EVOLUTION OF THE NASHOBA TERRANE, AN EARLY PALEozoic
GANDERIAN ARC REMNANT IN EASTERN MASSACHUSETTS

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INTRODUCTION

The Nashoba terrane is one of three geologic terranes that make up the bedrock of eastern Massachusetts, and its geological history has been difficult to fully decipher. Recently, however, various workers have been making progress unraveling the geological history of this enigmatic group of rocks and allowing them to be correlated with major tectonic events in the northern Appalachians. The geological history of the Nashoba terrane is basically a story of two arcs. The older metavolcanic and metasedimentary rocks in the terrane were formed in a Cambro-Ordovician peri-Gondwanan arc/back-arc setting, while the majority of the intruding plutonic rocks formed during a period of younger, Siluro-Devonian arc magmatism. This younger arc developed as the oceanic crust separating the Nashoba and Avalon terranes was subducted beneath the Nashoba terrane along the trailing edge of Ganderia prior to and during the early stages of the Acadian orogeny.

Today’s excursion is designed to provide participants with a general overview of the terrane and the fascinating story its rocks tell. The fault-bounded Nashoba terrane is now known to be an early Paleozoic arc/back-arc complex that was significantly metamorphosed in contrast to the terranes immediately on either side (Figure 1). East of the Nashoba terrane, across the prominent Bloody Bluff fault zone, is the composite Avalon terrane of southeastern New England. This terrane has many features similar to the type Avalon of eastern Newfoundland, including those critical for establishing it as a fragment of “Avalonia,” i.e., such as a major 590-630 Ma calc-alkaline plutonic-volcanic event and Cambrian platformal sediments bearing an Acado-Baltic fauna (e.g., Rast and Skehan, 1983; O’Brien et al., 1983; Williams and Hatcher, 1983; Thompson et al., 1996). In eastern Massachusetts the Avalon terrane is only weakly metamorphosed. West of the Nashoba terrane, across the Clinton-Newbury fault zone, lies the Merrimack belt (Zen et al., 1983; Robinson and Goldsmith, 1991). The eastern portion of the Merrimack belt largely consists of a thick sequence of calcareous metasiltstones, pelites and impure quartzites of Silurian and/or Devonian age (Zen et al., 1983; Robinson and Goldsmith, 1991; Lyons et al., 1997; Sorota, 2013). This belt was multiply deformed and metamorphosed during the Acadian and/or the Alleghanian orogeny (e.g., Billings, 1956; Osberg et al., 1989; Goldsmith, 1991a; Goldstein, 1994; Attenoukon, 2009). Just west of the Clinton-Newbury fault zone the metamorphic grade is that of the lower greenschist facies, but it increases towards upper amphibolite facies to the west (Zen et al., 1983; Robinson and Goldsmith, 1991; Goldsmith, 1991a).

Full recognition that the Nashoba rocks formed a separate terrane took place only in the early 1980’s (e.g., Zen et al., 1983; Williams and Hatcher, 1983) following recognition of the large fault zones that bound the terrane (Skehan 1968; Castle et al., 1976; Bell and Alvord, 1976). Since this time several published field trips have been run to the Nashoba terrane in Massachusetts, including those from the NEIGC meetings in 1976, 1984, 1986, 1998 and 2004, an excursion prepared for the 28th International Geological Congress (Zen, 1989) and excursions run in connection with the Geological Society of America Annual Meeting in Boston in 1993 (Cheney and Hepburn, 1993). Participants wishing further information on the Nashoba terrane may wish to consult these field guides, which include more detailed descriptions of some of the stops we will visit than space permits herein. Parts of today’s trip are condensed and updated from the three-day excursion in the Boston area from the 1993 GSA guidebook (Hepburn et al., 1993), and from the 1998 and 2004 NEIGC trips (Hepburn and Bailey, 1998, Trip C-3; Hepburn, 2004, Trip A-2). The bedrock map of Massachusetts (Zen et al., 1983) presents the most recent regional geological compilation. Accompanying that map is U.S.G.S. Professional Paper #1366 E-J (Hatch, 1991), which contains excellent summaries of the geology of eastern Massachusetts along with extensive bibliographies of the literature to that time. Those interested in detailed descriptions of many of the stratified units in eastern Massachusetts are referred to Bell and Alvord
NASHOBA TERRANE

