

Volcanic arc emplacement onto the southernmost Appalachian Laurentian shelf: Characteristics and constraints

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ABSTRACT

In the southernmost Appalachians, the Hillabee Greenstone, an Ordovician volcanic arc fragment, lies directly atop the outermost Laurentian Devonian–earliest Mississippian(?) shelf sequence at the structural top of the greenschist facies Talladega belt, the frontal metamorphic allochthon along this orogenic segment. The Hillabee Greenstone was emplaced between latest Devonian and middle Mississippian time. It and the uppermost Laurentian section were later repeated together within a series of map-scale imbricate slices of a postmetamorphic, dextral, transpressional, Alleghanian thrust duplex system that placed the high-grade eastern Blue Ridge allochthon atop the Talladega belt. Geochemical and geochronologic (U–Pb zircon) studies indicate that the Hillabee Greenstone's interstratified tholeiitic metabasalt and calc-alkaline metadacite/rhyolite formed within an extensional setting on continental crust ca. 460–470 Ma. Palinspastic reconstructions of the southern Appalachian Ordovician margin place the Hillabee Greenstone outboard of the present position of the Pine Mountain terrane and suggest links to Ordovician plutonism in the overlying eastern Blue Ridge, and possibly to widespread K-bentonite deposits within Ordovician platform units. The tectonic evolution of the Hillabee Greenstone exhibits many unusual and intriguing features, including: (1) premetamorphic emplacement along a basal cryptic thrust, which is remarkably concordant to both hanging wall and footwall sequences across its entire extent (>230 km), (2) forma-

tion, transport, and emplacement of the arc fragment accompanied by minimal deformation of the Hillabee Greenstone and underlying outer-margin shelf rocks, (3) emplacement temporally coincident with the adjacent collision of the younger, tectonically independent Ouachita volcanic arc with southeastern Laurentia. These features highlight strong contrasts in the Ordovician–Taconian evolution of the southern and northern parts of the Appalachian orogen.

Keywords: Appalachians, volcanic arc, Talladega belt, Hillabee, Blue Ridge.

INTRODUCTION

The Hillabee Greenstone is a bimodal sequence of tholeiitic metabasalt and subordinate interstratified calc-alkaline metadacite/rhyolite at the structural top of the lower greenschist facies Talladega belt, which is the frontal metamorphic thrust sheet in the southernmost Appalachians (Tull et al., 1998) (Fig. 1). In the Talladega belt, the Hillabee Greenstone structurally overlies fossiliferous, shallow-marine, Devonian to earliest Mississippian(?) rocks at the top of the Talladega Group, which represents the region's most outboard Laurentian margin cover sequence (Butts, 1926; Tull, 1982, 2002; Tull et al., 1988; Gastaldo, 1995). Fossils, an internal unconformity, and abundant primary structures indicate that the Talladega Group and underlying units (Fig. 2) are upright (Tull, 1982, 1998, 2002). The Hillabee Greenstone and underlying Laurentian shelf rocks occur within both the Talladega belt parautochthon, and large (10 to >200 km²) overlying imbricate slices (horses) of a regional, postmetamorphic, dextral, transpressional thrust duplex system of Alleghanian age;

they extend along strike for >230 km beneath the upper amphibolite facies eastern Blue Ridge allochthon (Fig. 2). For decades, geologists (e.g., Prouty, 1923; Neathery, 1973; Tull et al., 1978; Tull, 1979; Tull and Stow, 1980) have argued that the Hillabee Greenstone postdates underlying units because: (1) over its >230 km strike length, the internal Hillabee Greenstone stratigraphy maintains strict concordance with that of underlying upright units (Tull et al., 1998); (2) concordance also occurs within horses of the duplex, indicating that structural concordance is maintained both along strike, and for tens of kilometers across strike; (3) the Hillabee Greenstone and underlying units share the same parallel planar and linear metamorphic fabrics and facies, with no disruption of fabrics across the contact between them (Tull et al., 1978); and (4) concordant interlayering of Hillabee Greenstone and underlying units occurs on outcrop scale (Tull, 1979). These observations suggest that the Hillabee Greenstone is most reasonably interpreted as being of mid-Paleozoic age.

In contrast, zircon (5–50 mg samples) from a Hillabee Greenstone metadacite unit yielded ²⁰⁷Pb/²⁰⁶Pb ages between 444 Ma (2% discordant) and 462 Ma (6% discordant), indicating that the Hillabee Greenstone is older than underlying units and is thus separated from them by a cryptic fault (Russell, 1978; Russell et al., 1984). Tull et al. (1998a) suggested that these slightly discordant ages could represent a mixed age resulting from a xenocrystic component. Ion microprobe U–Pb analyses of Hillabee Greenstone metadacite zircons reported herein and by McClellan and Miller (2000), however, also yield Middle Ordovician ages (the geologic time scale used herein is the GTS2004 of Gradstein et al., 2004). In combination with field studies, these studies suggest

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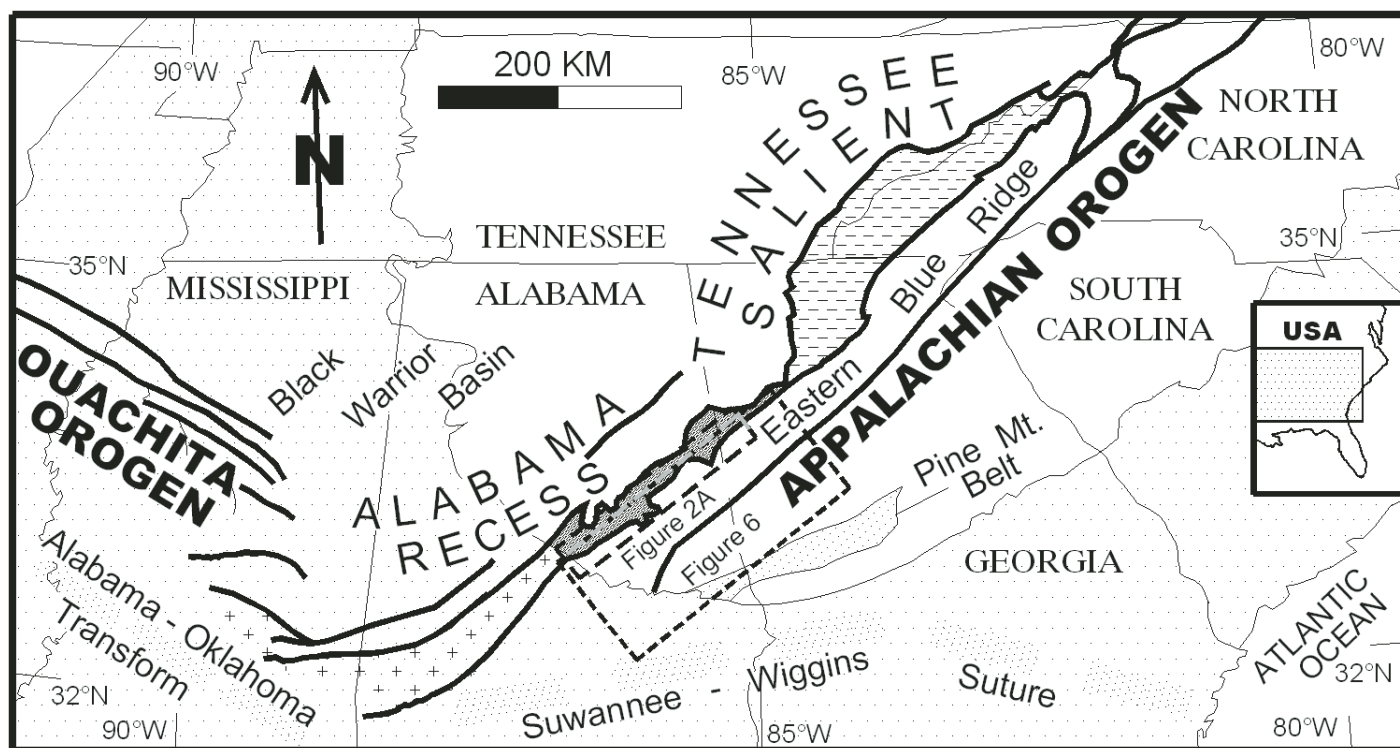


Figure 1. Generalized geologic map of the southern Appalachian and eastern Ouachita orogens. Solid and plus sign patterns are areas of Talladega belt outcrop and subcrop, respectively. Light stipple pattern—Mesozoic and Cenozoic rocks of the Gulf and Atlantic Coastal Plains. Heavy stipple pattern—locations of Alabama-Oklahoma transform fault and Suwannee-Wiggins late Paleozoic suture. Dashed pattern—distribution of late Proterozoic Ocoee Supergroup. Thick solid lines—faults. Location of Figures 2A and 6 are shown. (Modified from plate 9 of Thomas et al., 1989.)

that the Hillabee Greenstone is an accreted fragment of a previously more extensive Ordovician volcanic complex that was thrust onto the middle Paleozoic shelf along a cryptic fault (Hillabee Greenstone thrust, Fig. 2). In the following, we provide a description of the unit, its structural setting, and its implications for the evolution of the Ordovician margin of the southern Appalachian orogen.

