Isotopic Age Constraints and Metamorphic History of the Talladega Belt: New Evidence for Timing of Arc Magmatism and Terrane Emplacement along the Southern Laurentian Margin

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ABSTRACT

U-Pb and $^{40}Ar/^{39}Ar$ dates from the Talladega belt, southernmost Appalachians, provide insight into the timing and nature of pre-Alleghanian tectonism in this region. Low-grade metasedimentary rocks of the Talladega belt represent the outermost preserved portions of the southern Laurentian margin, thus recording the earliest orogenic events that affected the margin, in addition to later overprinting events. These rocks are structurally overlain by the Hillabee Greenstone metavolcanic sequence, from which metadacite yields an age of 470 ± 4 Ma (ion microprobe U-Pb zircon age). Hillabee geochemistry indicates formation in an arc or back-arc setting. We suggest correlation of the Hillabee Greenstone with 460–470-Ma arc-related rocks in the Dahlonega gold belt, which extends along strike with the Hillabee through Georgia and into North Carolina, and interpret the Hillabee as the southernmost volcanic expression of an Early-Middle Ordovician arc that formed outboard of Laurentia. Rocks of the Talladega belt, including the Hillabee, preserve a record of only one Paleozoic dynamothermal metamorphic event. $^{40}Ar/^{39}Ar$ dates are consistent with metamorphism following deposition of the youngest biostratigraphically dated unit, the Erin Slate, which contains early Mississippian *Periastron* plant fossils (360–350 Ma). Muscovite (closure temperature 350°–400°C) yields internally consistent ages between 334 and 320 Ma. Metamorphism of the Talladega belt, therefore, is constrained to the interval between 360 and 320 Ma. The pre- to synmetamorphic thrust contact between the Hillabee Greenstone and Talladega belt metasedimentary rocks must have formed after deposition of the Erin Slate at 360–350 Ma but before metamorphism of the Talladega belt (no later than ~320 Ma). We propose that the Ordovician Hillabee-Dahlonega arc terrane first collided with the Laurentian continental margin between 360 and 320 Ma, with variations in timing of deformation and metamorphic character along the collision zone.

Online enhancements: appendix tables.

Introduction

The geologic history of the Appalachian belt has long been held to comprise distinct Taconic (450–480 Ma), Acadian (410–360 Ma), and Alleghanian (325–265 Ma) orogenic events (Glover et al. 1983; Miller et al. 2000*b* and references therein). Geochronological and thermochronological studies, however, have challenged this interpretation for the southernmost Appalachians of Alabama and western Georgia (e.g., Steltenpohl and Kunk 1993; Guthrie et al. 1995; Steltenpohl et al. 2005). These studies suggest the tectonometamorphic history in the southernmost part of the orogen differs markedly in some aspects from that of the adjacent Appalachians in northeast Georgia, the Carolinas, and farther north. A late Paleozoic (Alleghanian) tectonic history is clear in the foreland of the southernmost Appalachians, where thrusts and folds de-

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form Cambrian through Pennsylvanian strata. However, the timing of pre-Alleghanian tectonism in this region is not well defined (Tull 1980; Glover et al. 1983; Steltenpohl and Moore 1988; Guthrie et al. 1995).

The southernmost extent of the Appalachian mountain chain is represented by Paleozoic and older rocks of Alabama and western Georgia that occupy a structural recess in the trace of the orogen (figs. 1, 2). The present-day Alabama recess represents a promontory on the Late Proterozoic–Early Cambrian Laurentian margin, formed during Late Proterozoic rifting of the margin; the shapes of the promontory and adjacent embayments (Ouachita to the west and Tennessee to the east) are interpreted to reflect transform offsets of the rift system (Thomas 1976, 1977, 1989; Thomas and Whiting 1995). In this region, the Talladega belt (fig. 2) represents the outermost preserved portions of the Laurentian margin and as such should record the earliest orogenic events that affected the region (e.g., Tull 2002). The Talladega belt comprises lower-greenschist facies clastic and carbonate rocks of Laurentian affinity, structurally overlain by metavolcanic rocks of the Hillabee Greenstone. While the age of the Hillabee and its stratigraphic or structural relationship to the underlying Laurentian rocks is of prime concern to Appalachian geologists (e.g., Horton et al. 1989), the nature of the contact between the metavolcanics and underlying strata, which contain the youngest metamorphosed fossiliferous rocks in the orogen south of the Boston basin (Gastaldo et al. 1993), has been an enduring source of controversy (Bearce 1973; Higgins and McConnell 1978; Horton et al. 1989; Tull 2002). We present new U-Pb isotopic dates on

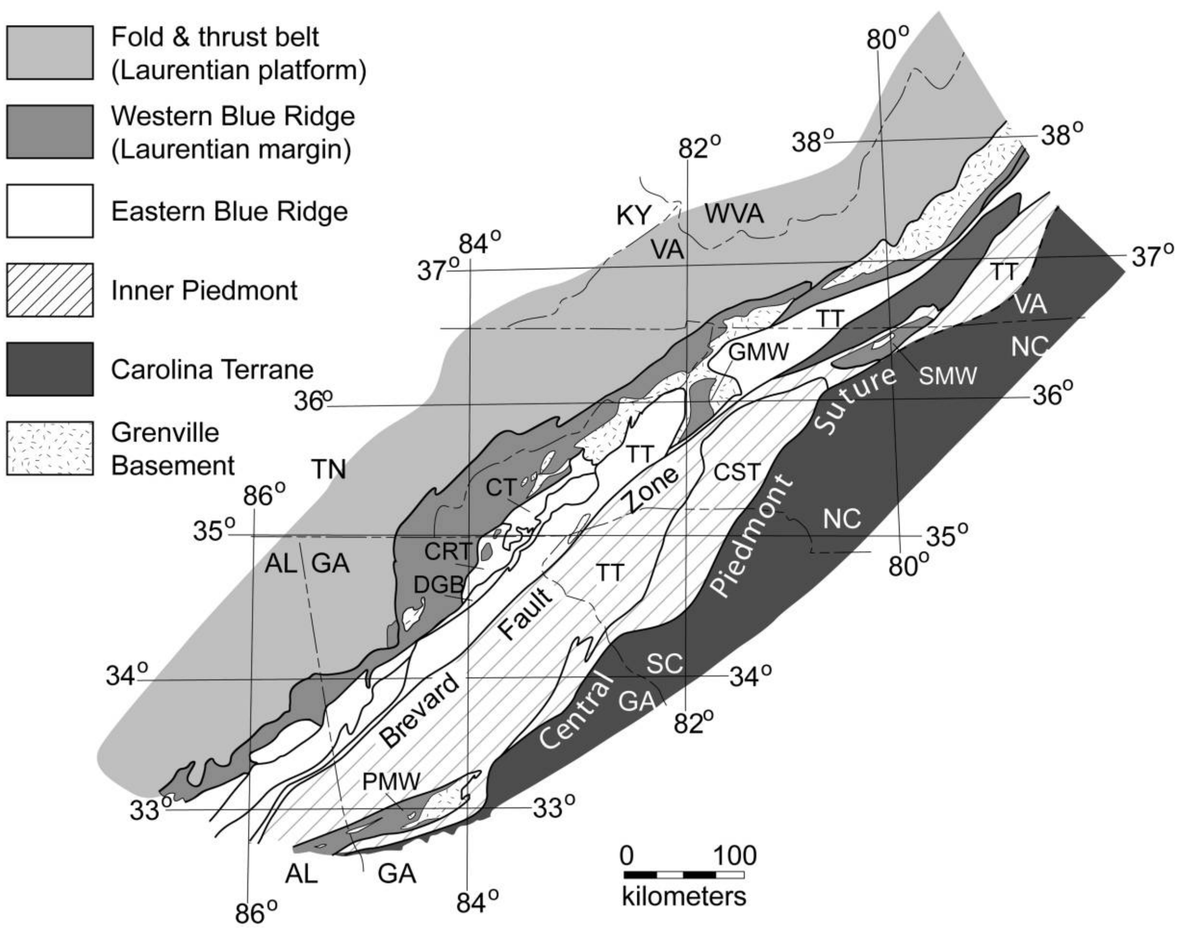

Figure 1. Index map of the southern Appalachians showing major divisions and terranes. *CRT* = Cowrock terrane; *CST* = Cat Square terrane; *CT* = Cartoogechaye terrane; *DGB* = Dahlonega gold belt; *GMW* = Grandfather Mountain window; *PMW* = Pine Mountain window; *SMW* = Sauratown Mountains window; *TT* = Tugaloo terrane. Modified from Hatcher (2004).