Cambro-Ordovician Metavolcanic and Metasedimentary Rocks

The rocks of the Nashoba terrane are distinct from those of the adjacent terranes and no geological units cross its bounding faults. To the south, the Nashoba terrane is continuous with portions of the Putnam terrane, although there are variations in the stratigraphy and formation names change across the Connecticut border (Rodgers, 1985; Goldsmith, 1991b). Bell and Alvord (1976) interpreted the older “stratified” rocks of the Nashoba terrane to represent a homoclinal sequence younging to the NW. However, it has become clear that the terrane is strongly deformed by multiple generations of overprinting folds that duplicate lithotectonic units and that it can be interpreted as a crustal-scale shear zone (Buchanan et al., 2014a, b). Furthermore, localized shear zones are present throughout the terrane (Stroud et al., 2009). Thus, a clear stratigraphic sequence cannot be recognized, and it is likely that the units represent more of a lithotectonic assemblage than a coherent stratigraphy.

In the east, the terrane is dominated by a sequence of largely mafic volcanic rocks and associated metasedimentary rocks (Marlboro Formation), while thick deposits of largely metasedimentary rocks (Nashoba Formation) are present to west (Figures 1, 2). Between these formations, two gneissose units have been mapped in the central part of Massachusetts: the Fish Brook Gneiss, largely orthogneiss, and the Shawsheen Gneiss, a paragneiss (Bell and Alvord, 1976; Zen et al., 1983, Goldsmith, 1991b). The Tadmuck Brook Schist [Stop 9] is a rusty weathering, sulfidic schist that occurs along the western boundary of the terrane over much of its length in northeastern Massachusetts (Zen et al., 1983). All of the metavolcanic and metasedimentary rocks have been polydeformed and metamorphosed under upper amphibolite facies conditions (sillimanite and sillimanite-K-feldspar zones) and are now amphibolites, various biotite-feldspar and feldspathic gneisses, schists, and calc-silicate gneisses (e.g., Bell and Alvord, 1976; Abu-Moustafa and Skehan, 1976; Hepburn and Munn, 1984; Goldsmith, 1991a; Kopera et al., 2006; Walsh et al., 2011a).

Most of the metavolcanic rocks of the Nashoba terrane occur in its eastern portion (Figure 1) and are included in the Marlboro Fm. or the Boxford Mbr. of the Nashoba Fm. Hornblende-plagioclase amphibolites dominate the eastern part of the Marlboro Formation [Stops 1, 3], but the Marlboro Fm. also contains felsic rocks, and gneisses of andesitic, dacitic or rhyolitic composition (DiNitto et al., 1984; Acaster and Bickford, 1999; Kopera et al., 2006) as well as subordinate metasedimentary rocks, generally micaceous schists [Stop 2] (Emerson, 1917; Bell and Alvord, 1976; DiNitto et al., 1984; Goldsmith, 1991b, Loan, 2011). The Fish Brook Gneiss is a light-colored fine- to medium-grained feldspathic biotite-quartz-feldspar gneiss with a distinctive “swirled” foliation of oriented biotite flakes (Castle, 1964, 1965; Bell and Alvord, 1976). This rock has been interpreted as either plutonic (Castle, 1964; Hepburn, 2004) or volcanic in origin (Bell and Alvord, 1976; Olszewski, 1980). Driving logistics with a group in urban settings prevent us from visiting the Fish Brook Gneiss on this excursion.

The Nashoba Fm. is composed largely of various biotite-feldspar-quartz gneisses and schists [Stops 6, 8] that are interpreted to have been derived largely from a volcanic source area (Bell and Alvord, 1976; Abu-Moustafa and Skehan, 1976; Loan, 2011). However, the Nashoba Fm. also includes a diversity of subordinate rocks, including rusty weathering sillimanite-bearing schist, impure quartzite, amphibolite, calc-silicate gneiss and impure marble [Stop 7].

