Refining temporal constraints on metamorphism in the Nashoba terrane, southeastern New England, through monazite dating

Misty M. Stroud[1], Ross J. Markwort[2], and J. Christopher Hepburn[3]
[1]DEPARTMENT OF GEOLOGICAL SCIENCES, UNIVERSITY OF FLORIDA, 241 WILLIAMSON HALL, GAINESVILLE, FLORIDA 32611, USA
[2]EXXONMOBIL, 800 BELL STREET, HOUSTON, TEXAS 77002, USA
[3]DEPARTMENT OF GEOLOGY AND GEOPHYSICS, BOSTON COLLEGE, 213 DEVLIN HALL, 140 COMMONWEALTH AVENUE, CHESTNUT HILL, MASSACHUSETTS 02467, USA

ABSTRACT

Electron-microprobe dating of monazite grains within high-grade mylonitic rocks of the Nashoba terrane in eastern Massachusetts provides new temporal constraints on metamorphism in southeastern New England. In situ dating of monazite grains from three fault zones has allowed the timing of multistage events to be discerned. Three distinct metamorphic events were detected in the Nashoba terrane. The first metamorphic event (M1) occurred from 435 to 400 Ma, with an average age of 423 Ma. A second metamorphic event (M2) occurred at ca. 390 Ma and was associated with widespread migmatization. A third metamorphic event (M3) occurred during the ca. 378–371 Ma time interval and was possibly associated with the Neoacadian orogeny. Intermittent monazite growth during the 360–305 Ma interval suggests that the main phase of metamorphism in the shear zones was complete, but the highly deformed fault zones acted as a conduit for fluid migration, which was responsible for the production of young monazite grains. By at least 345 Ma, the Nashoba terrane had cooled below the stability of sillimanite.

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INTRODUCTION

Acadian deformation in New England occurred during the Silurian-Devonian, but its timing and driving mechanism are unclear. In Newfoundland, the docking of Avalon was thought to be responsible for the Acadian orogeny (Dunning et al., 1990); although an Avalonian terrane is present in southernmost New England, some evidence suggests that it was still outboard of the New England Laurentian margin during the Devonian (Wintsch et al., 1992, 1993).

The Nashoba terrane (Fig. 1), an enigmatic lithotectonic zone in southeastern New England, likely played some role in the Acadian orogeny, given its present coordinates between the New England Avalon terrane to the east and Acadian-deformed rocks to the west. We conducted monazite dating of high-grade fault rocks in an area spanning the width of the Nashoba terrane so as to place the terrane into the larger tectonic framework of the Acadian orogeny and test models for the timing of Avalon terrane accretion.

GEOLOGIC BACKGROUND

The Nashoba terrane is an early Paleozoic peri-Gondwanan arc-backarc separated from the Merrimack terrane to the west by the Clinton-Newbury fault zone and from the Avalon terrane to the east by the Bloody Bluff fault (Fig. 1). It consists of mafic volcanic and volcanogenic sedimentary rocks now metamorphosed at sillimanite and sillimanite + K-feldspar conditions to amphibolites, biotite-feldspar gneisses, schists, calc-silicate gneisses, and feldspathic gneisses (Goldsmith, 1991b). The terrane is divided into two main formations: the primarily metavolcanic Marlboro Formation in the east and the metasedimentary rocks of the Nashoba Formation in the west (Fig. 1). Two other formations, the Shawsheen and Fish Brook gneisses, lie between the Nashoba and Marlboro Formations but are cut out by faults northeast and southwest of the study area (Goldsmith, 1991a). The terrane is intruded by Ordovician to Early Devonian peraluminous granites and pegmatites (Zartman and Naylor, 1984; Hill et al., 1984; Wones and Goldsmith, 1991; Hepburn et al., 1995), as well as similarly aged calc-alkaline diorites (Zartman and Naylor, 1984; Hon et al., 1986, 1993; Hepburn et al., 1995; Acaster and Bickford, 1999). The Carboniferous I-type Indian Head Hill Granite also intrudes the Nashoba terrane (Wones and Goldsmith, 1991; Hepburn et al., 1995; Acaster and Bickford, 1999). Previous work used the ages of these igneous rocks to attempt to bracket the timing of deformation. Hepburn et al. (1995) used the thermal ionization mass spectrometry (TIMS) method to date metamorphic monazite in the Fishbrook Gneiss, yielding a Silurian (425 ± 2 Ma) age, and monazite in a migmatite in the Nashoba Formation, yielding a Devonian (395 ± 2 Ma) age. While these data provide insight into the timing of monazite growth in these units, they are not structurally linked to a regional metamorphic event. One of the goals of this study is to elucidate the tectonic and metamorphic history of the Nashoba terrane, and thereby its potential role in the Acadian orogeny of southeastern New England.