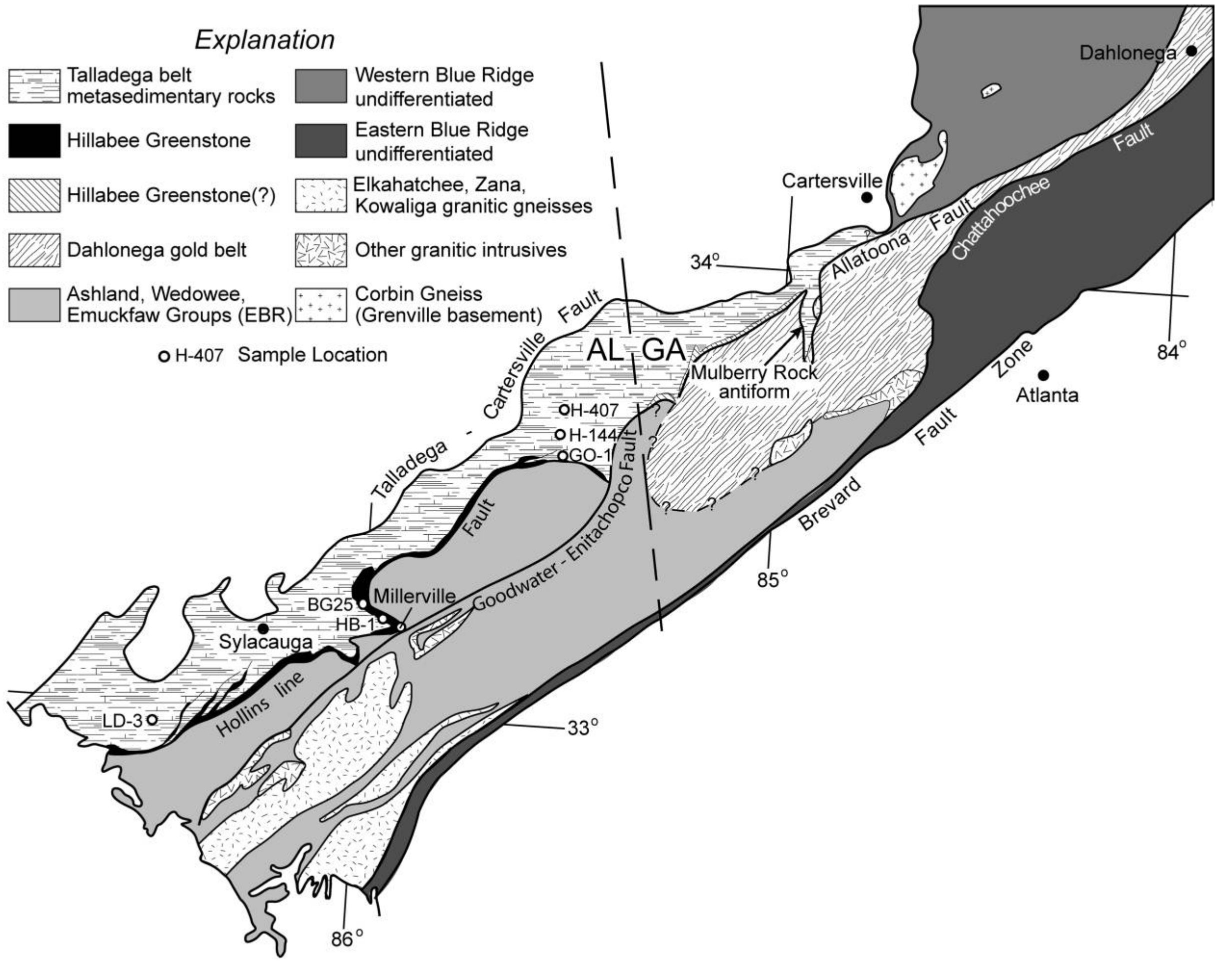

Figure 2. Tectonic map of the western and eastern Blue Ridge in the southernmost Appalachians, eastern Alabama, and western and central Georgia. Open circles indicate location of samples discussed in text.

zircons separated from metadacite in the Hillabee Greenstone that verify an Early Ordovician age. We also report $^{40}Ar/^{39}Ar$ mineral-cooling dates for minerals separated from both the Hillabee (hornblende and muscovite) and several units within the underlying metaclastic sequence. Combined, the U-Pb and $^{40}Ar/^{39}Ar$ dates allow us to explore key questions concerning timing of tectonometamorphic evolution of the Talladega belt and how this timing compares to that known from the Blue Ridge to the northeast.

Regional Geological Setting

The southern Appalachian orogen is divided into several large-scale lithotectonic units that represent Laurentian basement, passive margin, and accreted terranes of both Laurentian and exotic affinity (fig. 1). The western Blue Ridge geologic province comprises Grenville basement and Proterozoic to lower Paleozoic rifted-margin metasedimentary rocks that were thrust over Paleozoic sedimentary strata of the Valley and Ridge region. A major fault system separates the western Blue Ridge from the central and eastern Blue Ridge, both of which contain deeper water metasedimentary rocks, oceanic crustal fragments, and rare exposures of Grenville basement. Recently, the eastern Blue Ridge and Inner Piedmont have been separated into several discrete terranes based on detrital zircon ages (e.g., Bream and Hatcher 2002; Hatcher et al. 2002, 2004; Bream et al. 2004). Of these, only the Dahlonega gold belt can be traced as far south as western Georgia.

South of Cartersville, Georgia, the Talladega belt occupies a structural position similar to that of the western Blue Ridge (fig. 2). Its northwestern boundary is the Talladega-Cartersville fault, upon which rocks of the Talladega belt were thrust onto essentially unmetamorphosed Paleozoic rocks of the foreland fold-and-thrust belt. Medium- to high-grade metamorphic rocks of the Alabama Piedmont were thrust over the Talladega belt along the Hollins line fault (Tull 1977), which marks the southeastern boundary in Alabama, whereas in western Georgia, the Allatoona fault separates the belt from the overlying Dahlonega gold belt (McConnell and Costello 1980). At its northern end near Cartersville, the Talladega belt narrows to less than 500 m wide (Heuler and Tull 1988) and terminates against similar homogeneous turbiditic rocks of the western Blue Ridge (McConnell and Costello 1982). Holm and Tull (2002) suggested that the two sequences may be juxtaposed by unconformities. The southern end of the Talladega belt is overlapped by upper Cretaceous sediments of the Gulf Coastal Plain. Based on wells drilled through Coastal Plain sediments, the Talladega belt can be traced in the subsurface as far west as central Mississippi (Thomas 1989).

Talladega Belt Stratigraphy

Despite deformation and lower-greenschist facies metamorphism, mappable stratigraphic units occur throughout much of the length of the Talladega belt. Rare but significant fossils indicate that the metasedimentary rocks range in age from Cambrian to early Mississippian (Butts 1926; Tull et al. 1988; Gastaldo et al. 1993), and at least the older units can be correlated with fossiliferous, unmetamorphosed Paleozoic rocks of the foreland fold-and-thrust belt to the northwest (Butts 1926; Tull 1982; Guthrie 1985; Tull 1985; Tull et al. 1988; Johnson and Tull 2002). In a comprehensive summary of the stratigraphy and previous work in the Talladega belt, Tull (1982) proposed the following divisions: a lower siliciclastic sequence, the Kahatchee Mountain Group; a middle carbonate sequence, the Sylacauga Marble Group; an upper clastic sequence, the Talladega Group; and overlying metavolcanic rocks of the Hillabee Greenstone (fig. 3). In northeastern Alabama, units likely correlative with the Talladega Group were named the Heflin Phyllite, Able Gap Formation, and Chulafinnee Schist by Bearce (1973; fig. 3).

Stratigraphic and biostratigraphic relationships indicate correspondence of the Kahatchee Mountain Group with the lower Cambrian Chilhowee Group—the earliest drift sequence in the foreland—and of the fossiliferous Sylacauga Marble Group with the Cambro-Ordovician Shady through Knox carbonate platform sequence (Tull and Guthrie

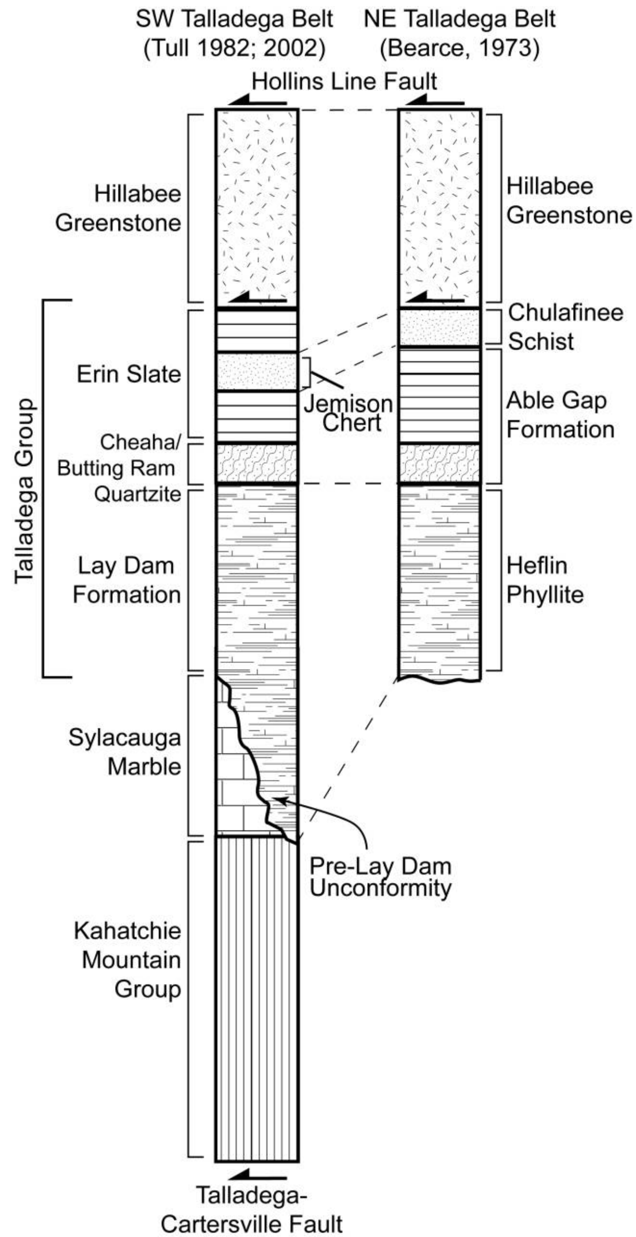

Figure 3. Stratigraphy of the Talladega belt and suggested correlations between the southwestern (Tull 1982, 2002) and northeastern (Bearce 1973) areas in Alabama.

1985). The Talladega Group is mainly a sequence of post–Knox Group siliciclastics deposited unconformably on these older units (Tull et al. 1988). Fossiliferous units in the Talladega Group (fig. 3) include the Silurian–Early Devonian Lay Dam Formation, the Early to Middle Devonian Jemison Chert, and the early Mississippian Erin Slate (Butts 1926; Carrington 1973; Tull et al. 1988; Gastaldo et al. 1993; Tull 2002). Although Tull (1982) originally interpreted the Jemison Chert as overlying the Erin Slate, more recently he has proposed a facies transition between the units (Tull 2002).

