

Cryptic crustal events elucidated through zone imaging and ion microprobe studies of zircon, southern Appalachian Blue Ridge, North Carolina–Georgia

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ABSTRACT

Compositional zoning reveals multistage growth histories and resorption events in zircon from a high-grade terrane in the eastern Blue Ridge of North Carolina and Georgia. These zoning patterns were used to guide high-resolution ion microprobe dating that places important constraints on the evolution of the southern Appalachian crust. Zircons from granulite facies metapelite have unzoned rims that yield concordant U-Pb ages of 495 ± 14 Ma. We interpret this as the time of rim growth, which occurred during peak metamorphism early in the protracted orogenic history of the region. Detrital cores, characterized by truncated euhedral zoning, are of Grenville age (1.04–1.26 Ga). Zircons from the Whiteside and Rabun plutons have well-defined, rounded, inherited cores and euhedral, oscillatory-zoned magmatic rims. Rims of Rabun zircons record magmatic crystallization at 374 ± 4 Ma, whereas Whiteside rims yield a 466 ± 10 Ma crystallization age. Cores from both plutons include 1.1–1.3 Ga and 2.6–2.7 Ga ages. These data indicate that there was no single, voluminous episode of plutonism in this area, that similar material underpinned the region at least from 370 to 470 Ma, and that previously unrecognized Archean basement or Archean basement–derived sedimentary rock was present in the southern Appalachians. Results of this study verify the value of combining zoning and ion microprobe studies: Using conventional U-Pb methods or ion microprobe dating without knowledge of zoning would have made interpreting the events recorded in these zircons and the ages that they yield difficult or impossible.

INTRODUCTION

The Appalachian Blue Ridge of North Carolina and Georgia records polyphase metamorphism and deformation during Paleozoic orogenies. Obtaining reliable ages of events that occurred during this period has proved difficult, hampering interpretation of the region's evolution. In light of the complex, high-temperature history of this area, we have undertaken a study of zircon, taking advantage of the fact that the U-Pb system in this mineral is the most robust of all known chronometers of ancient, high-temperature geologic events. Because of its resistance to alteration, recrystallization, and dissolution in melts and fluids, and its extremely low Pb diffusivity, zircon can retain its crystallization age through subsequent magmatic, metamorphic, and sedimentary processes. We have studied the zoning and age patterns of zircons from three samples from the eastern Blue Ridge near the Georgia–North Carolina border (samples, methods, and data are tabulated in Appendix A¹). Each sample was selected because of its probable complex history and the importance of documenting that history

¹GSA Data Repository item 9851, Appendix A, Blue Ridge zircons, samples, methods, and data, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301. E-mail: editing@geosociety.org.

Data Repository item 9851 contains additional material related to this article.

for understanding the tectonic evolution of the Blue Ridge. Growth histories of individual zircon grains were deduced from zoning, and provided the basis for selection of spots for analysis with the CAMECA ims 1270 high-resolution ion microprobe (IMP) at the University of California, Los Angeles. This combination of methods eliminates problems with discordance between $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages that result from mixed-age populations in multigrain samples or from ion probe spots that overlap growth zones of different ages, and it reduces uncertainty in identifying discordance that reflects Pb loss (e.g., Paterson et al., 1992; Miller et al., 1992; Hancher and Miller, 1993; Vavra et al. 1996).