METHODS

The timing of deformation in the Assabet River fault zone, Sulfur Hill shear zone, and Ball Hill fault zone (Fig. 2) was determined through in situ monazite dating coupled with the study of metamorphic mineral assemblages. To establish the absolute timing of individual tectonic and metamorphic episodes, we used the electron microprobe at the University of Massachusetts–Amherst to obtain in situ U-Th-Pb dates for monazite grains (Williams et al., 1999; Jercinovic and Williams, 2005). Due to the preservation of the petrologic context of the dated grains, it is possible to link radiometric dates with mineral assemblages and, therefore, metamorphic

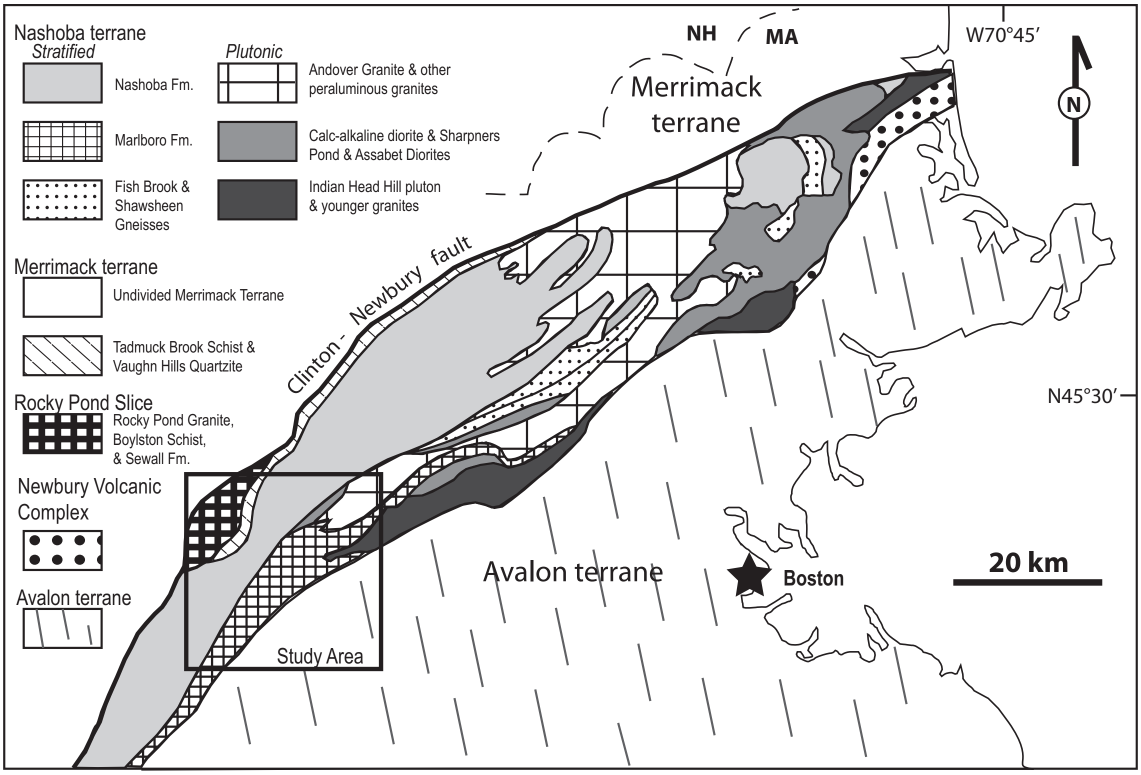

Figure 1. Generalized lithotectonic map of the Nashoba terrane (modified from Hepburn et al., 1995). Study area is outlined as black box.