DESCRIPTION AND TECTONIC SETTING OF THE METAVOLCANIC COMPLEX

Other than the dominantly mafic, but bimodal (SiO_2 gap of 14%) ~2.6-km-thick Hillabee Greenstone, Middle to Upper Ordovician rocks are absent in the Talladega belt. Structurally below the Hillabee Greenstone, the upright Lower Cambrian–uppermost Lower Ordovician (older than ca. 478 Ma) passive-margin shallow-marine carbonate shelf (now marble) is unconformably overlain by a Silurian(?)–Lower Devonian, turbiditic, Laurentia-derived, clastic wedge sequence (Tull, 2002). The Ordovician Hillabee Greenstone is thus completely surrounded by thrusts and, therefore, it is exotic to

the Talladega belt. Models for its origin and tectonic setting are entirely dependent upon inferences made from its stratigraphic, geochemical, and petrologic signatures. Field and textural evidence in conjunction with major- and trace-element geochemical data indicate that the protoliths of the mafic rocks were low-K, tholeiitic basalts and basaltic ash (Tull et al., 1978; Tull and Stow, 1979, 1980; Stow, 1979, 1982). Thick (up to ~165 m), mineralogically and chemically homogeneous, tabular bodies of porphyritic metaquartz dacite/rhyolite are interlayered with the mafic rocks and locally compose up to 25% of the Hillabee Greenstone sequence. These rocks originally extended over hundreds of square kilometers and are interpreted as large-volume (some sheets $>50 \text{ km}^3$) crystal tuffs (ignimbrites) (Tull et al., 1998). Tholeiitic basalt and calc-alkaline rhyolite/dacite suites, like the Hillabee Greenstone, commonly occur in zones of extending, attenuated continental crust, and plume-related sequences (e.g., Dusel-Bacon et al., 2004; Seaman et al., 1999; Moyer and Nealy, 1989; Hildreth et al., 1991).

Because of the lack of associated lithologies and sequences, chemical discrimination techniques that help delineate tectonomagmatic

environments of volcanic rocks offer one of the few ways to establish the paleotectonic setting of the Hillabee Greenstone. Compositionally, Hillabee Greenstone tholeiitic basalts compare most favorably with rocks formed in backarc, extensional environments (e.g., high average Y [23.9 ppm] and TiO_2 values [1.27 wt%]) (Tull et al., 1978; Tull and Stow, 1979, 1980; Durham, 1993; Tull et al., 1998). Various trace-element abundances (e.g., Nb, Ta, Yb, La) indicate that Hillabee Greenstone calc-alkaline felsic rocks are similar to typical arc volcanic and granitic rocks (Tull et al., 1998). Elemental abundance patterns, therefore, suggest that the Hillabee Greenstone formed in an extensional environment involving attenuated continental crust, and elemental discrimination diagrams indicate a volcanic arc signature. Felsic rocks commonly erupt in the early stages of backarc-basin opening, forming a bimodal volcanic suite with more voluminous basalts. In fact, the presence of this bimodal suite is characteristic of the earliest stages of backarc rifting during the initial formation of a backarc basin, and differentiates early backarc-basin rifting from more evolved backarc-basin spreading (Clift, 1995; Marsaglia, 1995).

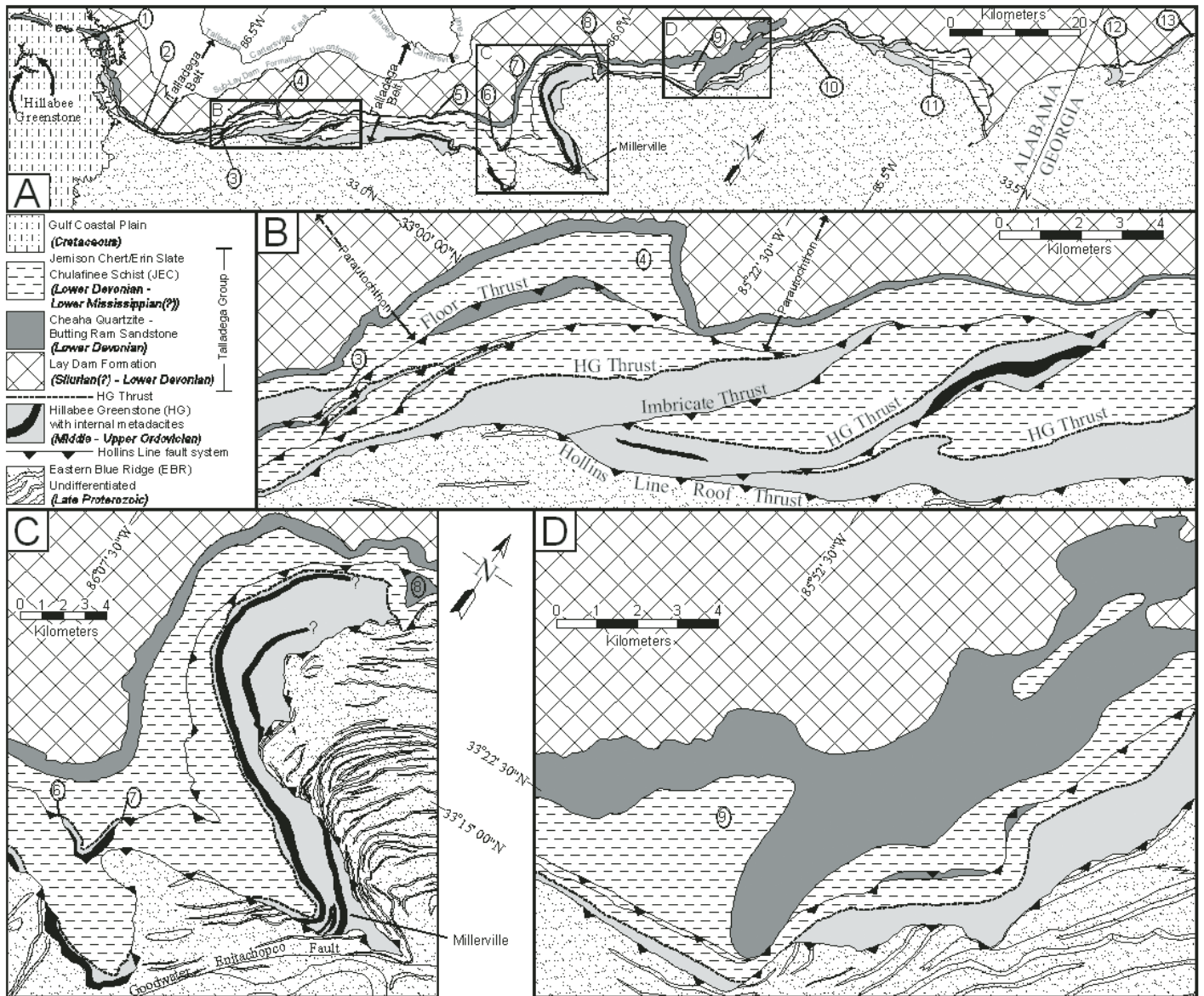


Figure 2. Geologic maps of the Talladega belt and northwestern part of the eastern Blue Ridge belt, Alabama and west Georgia. Numbered localities are referenced in text. B, C, and D focus upon the upper part of the Talladega belt parautochthon and the Hollins Line thrust duplex system. Location of A is shown in Figure 1.

AGE OF THE HILLABEE DACITES

Russell (1978) and Russell et al. (1984) reported conventional U-Pb analyses for multigrain zircon separates from two aliquots of the lower Hillabee Greenstone dacite collected 6 km northwest of Millerville (Fig. 2C). The nonmagnetic zircon fraction yielded a nearly concordant age of ca. 434 Ma with relatively high U (>1000 ppm) and Pb (~100 ppm) contents. A magnetic fraction yielded an older set of U-Pb and Pb-Pb ages, but with more discordance. Ion microprobe U-Pb analyses of 10 grains from a sample collected from the same

dacite 10.6 km northwest of Millerville yielded a range of $^{206}\text{Pb}/^{238}\text{U}$ ages from 447 to 502 Ma (McClellan et al., 2005). McClellan et al. (2005) proposed the best estimate of the age of crystallization to be 470 ± 4 Ma, with some inheritance of slightly older grains.

Data reported here are also from the lower metadacite collected 9.8 km northwest of Millerville, and they were analyzed using the sensitive high-resolution ion microprobe–reverse geometry (SHRIMP RG) (Compston et al., 1984; Compston and Williams, 1992). Analyses of 23 zircon grains yielded a range of $^{206}\text{Pb}/^{238}\text{U}$ ages from 342 to 472 Ma, and $^{207}\text{Pb}/^{206}\text{Pb}$ ages

ranged from 378 to 536 Ma; discordance ranged from 0 to 22% (Table DR1¹). All grains exhibited Th/U ratios indicative of an igneous origin (>0.2), regardless of the extent of discordance, and many were characterized by relatively high common Pb contents (up to 2.1% of measured ^{206}Pb). There were no observable core/overgrowth relations in any grains as imaged in both

¹GSA Data Repository item 2007044, U-Pb and Hf isotope data for Hillabee Greenstone and Talladega belt zircon populations, is available on the Web at <http://www.geosociety.org/pubs/ft2007.htm>. Requests may also be sent to editing@geosociety.org.