Metasedimentary rocks of the Talladega belt are overlain by metavolcanic rocks of the Hillabee Greenstone. Throughout most of the length of the belt, only the lowest few hundred meters of the Hillabee are preserved below the Hollins line fault, and locally it is cut out entirely (Tull 1982). Mafic lithologies dominate the unit, represented by foliated greenschist and fine-grained, massive greenstone. Subordinate interlayers of felsic material interpreted as metadacite are present only where the Hillabee exceeds a thickness of approximately 200 m (Tull et al. 1978; Tull 1982), most prominently in the Millerville area (fig. 2), where several laterally continuous intervals of metadacite range up to 300 m thick. Long (1981) demonstrated that the felsic material is similar to quartz dacite, and Durham (1993), in a detailed investigation of the mineralogy and geochemistry of the metadacites, interpreted the rocks as extrusive airfall crystal tuffs of calc-alkaline affinity.

Crystallization Age and Contact Relationships of the Hillabee Volcanic Suite

Previous Constraints and Interpretations. Controversy over the nature of the contact between the Hillabee Greenstone and underlying strata of the Talladega belt is closely tied to debate over the age of the volcanic rocks. A fault contact has been suggested, particularly by those working in the northeastern portion of the belt (e.g., Bearce 1973; Higgins et al. 1988). Mies (1992) mapped the Hillabee Greenstone as being entirely within the Hollins line shear zone and therefore not stratigraphically tied to the underlying rocks. This position is supported by Ordovician U-Pb ages obtained from Hillabee metadacite, interpreted by Russell (1978) to represent the crystallization age of the rocks. Tull et al. (1978) and Tull and Stow (1980), however, presented an alternative interpretation in which the Hillabee stratigraphically overlies (and is therefore younger than) sedimentary rocks of the Talladega belt. In these studies, the boundary between the Hillabee and the underlying Talladega Group was interpreted as conformable and gradational, based on (1) evidence that the Talladega belt stratigraphy is not overturned; (2) parallelism of the Hillabee contact with underlying rocks throughout much of the length of the Talladega belt; and (3) the presence of an apparent gradational contact between the Hillabee and the underlying rocks, described as a zone ranging from 30 to 100 m thick of interlayered mafic phyllite, aluminous phyllite, and phyllitic quartzite. Tull et al. (1998) argued that the conflicting Ordovician zircon dates cited above represent a mixing of age populations between its stratigraphically determined extrusion age of <400 Ma and the age of inherited crustal components of perhaps Grenvillian derivation (~1000 Ma).

If the contact between the Hillabee and the underlying Devonian to lower Mississippian metasedimentary rocks is stratigraphic, the Hillabee is unique and represents the youngest synorogenic mafic volcanic rocks recognized in the exposed southern Appalachians. A particularly appealing aspect of the "younger Hillabee" model lies in its straightforward explanation of the apparently similar tectonothermal histories of the volcanic and underlying fossiliferous rocks, since the low metamorphic grade of the Talladega belt is in sharp contrast with that of the amphibolite facies rocks of uncertain, probably exotic, affinity in the hanging wall of the Hollins line fault immediately southeast. On the other hand, if the Hillabee is Ordovician, a fault must separate it from the underlying rocks of the Talladega Group, and both the fault and the Hillabee should hold a previously overlooked record of orogenic activity affecting the southernmost Laurentian margin throughout most of the Paleozoic.

U-Pb Analysis. Zircons were separated for U-Pb analysis from a representative sample (BG25) of metadacite from the most extensive interval within the greenstone, near Millerville, Alabama (fig. 2). Metadacite was selected for U-Pb analysis because of the likelihood that it contained zircon, in contrast to the typical greenstone with which it is interlayered.

Procedures were as described by Miller et al. (2000*b*). Standard mineral separation techniques culminating in handpicking were used to select zircon grains for investigation. Zircons are uniformly weakly colored, euhedral prisms. About 50 grains were selected and mounted in epoxy with fragments of zircon standard, polished, and "mapped" by backscattered electron imaging using the JEOL 733 Superprobe at Rensselaer Polytechnic Institute. U-Pb analyses were performed using the IMS 1270 high-resolution ion microprobe at the University of California, Los Angeles, following techniques of Quidelleur et al. (1997). The ion beam was focused to a ~15 × 10-μm ellipse for analysis. Zircon AS3 (1099.1 ± 0.5 Ma; Paces and Miller 1993) was used as a standard.

Backscattered electron images (fig. 4) reveal very fine-scale, oscillatory, magmatic zoning and an absence of well-defined inherited cores or metamor-

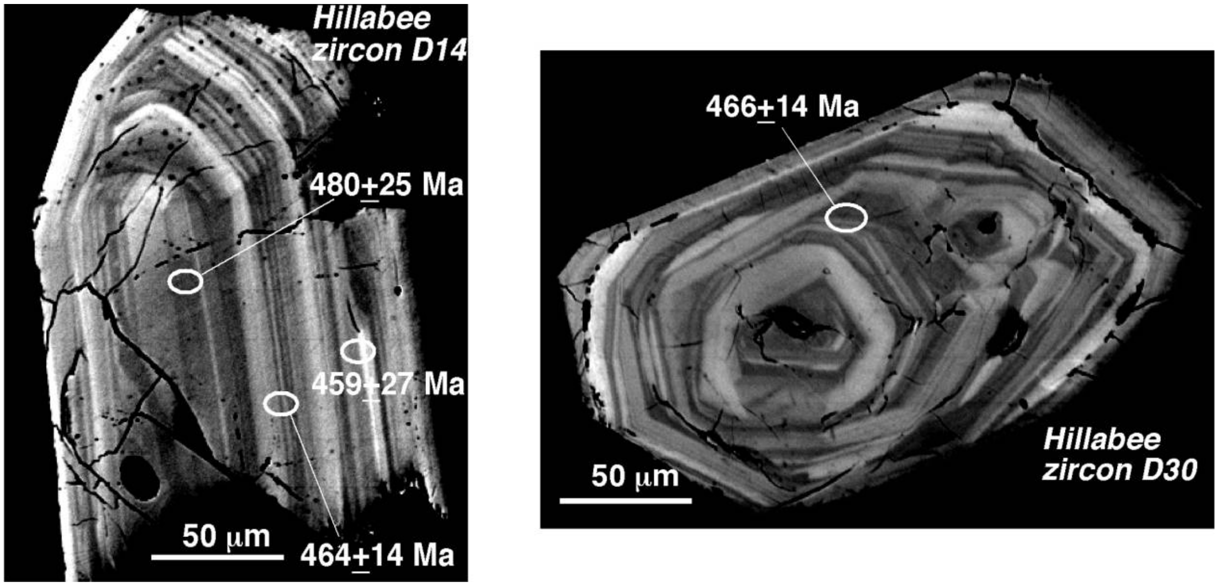

Figure 4. Backscattered electron images of zoning of typical Hillabee zircons. All zoning is interpreted to be magmatic. Ellipses show location, size, and shape of analytical spots. Although truncated magmatic zones were evident in some grains (including these two), there were no cores with distinctly different zoning and no ages for any suspected "inherited cores" older than ~500 Ma.

phic overgrowths. Rare truncations of zoning indicate resorption events, but the zoning inside truncation surfaces is similar to that outside of the surfaces.

We analyzed a total of 17 points on 10 zircon grains (table 1; fig. 5*a*). Two of the 17 were reversely discordant at the 2σ level. Relative precision of $^{206}Pb/^{238}U$ ages is much better than that of $^{207}Pb/^{235}U$ ages for zircons of this age, typically by a factor of at least 5 (abundance and count rate for ^{206}Pb are ~20 times as high as for ^{207}Pb, and the fraction of common ^{207}Pb is far higher). Therefore, we use the $^{206}Pb/^{238}U$ ages, and "age" in this section refers to $^{206}Pb/^{238}U$ age. All reported uncertainties in text, figures, and table 1 are $\pm 2\sigma$.

All spot analyses yielded ages between 447 and 502 Ma, with 2σ uncertainties of 11–27 m.yr. Pooling of all analyses yields an apparent age of 477 ± 3 Ma. However, the MSWD (mean squared weighted deviation; Wendt and Carl, 1991) is 5.2, meaning that the calculated uncertainty was seriously underestimated and further suggesting that these 17 analyses do not represent a single population, which should yield an MSWD near 1. A summed probability plot of all $^{206}Pb/^{238}U$ ages (fig. 5*b*) reveals a very strong peak centered at ~470 Ma, a lesser but distinct peak near 500 Ma reflecting four ages between 491 and 502 Ma, and a subtle shoulder at ~450 Ma that is a consequence of a single analysis at 447 Ma. Twelve analyses that fall between 459 and 484 Ma form the dominant peak; these analyses yield a pooled age of 470 ± 4 Ma (MSWD 0.9). We regard this as the best estimate of the true age of crystallization of this dacite and by implication of the greenstone with which it is interlayered. The 447-Ma analysis probably reflects modest Pb loss. The ages that approach 500 Ma may indicate inheritance of slightly older grains, although they are not from distinct cores.