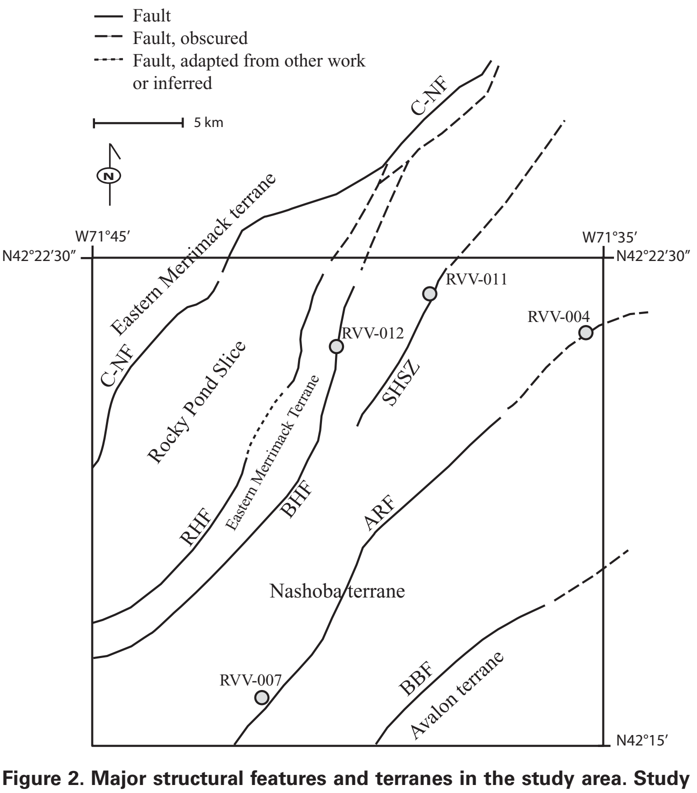

Figure 2. Major structural features and terranes in the study area. Study area is outlined as black box. C-NF—Clinton-Newbury fault; RHF—Rattlesnake Hill fault; BHF—Ball Hill fault; SHSZ—Sulfur Hill shear zone; ARF—Assabet River fault; BBF—Bloody Bluff fault.

events. A critical step in this method is compiling U, Th, Pb, and Y compositional maps to identify chemical zoning within single monazite grains. Some compositional zones correspond to resolvable age domains that are interpreted to record individual pulses of monazite growth. The <5 µm spatial resolution of the electron microprobe enables ages to be assigned to multiple domains within single grains, whereas conventional isotopic techniques would yield mixed ages.

Following the method set forth in Williams et al. (2006), 5–15 spots in each homogeneous chemical domain were analyzed for U, Th, and Pb in order to solve the decay equation outlined by Montel et al. (1996). The location of each spot analysis, as well as age for each spot analysis, is given in the supplementary data.[1] These analyses were then averaged to determine a date for that particular chemical domain. All spots analyzed for a domain were used in the calculation of the date and error unless otherwise noted. The short-term random error for a date is typically reduced to less than 1% (2σ of ~10 m.y. or less) with five or more analyses (Williams et al., 2006). Short-term random error is attributed to counting uncertainty of detectors, and minute variations in operating and environmental conditions. All dates are reported in millions of years before present (Ma) at the 95% confidence level, with 2σ errors that represent the short-term random error. Short- and long-term systematic errors are not figured into the reported dates and are caused by uncertainties in background levels of trace elements and the uncertainties for values of decay constants. To mitigate these systematic uncertainties, a consistency standard was run before each analytical session. Data from the consistency standard runs are reported in the supplementary data (see footnote 1).