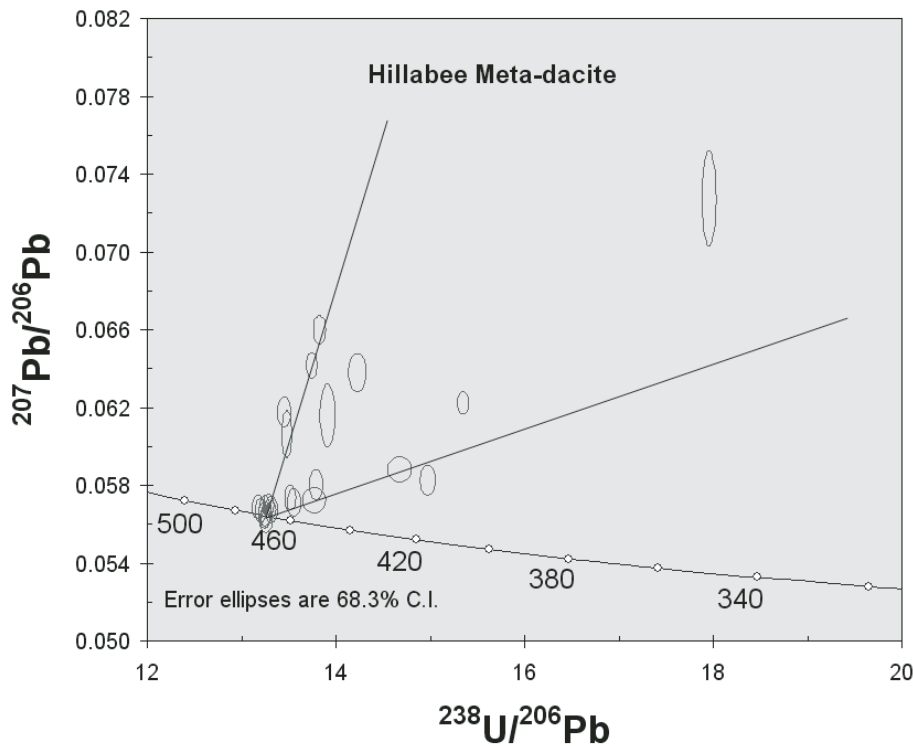


Figure 3. Terra-Wasserburg concordia diagram for Hillabee metadacite zircons showing discordance likely resulting from multi-episodic Pb-loss and/or variable common Pb compositions.

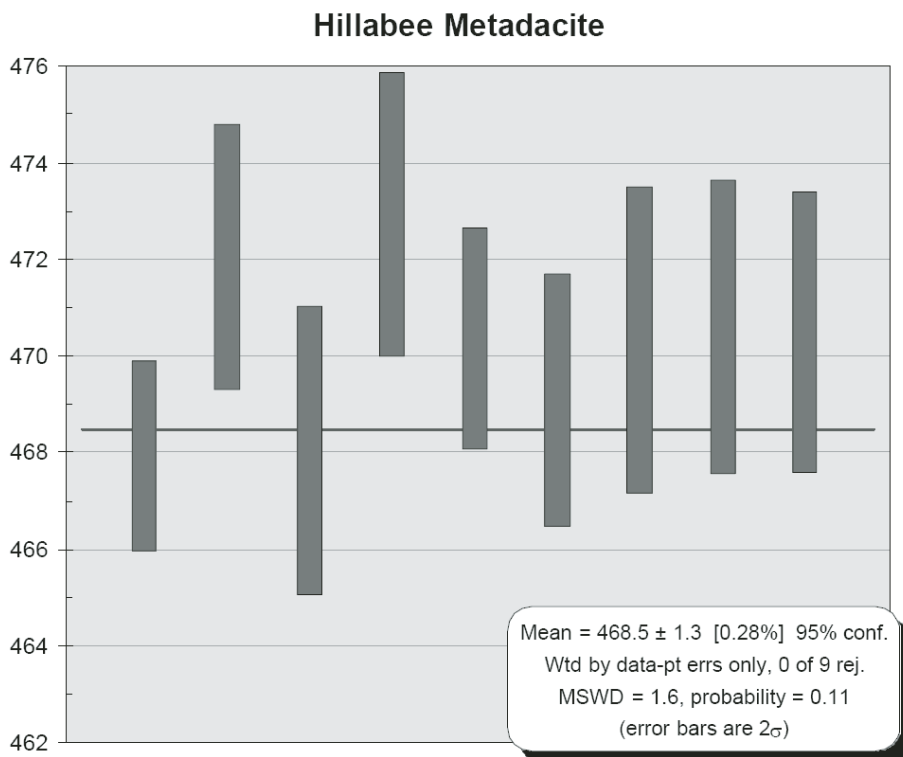


Figure 4. Error weighted mean $^{206}\text{Pb}/^{238}\text{U}$ age with 2σ errors for nine Hillabee metadacite zircons.

plane light and cathodoluminescence (CL). The overall pattern shown in Figure 3 is indicative of multiple episodes of Pb loss and/or mixing with one or more components of common Pb. This pattern makes it important to emphasize those grains with low common Pb contents in any age evaluation. Consequently, the best crystallization age estimate for this sample is based on the error weighted mean $^{206}\text{Pb}/^{208}\text{U}$ age determined from nine individual grains (Fig. 4). The nine $^{206}\text{Pb}/^{208}\text{U}$ ages used in this calculation were derived from the ^{207}Pb -based common Pb correction method and had common Pb contents $<0.05\%$ of measured ^{206}Pb and had small (<1 m.y.) differences in $^{206}\text{Pb}/^{208}\text{U}$ ages when compared to ages calculated using the ^{207}Pb -, ^{204}Pb -, and ^{208}Pb -based common Pb corrections methods, which used ca. 470 Ma common Pb compositions from Stacey and Kramers (1975). This approach produced an error weighted mean $^{206}\text{Pb}/^{208}\text{U}$ age of 468 ± 3 Ma (95% confidence interval [CI]). This age is in agreement with the 470 ± 4 Ma crystallization age estimate of McClellan et al. (2005), although no clear evidence of an older population of zircons was present in our data. The older $^{207}\text{Pb}/^{206}\text{Pb}$ ages (to 536 Ma) (Table DR1, see footnote 1) had relatively large errors due to low ^{207}Pb count rates and were all within 2σ of the mean $^{206}\text{Pb}/^{208}\text{U}$ age calculated from this sample. Consequently, they did not provide clear evidence of any older component in the zircons.

Evidence for involvement of older crust in the generation of the Hillabee Greenstone dacites is evident, however, in the Hf isotopic compositions of the zircons. Zircons normally contain Hf at the 1 wt% level and are characterized by very low Lu/Hf ratios. Zircons, therefore, can capture the Hf isotopic composition of the melt from which they crystallized and are unlikely to have their Hf isotopic compositions altered subsequent to crystallization (e.g., Amelin et al., 2000; Machado and Simonetti, 2001; Griffin et al., 2002; Goodge and Vervoort, 2006). For the Hillabee Greenstone zircons, initial Hf isotopic compositions for five grains based on an age of 468 Ma and the Hf parameters of Patchett et al. (2004) ranged from -4 to -8 epsilon units and yielded depleted mantle model ages of 1.0–1.1 Ga, using measured Lu/Hf ratios and the depleted mantle parameters of Nowell et al. (1998) (Table DR2, see footnote 1). The variation in initial Hf isotopic compositions suggests that marginally distinct sources were contributing magma that was not thoroughly mixed prior to eruption (e.g., Griffin et al., 2002) or that the larger volumes of zircon ablated for Hf analysis compared to U-Pb analyses led to sampling of some xenocrystic components within individual grains. Overall, however, the low initial epsilon values clearly suggest that

older lithosphere, probably Mesoproterozoic, was involved in the generation of the felsic Hillabee Greenstone magmas.

STRUCTURAL SETTING OF THE HILLABEE METAVOLCANIC COMPLEX

The southeast (upper) flank of the Talladega belt is a structurally complex zone characterized by postmetamorphic imbricate faulting (Hollins Line fault system) that produced large thrust horses of Talladega belt units beneath the high-grade eastern Blue Ridge allochthon (Fig. 2). This fault system is a transpressional footwall thrust duplex (Moore and Tull, 1989; Tull, 1995) represented by: (1) a roof thrust (Hollins Line fault), (2) large, dextrally offset imbricate slices containing the Hillabee Greenstone and upper Talladega Group, and (3) a floor thrust (Fig. 2B). The imbricate faults extend obliquely from the floor to the roof thrust in an en-echelon-right sense. Below the floor thrust, the Talladega belt parautochthon also contains the Hillabee Greenstone and the structurally underlying Talladega Group. The roof thrust separates lower greenschist facies footwall rocks from the overlying upper amphibolite facies eastern Blue Ridge. The imbricate faults and the floor thrust cut the metamorphic fabrics but separate rocks of the same metamorphic grade. The Hillabee Greenstone, therefore, must be separated from the underlying units within the parautochthon and the imbricates by the premetamorphic cryptic Hillabee Greenstone thrust that predates the Hollins Line duplex (Fig. 2).

Throughout its >230 km strike length in both the parautochthon and the duplex horses, the base of the Hillabee Greenstone is in contact with three stratigraphically equivalent units, the Devonian–earliest Mississippian(?) Jemison Chert, Erin Slate, and Chulafinnee Schist, here termed the JEC interval (Butts, 1926; Bearce, 1973; Tull, 2002). Additionally, the Hillabee Greenstone thrust maintains a nearly constant distance above the base of the JEC (Fig. 2) and is never in contact with units stratigraphically beneath the JEC. Along most of its length, the Hillabee Greenstone is only a few hundred meters thick, but in the center of the belt, it is as thick as 2.6 km (Fig. 2C). At most localities where it is >300 m thick, tabular metadacite units occur within the Hillabee Greenstone parallel to the structural base.

Structural and Stratigraphic Relationships in the Parautochthon

To the southwest, the Hillabee Greenstone lies atop the JEC in the parautochthon (Fig. 2A),

which in turn overlies the Butting Ram Quartzite, a conglomeratic metasandstone. From beneath the coastal plain (Fig. 2A, point 1), the Hillabee Greenstone maintains a concordant position above the base of the JEC for 27 km to point 3, except for a short gap where the roof thrust lies at the top of the JEC (Fig. 2A, point 2). With the exception of a decapitated fold pair near point 4, from points 3–6 (Figs. 2A–2C), the floor thrust lies at the approximate level of the top of the JEC interval, and imbricate slices containing the Butting Ram, JEC, and Hillabee Greenstone truncate obliquely against it. Northeast of point 5 (Fig. 2A), the unit equivalent to the Butting Ram is the Cheaha Quartzite, which is overlain by a somewhat thickened JEC composed of thinly laminated carbonaceous sericite phyllite and slate, interlayered with metasandstone, slaty quartzite, and rare, thinly laminated marble (Tull, 2002). Between points 6 and 7 (Fig. 2C), the Hillabee Greenstone reappears within the parautochthon above the JEC and is separated from the Cheaha by approximately the same distance that the JEC separates the Hillabee Greenstone from the Butting Ram. The Hillabee Greenstone reappears within the parautochthon between points 10 and 11, and 12 and 13 (Fig. 2A).