Metamorphic History of the Talladega Belt

Previous Constraints and Interpretations. Rocks of the Talladega belt are interpreted as having experienced one Paleozoic, prograde, dynamothermal metamorphic event (Tull 1982). Petrogenetic grid treatment of metamorphic mineral assemblages documents lower-greenschist facies conditions for this regional metamorphic event (general conditions ~350°C at ~3.5 kbar pressure; Tull and Stow 1980; Carter 1985; Lim 1998; Tull et al. 1998; McDonald 2000). This is supported by the study of quartz microstructures in the Jemison Chert by King and Keller (1992) and by Weaver Index (illite crystallinity) investigations by Guthrie (1989) from the southwestern part of the belt. On the basis of illite crystallinity and petrogenetic grid analysis, Guthrie (1989) concluded that rocks of the Talla-

Table 1. U-Pb Zircon Data for Metadacite Sample, Hillabee Greenstone

Analysis	$^{206}Pb^*/^{238}U$	$^{207}Pb^*/^{235}U$	$^{207}Pb^*/^{206}Pb^*$	Age (Ma) $^{206}Pb/^{238}U$	Age (Ma) $^{207}Pb/^{235}U$	Age (Ma) $^{207}Pb/^{206}Pb$	Radiogenic ^{206}Pb (%)
Hil_d2_sp1	.0761 ± .0018	.540 ± .102	.0515 ± .0092	473 ± 11	439 ± 67	264 ± 412	97.1
Hil_d6_sp1	.0792 ± .0024	.607 ± .128	.0556 ± .0108	491 ± 15	482 ± 80	436 ± 434	96.8
Hil_d6_sp2	.0809 ± .0022	.605 ± .136	.0542 ± .0114	501 ± 14	480 ± 86	380 ± 474	96.8
Hil_d7_sp1	.0746 ± .0016	.531 ± .042	.0517 ± .0038	464 ± 10	433 ± 28	270 ± 170	98.4
Hil_d7_sp2	.0809 ± .0022	.605 ± .056	.0542 ± .0046	502 ± 13	480 ± 35	379 ± 190	98.3
Hil_d8_sp1	.0772 ± .0032	.558 ± .176	.0524 ± .0156	480 ± 19	450 ± 114	301 ± 676	95.7
Hil_d8_sp2	.0798 ± .0016	.608 ± .102	.0552 ± .0086	495 ± 10	482 ± 64	422 ± 350	97.4
Hil_d8_sp3	.0753 ± .0024	.574 ± .224	.0553 ± .0204	468 ± 15	461 ± 144	425 ± 826	93.7
Hil_d10_sp1	.0768 ± .0026	.551 ± .228	.0520 ± .0206	477 ± 15	446 ± 150	286 ± 906	93.5
Hil_d10_sp2	.0780 ± .0026	.515 ± .074	.0479 ± .0064	484 ± 16	422 ± 49	95 ± 316	97.2
Hil_d14_sp1	.0773 ± .0042	.517 ± .300	.0485 ± .0266	480 ± 25	423 ± 200	122 ± 1294	91.0
Hil_d14_sp2	.0738 ± .0044	.616 ± .256	.0606 ± .00234	459 ± 27	487 ± 160	624 ± 834	95.8
Hil_d14_sp3	.0747 ± .0022	.515 ± .142	.0500 ± .0132	464 ± 14	422 ± 96	197 ± 608	95.5
Hil_d17_sp1	.0764 ± .0022	.580 ± .162	.0550 ± .0146	475 ± 13	464 ± 105	413 ± 596	96.0
Hil_d17_sp2	.0718 ± .0024	.548 ± .208	.0554 ± .0200	447 ± 14	444 ± 136	426 ± 808	93.6
Hil_d22_sp1	.0750 ± .0024	.575 ± .128	.0556 ± .0116	467 ± 14	461 ± 82	434 ± 466	95.7
Hil_d30_sp1	.0750 ± .0024	.550 ± .166	.0532 ± .0154	466 ± 14	445 ± 109	335 ± 652	95.3

Note. Name of each analysis consists of zircon grain number (e.g., Hil_d2) followed by spot number on zircon grain (sp1, sp2, sp3). Pb* indicates radiogenic Pb (corrected for common Pb using measured ^{204}Pb). Data are given ±2 SE.

dega belt were subjected to low-grade metamorphic conditions at temperatures ranging from 280° to <400°C and pressures ranging from 1 to 3 kbar. Conodonts obtained from the Gantts Quarry Formation of the upper Sylacauga Marble Group in the southwestern part of the Talladega belt in Talladega County have a color alteration index of 5.5, indicating host-rock temperatures of about 350°C (Tull et al. 1988). Conditions of metamorphism generally increase structurally upward, from northwest to southeast, across the strike of the Talladega belt (Bocz-Garrett 1989; Guthrie 1989).

The timing of metamorphism in rocks of the Talladega belt has been a topic of debate for many years. Tull (1980) and Guthrie (1989) have argued that these metasedimentary rocks lack evidence for polymetamorphism. Tull et al. (1988) interpreted metamorphism as resulting from a post–Middle Devonian, Acadian event, based on the presumption that the Middle Devonian Jemison Chert (Talladega Group) is the youngest rock unit in the Talladega belt. Late Devonian metamorphism appeared to be compatible with K-Ar whole-rock metamorphic ages reported by Kish (1990). However, one of Kish's (1990) samples from the Jemison Chert (fig. 3), among the structurally highest units in the belt, has an age of 329 ±7 Ma. Kish stated that this particular sample was near the Alleghanian Hollins line fault, which emplaced the eastern Blue Ridge onto the Talladega belt, and he interpreted the anomalously young age (compared to the rest of his samples) as reflecting argon loss due to thrust emplacement of "deep-seated, hot rocks" of the eastern Blue Ridge onto the Talladega belt (Kish 1990, p. 652). Later, however, Gastaldo et al. (1993) discovered in situ early Mississippian *Periastron* plant fossils in the Erin Slate (fig. 3) in the central part of the Talladega belt, indicating that metamorphism must have occurred later than was previously thought and probably was the result of Alleghanian heating rather than the Acadian event. U-Pb zircon data (Student and Sinha 1992) and $^{40}Ar/^{39}Ar$ mineral-cooling dates (Steltenpohl and Kunk 1993) documented Alleghanian metamorphism of the Pine Mountain and Uchee terranes in the easternmost parts of the exposed Appalachians in Alabama, further suggesting that the Alleghanian event may have been more widespread than was previously thought.

$^{40}Ar/^{39}Ar$: Methods. Mineral separations for $^{40}Ar/^{39}Ar$ isotopic analysis were done at Auburn University, using standard ultrasonic cleaning and heavy liquid and magnetic separation techniques. Mineral separates were examined for purity using a standard binocular microscope. The mineral samples, together with aliquots of the monitor mineral MMhb-1, were encapsulated in tinfoil and sealed under vacuum in fused silica vials at the U.S. Geological Survey (USGS), Denver, Colorado. The geometry of the samples and monitors was measured and recorded. The sample vials were sealed in an aluminum irradiation can and irradiated at the USGS TRIGA reactor (Dalrymple et al. 1981) in Denver. After irradiation, the samples and monitors were analyzed by M. Kunk, USGS, Denver. The samples were placed in the sidearm assembly of a low blank double vacuum furnace, similar in design to that described by Staudacher et al. (1978). After the tin packaging was melted at 350°C, samples were heated

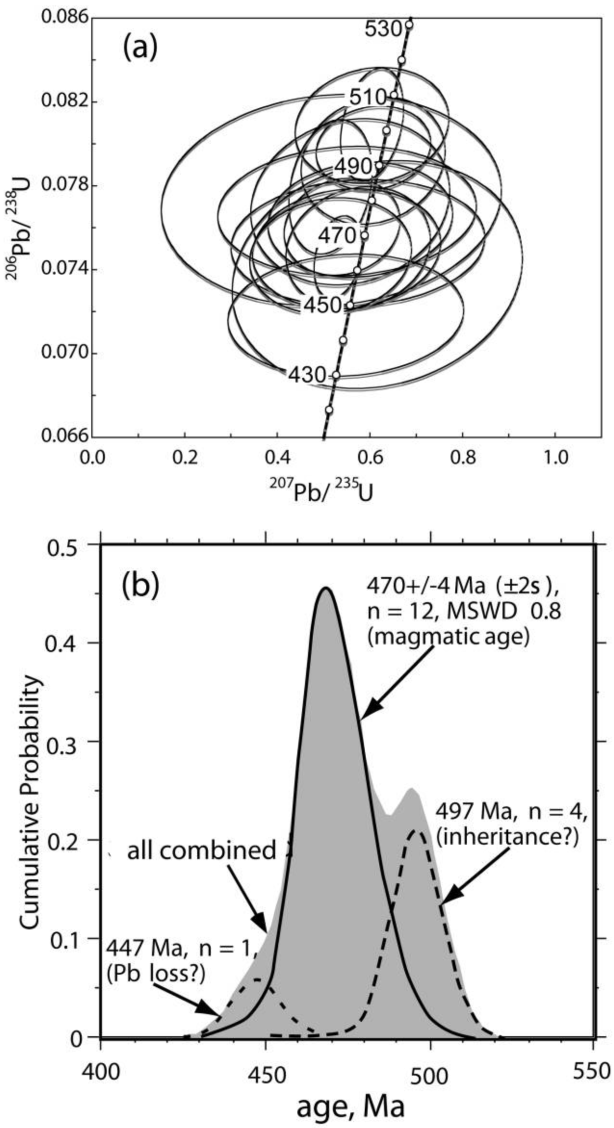

Figure 5. *a*, Concordia plot of the Hillabee zircon analyses. Data point error ellipses are 2σ. *b*, Cumulative probability plot of the Hillabee zircon $^{206}Pb/^{238}U$ analyses. Gray area represents the summation of the Gaussian distributions of all 17 analyses. Dashed lines represent a single younger analysis and the summation of four older analyses that are responsible for the older peak that is evident when all analyses are grouped. Solid line is the sum of the other 12 analyses, which we believe provides the best estimate of true age of crystallization.

in a stepwise manner to extract their argon. The gas was cleaned using SAES ST707, ST101, and titanium metal getters before analysis in a VG 1200b rare-gas mass spectrometer for argon isotopic composition. These data were then reduced using the computer program ArAr* (Haugerud and Kunk 1989). Corrections for production of interfering isotopes were those of Dalrymple et al. (1981). Decay constants are those recommended by Steiger and Jäger (1977). The age used for MMhb-1 is 519.4 ± 2.5 Ma (Alexander et al. 1978; Dalrymple et al. 1981). Plateau ages calculated by ArAr* (Haugerud and Kunk 1989) follow the original definition of Fleck et al. (1977). The method of calculation of ages and errors, as well as plateau ages and errors, is described by Haugerud and Kunk (1989). Additional analytical techniques and a discussion of error estimates and closure temperatures are described elsewhere (Steltenpohl and Kunk 1993). Additionally, preferred ages were calculated for some samples from the raw data by weighted-average analysis at the 2σ level. These raw data and sample locations are presented in table A1, available in the online edition or from the *Journal of Geology* office.