[1]GSA Data Repository item 2009282, Table DR1 and Figures DR1–DR4, is available at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

METAMORPHIC EVENTS

The earliest metamorphic event recorded in the Nashoba terrane (M1) is represented by the assemblages sillimanite-muscovite-biotite and sillimanite-garnet-biotite-muscovite in the Nashoba Formation (Munn, 1987; Bober, 1990; Jerden, 1997). This event is poorly preserved owing to the near-complete textural equilibrium achieved by the second metamorphic event (M2), and it is recognized by fine-grained sillimanite and fibrolite preserved in feldspar or garnet porphyroblasts. The conditions of this event in the Nashoba Formation can be constrained by the absence of staurolite, the presence of muscovite, and the stability of sillimanite. These constraints suggest that M1 brought the terrane to temperatures over 600 °C at a pressure between 3.2 and 4.8 kbar.

The second metamorphic event affecting the Nashoba terrane (M2) is recognized by sillimanite–K-feldspar–biotite and sillimanite–K-feldspar–biotite–garnet assemblages (Abu-Moustafa and Skehan, 1976; Munn, 1987; Bober, 1990). The sillimanite forms large prismatic crystals and is commonly fractured or boudinaged (Jerden, 1997; Markwort, 2007). These assemblages are associated with migmatite in the Nashoba Formation and may indicate pressure-temperature (*P-T*) conditions along or above the wet granite solidus. The absence of prograde muscovite and the presence of K-feldspar along with the stability of sillimanite and the presence of migmatite suggest temperatures greater than 650 °C for M2 at pressures of 2.5–4.5 kbar.

The third metamorphic event affecting the Nashoba terrane (M3) is represented by the retrograde assemblages chlorite-sericite-quartz and chlorite-biotite-muscovite-quartz. These minerals overprinted earlier assemblages in the Nashoba Formation. In the Nashoba Formation, samples have the assemblage sillimanite–K-feldspar–biotite, but sericite has replaced much of the sillimanite, and some biotite is replaced by chlorite. Figure 3 shows the estimated *P-T* conditions for the three metamorphic events in the Nashoba terrane (Markwort, 2007).

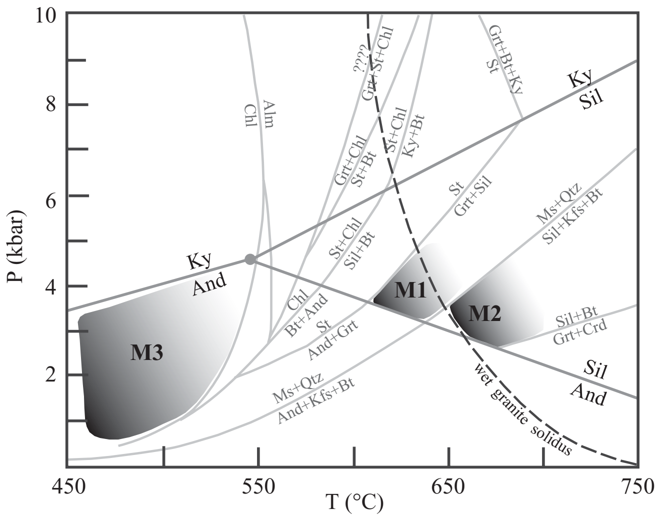

Figure 3. Petrogenetic grid after Holland and Powell (1998). Shaded areas represent pressure-temperature (*P-T*) estimates for different metamorphic events in the Nashoba Formation based on observed mineral assemblages and on assemblages reported by Munn (1987) and Jerden (1997). Mineral abbreviations from Kretz (1983).

RESULTS

After all of the monazite grains were analyzed and their various crystal domains were dated, Gaussian probability distributions were plotted for each dated domain. Each curve's peak is at the mean age for that domain, the width of the curve reflects the 2σ confidence interval for short-term random error, and the area beneath the curve is 1. A single curve summarizing all of the data was then constructed by summing each individual probability distribution curve (Fig. 4). This curve has peaks where there are multiple dates that overlap within error and troughs where no dates were recorded. The height of these peaks and troughs are of arbitrary scale, but they represent the relative frequency of the reported dates. From this curve, populations of similar dates were identified, and the individual crystal domains they represented were subsequently studied together. These populations included the date ranges (in Ma) 435–400, 400–385, 385–360, and 360–305. In some cases, these populations could be further classified or subdivided on the basis of core-rim relationships, grain texture, or chemical zoning. In other cases, populations of similar dates shared little else in common.