Age of Metavolcanic and Metasedimentary Rocks

One of the most difficult problems in the Nashoba terrane has been to establish the original age of the metavolcanic rocks, largely due to the paucity of adequate zircons in the mafic rocks of the Marlboro and Nashoba Fms. Earlier attempts to date these rocks will not be reviewed here, but interested readers are referred to discussions in the following: Bell and Alvord (1976); Olszewski (1980); Hill et al. (1984a, b); Zartman and Naylor (1984); DiNitto et al. (1984); and Acaster and Bickford (1999). It has long been recognized that the stratified rocks in the Nashoba terrane have been intruded by the Sharpners Pond Diorite dated at 430 ± 5 Ma (Zartman and Naylor, 1984) and are therefore pre-middle Silurian. However, recently
The metasedimentary rocks in the Nashoba terrane are crystalline and not fossiliferous. Preliminary U-Pb detrital zircon LA-ICP-MS geochronology results from selected units of the Nashoba terrane in central Massachusetts (Loan et al., 2011; Loan, 2011) indicate they include rocks that are younger than ~460-470 Ma, the ages of the youngest zircon populations. Walsh et al. (2013), however, report even younger potential ages for the deposition of the Nashoba Fm. (450-400 Ma) in areas to the SW, based on U-Pb SHRIMP detrital zircon analyses.

**Deformation & Metamorphism**

In central Massachusetts the stratified rocks of the Nashoba terrane generally dip moderately to steeply to the northwest. In addition to folds, major shear zones are present throughout the terrane (Castle et al., 1976; Zen et al., 1983; Goldsmith, 1991a) and range from those of regional extent, such as the Assabet River fault in the central portion of the terrane (Figure 1), to small shear zones seen at outcrop scale. Rarely is any large outcrop seen without some evidence of shearing and the entire terrane can be thought of as a mid-crustal shear zone (e.g., Skehan, 1968; Barosh, 1982). Major faults, such as the Bloody Bluff and Assabet River fault zones, generally show an earlier ductile phase or phases of shearing followed by younger, more brittle, faulting.

The metavolcanic and metasedimentary rocks of the Nashoba terrane have been polymetamorphosed (e.g., Castle, 1964; Skehan and Abu-Moustafa, 1976; Abu-Mousafa and Skehan, 1976; Hepburn and Munn, 1984; Bober, 1989; Stroud et al., 2009) to middle and upper amphibolite facies (sillimanite and sillimanite-K feldspar zones) metamorphic conditions in a generally lower pressure-higher temperature andalusite-sillimanite facies series (Goldsmith 1991a). However, in central Massachusetts early kyanite pseudomorphs replaced by sillimanite have been found in a few localities (Bober, 1989) and kyanite becomes increasing prevalent to the SW (Walsh et al., 2011a). Migmatites are present in the higher grade portions of the Nashoba Formation, particularly toward the northeast in Massachusetts (Castle, 1964; Hepburn et al., 1987, 1995; Buchanan et al., 2014a). Preliminary electron microprobe age determination studies on monazites from shear zones within the Nashoba terrane (Stroud et al., 2009) indicate the earliest, M1, metamorphism took place during the period ca. 435-400 Ma, (average 423 Ma), more or less contemporaneous with intrusion of intermediate-composition and granitic plutons into the terrane. This timing is further constrained by a U-Pb ID-TIMS age of 425 ± 3 Ma on metamorphic monazite from the Fish Brook Gneiss (Hepburn et al., 1995). A second high-grade metamorphism, M2, took place ~400-385 Ma (Stroud et al., 2009; Hepburn et al., 1995) that included melting and migmatization in rocks of the correct composition. A third period of major metamorphism and monazite growth occurred ~385-360 Ma. While Stroud et al. (2009) attributed monazite growth at this time to Neocadrian fluid introduction, recent work by Walsh et al. (2011a; 2013) and Buchanan et al. (2014a, b) suggest instead that major periods of high-grade metamorphism and migmatization likely occurred during and/or after this time. Further studies to better refine the conditions and timing of metamorphism in the Nashoba terrane are currently underway.
Figure 1. Simplified geologic map of Nashoba terrane with excursion stops. ARZ - Assabet River fault zone.
Silurian to Carboniferous Plutonic Rocks