Lay Dam Formation (=Heflin Phyllite). Three samples from the Lay Dam Formation, muscovite H144 and H407 and K-feldspar LD3 (fig. 3), were analyzed. Sample H144 is a relatively pure sericite-chlorite phyllite with only minor quartz. The age spectrum (fig. 6) for the fine-grained (0.25–0.4 mm) white mica that forms the dominant phyllitic cleavage in sample H144 has a saddle-shaped profile reflecting minor extraneous argon. The minimum-age heating step in the saddle is 327.6 ± 0.7 Ma, which is interpreted

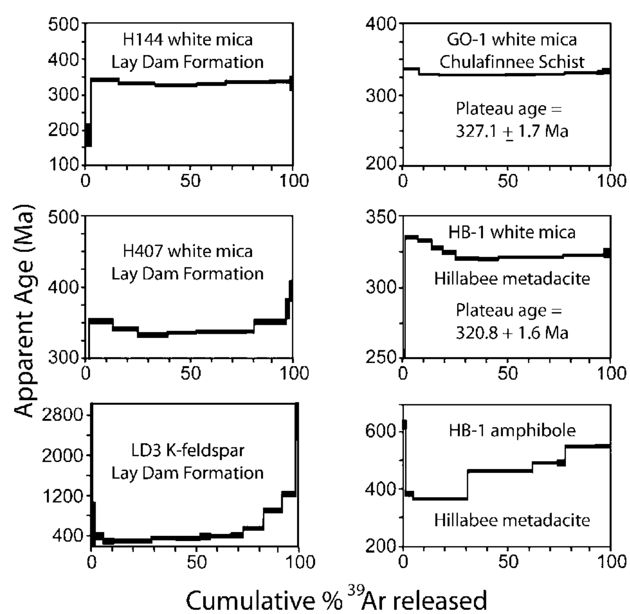

Figure 6. $^{40}Ar/^{39}Ar$ incremental release age spectra of minerals from the Talladega belt. Sample locations are shown in figure 2.

as a maximum age of postmetamorphic cooling from metamorphism for this sample.

K-feldspar was separated from sample LD3, a granite gneiss boulder from the metadiamictite near the base of the Lay Dam Formation. A granite gneiss clast from the same unit in a nearby outcrop contains zircons dated at ~1.1 Ga (Telle et al. 1979), indicating a Mesoproterozoic basement source for the boulder. The release spectrum for this K-feldspar sample (fig. 6) is a diffusional profile with an oldest, highest-temperature age step of ~1205 Ma, indicating that this sample may retain gas related to the original Mesoproterozoic thermal history. Dates for the sample progressively step down to a saddle minimum of 300 Ma and then climb back up in the low-temperature heating steps, indicating the presence of extraneous argon. The data for LD3 indicate Carboniferous thermal overprinting of a Mesoproterozoic basement clast in the Lay Dam Formation.

Lay Dam sample H407 is a laminated calcareous chlorite-sericite phyllite. Petrographic observations document two distinct muscovite grain-size populations: larger (0.45–0.5 mm) muscovite grains, interpreted as detrital grains (McDonald 2000), are surrounded by finer muscovite grains (0.25–0.3 mm) that define the phyllitic cleavage. Isotopic analysis of mica separated from sample H407 (fig. 6) reveals a saddle-shaped profile, probably reflecting extraneous argon, with a minimum step of ~334 Ma that places a maximum on the age of cooling through Ar closure. The distinct stepping up of ages in the higher-temperature parts of the release spectrum for sample H407 (the right-hand side of spectrum steps up to ~422 Ma) probably reflects its older detrital muscovite component.

Jemison Chert (=Chulafinnee Schist). Muscovite was separated and analyzed from sample GO-1 of the Jemison Chert, a schistose quartzite with small muscovite grains (0.1–0.25 mm) dispersed throughout the layers and along cleavage surfaces. This sample provides the simplest release spectrum of all of the analyzed Talladega belt specimens, having a plateau age of 327.1 ± 1.7 Ma (fig. 6).

Hillabee Greenstone. Sample HB-1 is metadacite interlayered with metabasaltic rocks of the Hillabee Greenstone, similar to the U-Pb sample. Hillabee metadacite is typically mylonitic, consisting of hornblende and plagioclase porphyroclasts wrapped by a dynamically recrystallized matrix of quartz, white mica, epidote, and actinolite. The porphyroclasts are interpreted as having originated as volcanic phenocrysts from a porphyritic dacite (Tull et al. 1978). Both hornblende and muscovite were separated from sample HB-1 for $^{40}Ar/^{39}Ar$ analysis. The hornblende porphyroclasts we analyzed contained quartz and plagioclase inclusions. Along the periphery and within fractures in the hornblende porphyroclasts, epidote and actinolite have replaced hornblende. The age-release spectrum for hornblende from HB-1 (fig. 6) has highest-temperature steps of ~550 Ma that step downward in age to ~365 Ma in a consistent, though blocky, stair-stepped fashion with decreasing temperature. The disturbed spectrum is probably due to the sheared, partly altered, and inclusion-bearing nature of the hornblende grains. The trough in the spectrum has a minimum age of 365 ± 1 Ma. Analysis using various $^{36}Ar/^{40}Ar$ versus $^{39}Ar/^{40}Ar$ isotope correlation plots did not help to elucidate the nature of the disturbance of the argon isotopic system within this sample.

Muscovite grains separated from the same Hillabee metadacite sample, HB-1, defined the schistosity and were generally less than 5 mm in length. The muscovite analysis yielded a plateau age of 320.9 ± 1.6 Ma (fig. 6), which is consistent with our other muscovite dates.

Interpretation of the ^{40}Ar/^{39}Ar Results. All of the $^{40}Ar/^{39}Ar$ dates generated from Talladega belt metasedimentary rocks are consistent with metamorphism following early Mississippian deposition of the youngest biostratigraphically dated unit, the Erin Slate Member of the Lay Dam Formation (*Periastron* is biostratigraphically restricted to ~360–350 Ma; Gastaldo et al. 1993). Muscovite, with a closure temperature in the range of ~350°–400°C, provides the simplest spectra to interpret, and muscovite ages are internally consistent and restricted in age range to between 334 and 320 Ma. Metamorphism of the Talladega belt, therefore, is constrained to the time interval between ~360 and 320 Ma. Sutter et al. (1985) argue that the first separable minerals from a prograde sequence that crystallize near or within their given metamorphic index zone can be used to date the thermal maximum because they formed near the temperature conditions for argon closure. Given that the ~350°C peak metamorphic temperature for rocks we analyzed approximately coincides with the muscovite closure temperature (Purdy and Jäger 1976; Cliff and Cohen 1980; Harrison and McDougall 1981; Hodges 1991), the peak might have occurred close to ~334 Ma (see also Coker et al. 1995), which is consistent with the <300 Ma date for K-feldspar sample LD3 (closure temperature ~250°C). Otherwise, the ~334 Ma date could reflect slow uplift and cooling from an earlier Mississippian peak that was sustained and never elevated above ~350°C.

Our inferred ~334–320 Ma metamorphic peak conflicts with Kish's (1990) K-Ar dates; with the exception of one sample dated at ~329 Ma, the other dates are older than the youngest fossils (i.e., earliest Mississippian; Gastaldo et al. 1993) in Talladega belt rocks. Spurious conventional K-Ar ages on slates are well documented and may be the result of (1) extraneous argon trapped in crystals, (2) the incorporation of detrital or diagenetic grains, or (3) one or more generations of white mica that formed from one or more cleavage-forming assemblages (Wintsch et al. 1996). The gradual stepping up of ages in the higher-temperature steps of the release spectrum for Lay Dam sample H407 (fig. 6), combined with petrographic observations, supports the presence of older detrital muscovite in this sample. The integrated age of 344 ± 2 Ma calculated for sample H407 is a good illustration of how a conventional K-Ar date for this sample would have overestimated the cooling age by more than 10 m.yr. A more extreme example is K-feldspar sample LD3; a conventional K-Ar date on this sample would have overestimated the time of closure by more than 190 m.yr. We suggest that incorporation of older detrital grains and other sources for extraneous argon trapped in crystals may have resulted in Kish's (1990) overestimation for the time of peak metamorphism in rocks of the Talladega belt based on conventional argon dates.

Our $^{40}Ar/^{39}Ar$ data appear to support Kish's (1990) interpretation for Alleghanian thrust emplacement of deep-seated, hot rocks of the eastern Blue Ridge on relatively cold ones of the Talladega belt, causing additional heating and argon loss. Comparison of our analyses for samples H407, H144, and GO-1, which lie in an across-strike transect at 14.5, 8, and 0.5 km, respectively, from the Hollins line fault (fig. 2), demonstrates progressive flattening of the spectra approaching the Hollins line fault. The less disturbed, or more fully reset, spectra nearer to the fault supports Kish's (1990) idea of heating from above during emplacement of an already hot eastern Blue Ridge; we would add, however, that samples more distant appear to retain old gas as either detrital or some other extraneous component(s). Retrogressive features preserved along the Hollins line fault might reflect "last gasp" stages of oblique thrust–right slip shearing that is documented along at least parts of its length (Mies 1992; Tull 1995). Illite crystallinity investigations (Bocz-Garrett 1989; Guthrie 1989) also record an inverted metamorphic gradient in at least the structurally lowest rocks of the Talladega belt. A similar trend of downward-decreasing grade was also noted by Erickson (1985) to continue beneath the Talladega-Cartersville thrust into units of the Valley and Ridge in Alabama. Although such a pattern is consistent with the patterns of ages and isotopic signatures of our $^{40}Ar/^{39}Ar$ data, more work is needed to test inverted metamorphism in the Talladega belt.