AGE OF METAMORPHIC EVENTS

M1 Metamorphism: 435–400 Ma

The first metamorphic event affecting the Nashoba terrane occurred during the 435–400 Ma time interval (Fig. 4). These dated monazite domains represent points along a *P-T-t* path and are not necessarily peak metamorphic conditions (Williams et al., 1999). Dates from this study and existing isotopic ages in the range 400–430 Ma (Hepburn et al., 1995; Acaster and Bickford, 1999; R.P. Wintsch, 2007, personal commun.) demonstrate that this event was widespread temporally and regionally, affecting the western and eastern parts of the Nashoba Formation, the Fish Brook Gneiss, and the Marlboro Formation.

Grains yielding M1 ages make up the largest peak of ages in the age summary diagram (Fig. 4). No chemical or textural evidence could be found in the grains to support division of the age domain into smaller intervals of time. Figure 4 illustrates the date probability distribution curve for each analyzed domain in this date range. The prominent dark curve is the total summed probability curve for this date range. We interpret this age to represent the average age of a potentially long period of regional metamorphism that may have lasted up to 30 m.y.

Coincident with the younger end of this period, the younger pegmatitic phase of the Andover Granite (Fig. 1) has been assigned ages from 415 to 408 Ma (Zartman and Naylor, 1984; Hill et al., 1984; Hepburn et al., 1995; Acaster and Bickford, 1999). Five monazite grains (two from the Sulfur Hill shear zone and three from the Assabet River fault zone) exhibit age domains within this range and may reflect a thermal pulse corresponding to this widespread intrusion.

It is possible that a more extensive and detailed geochronological study might be able to resolve this 30 m.y. period into two or more pulses; however, the current data have a roughly Gaussian distribution and do not support such a conclusion. Monazite grains yielding M1 ages have little or no evidence of deviatoric stress, suggesting that M1 was at least in part a static thermal event. This corroborates the earlier observation that M1 sillimanite occurs as random fabric fibrolite inclusions in other minerals.

M2 Metamorphism: 400–385 Ma

There are only four grains in the 400–385 Ma date range. One grain from the Sulfur Hill shear zone and one grain from the Ball Hill fault zones have overgrowth rim domains low in Y and dates ranging from 392 to 397 Ma. Two grains from the Assabet River fault zone are small and irregularly shaped and have similarly low Y dated at 390 ± 6 Ma and 393 ± 16 Ma, respectively. These four domains form a distinct age

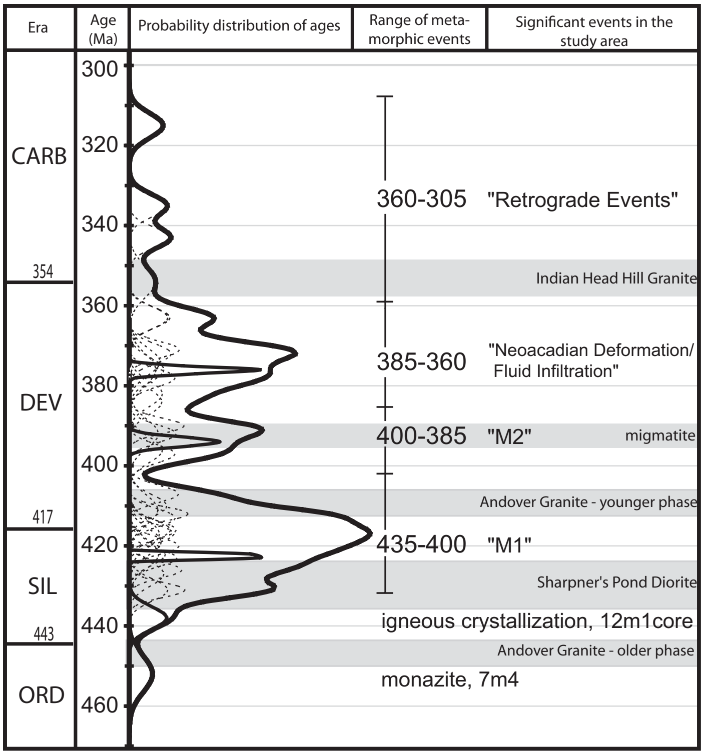

Figure 4. Summary of all monazite ages from all four samples. Large solid curve represents the sum of every monazite domain's age probability distribution; small solid curve represents weighted mean ages of different monazite groups; dashed curves are age probability distributions for each analyzed monazite domain. Each age group is labeled according to its interpretations discussed in the text.