GEOLOGIC SETTING

The southern Appalachian Blue Ridge province is divided into eastern and western parts by the east-dipping Hayesville fault (Fig. 1). The Hayesville fault places the structurally complex eastern Blue Ridge assemblage of distal clastic metasedimentary rocks, mafic to ultramafic bodies, deformed felsic intrusive rocks, and Grenville basement over the more proximal metasedimentary rocks and basement of the western Blue Ridge. Metamorphic grade decreases regularly to the northwest across the fault, from granulite facies in the vicinity of Winding Stair Gap to greenschist facies 50 km northwest (e.g., Eckert et al., 1989). The eastern Blue Ridge has been interpreted to be closely tied in stratigraphy and tectonic history to the adjacent Inner Piedmont (e.g., Hatcher, 1978); together, the two areas comprise the Piedmont terrane. In contrast to the western Blue Ridge—clearly of Laurentian (native North American) affinity—the origin of the Piedmont terrane is controversial: It may be an exotic terrane accreted during early Paleozoic orogeny (e.g., Horton et al., 1989; Hibbard and Samson, 1995) or a distal North American assemblage deposited on both oceanic and rifted continental crust (e.g., Hatcher, 1978). The tectonic history of this region is dominated by polyphase contraction in response to closing of ocean basins that separated Laurentia from other landmasses. Contractual events are identified, with varying clarity, as the Penobscottian or Potomac (ca. 500 Ma), Taconic (ca. 450–480 Ma), Acadian (ca. 350–400 Ma), and Alleghanian (ca. 250–330 Ma) orogenies (e.g., Hatcher, 1989; Hibbard and Samson, 1995). Sinha (1997) suggested that, to the north in Virginia, the Taconic orogeny is restricted to ca. 458–467 Ma.

Our samples were collected within the eastern Blue Ridge from Winding Stair Gap, the Whiteside pluton, and the Rabun pluton (Fig. 1). Winding Stair Gap exposes primarily metasedimentary rocks at granulite grade within the “culmination of metamorphism in the southern Appalachians” (Absher and McSween, 1985). Peak conditions are estimated to have been ca. 750–840 °C at 7–10 kb (cf. Absher and McSween, 1985; Eckert et al., 1989), although recent work suggests a more complex history with the peak occurring under high-*P* granulite facies conditions (kyanite stable), with abundant sillimanite forming during high-*T* retrograde decompression (Moecher, 1997). Peak metamorphism in the Blue Ridge is com-

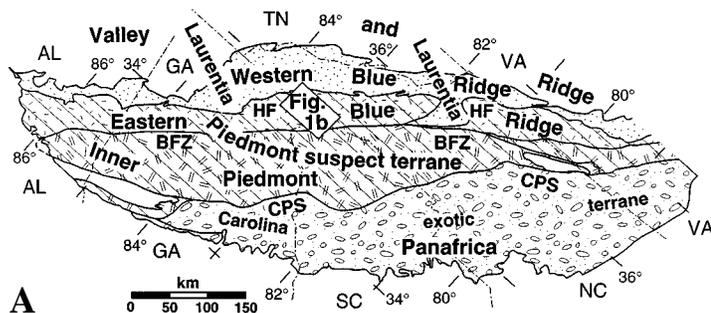
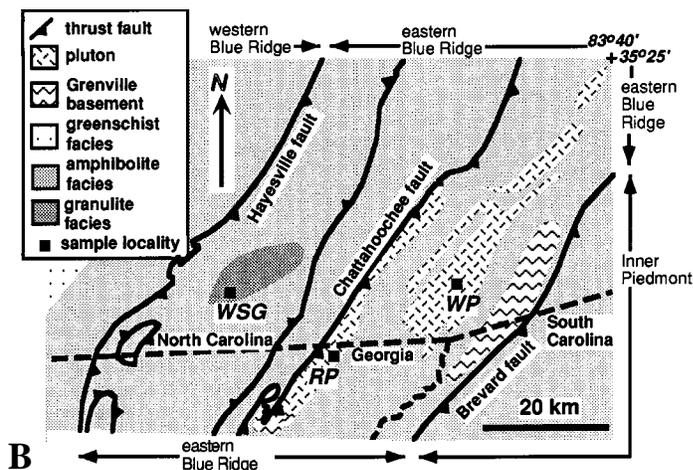


Figure 1. A: Major tectonic units of the southern Appalachians and location of B. HF—Hayesville fault; BFZ—Brevard fault zone; CPS—Central Piedmont suture, AL—Alabama, GA—Georgia, TN—Tennessee, VA—Virginia, NC—North Carolina, SC—South Carolina. **B:** Geologic setting of study area, showing areal distribution of peak metamorphic grade. Sample localities: WSG—Winding Stair Gap, RP—Rabun pluton, WP—Whiteside pluton.