The Nashoba terrane experienced widespread plutonism from the mid-Silurian to the mid-Devonian, with younger granitic rocks emplaced during the Mississippian. The earlier of these magmatism involved the broadly contemporaneous intrusion of two distinctly different magma types: intermediate composition dioritic to tonalitic calc-alkaline magmas and aluminous granites (Castle, 1964; Zartman and Naylor, 1984; Wones and Goldsmith, 1991; Hepburn et al., 1987, 1995). The intermediate composition plutons are typified by the Sharpners Pond, Straw Hollow and Assabet Quartz Diorites [Stop 5]. These plutons are undeformed to weakly foliated (except near major shear zones) hornblende and hornblende-biotite diorites and/or tonalities that may contain minor gabbroic cumulates or more granitic fractionates (Castle, 1964, 1965; Hill et al., 1984a, b; Hon et al., 1986, 1993; Wones and Goldsmith, 1991). Geochemically these plutons are calc-alkaline and have major and trace element distributions similar to those developed in continental arcs (Hill et al., 1984a, b; Hill, 1985; Hepburn et al., 1987; Hon et al., 1986, 1993; Wones and Goldsmith, 1991 Kay, 2012). Wones and Goldsmith (1991) indicate that the mineralogy of these plutons is characteristic of lower pressure I-type calc-alkaline intrusions. Ages for these plutons range from 430 ± 5 Ma for the Sharpners Pond Diorite (U-Pb, Zartman and Naylor, 1984) to 385 ± 10 for the Straw Hollow Diorite (Acaster and Bickford, 1999).

Granitic rocks, most of which have been included within the Andover Granite (Castle, 1964, 1965; Zen et al., 1983; Wones and Goldsmith, 1991) form an appreciable portion of the Nashoba terrane, particularly toward northeastern Massachusetts (Figure 1). Castle (1964) divided the Andover into a number of different phases based upon mineralogy, texture and the presence or absence of foliation. The Andover includes granites that range in composition from metaluminous to peraluminous and vary from foliated biotite and biotite-muscovite granite to unfoliated garnet-bearing muscovite granite and pegmatite. The more foliated
rocks were traditionally interpreted to be pre-to syn-kinematic, whereas the unfoliated granites were considered post-kinematic (Castle, 1964; Zartman and Naylor, 1984; Hill et al., 1984a; Wones and Goldsmith, 1991). However, it is not clear that the foliation in the granites was produced everywhere at the same time, and it may have at least partially formed in response to major shear zones. Given its complexity, and the propensity for the Andover to have a large component of source rock inheritance in its zircons, it is not surprising that it has been difficult to obtain a satisfactory age for the granitic rocks included in the Andover, and age estimates have ranged from Ordovician to Devonian. Readers are referred to Zartman and Naylor (1984), Hill et al. (1984a, b) and Wones and Goldsmith (1991) for information on the earlier attempts to date the Andover. Recent U-Pb dates, however, show that what were believed to be the youngest and oldest phases of the Andover are both Early Devonian. Igneous monazite from an unfoliated medium-to-coarse-grained muscovitic phase of the Andover Granite in Bedford, MA, interpreted to be one of the youngest phases, gives an age of $412 \pm 2$ Ma (ID-TIMS, Hepburn et al., 1995; Hepburn, 2004), while foliated biotitic granites in both Hudson (Stop 4) and Andover, MA., thought to be representative of the oldest granitic phase, both give ages of $419 \pm 1$ Ma (U-Pb CA-TIMS, Dabrowski et al., 2013, Dabrowski, 2014). These dates fit well with geologic evidence that granites and diorites intruded in several pulses. Trace element and isotopic chemistry indicate that most of the granites are the result of crustal anatexis and not simply fractionates of the calc-alkaline magmas (Hill et al., 1984a; Hill, 1985; Hon et al. 1986, 1993; Kay et al., 2011; Kay, 2012; Dabrowski et al., 2013). However, it is thought likely that the intrusion of the diorites contributed heat to the crust for anatexis of metasedimentary rocks, which in turn led to at least some of the granite formation (Wones and Goldsmith, 1991; Hepburn et al., 1995; Dabrowski, 2014).