range and are chemically similar. The 400–385 Ma event is interpreted to represent the second metamorphism (M2) in the Nashoba terrane that was responsible for widespread migmatization, especially in the northwest portions of the Nashoba Formation. Hepburn et al. (1995) reported a TIMS U-Pb monazite age of 395 ± 2 Ma for a migmatitic leucosome in a stratigraphic position similar to that of the sample taken from the Sulfur Hill shear zone in the northwest portion of the Nashoba Formation. In our study, samples from all three faults contain ca. 395 Ma monazite growth domains, suggesting that the sample of Hepburn et al. (1995), located more than 30 km away from our sample, was not a restricted melting event but was part of a regional metamorphic event, M2.

M3 Metamorphism: 385–360 Ma

Metamorphism in the 385–360 Ma date range has been undocumented in the Nashoba terrane until now. Chemical similarities that corresponded to core-rim relationships allowed this range to be split into two groups. Four grains from samples taken from the Sulfur Hill shear zone and Assabet River fault zone have similar low-Y cores with dates from 382 to 372 Ma. Five grains from the Sulfur Hill shear zone and Assabet River fault zone have similar high-Y rim or mantle domains dated from 384 to 363 Ma. All but one of these rims or mantles truncate earlier domains and are interpreted to be recrystallized. Data from this age range are summarized in Figure 4.

One of the monazite grains (grain 12m2; Fig. 5) from the Ball Hill fault zone is located in a thin zone around a feldspar porphyroclast where smaller grains were recrystallizing in order to minimize strain. The altered monazite appears to have been involved in grain-size reduction processes and feldspar subgrain formation. The monazite grain includes three dated domains (Fig. 5). In one domain, three of five spot analyses yield a date of 383 ± 7 Ma, while the other two spots indicate an age of ca. 426 Ma. The ca. 426 Ma age exhibited by the two spot analyses is similar to the other two domains in the grain dated at 426 ± 6 Ma. The three younger spots in the grain, in addition to the grain's proximity to a recrystallizing feldspar grain, are interpreted to represent the initiation of recrystallization of the monazite grain. The 383 Ma domain is the youngest age obtained from the Ball Hill fault zone, and, given the monazite grain's location proximal to a ductilely deformed feldspar, it indicates a temperature greater than ~450 °C at that time.

Similar to the aforementioned grain in the Ball Hill fault zone, a monazite grain (grain 11m5; Fig. 5) from the Sulfur Hill shear zone is interpreted to have undergone recrystallization. The grain's metamorphic core domain is 382 ± 4 Ma, and it has three recrystallized domains truncating the core and each other, dated at 374 Ma, 369 Ma, and 363 Ma. This grain's location is similar to 12m2's—near the margin of a large feldspar aggregate. The feldspar formed subgrains and smaller recrystallized grains, especially near its margins, presumably to reduce the strain associated with shearing. All domains in this grain are interpreted to have formed successively as the feldspar porphyroclast formed subgrains and recrystallized near its margins in response to shearing. Feldspar was deforming via ductile processes, so temperatures in the Sulfur Hill shear zone at this time must have been higher than ~450 °C.

Younger Events: 360–305 Ma

Two grains from both the Sulfur Hill shear zone and the Assabet River fault zone have domains yielding dates in the interval 360–305 Ma. Most of these domains truncate other chemical domains, indicating that they probably formed via recrystallization during fluid-mineral interactions. This indicates both the presence of fluids and the possibility of temperatures as low as 400 °C (Poitrasson et al., 1996). Because the dates are scattered over 50 m.y. throughout the Late Devonian and Carboniferous, they are interpreted to represent discrete hydrothermal events of lower metamorphic grade restricted to limited areas in the vicinity of faults, shear zones, and other conduits for fluid infiltration.