Structural and Stratigraphic Relationships within Imbricate Horses of the Duplex

Imbricate slices containing the Hillabee Greenstone and the structurally underlying upper Talladega Group occur along the duplex from coastal plain inliers to near the Alabama–Georgia border (Fig. 2A) and are of the same metamorphic grade as the parautochthon. Most of these slices were detached near the base of the JEC, and thus they contain in descending order: the Hillabee Greenstone, the JEC, and, locally, the Butting Ram or Cheaha Quartzite. For most of their lengths, the fault splays joining the floor and roof thrusts are parallel to the internal stratigraphy of the horses. Once these faults join the floor thrust, stratigraphy within both the horses and the parautochthon are parallel to the floor thrust for large distances. At several locations, however, postmetamorphic, map-scale dextral folds within the parautochthon (Figs. 2A–2D, points 4, 9, and 12) and the imbricate slices (Fig. 2C, point 8) are cut by the floor thrust (Tull, 1995). The regional en-echelon-right map pattern and dextral folding indicate that the imbricate slices resulted from oblique dextral thrusting (Tull, 1995).

Within the imbricates, the JEC consists of lithologies similar to those in the parautochthon. Locally, the imbricates contain metasandstone/metaconglomerate correlative with the Butting

Ram or Cheaha Quartzite. The distance between the base of the Hillabee Greenstone and the top of the underlying metasandstone/metaconglomerate unit within the imbricates is similar to that between the base of the Hillabee Greenstone and the top of the Butting Ram or Cheaha Quartzite in the parautochthon. Where an internal stratigraphy can be observed within the Hillabee Greenstone (e.g., compositional layering in laminated mafic phyllite, stratabound massive sulfide zones, and tabular metadacite sheets), it parallels the stratigraphy within the Laurentian units below the Hillabee Greenstone thrust (Tull and Stow, 1982; Tull et al., 1998). Thus, there is remarkable concordance between the Hillabee Greenstone and underlying Talladega Group units, both along their entire 230 km strike length and across strike in the down-dip positions of the imbricate slices, which must have extended palinspastically >20 km south-eastward. These relationships indicate that the Hillabee Greenstone thrust at the base of the Hillabee Greenstone, which can be mapped palinspastically over >4600 km², had essentially a “flat-on-flat” geometry over its entire exposure area. In contrast, the roof thrust (Hollins Line fault) is discordant to stratigraphy and structure in both hanging wall and footwall (Figs. 2C and 2D). Thus, the Hillabee Greenstone appears to have been a large, continuous (>4600 km²) sheet of intact volcanic rocks, with no evidence that either it or its footwall was dismembered or significantly deformed prior to or during emplacement (i.e., prior to Alleghanian Hollins Line thrust duplexing).

TIME OF EMPLACEMENT OF THE METAVOLCANIC COMPLEX

Because the Hillabee Greenstone and the upright, underlying Talladega Group are of the same metamorphic grade and carry the same concordant metamorphic fabrics, premetamorphic emplacement of the Hillabee Greenstone is constrained by both the youngest stratigraphic age of the underlying Talladega Group and the age of Talladega belt metamorphism. Whereas the lower half of the Jemison Chert is most likely at least mid-Emsian (late Early Devonian; ca. 407–397 Ma), but no younger than Frasnian (early Late Devonian; ca. 385–374 Ma) based on a well-documented marine invertebrate assemblage (Butts, 1926; Tull, 2002), the age of the uppermost JEC interval is not as well constrained. The uppermost Erin contains *Veryhachium*, a marine acritarch found in Devonian and older rocks in eastern North America, but which is very rare worldwide in the Carboniferous (Tull et al., 1989), and *Periastron reticulatum* (Unger, 1856; Scott and Jeffrey,

1914; Read and Campbell, 1939; Beck, 1978; Gastaldo, 1995), a rare and unusual aquatic or semi-aquatic plant ranging from Late Devonian (Fammenian) to Early Mississippian (Tournaisian), ca. 375–345 Ma. Peak metamorphism in the Talladega belt, therefore, must have been after 375 Ma (Fammenian), or possibly 359 Ma (lowermost Tournaisian).

Estimates of the time of Talladega belt metamorphism based on conventional K/Ar, Rb/Sr, and $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock slate ages (some from the JEC) cluster between ca. 370 and 400 Ma (Wampler et al., 1970; Tull, 1982; Kish, 1990; Durham, 1993; S. Kish, 2003, personal commun.). Because the oldest ages apparently predate the stratigraphic age of the uppermost JEC, they probably reflect the presence of older (detrital) K(Rb)-bearing phases in these rocks, a point of concern for any interpretation of K-Ar or Rb/Sr ages from metapelites (Kish, 1990). The younger ca. 370 Ma K/Ar and Rb/Sr ages (Wampler et al., 1970; Tull, 1982; Kish, 1990), however, could accommodate the oldest possible stratigraphic age (Fammenian) for the uppermost Erin. The $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of white micas from Talladega belt metasedimentary and meta-igneous rocks, however, generally result in younger ages (321–334 Ma) (McClellan et al., 2005), although $^{40}\text{Ar}/^{39}\text{Ar}$ dating of two samples by Kish (2003, personal commun.) resulted in ages compatible with the older conventional K-Ar and Rb/Sr work.

The $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 333.8 ± 1.7 Ma (hornblende) and 327.4 ± 1.6 Ma (muscovite) from eastern Blue Ridge amphibolite facies rocks have been cited as evidence that Talladega belt metamorphism resulted from emplacement of the relatively hot eastern Blue Ridge over the Talladega belt (Kish, 1990; Steltenpohl et al., 2005). This scenario seems unlikely, however, because thrust emplacement of the eastern Blue Ridge would likely have resulted in the upward cooling of, and injection of volatiles into the eastern Blue Ridge, causing widespread retrograde metamorphism in the lower part of the eastern Blue Ridge, which is not observed. Most $^{40}\text{Ar}/^{39}\text{Ar}$ analyses of white mica from the Talladega belt (McClellan et al., 2005) do not define plateaus and are commonly sigmoidal or saddle-shaped; only two samples have defined plateau ages of 327.1 ± 1.7 and 320.8 ± 1.6 Ma. The $^{40}\text{Ar}/^{39}\text{Ar}$ dates of white mica that grew below closure temperature, as may be the case in the Talladega belt, do not reflect a time of cooling and may not reflect the time of mica growth, because they are susceptible to Ar loss from prolonged thermal events, thermal pulses, and/or exhumation (Markley et al., 1998, 2002). Because of the inherent difficulty in assigning meaningful ages to $^{40}\text{Ar}/^{39}\text{Ar}$ results that do not

show plateau release spectra (Kunk et al., 2005), as well as issues of detrital influence in conventional K-Ar whole-rock dating, determining the metamorphic history of the Talladega belt is not straightforward. Based on the ages of syn- to postkinematic igneous intrusions, peak metamorphism in the eastern Blue Ridge was probably ca. 366–370 Ma (Russell, 1978; Russell et al., 1987; Moore et al., 1987; Steltenpohl et al., 2005). The ca. 334–327 Ma eastern Blue Ridge cooling ages (see previous) probably date uplift of the eastern Blue Ridge and are similar to the Talladega belt white mica ages, and thus both sets of ages probably date uplift of both allochthons.

The important difference in interpretation of these similar mica ages from the eastern Blue Ridge and Talladega belt is that Talladega belt ages are not cooling ages, and that Talladega belt metamorphism was characterized by temperatures below 400 °C, and probably below 350 °C, between ca. 330 and 375 Ma (Fammenian), possibly, but not necessarily, coeval with higher-grade metamorphism in the eastern Blue Ridge between 366 and 370 Ma. In the most liberal interpretation, this restricts emplacement of the Hillabee Greenstone upon the Talladega Group between ca. 375 (oldest possible uppermost Talladega Group depositional age) and ca. 330 Ma (youngest metamorphic age). Because the “flat-on-flat” trajectory of the Hillabee Greenstone thrust (see previous) requires that neither the Hillabee Greenstone nor its footwall were extensively deformed (folded) over its entire mapped extent prior to Hillabee Greenstone emplacement, the Hillabee Greenstone must have remained essentially undeformed and minimally metamorphosed (<350 °C) in a structurally high position from the time of its formation until its emplacement upon the shelf units, i.e., for more than 90 m.y. (Fig. 5).

PALEOTECTONIC POSITION OF THE EASTERN BLUE RIDGE ALLOCHTHON

The amphibolite facies eastern Blue Ridge allochthon locally rests upon the Talladega belt parautochthon, but along most of the length of the Hollins Line fault, the eastern Blue Ridge lies above duplex horses in direct contact with the Hillabee Greenstone (Fig. 2). Regionally, the eastern Blue Ridge is a composite terrane (Jefferson terrane of Horton et al., 1989) that may include parts of the Laurentian outer margin cover sequence, as well as accreted components of accretionary prism, ophiolitic, and island arc affinity. In Alabama, it is >10 km thick and consists of the structurally lower Ashland Supergroup, the structurally upper Wedowee Group, and overlying Emuckfaw Formation (Fig. 6)

(Adams, 1926; Neathery, 1975; Tull, 1978). All three sequences are dominated by pelitic rocks and have been proposed to be separated by stratigraphic contacts (Muangnoicharoen, 1975; Neathery and Reynolds, 1973; Tull, 1987; Allison, 1992). Orthoamphibolite is a minor part (~7%) of the lower Ashland Supergroup and the Wedowee Group. Based on geologic setting and geochemical, textural, and mineralogic criteria, these rocks are interpreted to be seafloor tholeiitic basalts and associated sills intercalated with deep-water turbiditic sediments (Tull, 1978; Thomas et al., 1980; Stow et al., 1984; Drummond et al., 1988). Because of its tectonic base, the age and composition of the eastern Blue Ridge basement is unknown. The Ashland is cut out near the state line, but the Wedowee and Emuckfaw extend northeastward into Georgia (Fig. 6). All of these eastern Blue Ridge units are considered to be Neoproterozoic to Cambrian(?) in age (see following).