Discussion

Timing of Metamorphism in the Southernmost Appalachian Blue Ridge. Parts of the western and eastern Blue Ridge to the northeast have yielded clear evidence for Taconian metamorphism (Moecher and Miller 2000; Stewart and Miller 2001; Eckert 2002; Liogys and Tracy 2002; Moecher et al. 2004) that is commonly ascribed to collision of Laurentia with a volcanic arc. In contrast, evidence for Taconian metamorphism is lacking in the southernmost Appalachian Blue Ridge. Rocks of the Alabama Blue Ridge appear to have undergone one prograde Barrovian metamorphic event (Tull 1978; Guthrie et al. 1995). Existing $^{40}Ar/^{39}Ar$ data are consistent with mid-Carboniferous tectonothermal activity (Guthrie et al. 1995; Steltenpohl et al. 2005). In the Talladega belt, Tull (1998) ascertained that only mild folding affected Cambro-Ordovician strata before development of a pre-Devonian unconformity (fig. 3), and mineral assemblages and metamorphic fabrics are comparable in rocks below and above the unconformity (Tull and Guthrie 1985). Mineral assemblages and fabrics in the Hillabee Greenstone are also consistent with a single prograde lower-greenschist metamorphism, as indicated by varying proportions of chlorite, actinolite, albite, and epidote-group minerals in greenstone and greenschist (Tull et al. 1978; Tull and Stow 1980; Mies 1992; E. A. McClellan, unpublished data).

Similarly, only one episode of prograde metamorphism has been recognized in rocks of the Dahlonega gold belt along strike to the northeast (fig. 2) (McConnell and Abrams 1984), and this and other eastern Blue Ridge units in northern Georgia yield hornblende $^{40}Ar/^{39}Ar$ plateau ages ranging from ~330 to 322 Ma (Dallmeyer 1988), indicating cooling through ~500°C in mid-Carboniferous times. Data reported in the past few years document separate ~350-Ma (Neoacadian) and ~330-Ma (early Alleghanian) metamorphic events in the eastern Blue Ridge and Inner Piedmont (Dennis and Wright 1997; Carrigan et al. 2001; Kohn 2001; Bream 2002; Cyphers and Hatcher 2006; Merschat et al. 2006; Stahr et al. 2006; Hames et al. 2007; McDonald et al. 2007). The Ar ages reported here, as well as those from the Dahlonega gold belt data (above), may record uplift and cooling after the Neoacadian event; however, we suggest that early Alleghanian metamorphism is more likely because (1) metamorphic temperatures of the Talladega belt samples are in the range of the blocking temperature for Ar in muscovite (see "Interpretation of the $^{40}Ar/^{39}Ar$ Results"), and (2) Neoacadian metamorphism would require very rapid tectonic burial and metamorphism of early Mississippian (~350 Ma) strata in the Talladega belt. Recently reported laser $^{40}Ar/^{39}Ar$ single-crystal muscovite ages (ca. 335–330 Ma) from low-grade metamorphic rocks in the Georgia and western North Carolina Blue Ridge (Hames et al. 2007) confirm that the effects of early Mississippian (Visean) deformation and metamorphism are widespread through the area.

Emplacement of the Hillabee Greenstone. The Hillabee Greenstone contains lower-greenschist facies assemblages that are compatible with conditions recorded by the structurally underlying Talladega Group rocks (e.g., Tull et al. 1978; Barineau and Tull 2001) but markedly lower than those preserved in the overlying Hollins line thrust sheet. Mies (1992) mapped the Hollins line fault in northeastern Alabama (Cleburne County) as a broad shear zone, which he termed the Hollins line shear zone, characterized by amphibolite facies mineral assemblages in the hanging wall (Ashland/Wedowee sequence) and greenschist facies assemblages in the footwall (Talladega Group, including quartzite, sheared micaceous quartzite, muscovite phyllite, and muscovite button schist), separated by an intervening mixture of greenstone and associated shear zone tectonites (Hillabee mixed zone). In his interpretation, the Hillabee mixed zone lies solely within the Hollins line shear zone, with uncertain relationship to hanging wall or footwall units. Kinematic analysis, based on mesoscopic structures and quartz crystallographic fabrics, indicated predominantly top-to-west displacement in footwall rocks and Hillabee mixed zone and top-to-west and top-to-northwest displacement in hanging wall rocks.

Data from our mapping in the Millerville area (fig. 2) are consistent with Mies's (1992) overall interpretation of a wide zone of deformation. In this area, however, a distinct contact between the Hillabee and underlying rocks is readily traceable along strike as a zone of intense shearing that variably affected both hanging wall and footwall rocks, and sheared lithologies within the zone can be traced into unsheared equivalents to either side. Structural details in the Millerville area are vital for showing a shear zone at the base of the Hillabee Greenstone and are the subject of a manuscript currently in preparation. We therefore recognize this zone, here called the Hillabee shear zone, as a distinct boundary, separable from the overlying Hollins line fault. In an excellent exposure on the West Fork of Hatchet Creek (Millerville area; McClellan 2005), the contact between mafic and quartzose rocks is sharp, and foliation in the sheared Hillabee rocks is slightly oblique to that in quartzose phyllite of the Talladega Group. Locally, the contact may appear gradational (e.g., Tull and Stow 1980) as a result of repetition of lithologies. However, no compositional transition between mafic and quartzose lithologies is apparent, and the repetition may be explained by tight folding or imbrication of the contact.

Conditions of shearing are constrained to greenschist facies by mineral assemblages and microstructures in the Hillabee metadacite, in which mylonitic textures are particularly well developed, including (1) larger relict quartz grains that display prevalent undulose extinction and subgrain development, surrounded by smaller dynamically recrystallized grains; (2) feldspars that display brittle fracturing, bent twins, and patchy undulose extinction, likely due to small-scale fractures (Tullis and Yund 1987); and (3) brittle fracturing of hornblende, with growth of syndeformational, aligned acicular actinolite, chlorite, and epidote in fractures between segments. A mineral-stretching lineation, visible on the mesoscopic scale, was produced by separation and extension of fractured hornblende segments (Vinson and McClellan 1997; McClellan 1998). Based on the synmetamorphic character of the Hillabee shear zone, the lack of evidence for more than one metamorphic episode in the Talladega belt (see above), and the isotopic and biostratigraphic dates discussed earlier, we infer that the Middle Ordovician Hillabee Greenstone was emplaced onto the early Mississippian to post–Middle Ordovician Talladega Group before or during metamorphism of the Talladega Group footwall units (i.e., no later than ~320 Ma).

Along-Strike Correlations. Based on geochemical and geochronological similarities discussed below, we correlate the Hillabee Greenstone with metaigneous rocks in the Dahlonega gold belt, as has been suggested by other geologists over the years (e.g., McConnell 1980; Drake et al. 1989; Gillon 2001; Thomas et al. 2001; McClellan et al. 2005; Holm et al. 2006). Hillabee metabasaltic rocks can be traced into western Georgia (fig. 2; Heuler 1993; Holm and Farmer 2002; Holm et al. 2006) and lie nearly along strike with mafic rocks in the Dahlonega gold belt, although they are separated by the Allatoona fault. North of the Mulberry Rock antiform (fig. 2), the Allatoona fault corresponds to a distinct lithologic and metamorphic break and is marked by ductile shearing and retrograde metamorphism (McConnell and Abrams 1984). South of this area and toward the Alabama state line, however, delineation of the Allatoona fault is complicated by pervasive imbricate faulting (Crawford and Cressler 1982; Holm and Farmer 2002) and has been variously equated with the Hollins line fault (Heuler 1993) or the Goodwater-Enitachopco fault (Bentley and Neathery 1970; Hatcher et al. 1990), although the latter fault was interpreted as a normal fault that cuts the Hollins line thrust (Tull et al. 1985). If the Hillabee-Dahlonega correlation is correct, however, the Allatoona fault and the Hillabee shear zone may represent essentially the same structural level, although perhaps as parts of a broader zone rather than as one discrete fault.

Geochemical and Age Similarities. Whole-rock geochemical analyses and numerous Ordovician U-Pb zircon ages have been obtained from metavolcanic and metaplutonic rocks in the southern Appalachians, including the Hillabee Greenstone (Thomas 2001; McDowell et al. 2002; Settles 2002), and whole-rock geochemical data confirm an arc-related setting for some of these mafic sequences. Based on the overall geochemical trends, stratigraphic relationships, and the association of the metabasalts with felsic rocks having calc-alkaline affinities, the Hillabee Greenstone was interpreted as having formed in an arc or back-arc setting, possibly along an active continental margin (Tull et al. 1978, 1998; Tull and Stow 1980; Durham 1993). Similarly, metaigneous rocks in the Dahlonega gold belt in central Georgia (Higgins and McConnell 1978; McConnell and Abrams 1984) and probable correlatives to the northeast, the Lake Burton (Hopson 1989) and Sally Free (Settles 2002) mafic complexes, comprise metabasaltic rocks with interlayered felsic extrusives and intrusives and volcaniclastic rocks. Past and recent studies of major- and trace-element chemistry of the mafic and felsic metavolcanics, as well as field evidence, point to an arc/back-arc affinity for most of the these rocks (McConnell and Abrams 1984, 1986; German 1985; Gillon 1989; Hopson 1989; Thomas 2001; Settles 2002; Das and Holm 2005), distinct from MORB (mid-ocean ridge basalt)-like geochemical signatures seen in other mafic complexes to the northeast (Long and Miller 1983; Morman et al. 1999; Meyer et al. 2001). Tectonic discrimination diagrams (figs. 7, 8) show strong geochemical similarity between Dahlonega gold belt and Hillabee Greenstone rocks and those from collisional or arc environments.