One grain from the Sulfur Hill shear zone (grain 11m1; Fig. 5) has a 343 Ma recrystallized rim and a slightly older, 345 Ma core. The morphology of the grain strongly suggests that it pseudomorphed from a sillimanite crystal—the monazite, along with quartz and biotite grains, inherited one of the basal partings commonly found in sillimanite. The morphology of the grain indicates that sillimanite was no longer stable by 345 Ma. This is in agreement with $^{40}Ar/^{39}Ar$ isotopic hornblende ages in the Nashoba terrane of 354–325 Ma that are suggestive of temperatures below ~500 °C by this time (Hepburn et al., 1987).

Other recrystallized rims throughout this interval may indicate infusions of fluids, subsequent reactivation of fault zones, and retrograde metamorphism, but further study is required to give these dates geological significance. The 345 Ma date is taken to be the minimum age of sillimanite stability in the Nashoba terrane, indicating temperatures less than ~550 °C by this time.

CONCLUSIONS

Two grains, one each from the Assabet River fault zone and Ball Hill fault zone, yield ages older than M1. Grain 7m4 from the Assabet River fault zone yields an age of 452 ± 10 Ma and was initially interpreted to

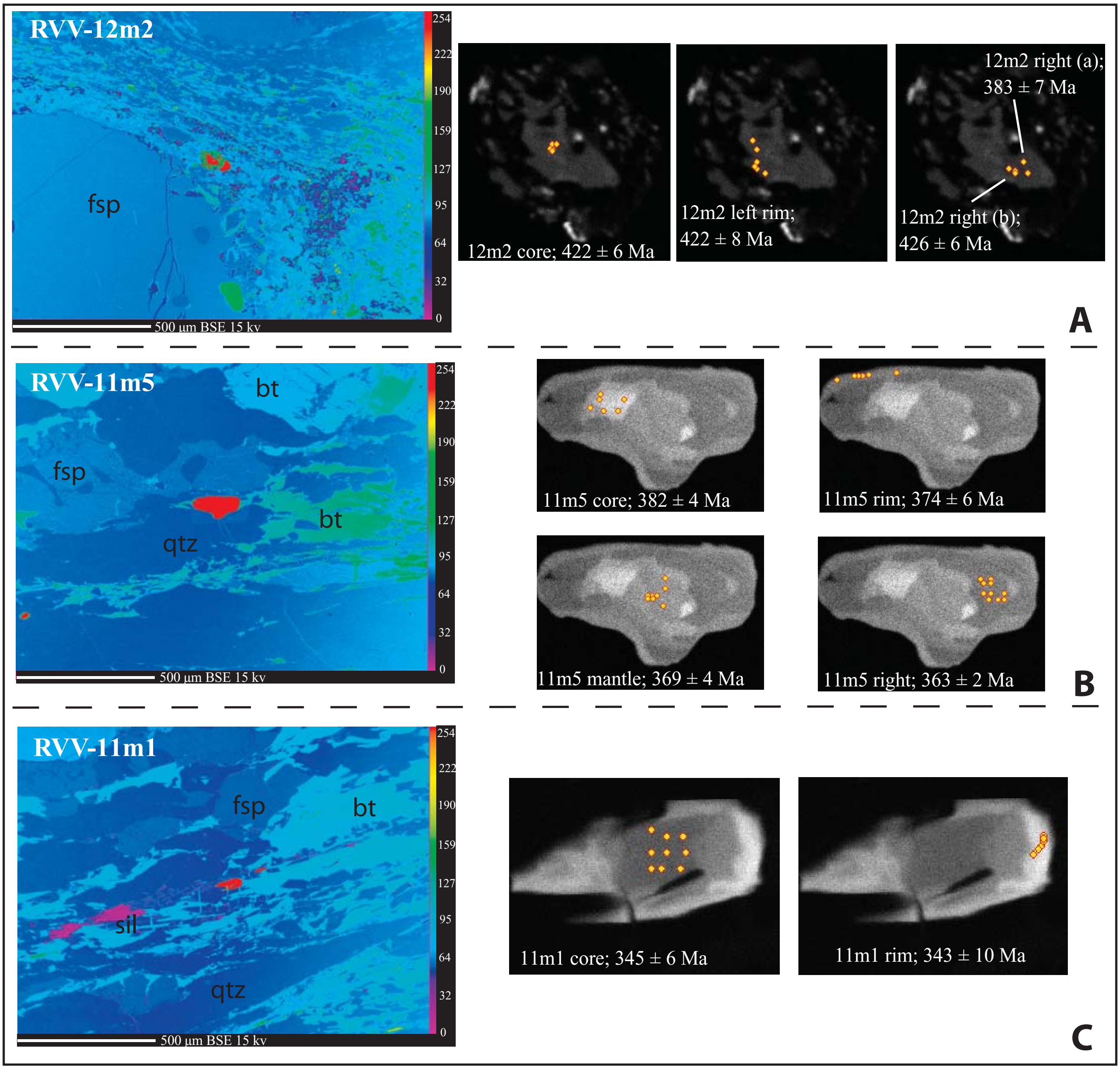

Figure 5. Color-enhanced backscattered electron (BSE) image (left) of polished sections illustrating location of monazite grains. BSE image (right) illustrating spot analyses locations of grains shown by yellow dots with red outlines. (A) RVV-012m2; (B) RVV-011m5; and (C) RVV-011m1. Scale bar is shown at bottom of color-enhanced backscattered image. The relationship of monazite grains to other minerals is discussed in the text.

be detrital based on: (1) its small, rounded morphology, a common characteristic of detrital grains; and (2) its date, which lies within the range of known detrital ages in the correlative Putnam terrane in Connecticut (R.P. Wintsch, 2007, personal commun.). Recent U-Pb sensitive high-resolution ion microprobe (SHRIMP) ages (515 ± 4 Ma) on zircons within the cross-cutting Grafton gneiss indicate the Marlboro Formation is at least Cambrian in age (Walsh et al., 2009). This interpretation means the grain from the Assabet River fault zone may represent a thermal pulse associated with the older phase of the Andover Granite. Either way, its