Sill-like granitic plutons are abundant within the eastern Blue Ridge. The premetamorphic Elkahatchee Quartz Diorite (Figs. 5 and 6), the oldest (490–496 Ma; Russell, 1978) and largest (>790 km²), is a petrologically and geochemically metaluminous (I-type) biotite tonalite-granodiorite that intrudes both the Wedowee and the Ashland (Drummond, 1986; Allison, 1992; Drummond et al., 1994) groups. Somewhat younger (ca. 460 Ma U/Pb zircon and Rb/Sr whole-rock; Russell, 1978; Russell et al., 1987) premetamorphic Ordovician I-type plutons, the Zana and Kowaliga granitic, granodioritic, and tonalitic gneisses, intrude the Emuckfaw (Fig. 6) (Drummond et al., 1997). The equivalent eastern Blue Ridge sequences in Georgia also contain Ordovician plutons (e.g., Villa Rica Gneiss, ca. 460 Ma; Thomas, 2001). Other Ordovician plutons are southeast of the Brevard zone in the inner Piedmont, and these include the Farmville pluton (ca. 460 Ma; Grimes et al., 1997) within the Opelika Complex, a possible correlative of the eastern Blue Ridge sequence in Alabama (Bentley and Neathery, 1970), and the Franklin gneiss in Georgia (ca. 462 Ma; Seal and Kish, 1990) (Figs. 5 and 6).

A suite of Devonian granitic plutons (Rockford-type) intrudes the Wedowee Group and Ashland Supergroup (Fig. 6) (Russell et al., 1987; Drummond, 1986; Allison, 1992; Drummond et al., 1988, 1997). Rockford-type granitic and trondhjemitic dikes with an interpreted crystallization age of 369 Ma (Steltenpohl et al., 2005) intruded the Elkahatchee sequentially during progressive dynamothermal deformation (Moore et al., 1987). Some zircon fractions from these dikes, and other Rockford-type granitoids show evidence of a Middle Proterozoic inherited age component (Russell et al., 1987;

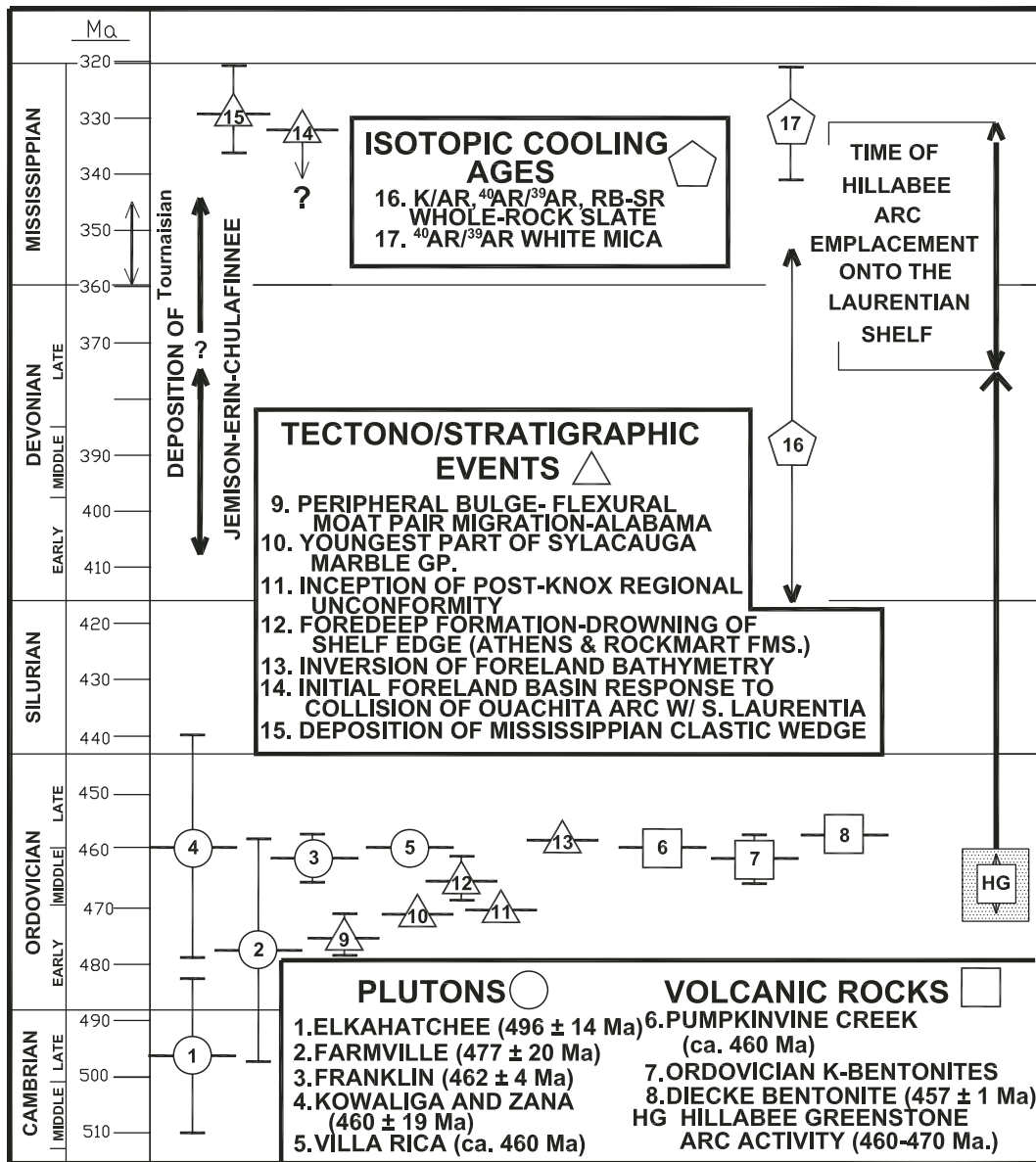


Figure 5. Timing of events possibly related to the formation and emplacement of the Hillabee Greenstone. See text for explanation.

Steltenpohl et al., 2005). The peraluminous bulk composition (S-type) of these granitoids is indicative of a crustal source; they are believed to have been derived from the migmatitic Ashland Supergroup via anatexis during peak metamorphism (Drummond, 1986; Drummond et al., 1988; Allison, 1992). Thus, it is likely that anatectic melting of part of the eastern Blue Ridge sequence supplied Grenvillian age xenocrystic zircons to these Devonian granitoids, suggesting a likely Grenville source for the eastern Blue Ridge metasediments, compatible with the Hf isotopic compositions of zircons from the Hillabee Greenstone metadacite.

The paleotectonic position of the Alabama/Georgia eastern Blue Ridge prior to Alleghanian thrusting is critical to understanding the

paleotectonic position and emplacement of the Hillabee Greenstone. Simple strike-perpendicular restoration of lower Paleozoic foreland and Talladega belt carbonate-shelf strata indicates that the Talladega belt must be palinspastically restored to at least the present location of the Pine Mountain internal basement massif (Fig. 1) (Ferrill and Thomas, 1988; Thomas, 2004). The proposed Suwanee-Wiggins suture zone to the southeast (Fig. 1) probably marks the outboard limit of Laurentian crust and the leading edge of Gondwanan crust, i.e., the locus of Alleghanian continent-continent collision (Horton et al., 1989). Thus, the distal part of the carbonate shelf (Talladega belt's Lower Cambrian-uppermost Lower Ordovician Sylacauga Marble Group; Tull et al., 1988) originally extended

approximately to the edge of the Laurentian rifted margin. Prior to Alleghanian thrusting, therefore, the eastern Blue Ridge marginal basin must have lain either along the outermost rifted margin on thinned continental or oceanic crust.