Thomas (2001) and Das and Holm (2005) determined U-Pb zircon ages of 460–470 Ma from three felsic gneisses, interpreted as metadacites, within the Dahlonega gold belt and correlative Lake Burton complex and a slightly younger age of 458 ± 3 Ma from a synkinematic intrusive within the gold belt. Bream (2003) reported an age of

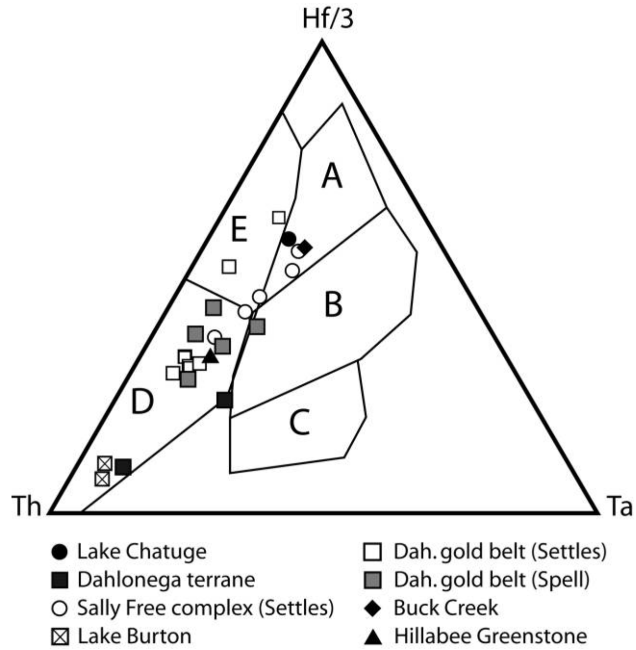

Figure 7. Hf/3-Th-Ta tectonic discrimination diagram (Wood 1980) for key extrusive mafic samples from the Southern Appalachians. Includes data from Settles (2002) and Spell and Norrell (1990). Unreferenced data and localities are from Thomas (2001). Fields: A = N-type MORB; B = E-type MORB and tholeiitic within-plate basalts (WPB); C = alkaline WPB; D = destructive plate margin basalts (calc-alkaline); E = destructive plate margin basalts (primitive arc tholeiite).

482 ± 4 Ma from a metarhyodacite in the Sally Free complex. The overlap, within error, of the Dahlonega metadacite ages from Thomas (2001) with the Hillabee age reported here (fig. 9) and the similarity in chemistry and tectonic setting support correlation of the Hillabee Greenstone with the metaigneous rocks in the Dahlonega terrane.

Drake et al. (1989) noted that Taconic deformation in the northern Appalachians could be related to the attempted subduction of the Laurentian craton beneath an Ordovician island arc, but no such model could be applied to the southern Appalachians because no Ordovician arcs had been recognized (Drake et al. 1989). A stronger argument for a significant Ordovician arc system in the southern Appalachians exists if we consider the age, tectonic environment, and likely correlation of the Dahlonega and Hillabee rocks. Based on data from the previous studies cited above and our new data, we interpret the Hillabee Greenstone as the southernmost volcanic expression of an Early to Middle Ordovician arc complex formed outboard of Laurentia.

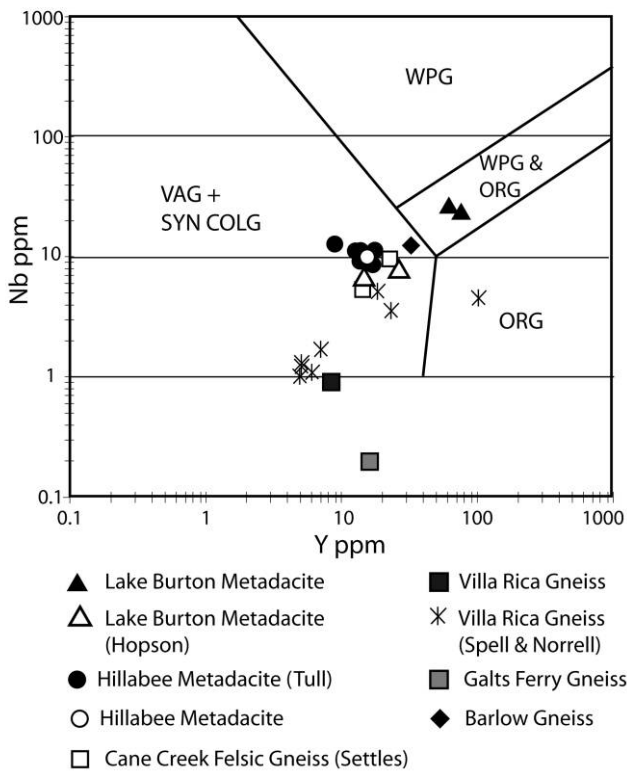

Figure 8. Nb-Y discrimination diagram (Pearce et al. 1984) of felsic intrusive samples from the Dahlonega gold belt and Hillabee Greenstone. Includes data from Settles (2002), Spell and Norrell (1990), Hopson (1989), and Tull et al. (1998). Unreferenced data and localities are from Thomas (2001). *VAG* = volcanic arc granitoid; *SYN COLG* = syncollisional granitoid; *WPG* = within-plate granitoid; *ORG* = ocean ridge granitoid.

Possible Plutonic Roots of This Arc. Connecting the Hillabee-Dahlonega arc with its plutonic roots is obscured by the complex structural relationships between the Hillabee and Dahlonega composite terrane and plutons in other thrust sheets in the eastern Blue Ridge and Inner Piedmont. There are numerous Early to Middle Ordovician intrusions exposed in the southernmost Appalachian eastern Blue Ridge and Inner Piedmont with similar crystallization ages and arc-like geochemical signatures. The largest intrusion in the eastern Blue Ridge, the Elkahatchee Quartz Diorite (fig. 2), was dated by an Rb-Sr whole-rock isochron as Early Ordovician (~490 Ma), and U-Pb analysis of total populations of zircon were similar (Russell 1978). Based on the petrology and setting of the Elkahatchee, Drummond et al. (1994) interpreted it as a subduction-related batholith. The Kowaliga Gneiss of the Alabama eastern Blue Ridge is another batholith-sized granodioritic pluton, dated at ~458 Ma (Russell 1978; using total populations of zircons). Smaller, tabular sheets of Zana Granite lying between the Elkahatchee and Kowliga intrusions are dated at ~460 Ma (Russell 1978; total populations of zircons). The Persimmon Creek Gneiss, which intrudes the high-grade metasedimentary rocks of the Cowrock terrane of northeastern Georgia and southwestern North Carolina (fig. 1), is interpreted as representing a subduction-related, intermediate pluton and has yielded U-Pb magmatic ages of 468 Ma (McDowell et al. 2002). Similar plutonic bodies in the Inner Piedmont include the Farmville metagranite (~460 Ma by U-Pb methods; Grimes et al. 1997) and the Franklin Gneiss (~462 Ma by Rb/Sr methods; Seal and Kish 1990). The sheer volume and relatively large size of Ordovician plutons in the southernmost Appalachians dwarf all other plutonic bodies of any age combined, consistent with the interpretation that they represent the infrastructural levels of an Early to Middle Ordovician arc or perhaps more than one arc.

Implications for the Paleogeography of the Early to Middle Ordovician Margin. Paleogeographic reconstructions of Laurentia in the Ordovician (e.g., Dalziel 1997; Mac Niocaill et al. 1997; Ross and Scotese 1997; Christiansen and Stouge 1999; Lees et al. 2002) commonly depict an open ocean along the southernmost margin, with the exception of the drifting Precordillera terrane (Thomas 1991). Clearly, the relationship of the Hillabee-Dahlonega arc with Laurentia and outboard southern Appalachian terranes has significant implications for the paleogeography of the Early to Middle Ordovician margin. Modern subduction zones are highly complex, and the along-

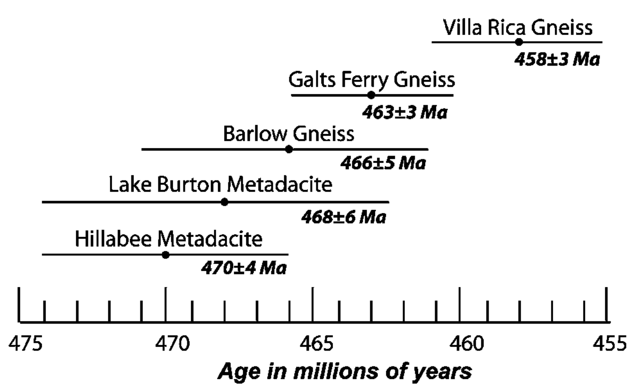

Figure 9. U-Pb ages of felsic extrusive and intrusive (?) rocks from the Dahlonega gold belt (Thomas 2001) compared with that of metadacite from the Hillabee Greenstone (McClellan and Miller 2000; this study).

strike history of different segments in a single arc system may vary by tens of millions of years (e.g., Hamilton 1995). Such complexities may have resulted in significant differences along the Hillabee-Dahlonega arc system in the character of the arc, its interaction with the Laurentian microcontinental fragments, and its subsequent structural fate.

The Late Proterozoic rifted Laurentian margin was characterized by alternating promontories and embayments that subsequently controlled syn- and postrift deposition as well as growth of the Appalachian orogenic belt (e.g., Thomas 1977, 1991; Thomas and Whiting 1995). Significant features of this irregular margin include (1) the Alabama-Oklahoma transform (Thomas 1991), which facilitated the drifting of the Precordillera terrane toward its ultimate collision with Gondwana (Astini and Thomas 1999) and may have marked the southern terminus of subduction outboard of the Laurentian margin in Early to Middle Ordovician time; and (2) the embayments that typically comprise wide zones of thinned continental crust, locally punctuated by marginal plateaus or microcontinental blocks (Thomas 1993). Microcontinental blocks of potential Laurentian affinity that may have been situated outboard of the margin at that time include the Tugaloo, Cartoogechaye, and Cowrock terranes (Bream et al. 2004; Hatcher et al. 2004).