textural position within a garnet porphyroblast indicates that it predates at least some of the metamorphism that began ca. 425 Ma. The other grain that predates M1 is found within a medium- to coarse-grained mylonitized granite and yields an age of 438 ± 4 Ma. This granite was emplaced in a limited zone along the contact between the Tadmuck Brook Schist (Fig. 1) and the Nashoba Formation and was observed to intrude the Tadmuck Brook Schist. The igneous protolith age of the mylonite in the Ball Hill fault zone provides a minimum age for the deposition of the Tadmuck Brook Schist and a maximum age for deformation along the Ball Hill fault zone.

The Nashoba terrane experienced two amphibolite-grade metamorphic events. The earliest metamorphism (M1) may have lasted some 30 m.y.

and has an average age of 423 Ma. A concentric monazite overgrowth in a sample from the Sulfur Hill shear zone suggests that this may have been largely a static thermal event. Heat generated by a subduction zone and the associated I-type intrusions (such as the 430 Ma Sharpner's Pond Diorite) may have been the impetus for M1 conditions. Later metamorphism (M2) produced anatectic conditions around 394 Ma. The last major metamorphic event (M3) occurred at ca. 376 Ma and may have been related to the Neoacadian orogeny (van Staal and Whalen, 2006).

M3 likely reflects fluid infiltration into shear zones and is possibly correlative with more widespread chlorite-zone metamorphism in the adjacent Rocky Pond slice and Merrimack terrane. Fluid infiltration in shear zones is evidenced by recrystallized monazite rims in the range 372–305 Ma. By 345 Ma, the terrane had cooled below the stability of sillimanite (~550 °C) and had probably done so earlier (e.g., hornblende cooling ages of 354–325 Ma; Hepburn et al., 1987). All three distinct metamorphic events occurred in the Silurian-Devonian to Devonian. Since no major pulses of metamorphism occurred after the Devonian, we infer that the Devonian is the youngest possible age of Avalon accretion. These data support the interpretation that the docking of the Avalon terrane in eastern Massachusetts was a Late Silurian to Devonian event and strongly suggest that the Avalon terrane was not still outboard of the New England Laurentian margin at that time.

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