The latest Cambrian Elkahatchee pluton requires that the eastern Blue Ridge strata are Cambrian or older, but no stratigraphic linkage can be established with Laurentian margin Cambrian rocks. The closest lithotectonic association is the Neoproterozoic rift-facies Ocoee Supergroup, which formed upon thinned continental basement along the Tennessee salient (Fig. 1). The absence of basement rocks, the great thickness (>10 km), and lithologic associations (tholeiitic rift and/or ocean floor basalts and deep-water turbiditic sediments) suggest

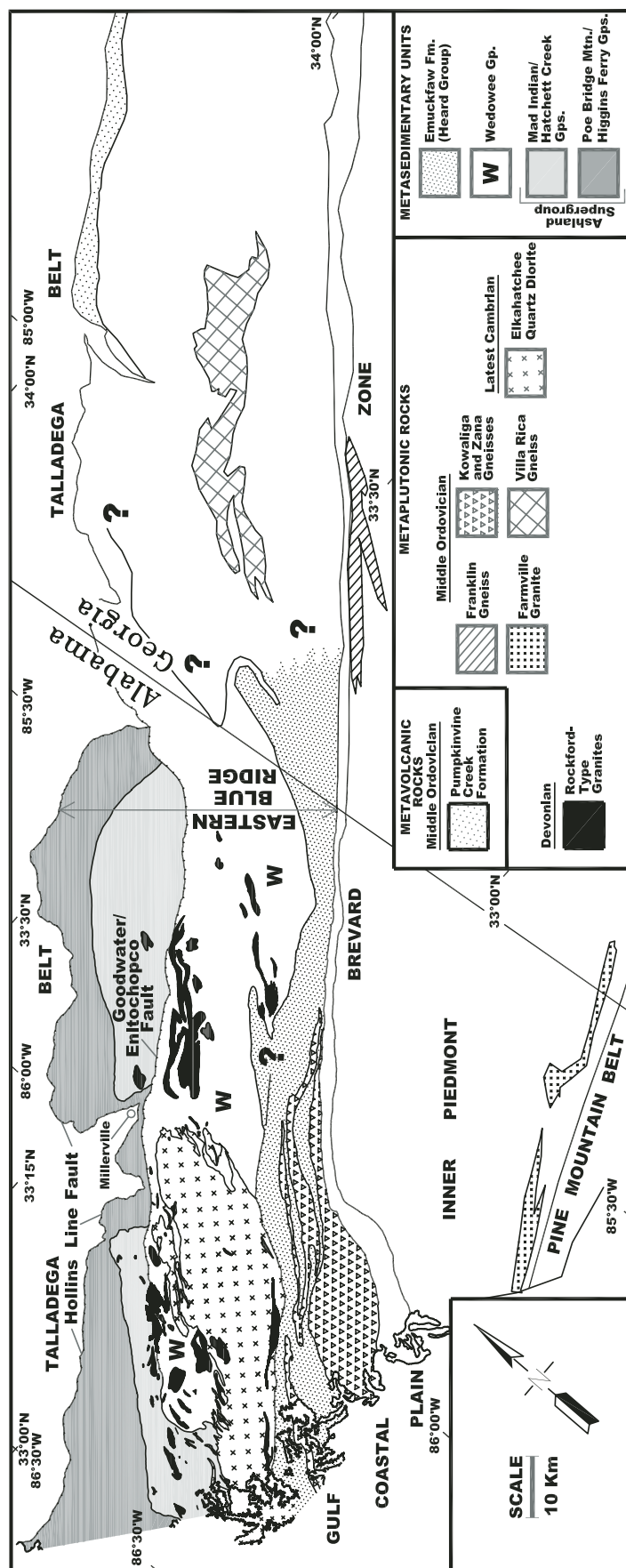


Figure 6. Geologic map of the eastern Blue Ridge, Alabama and west Georgia, showing the distribution of plutons and lithostratigraphy discussed in the text.

that the eastern Blue Ridge represents syn- to postrift sediments, such as a slope-rise sequence along a rifted continental margin, rather than an intraoceanic complex. The Neoproterozoic-Cambrian margin of southeastern Laurentia must have been flanked by a clastic continental slope-rise outer-margin prism, but no candidates for this tectonic entity other than the eastern Blue Ridge's Ashland-Wedowee sequence are known (Tull, 1978; Thomas et al., 1980; Stow et al., 1984; Drummond et al., 1988, 1994, 1997). Its current tectonic position in fault contact immediately above the Laurentian outer-shelf stratigraphy and the common presence of Middle Proterozoic relict zircons within melts likely incorporated during anatexis of eastern Blue Ridge units (Russell, 1978; Steltenpohl et al., 2005) suggest that the bulk of the Alabama/West Georgia eastern Blue Ridge formed near or at the Laurentian rifted margin during or following Rodinian rifting. If this sequence was not marginal to Laurentia during the formation of Iapetus, it must represent the marginal basin of a microcontinent with Grenville-age basement. An exotic microcontinent eastern Blue Ridge, formed as a Laurentia-facing marginal basin intruded by Cambrian-Ordovician suprasubduction zone plutons, requires eastward subduction of the Laurentian margin beneath the microcontinent, followed by the tectonic removal of the entire original Laurentian slope-rise sequence and the intervening accretionary prism, and subsequent direct juxtaposition of the exotic eastern Blue Ridge with Laurentian shelf units. We consider this to be an unlikely scenario.

Cordillera-type subduction along this margin, however, raises questions about the nature of potential tectonic interactions with the foreland-Talladega belt outer-shelf sequence flanking the eastern Blue Ridge to the northwest. No significant Taconic compressional deformation reached the most distally preserved part of the lower Paleozoic shelf (Talladega belt), which occurred palinspastically near the pre-Taconic rifted margin (Tull, 1998; Thomas, 2004). However, several mild episodes of Ordovician lithospheric flexing, possibly resulting from migration of peripheral bulges, are recorded within the foreland carbonate shelf (Mussman and Read, 1986; Robertson et al., 1988; Shaw et al., 1990). The late Middle Ordovician foreland basin clastic wedge in Alabama restores to very near the rifted outer margin of continental crust and thus could have prograded only a short distance cratonward onto the carbonate shelf from uplifts along the edge of the rifted margin (Thomas, 2004). Therefore, although terranes may have been assembled and accreted along the eastern Laurentian margin during the Taconic orogeny (Hatcher, 1989, 1999; Hibbard, 2000), they

must have remained at or southeast of the rifted margin and could not have been obducted onto Laurentian crust in Alabama until Alleghanian thrusting (Thomas, 2004).

MODEL FOR THE PALEOTECTONIC SETTING OF THE HILLABEE GREENSTONE

Our model for the Hillabee Greenstone's paleotectonic setting incorporates the following constraints: (1) the eastern Blue Ridge is interpreted as slope-rise deposits adjacent to Laurentia, containing suprasubduction latest Cambrian–Ordovician plutons (see previous); (2) the Hillabee Greenstone formed as an Ordovician suprasubduction volcanic complex in a backarc setting, probably involving Mesoproterozoic continental crust; and (3) the Hillabee Greenstone currently lies directly above Laurentian Talladega belt outer-shelf strata. With these constraints, the number of reasonable tectonic scenarios that can explain the emplacement of the Hillabee Greenstone is limited. The requirement that the Hillabee Greenstone formed as part of a continental arc system, its structural position between the Laurentian shelf and slope-rise strata, and age similarity to eastern Blue Ridge suprasubduction plutonism and continental-margin K-bentonite activity (see following) all argue strongly that the Hillabee Greenstone is native to Laurentia, and it was not part of an exotic island arc.

If the Alabama/West Georgia eastern Blue Ridge is part of the Laurentian slope-rise sequence, then the backarc Hillabee Greenstone could not have formed significantly inboard of this sequence without resulting in suprasubduction magmatic intrusion into the Laurentian shelf sequence. It must, therefore, have formed just outboard of the shelf edge atop or immediately adjacent to the eastern Blue Ridge marginal basin; accordingly, the Lower Paleozoic eastern Blue Ridge plutonic bodies likely formed near the core of a continental-margin arc. If the Neoproterozoic–Cambrian(?) eastern Blue Ridge strata formed the core of the arc during this time span, serving as the recipient (arc basement) of subduction-generated magmas (Drummond et al., 1997), then the present eastern Blue Ridge erosional surface is several kilometers beneath the former arc volcanic carapace, and the bulk of the arc volcanic rocks would now be absent due to erosion. A ca. 460–470 Ma Hillabee Greenstone would then be cogenetic with the eastern Blue Ridge plutonic complexes and could have constituted part of that overlying volcanic carapace in a backarc position. This scenario provides the simplest initial setting for later Hillabee Greenstone emplacement

onto the shelf because the rearward portion of the arc would lie adjacent to the Laurentian shelf edge. A Hillabee Greenstone backarc facing the shelf would likely have been a region of subsidence rather than uplift and could not have easily shed significant quantities of sediment onto the shelf. Additionally, any record of volcanic activity in the Talladega belt associated with a Middle Ordovician arc-backarc would have been removed from the beneath the sub-Lay Dam Formation unconformity, which separates this Silurian(?)–Lower Devonian unit from the uppermost Sylacauga Marble Group (Tull, 1998).

Ordovician K-bentonites preserved in the eastern and central North American platform and foreland basin successions originated from a major felsic volcanic system(s), probably associated with continental-margin arc volcanism. They are most numerous, thickest, and widespread in upper Middle Ordovician strata (mid-Mohawkian), and they thicken systematically southeastward into the southern Appalachians, suggesting a source southeast of the palinspastic position of foreland thrust sheets (Kolata et al., 1998). Two of the most extensive, the 454.5–457.1 Ma Deicke and 453.1 Ma Millbrig (Tucker, 1992; Tucker and McKerrow, 1995; Samson et al., 1989), are thickest in Alabama and northwest Georgia, and southeast Tennessee, respectively (Kolata et al., 1998). Nd and Sr isotopic data from apatite and the presence of an inherited zircon component are consistent with magma generation via anatexis of evolved crust, e.g., a continental-margin volcanic arc (Samson et al., 1989). The Hillabee Greenstone does not clearly overlap these two K-bentonites in age (Fig. 5), but could be an older (by ~10 m.y.) part of the same arc system.

CONTRASTS WITH ISLAND ARC–CONTINENT COLLISION ZONES

The relationships between the Hillabee Greenstone arc fragment and its footwall and hanging-wall rocks (see previous) suggest that the Hillabee Greenstone's structural and stratigraphic setting is anomalous relative to most accreted volcanic complexes such as island arcs or ophiolitic fragments, including those in the northern Appalachians, where arcs and oceanic fragments were obducted onto the Laurentian margin during the Ordovician Taconic orogeny. Contrasts between the Hillabee Greenstone and other accreted arc complexes are discussed next.

