and Sparks, 1988; McCarthy and Patiño Douce, 1997).

An alternative to rapid magmatic events is shielding of a substantial fraction of zircon grains from melt for much of the event. The thick rims on all but the dike zircons require that they were eventually immersed in melt, but, if effective immersion in zircon-undersaturated melt only lasted thousands of years, they could have survived. Although melting is likely to begin at relatively low temperatures, melt fractions are thought commonly to remain small until biotite begins to dehydrate, at which point melt fraction increases rapidly and mobilization may be induced (Vielzeuf and Holloway, 1988; Gardien and others, 1995). As long as the melt fraction is quite small, many zircons may reside either as inclusions in larger grains or in very small melt pools which they can effectively saturate (dissolution of a 200 μm zircon will saturate a 1.5 mm melt pool at 900°C; compare Watson and Harrison, 1983). If they are thus preserved until the melt is mobilized, their chances of survival are greatly enhanced, because ascent and attendant cooling to whole-melt saturation temperatures of ~750°C are likely to be much faster than regional heating (Watson, 1996). The substantial proportion of zircon commonly included inside biotite (Bea, 1996a,b) provides an especially appealing way to preserve zircon: biotite breakdown may almost simultaneously release zircon into the melt, induce large-scale melting, and trigger ascent.

We emphasize that the petrogenetic problem posed by inheritance here is a common one that has not been satisfactorily addressed. Most granitic rocks with zircon inheritance have relatively low Zr concentrations and low zircon saturation temperatures (<150-200 ppm, <~800°C), and yet favored models for granite generation require temperatures $\geq$850°C. Either there is a problem with application of the zircon geothermometer, or the models for magma generation are wrong, or some kinetic factor like those discussed above permits retention of metastable zircon in hot granitic magmas.

SUMMARY

1. Plutons in the eastern Blue Ridge were emplaced during both the Ordovician (Taconian orogeny, ~470 Ma) and Devonian (Acadian orogeny, ~380 Ma). A dike interpreted to be representative of a regional swarm of trondhjemite dikes was emplaced during the intervening interval (~415 Ma). Though they mark important events in Blue Ridge history, these intrusions are neither extensive enough nor sufficiently coherent in time to have constituted a magmatic arc.

2. Almost all the investigated zircon grains have inherited cores that document an ancient crustal contribution. Most of the cores are consistent with regional geology (primarily Grenville ages of 1.0-1.25 Ga), but 1.4 Ga and 2.6-2.9+ Ga cores represent material that is not exposed in the southern Appalachians. The Archean cores are especially surprising, because the nearest present exposure of rocks of this age is 1000 km away across an Early Proterozoic terrane that is not represented among the zircon cores. The mismatch of zircon core ages with known basement and detrital zircons from the region suggests either the presence of distinctive, previously unknown crustal material in what was southeastern Laurentia or accretion of a far-travelled terrane as part of the Blue Ridge.

3. Abundant cores indicate either maintenance of saturation of the melt in zircon or preservation of metastable relics in an undersaturated melt. Low Zr concentrations in rocks indicate melt saturation only at relatively low magmatic temperatures (~750°C or less). It is possible that melts were generated at higher temperatures, with some zircons surviving because of relatively brief exposure to melt resulting from either rapid melting and extraction or shielding inside host grains. Similar processes may explain common low zircon saturation temperatures for granitic rocks with inherited zircon.

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