In addition to the Andover Granite, two other granites are prominent in the Nashoba terrane along its eastern margin (Figure 1). These include the granite of the Indian Head Hill pluton and the “Sgr” granite (Silurian granite) of Zen et al. (1983). The “Sgr” granite, informally re-designated the Sudbury Granite for exposures in that town (Kohut, 1999; Dabrowski, 2014), includes a distinctive suite of unfoliated orange-pink biotite granites (Wones and Goldsmith, 1991) that occur along the eastern side of the terrane adjacent to the Bloody Bluff fault zone (Stop 10). Recent dating has shown this granite to have an age of $420$ Ma (U-Pb CA-TIMS; Dabrowski, 2014) (i.e., barely Silurian on the most recent GSA Geological Time Scale, Walker et al., 2012; E-an Zen and his co-workers had a discerning eye!). The Indian Head Hill pluton also occurs along the Bloody Bluff fault zone and is observed to crosscut an older dioritic intrusion. This granite is a pinkish weathering, light-gray, fine- to medium-grained, massive, biotite granite to granodiorite (Hepburn and DiNitto, 1978; DiNitto et al., 1984; Wones and Goldsmith, 1991; Koper et al., 2006). It has been well dated at $349 \pm 4$ Ma (U-Pb zircon and titanite; Hepburn et al., 1995; see also Acaster and Bickford, 1999). Even younger tonalite ($323 \pm 3$ Ma) and pegmatite ($326 \pm 3$ Ma) (Walsh et al., 2013) occur in the terrane to the southwest indicating that plutonism in the Nashoba terrane in Massachusetts extended well into the Mississippian.

**Geochemistry and Formation of the Cambro-Ordovician Rocks**

Geochemistry indicates that the mafic rocks in the Marlboro Fm. have a range in composition from tholeiitic to calc-alkaline basalt and basaltic andesite and plot on tectonic discrimination diagrams in MORB and arc-related fields (DiNitto et al., 1984; Oakes-Coyne et al., 1996; Kay et al., 2011; Kay, 2012). Those from the Nashoba Fm. are generally similar, but have a wider range of compositions and include samples showing both a strong arc component as well as those with depleted REE MORB signatures, and even a few having more alkaline compositions (Kay, 2012). The intermediate to felsic gneisses in the Marlboro and Nashoba Fms. range in composition from andesitic to dacitic composition. All have calc-alkaline compositions, are typical of arc rocks, and plot in volcanic arc granitic fields on granitic discrimination diagrams (Wones and Goldsmith, 1991; Kay et al., 2011; Kay, 2012). The Fish Brook Gneiss is also calc-alkaline, although it is more evolved than the intermediate and felsic rocks in the Marlboro and Nashoba Fms. In short, the geochemistry of the volcanic rocks and Fish Brook Gneiss are entirely consistent with their formation in a volcanic arc/back-arc basin setting (Wones and Goldsmith, 1991; Hepburn et al., 1995; Kay et al., 2011; Kay, 2012).
Newly determined Sm-Nd isotopic data (Kay et al., 2011; Kay, 2012) help to further clarify the original tectonic setting. Amphibolites in the Marlboro and Nashoba Formations have high $\varepsilon_{Nd}$ values (+4 to +7.5) consistent with their formation in a primitive volcanic arc with only minimal interaction between arc magmas and crust. The intermediate and felsic gneisses have more moderate $\varepsilon_{Nd}$ values between +1.2 and –0.75, possibly indicating a mixture of juvenile arc magmas and an evolved (likely basement) source. Depleted mantle model ages of 1.2 to 1.6 Ga indicate a Mesoproterozoic or older age for this source. Metasedimentary rocks from the Marlboro and Nashoba Fms. have negative $\varepsilon_{Nd}$ values between –6 and –8.3 indicating derivation primarily from an isotopically evolved source (or sources). The model ages of these metasedimentary rocks (1.6 to 1.8 Ga) indicate a source area of Paleoproterozoic or older age. Detrital zircons (Loan et al., 2011; Loan 2011; Olszewski, 1980) and Nd isotopes from the Andover Granite (Hill et al., 1984a, b; Kay, 2012) indicate the presence of both Mesoproterozoic and Paleoproterozoic crustal material in the terrane. The detrital zircon suites along with the $\varepsilon_{Nd}$ values and model ages of the intermediate, felsic and metasedimentary rocks indicate that the basement to the Nashoba terrane is typical of Ganderian crust, and not Avalonian crust (e.g., Murphy and Nance, 2002; Murphy et al., 2004; Samson et al., 2000; Schofield and D’Lemos, 2000; Rogers et al., 2006; Hibbard et al., 2007; Satkoski et al., 2010; Pollock et al., 2009, 2012; Kay, 2012).