Unlike most accreted island arc complexes, the Hillabee Greenstone is not associated with the following common and distinctive features: (1) preserved subduction complex materials in its footwall or hanging wall, such as zones of

high-pressure metamorphism, e.g., in eastern Papua New Guinea (Hamilton, 1979, 1988) and the Rowe-Hawley belt of Vermont (Stanley and Ratcliffe, 1985; Kim et al., 2003); (2) olistostrome and mélange accumulations, e.g., in the St. Daniel Formation of Quebec (Schroetter et al., 2006) and the northern Qilian Mountains of China (Xia et al., 2003); (3) deep-water metasedimentary sequences such as accretionary wedge material, e.g., in eastern Papua New Guinea (Hamilton, 1979, 1988), the northern Qilian Mountains (Xia et al., 2003), and the Ouachita orogen (Viele and Thomas, 1989); (4) arc rocks proper, e.g., in the Coastal Complex of Newfoundland (Jenner et al., 1991), the Rowe-Hawley belt of Vermont (Ratcliffe et al., 1998), and the northern Qilian Mountains (Xia et al., 2003); (5) ophiolitic fragments derived from forearcs, backarcs, and traditional oceanic crust and mantle, e.g., in the Bay of Islands (Jenner et al., 1991) and Baie Verte of Newfoundland (Dunning and Krogh, 1985; Waldron and van Staal, 2001), the Thetford Mines (Oshin and Crocket, 1986) and Mount Orford ophiolites of Quebec (Whitehead et al., 2000; Schroetter et al., 2002), and the northern Qilian Mountains (Xia et al., 2003); or (6) plutonic rocks or dikes, e.g., the Mount Norris Intrusive Suite of Vermont and the Bolton Igneous Group of Quebec (Kim et al., 2003). In these and other examples of accreted arc sequences, the arc complex does not lie directly atop continental-margin shallow-shelf rocks as in the Talladega belt. In the northern Appalachians, for example, Neoproterozoic–early Paleozoic rift-related clastic rocks (e.g., Green Mountain thrust slices) intervene between the arc rocks and the continental shelf rocks (Kim et al., 2003). There is no evidence that the Hillabee Greenstone or underlying Talladega belt metasediments experienced significant Ordovician deformation, like Appalachian arc complexes to the north. Taconic thrust faults are not recognized within the presently preserved thrust belt, suggesting that the front of Taconic compressional deformation did not reach the palinspastic location of the trailing part of the thrust belt, i.e., the pre-Taconic rifted margin (Thomas, 2004). Thus, an exotic Hillabee Greenstone could not have been accreted to Laurentia during the Taconic orogeny.

DISCUSSION

When the Hillabee Greenstone and the eastern Blue Ridge databases are compared with most other accreted arc complexes, several important differences are apparent, including: (1) The absence of tectonic features like blueschist belts, ultramafic sequences or blocks (ophiolite fragments), mélange accumulations,

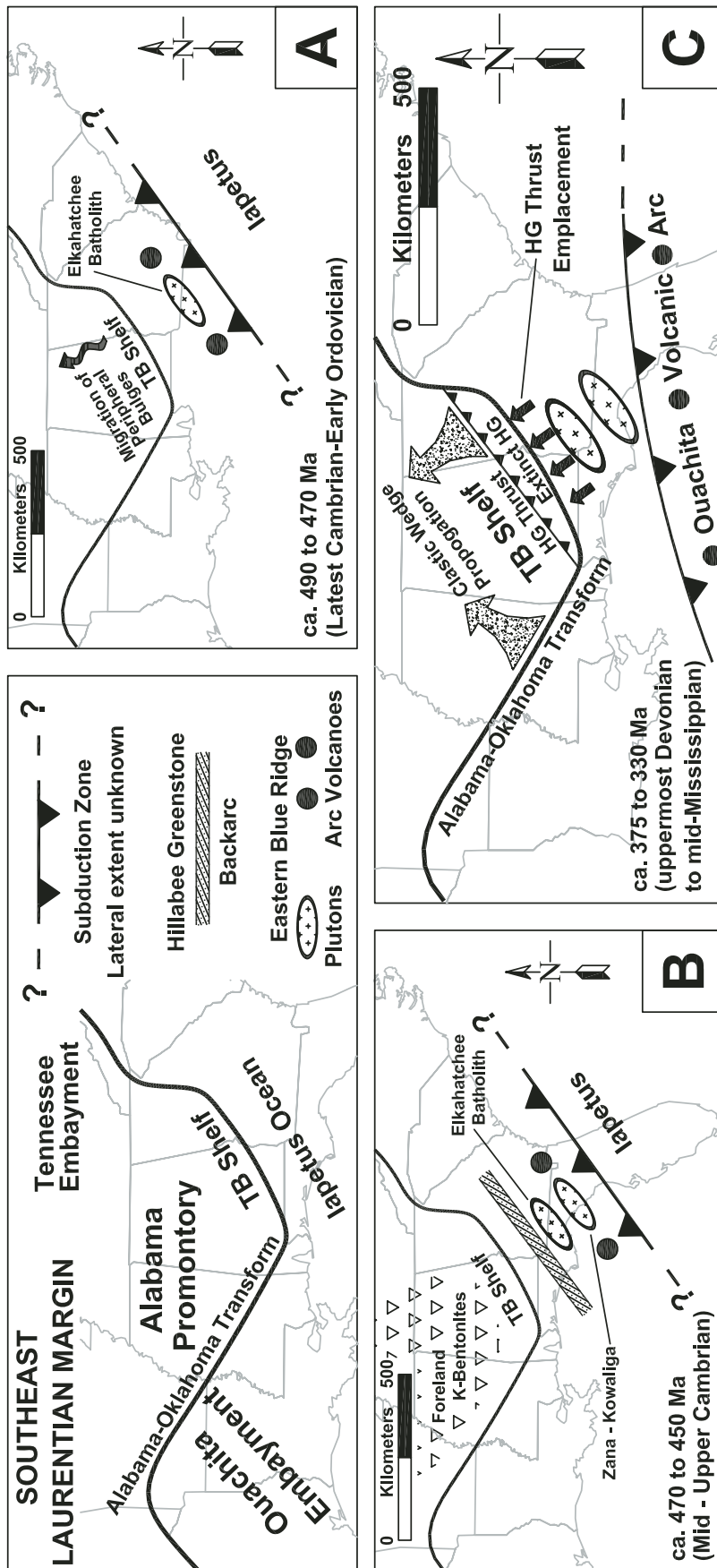


Figure 7. Model for the tectonic evolution of the Hillabee Greenstone backarc along the southeast margin of the Alabama promontory. See text for explanation. TB—Talladega belt.

and accretionary wedge material. (2) Some accretion models involve reversals in subduction polarity, resulting in complex intrusive relationships, such as multiple plutonic/volcanic episodes in the arc, but the Hillabee Greenstone is not cut by younger intrusives. (3) Accretion of an exotic Ordovician arc(s) is commonly viewed as a major feature of the Taconic orogeny in the northern Appalachians (Karabinos et al., 1998; van Staal et al., 1998), and it involved major compressional deformation and telescoping of the Laurentian margin cover sequence and basement far inboard of the shelf edge. In contrast, no accretionary terranes could have been obducted onto Laurentian crust across the Alabama margin until Alleghanian thrusting (Thomas, 2004). Instead, any such terranes, such as an exotic Hillabee Greenstone or eastern Blue Ridge arc, must have remained at or southeast of the Laurentian rifted margin. Finally, these constraints indicate that, subsequent to its formation, the Hillabee Greenstone arc fragment remained essentially undeformed and below greenschist facies for >90 m.y., until its Late Devonian or Mississippian emplacement (Fig. 5).

A model in which both the Hillabee Greenstone and the eastern Blue Ridge are native to Laurentia and the igneous activity occurred in response to a common tectonic regime reflecting Ordovician subduction along the Laurentian margin (Fig. 7), as proposed here, provides the simplest and most comprehensive fit with observations and explains the many contrasts with accreted exotic island arc complexes. This model places the Hillabee Greenstone outboard of, but adjacent to, the shelf upon which it could be directly emplaced during later compressive deformation (Figs. 5 and 7). The proposed continental-margin subduction activity could also have produced the foreland suite of Ordovician K-bentonites, as well as the lithospheric flexuring events recorded on the shelf (Fig. 7). In contrast to the northern Appalachian Taconic arcs, however, no exotic Ordovician arc(s) would have collided along the Alabama promontory, and thus, there was no collisional Taconic orogeny along this segment of the margin. This contrast could be accommodated by the presence of one or more transform faults north of the location of the subduction polarity was reversed.

Hillabee Arc Emplacement onto the Laurentian Shelf

In the Talladega belt, the Laurentian carbonate platform foundered and was tilted and eroded prior to or during(?) the formation of the >2.5-km-thick Silurian(?)–Lower Devonian Lay Dam clastic wedge (Tull and Telle, 1989;

Tull, 1998), corresponding in time to the early Acadian orogeny. This turbiditic/olistostromal unit received detritus from uplifts to the immediate southeast, including the underlying carbonate shelf and Grenville basement, but with no evidence of a volcanic source (Tull and Telle, 1989; Lim, 1998), indicating that the Hillabee Greenstone was outboard of the basement/cover uplifts, possibly covered by younger units, and thus unable to supply detritus to the Lay Dam basin. Detrital zircons from the Butting Ram Quartzite, for example, yield U/Pb ages of 920–1320 Ma, but Paleozoic zircons are absent (Table DR1, see footnote 1). Following restabilization of the margin and deposition of the Butting Ram and Cheaha Quartzites and JEC interval, the Alabama/West Georgia eastern Blue Ridge was intruded by the S-type, Rockford-type plutons (Fig. 6), which did not intrude the Talladega belt. The JEC interval represents a “starved basin” sequence during which no major source of orogenically derived sediment was entering the basin (Tull, 2002), but these organic-rich rocks may have been deposited during initial flexural subsidence and subaqueous orogenic loading of the margin as the Hillabee Greenstone was being moved onto that margin.