monly thought to have occurred during the Taconic orogeny (e.g., Hatcher, 1989), but evidence for an Acadian or even early Alleghanian peak elsewhere in the southern Appalachians (e.g., Osberg et al., 1989; Quinn and Wright, 1993; Dennis and Wright, 1997), combined with the polymetamorphic history suggested by Moecher, suggests a complex regional and local history. Adding to this uncertainty is the pre-orogenic history of the regional basement, which is known to have experienced Grenville-age metamorphism (ca. 1.0–1.2 Ga). McLellan et al. (1989) in fact suggested that the highest-grade assemblage at Winding Stair Gap is Grenvillian. Dating of the metamorphic peak for granulite facies metasedimentary rocks like these is difficult by conventional methods because K-Ar and Rb-Sr systems do not close until much lower temperatures and most or all zircon is likely to be detrital. Depositional age and provenance of the Winding Stair Gap

metasedimentary rocks are also in question: They could be as old as pre-Grenville, or as young as Ordovician, and they could have been derived from either juvenile or mature crust.

The Whiteside and Rabun plutons are part of a belt of intrusions in the eastern Blue Ridge whose ages have heretofore been constrained only as early to middle Paleozoic (Miller et al., 1997). It has been unclear whether they were emplaced coevally or over a protracted interval. Dating has been hampered by inheritance and probable Pb loss from zircons and by Sr isotopic heterogeneity and low Rb/Sr. Furthermore, the Rabun and Whiteside plutons are currently mapped as heterogeneous and may locally include granitoids of Grenville age. The dominant lithologies, which we sampled, are felsic and peraluminous, but the trondhjemitic Whiteside is much more geochemically primitive (low incompatible element concentrations, Sr_1 ca. 0.704, ϵ_{Nd} ca. +3) than the granodioritic Rabun (Sr_1 ca. 0.706, ϵ_{Nd} ca. -2) (Miller et al., 1997).

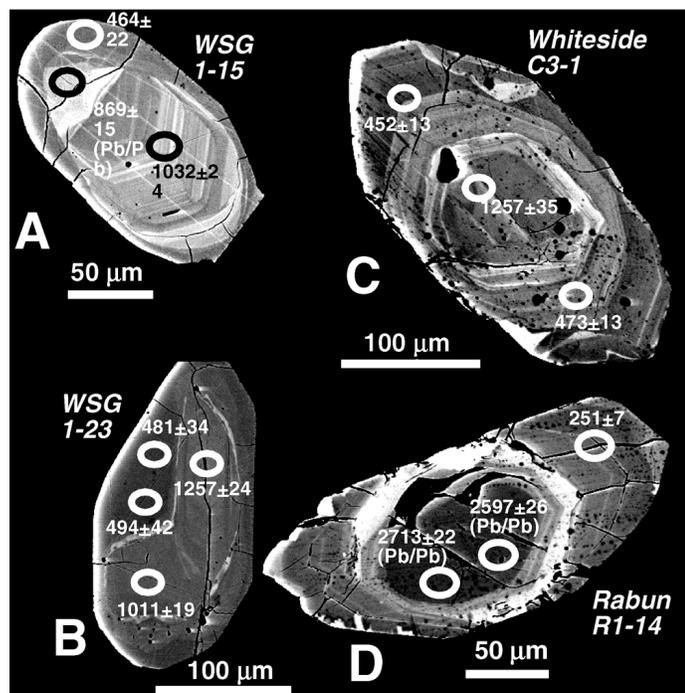


Figure 2. Backscattered-electron images of representative zircons, showing locations and sizes of analytical points and ages determined for each point. Ages are based on $^{206}\text{Pb}/^{238}\text{U}$ ratio unless otherwise stated. Stated errors are $\pm 1\sigma$. Two points, located in cracked, U-rich zones, are discordant (869 Ma point in A and 251 Ma point in D); they are interpreted to reflect radiogenic Pb loss.