By Early to Middle Ordovician time, subduction had begun along the southern Laurentian margin. East-dipping subduction has frequently been suggested (e.g., Hatcher 1987; Higgins et al. 1988; Drake et al. 1989; Stewart et al. 1997; Stewart and Miller 2001; Miller et al. 2006), whereas Drummond et al. (1994, 1997) presented evidence that the Elkahatchee Quartz Diorite (fig. 2) represents continental margin magmatism associated with subduction of young, hot oceanic crust westward beneath Laurentia. This apparent conundrum may be explained if the ~490-Ma Elkahatchee batholith represents an older episode of subduction. We offer a conceptual model (fig. 10) in which initial rifting produced the main Iapetus spreading ridge and also a smaller basin that separated the Cowrock and Cartoogechaye blocks from the Laurentian margin. As plate motions changed, west-dipping subduction initiated beneath the outermost margin of Laurentia, forming an arc represented by the ~490-Ma Elkatchee batholith and perhaps also the ~482-Ma Sally Free mafic complex (Settles 2002). The west-dipping zone ultimately slowed and became inactive, perhaps as the central spreading ridge approached the trench (e.g., Shervais 2001), and was replaced by east-dipping subduction on the opposite side of the basin.

The Cowrock and Cartoogechaye blocks both contain mafic-ultramafic complexes (Lake Chatuge and Buck Creek, respectively) interpreted as remnants of mid-ocean ridge or back-arc basin crust (Thomas 2001 and references therein) that experienced Taconian high-pressure granulite facies metamorphism (Meen 1988; Emilio 1998). In addition, migmatitic gneiss in the Cartoogechaye terrane recorded granulite facies conditions, with a thermal peak at 458 ± 1 Ma (Moecher et al. 2004). Miller et al. (2000*a*, 2006) documented a slightly older age for eclogite facies metamorphism in the eastern Blue Ridge southwest of the Grandfather Mountain window (fig. 1). Because this metamorphic event was essentially coeval with the youngest documented magmatism in the Dahlonega gold belt (fig. 9), we infer that the Cowrock and Cartoogechaye blocks were situated on the lower plate of the east-dipping subduction zone and that the high-grade metamorphic conditions were attained during attempted subduction of the microcontinental fragments and adjacent oceanic crust, concurrent with formation of the Hillabee-Dahlonega arc in the upper plate. Subduction eventually ceased, perhaps as a result of collision with young, hot crust produced at the Galateian ridge (fig. 10), and motion was transferred to new subduction zones and/or transforms outboard of the arc. Subsequent buoyant rise of the subducted Cowrock and Cartoogechaye blocks uplifted the leading edge of the arc, resulting in partial "obduction" in the sense of Shervais (2001), albeit onto the microcontinental blocks and surrounding transitional crust instead of a continental passive margin. This could have allowed the arc to remain at shallow levels until caught up in later convergence, when its northern part was carried passively westward on the back of the Cowrock-Cartoogechaye terranes, whereas the southern part was thrust over the earlier-formed Elkahatchee arc and emplaced against the Laurentian shelf deposits. Tests of this "two-subduction-zone" (fig. 10) model require more extensive geochronological and geochemical comparisons between elements of the two proposed arc systems as well as consideration of contact relationships and distribution of potentially correlative tectonic blocks throughout the Blue Ridge and Piedmont in the southernmost Appalachians and of the potential role of dextral strike-slip faulting, which has been recognized along the entire Appalachian margin (e.g., Adams et al. 1995).

Conclusions

(1) The Hillabee Greenstone, at ~470 Ma, is older than underlying metasedimentary rocks of the Tal-

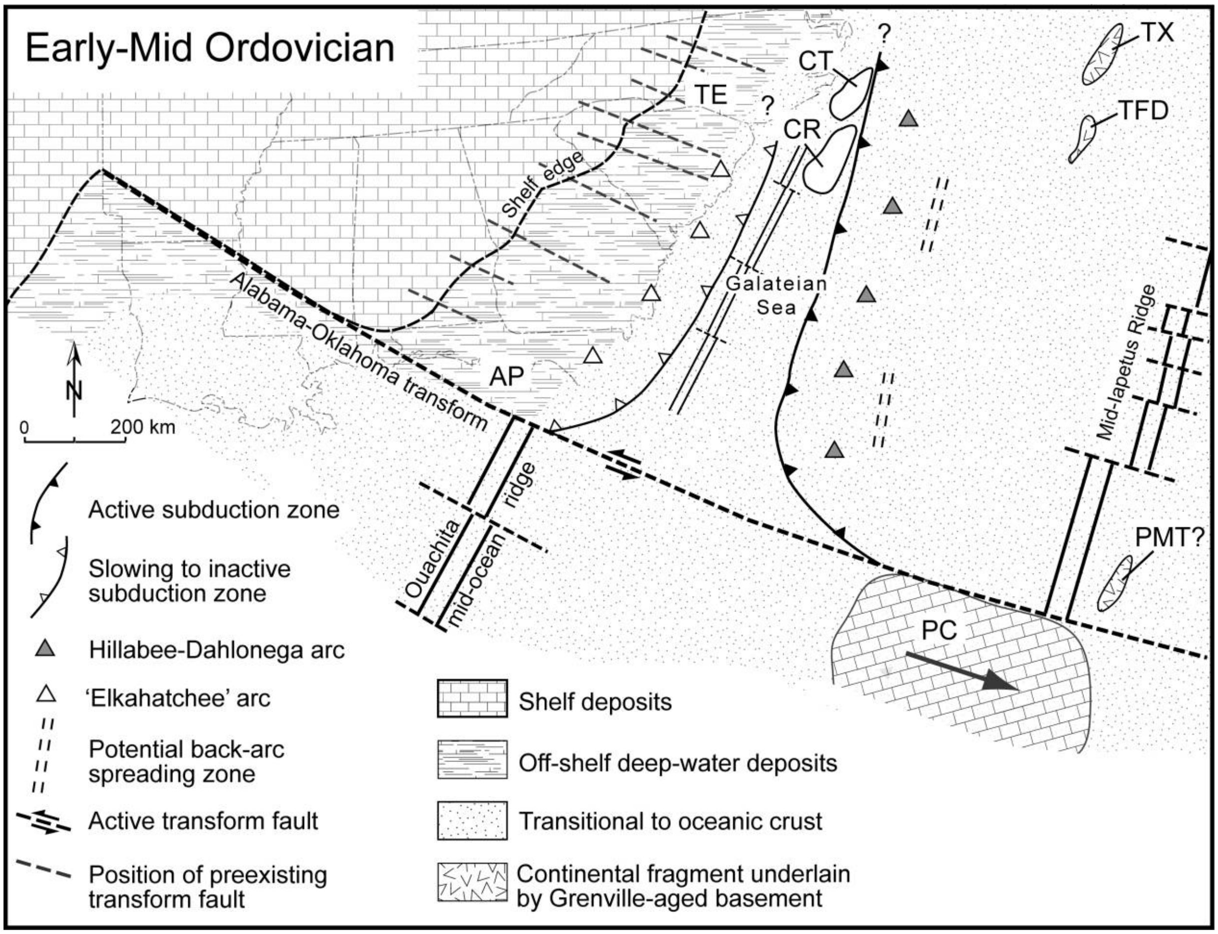

Figure 10. Paleogeographic model of the Early to Middle Ordovician Laurentian margin, depicting west-dipping subduction and arc formation at ~490 Ma, followed by east-dipping subduction and formation of the Hillabee-Dahlonega arc at ~470 Ma. The intervening small ocean basin is referred to as the Galateian Sea, for a minor Greek goddess (nymph) of the sea. See text for full explanation. *AP* = Alabama promontory; *TE* = Tennessee embayment. Microcontinental fragments and other terranes include *CR* = Cowrock terrane; *CT* = Cartoogechaye terrane; *PC* = Precordillera terrane; *PMT* = Pine Mountain terrane; *TFD* = Tallulah Falls dome; *TX* = Toxaway dome. Shape of rifted continental margin and location of shelf edge and deposits after Thomas (1989, 1991).

ladega belt, the youngest of which was deposited at 360–350 Ma (Erin Slate). (2) The contact between the Hillabee and the underlying rocks is a ductile fault (Hillabee shear zone), a lower-greenschist facies pre- to synmetamorphic fault that must have formed after deposition of the Erin Slate but before or during metamorphism of the footwall (Talladega belt metasedimentary rocks) and hanging wall (Hillabee) blocks. (3) This metamorphic episode occurred no later than ~320 Ma, perhaps during hot emplacement of the Hollins line thrust sheet. (4) The Hillabee Greenstone is correlative with 470–460-Ma arc-related rocks of the Dahlonega gold belt. (5) Initial deformation and metamorphism occurred along the southernmost Laurentian margin between ~350 and 320 Ma, in response to collision with the Ordovician Hillabee-Dahlonega arc terrane. Our data are most consistent with a recently documented early Alleghanian (~330 Ma) age of deformation and metamorphism, while evidence of Taconian tectonism, documented farther to the northeast, is entirely lacking in this area. (6) Paleogeographic models of the Early to Middle Ordovician southern Laurentian margin and outboard arc must explain observed variations in deformation and metamorphism along the arc-continental margin boundary, which may involve the geometry of the existing rifted margin, the position of microcontinental fragments relative to the subduction zone(s) and developing arc, potential segmentation of the arc along transform faults, possible existence of an earlier episode of subduction, and polarity of the subduction zone(s).

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