The constraints already outlined indicate that the Hillabee Greenstone remained essentially undeformed for a significant time interval (>90 m.y.) following its formation, until latest Devonian to mid-Mississippian emplacement upon the shelf along the Hillabee Greenstone thrust (Fig. 5). This implies that the Hillabee Greenstone metavolcanic complex was inactive over that time interval, although the time span of eastern Blue Ridge plutonism demonstrates a longer interval of arc activity. When it was emplaced in a concordant, flat-on-flat geometry atop the shelf sequence, the Hillabee Greenstone appears to have been a continuous (>230 km along by tens of kilometers across strike) sheet of intact, precollision, volcanic rocks, with no evidence that it was dismembered prior to Alleghanian thrust duplexing, unlike the dismembered state that characterizes most known accreted arc complexes (see previous). During the time interval of Hillabee Greenstone thrusting onto the shelf (late Acadian, neo-Acadian, or earliest Alleghanian orogenies?), foreland shelf strata currently within later-formed (Alleghanian) thrust sheets immediately northwest of the Talladega belt surprisingly provide no evidence of deformation, such as thrust imbrication or angular unconformities. This indicates that compressive stresses related to Hillabee Greenstone emplacement were not translated far into the Laurentian platform, and that the Hillabee Greenstone thrust must have been a relatively

shallow-level thrust. A shallow setting is also supported by the observed flat-on-flat thrust geometry. For these reasons, we interpret the Hillabee Greenstone thrust to be a premetamorphic thrust, later overprinted by the greenschist facies fabrics. McClellan et al. (2005), however, interpreted the Hillabee Greenstone thrust to be synmetamorphic because they linked greenschist facies mylonitic fabrics in the metadacites with the spatially separate basal Hillabee Greenstone thrust. The mylonitic fabrics in the metadacites, however, were produced by the same peak dynamothermal event responsible for the typical greenschist facies fabrics that are pervasive throughout the entire Talladega belt. If thrusting had been synmetamorphic, the thrust at the base of the Hillabee Greenstone allochthon would have been >10 km deep, and it is unlikely that a thrust sheet this thick, and with the required horizontal component of displacement, could have been emplaced upon the shelf without propagating thrusts or other deformation features far into the adjacent platform rocks. Following emplacement, probably as the Hillabee Greenstone and underlying Talladega belt units were loaded by younger, more outboard, out-of-sequence thrust sheets, the Hillabee Greenstone and underlying units were buried to ~12 to ~15 km and subjected to lower greenschist facies metamorphism and associated ductile deformation.

Relationships with Adjacent Arc Complexes

Pumpkinvine Creek Formation, North Georgia

The Pumpkinvine Creek Formation is a bimodal metavolcanic complex that lies along strike to the northeast of the Hillabee Greenstone in Georgia (Fig. 6), and it has many similarities to the Hillabee Greenstone (McConnell, 1980; Das and Holm, 2005; Holm and Das, 2005). U/Pb zircon analyses of a felsic phase of the unit yield an age of ca. 460 Ma (Thomas, 2001; Holm and Das, in review), similar to that of the Hillabee Greenstone. This unit and associated metasedimentary rocks are >4 km thick and may extend northeastward for ~220 km within the Dahlonga Gold Belt, a possible continuation of the eastern Blue Ridge Ashland-Wedowee belt. The Pumpkinvine Creek Formation and Hillabee Greenstone are geochemically similar and chemical tectonic discrimination techniques also suggest a backarc suprasubduction zone setting for the Pumpkinvine Creek Formation (McConnell, 1980; Holm and Das, 2005). There are, however, some important differences between the two sequences. For example, the Pumpkinvine Creek Formation is part of the eastern Blue Ridge allochthon, in

thrust contact above the Talladega belt along the late kinematic Allatoona fault, and thus it is in a significantly different structural position from the Hillabee Greenstone. In addition, the Pumpkinvine Creek Formation is a higher metamorphic grade (middle amphibolite facies). Its stratigraphic association with dominantly pelitic metasedimentary rocks (Canton Schist) also differentiates it from the Hillabee Greenstone. If the two units are parts of the same volcanic arc complex, then they must have had significant differences in their timing and modes of emplacement, implying that they were partitioned into two different structural positions along strike prior to metamorphism. The stratigraphic and structural relationship between the Pumpkinvine Creek Formation and the adjacent eastern Blue Ridge stratigraphy is enigmatic (Das and Holm, 2005; Holm and Das, 2005), but it is possible that the Ordovician Pumpkinvine Creek Formation stratigraphically overlies other eastern Blue Ridge units and is thus autochthonous with respect to the eastern Blue Ridge. If so, it could represent a rare remnant of an eastern Blue Ridge volcanic carapace, and it could be comagmatic with nearby I-type Ordovician plutons (Das and Holm, 2005; Holm and Das, 2005), as suggested above for the Hillabee Greenstone.

Ouachita Orogen Connection?

Immediately southwest of the Laurentian margin segment considered here, the early Paleozoic margin along Laurentia's southern flank consisted of a large transform fault system (Alabama-Oklahoma transform) overlapped by deep-water off-slope facies, separating what was the Alabama promontory from the Ouachita embayment (Thomas, 1993) (Figs. 1 and 7). Southward from the Laurentian foreland across this former transform boundary, the Ouachita orogen (Fig. 1) consists of a series of exotic tectonic elements, including a leading accretionary prism, subduction complex, forearc basin, and remnants of an accreted continental-margin volcanic arc (Viele and Thomas, 1989). This exotic arc was active during southward subduction of Laurentia beneath the arc during the Mississippian–early Pennsylvanian (and possibly earlier), and thus it was tectonically independent of the Hillabee Greenstone (Fig. 7C). The Ouachita accretionary prism initially overrode Laurentian continental crust obliquely, producing a synorogenic clastic wedge that appeared on the shelf during the late Meramecian (prior to 333 Ma) (Fig. 7C). Earliest arc-continent collision and subsequent tectonic loading along the extreme southeast corner of the Alabama promontory (Thomas, 2004) occurred essentially where the south-

western part of the now-extinct Hillabee Greenstone arc was being emplaced onto the Laurentian shelf (Fig. 7C). The Ouachita subduction complex continued to run aground during the Mississippian-Pennsylvanian, tectonically loading the southern Laurentian margin and abruptly producing a clastic wedge that prograded northeastward across the passive-margin carbonate platform rocks of the Black Warrior basin (Figs. 1 and 7C). Subduction ended in the Desmoinean-Permian, shortly after the leading edge of the subduction complex had overridden continental crust <100 km (Thomas, 2004). Initial accretion of the Ouachita arc along the corner of the Alabama promontory thus may have occurred during the same time interval as the emplacement of the Hillabee Greenstone atop the adjacent southeast margin of that promontory (Fig. 5). It seems probable, therefore, that initial northwestward-directed collision of part of the Ouachita arc with the promontory could have driven the now extinct Hillabee Greenstone backarc fragment from just outboard of the shelf edge, perhaps from atop the margin of the eastern Blue Ridge, onto the edge of the shelf. Later Alleghanian collision could have in turn propagated a thrust beneath the eastern Blue Ridge and moved it into its current position atop the Hillabee Greenstone (Talladega belt) (Fig. 2).

The initial Ouachita clastic wedge began to spread northeastward into northwestern Alabama once the Ouachita arc orogenic load became subaerial (Figs. 5 and 7C). This material, represented by sandstone and mudstone facies (Pride Mountain and Hartselle Formations) and then the Floyd Shale, spread northeastward across Lower Mississippian carbonate rocks in the Black Warrior basin (Fig. 1) (Thomas, 1972). An essentially coeval, but apparently tectonically independent, clastic wedge prograded westward across carbonate facies along the southeastern side of the Alabama promontory in Georgia (Fig. 7C) (Thomas and Cramer, 1979). To the southwest, this southeast-derived wedge is obliquely covered by the Talladega belt thrust sheet, and its extent is not known in Alabama. The clastic wedge along the southeastern side of the promontory could have resulted from uplifts associated with either the emplacement of the Hillabee Greenstone along that margin, or the burial of the Hillabee Greenstone and the underlying shelf sequence beneath higher thrust sheets, when the orogenic uplift there became subaerial. The timing of this clastic wedge corresponds closely with $^{40}\text{Ar}/^{39}\text{Ar}$ white mica ages from the Talladega belt (Fig. 5), suggesting that these ages might record uplift of the Talladega allochthon.

CONCLUSIONS

Our U/Pb zircon studies suggest a Middle Ordovician age (ca. 468 Ma) for the Hillabee Greenstone and require that it is allochthonous relative to the immediately underlying, upright Devonian-Mississippian(?) Talladega belt stratigraphy. Hillabee Greenstone bimodal volcanism likely occurred within an extensional setting within a suprasubduction zone environment that developed atop Upper Proterozoic–Lower Cambrian(?) units of the Laurentian eastern Blue Ridge. The Hillabee Greenstone metavolcanic complex contains no significant sediments, is not cut by later intrusives, and is not associated with ultramafic or high-pressure rocks. The volcanic complex was likely emplaced upon the middle Paleozoic Laurentian shelf along a cryptic thrust that had flat-on-flat geometry, most probably prior to ca. 330 Ma, but possibly as early as ca. 375 Ma. The younger part of this age range corresponds with collision of the Ouachita arc with the corner of the Alabama promontory and with the initiation of clastic wedge propagation onto the edge of the foreland. Collision of the tectonically independent Ouachita arc may have been the impetus that drove the now extinct Hillabee Greenstone backarc atop the adjacent shelf.

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