ZONING AND AGES OF ZIRCONS

The backscattered-electron (BSE) zoning patterns of almost all grains indicate relatively straightforward two-stage growth histories (Fig. 2). Cores of Winding Stair Gap zircons commonly have euhedral, oscillatory zoning that is truncated and surrounded by a darker (lower mean atomic number), unzoned overgrowth a few micrometers to 50 μm thick. The grains have low aspect ratios and round shapes with poorly developed crystal faces. Concordant core ages range from 1.01 to 1.26 Ga; two slightly discordant cores have Pb/U ages of about 800 Ma (Fig. 3). We interpret the cores of Winding Stair Gap zircons to be detrital fragments derived from igneous sources. Rims, which yield a weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age of 495 ± 14 Ma (2σ ; mean squared weighted deviation [MSWD] = 0.69), are metamorphic overgrowths formed at high grade when the growth rate of zircon was appreciable (cf. Hanchar and Miller, 1993). It is unlikely that growth occurred as a result of reactions involving breakdown of Zr-rich phases or generation of melt. Of the possible hosts for substantial Zr, hornblende is absent and garnet does not show evidence for appreciable resorption (cf. Fraser et al., 1997). Furthermore, Winding Stair Gap zircons lack the oscillatory-zoned, euhedral rims that suggest growth from melt (e.g., Roberts and Finger, 1997). More likely, the rims reflect textural readjustment—growth of large zircon grains at the expense of small ones, or Ostwald ripening—that was most effective at high-grade conditions, but we are uncertain whether this growth rate “peak” coincided with the maximum temperature, or was a response to an additional factor such as an influx of fluid (cf. Ayers et al. 1996).

One Winding Stair Gap grain has an irregularly shaped double core, with a 1.26 Ga, euhedral, zoned part and a 1.01 Ga unzoned part that is probably a Grenville metamorphic overgrowth (Fig. 2B). The composite core is discontinuously surrounded by a thin bright zone, and entirely surrounded by a typical metamorphic overgrowth.

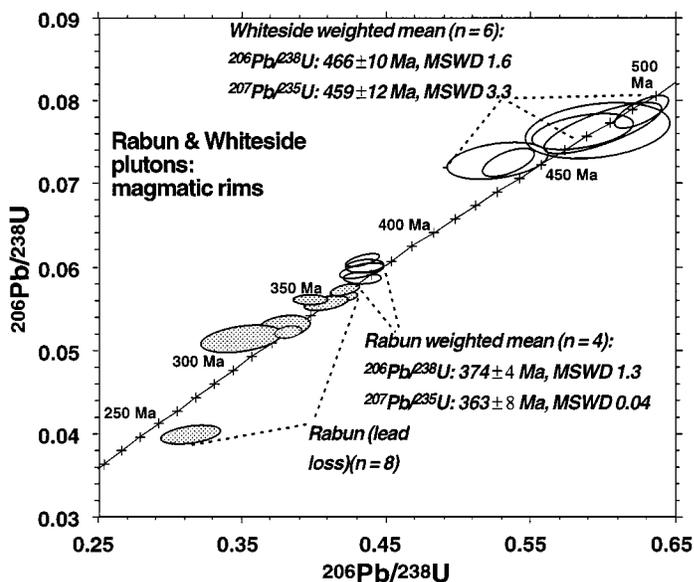
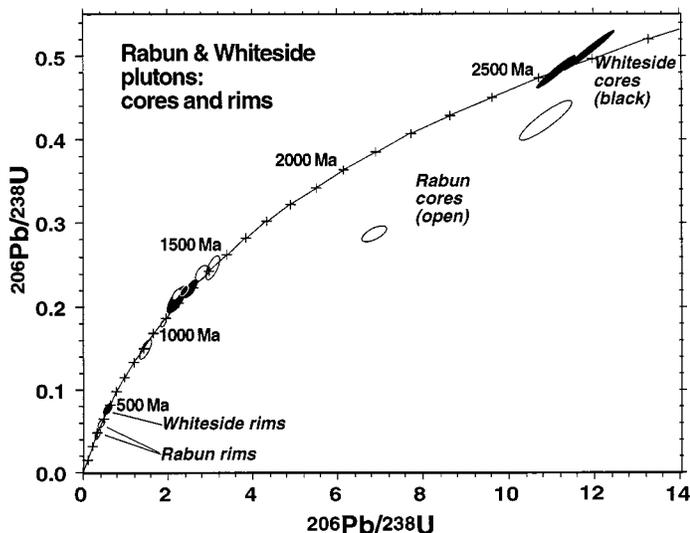
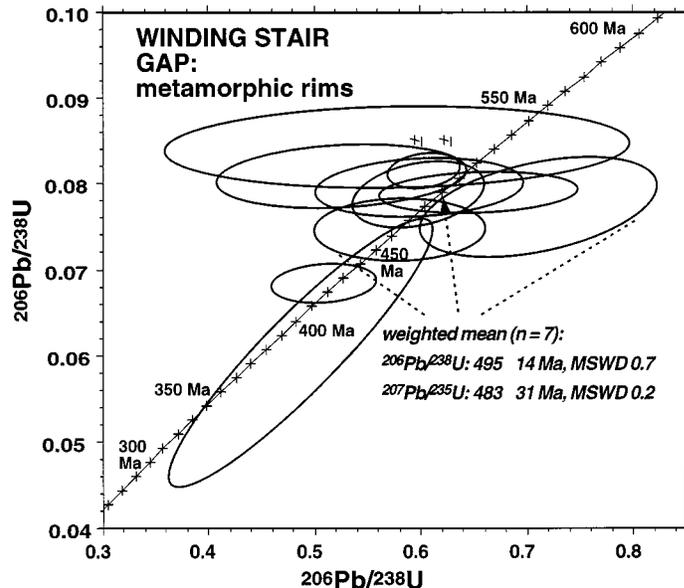
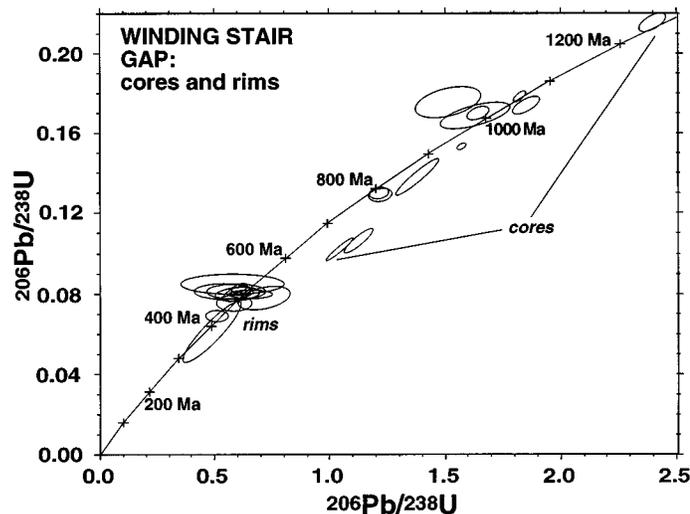


Figure 3. Pb-U concordia plots of analytical data. Error ellipses are $\pm 1\sigma$; stated errors for pooled data are $\pm 2\sigma$; MSWD = mean squared weighted deviation.

Both Whiteside and Rabun pluton zircons generally have dark (in BSE), rounded cores without evident zoning that we interpret to be inherited (Fig. 2, C and D). Cores are mostly between 1.10 and 1.28 Ga, but a single core from each is 2.6–2.7 Ga and one Rabun core is 1.4 Ga. All grains from each sample have thick, bright, oscillatory-zoned magmatic rims. Zircons range from acicular to more nearly equant, but all have euhedral external morphology. Eight of 12 rim analyses of Rabun zircons yield $^{206}\text{Pb}/^{238}\text{U}$ ages of 251 to 357 Ma and appear to reflect Pb loss, consistent with their cracked, presumably radiation-damaged, appearance (Fig. 2D). Inclusion of any or all of these points in the Rabun rim population yields a MSWD $\gg 1$. The other four rims yield a $^{206}\text{Pb}/^{238}\text{U}$ age of 374 ± 4 Ma (2σ ; MSWD 1.3), which we accept as a reliable estimate of the true crystallization age. The mean age of six Whiteside rims is 466 ± 10 Ma (2σ ; MSWD = 1.6).

DISCUSSION AND INTERPRETATION

Winding Stair Gap Rocks: Provenance, Depositional Age, and Timing of Peak Metamorphism

Our limited sampling does not preclude the presence of older detrital material, but it is clear that the principal source of the sediments was a Grenville terrane, consistent with the oldest basement currently exposed in

the region. The 1.01 Ga metamorphic zone in the composite grain appears to have been truncated during sedimentary transport prior to growth of the outer metamorphic rim, placing a post-Grenville upper limit on age of sedimentation. The slightly discordant, ca. 800 Ma cores could be derived from pre-rifting or early synrifting igneous rocks from the Laurentian margin (e.g., Tollo and Aleinikoff, 1996) and therefore may indicate a younger maximum sediment age; alternatively, they may simply be partially reset Grenville zircons. The abundant Grenville cores suggest a continental source.

The metamorphic rim age of 495 ± 14 Ma, the post-Grenville sedimentation age, and the absence of Acadian or younger ages together indicate peak metamorphism during early stages of the orogenic history of the Appalachians. If Moecher's (1997) interpretation of a complex history of Winding Stair Gap metamorphism with an early high-pressure (kyanite) peak is correct, we suspect that zircon growth occurred during this stage, and that our data reflect its age. This age could indicate metamorphism during the Penobscottian or Potomac orogeny, or it may suggest that the Taconic orogeny began earlier than previously believed or was continuous with the Penobscottian-Potomac. It appears to link this metamorphism and accompanying deformation to the uplift that yielded the Sevier clastic wedge of the same age in the Appalachian foreland. In any case, the age

demonstrates that sediment had been tectonically buried to depths exceeding 25–30 km and heated to about 800°, and therefore that orogeny was well underway, by about 500 Ma.

Rabun and Whiteside Plutons: Ages, Timing of Deformation, and Nature of Ancient Basement

The nearly 100 m.y. disparity between the ages of the Whiteside and Rabun plutons demonstrates that they are not part of a single intrusive episode. Plutonism here was apparently rather sparse and sporadic. The age of the Rabun pluton establishes a maximum age for movement on the Chattahoochee fault, which truncates it. The pluton crosscuts one but is concordant with another major regional foliation (S2); yet another deformational fabric overprints, but does not obscure, the magmatic fabric. In contrast, the Whiteside pluton, though also locally crosscutting an early foliation, has a dominantly metamorphic fabric consistent with its crystallization earlier in the tectonic history of the eastern Blue Ridge.

The zircon inheritance of these two plutons is strikingly similar despite their differences in age and petrochemistry. Both must either have been generated in or passed through continental crust that included both Grenville and Late Archean components, implying that the eastern Blue Ridge remained connected to the same, or very similar, deep crust during the Taconic to Acadian interval represented by these intrusions. The very strong inheritance in the Whiteside pluton is surprising in light of its primitive composition. A great majority of grains for which we obtained images (almost 50) had obvious inherited cores, and the U-Pb data document that they are ancient (0.6 to 2.2 b.y. older than the pluton), yet the isotopic composition of the rocks suggests little ancient crustal contribution.

Apparently the terrane from which the Winding Stair Gap sediments were derived differed significantly from the terrane through which plutons ascended. The ancient rocks (or metasedimentary rocks derived from ancient rocks), indicated by zircon inheritance in the plutons, may simply not have been exposed at the surface, or they may reflect an easterly part of Laurentia that was the root zone for the thrust sheet carrying the plutons. Alternatively, they may have been part of an underthrust exotic terrane emplaced beneath Laurentia in early or pre-Taconic time. To our knowledge, there are no known rocks of Archean age or provenance between the Superior province and the Appalachians. It is possible that the Blue Ridge zircons with Archean cores were derived from a Gondwana fragment of Archean age that was underthrust during Grenville or early Paleozoic collision, and left behind by subsequent rifting (cf. Mueller et al., 1994; Unrug, 1997).

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