TECTORIC MODEL FOR THE EVOLUTION OF THE NASHOBA TERRANE

The Nashoba terrane is interpreted to have formed in a peri-Gondwanan arc/back-arc setting in the early Paleozoic. We interpret that, initially, Cambrian basaltic magmas of the Marlboro Fm. formed in a primitive arc on rifted or attenuated Ganderian crust and were largely unimpeded in their ascent to erupt as arc and back-arc tholeiites, with minimal incorporation of continental material (Kay et al., 2011, Kay, 2012). As the volcanic pile thickened, basaltic magma ascent was hindered, underwent fractional crystallization and wallrock assimilation, and erupted as transitional to calc-alkaline basalts. Eventually, the continuation of this process led to the eruption of andesitic and dacitic volcanic rocks with a greater incorporation of underlying basement material. The greater volume of metasedimentary rocks and the mix of arc, MORB and alkalic geochemical signatures in the Nashoba Fm indicate a setting dominated by a back-arc component (Kay, 2012). Most likely the Nashoba Formation developed in a widening arc/back-arc system as the distance between the arc and back-arc volcanic centers increased as the arc became extensional in nature, likely due to slab roll-back (e.g., van Staal et al., 2009; Fyffe et al., 2009, 2011; van Staal and Barr, 2012).

The Ganderian affinity of the basement and ca. 500 Ma age for the metavolcanic arc rocks of the Marlboro Fm. suggest a relationship between the Nashoba terrane and Penobscot arc activity in the northern Appalachians (e.g., van Staal et al., 2009; Fyffe et al., 2011; van Staal and Barr, 2012). This activity formed along the Amazonian margin of Gondwana during the mid- to late Cambrian, ca. 514-485 Ma (e.g., Fyffe, et al., 2011; Pollock et al., 2012; van Staal and Barr, 2012), and has been associated with the breakoff of Ganderia from western Gondwana at ~505 Ma (e.g., Schultz et al., 2008; van Staal et al., 2009). Penobscot arc activity is well documented along the eastern side of Ganderia in the New River and Annidale terranes in southern New Brunswick as well as elsewhere in the northern Appalachians (e.g., Nova Scotia, Newfoundland) (e.g., Fyffe et al., 2011; Johnson et al. 2012; van Staal and Barr, 2012; and additional references therein). In these areas, subduction roll-back during Penobscot arc activity led to formation of an extensional, NW migrating arc/back-arc system that may have produced a number of arcs and intervening back-arc basins, (e.g., van Staal et al., 2009; Fyffe et al., 2009, 2011). The Penobscot arcs formed on extended and rifted blocks of Ganderian crust such as are exposed in the Brookville and New River terranes in southern New Brunswick (Fyffe et al., 2011; Pollock et al., 2012). Penobscot arc remnants show the influence of this basement in both their detrital zircon and $\varepsilon_{Nd}$ data, in a similar fashion to that of the Nashoba terrane (e.g., Fyffe et al., 2009, 2011, Kay et al., 2011; Kay, 2012). Volcanic rocks in the Cambrian Ellsworth terrane of eastern Maine are contemporaneous with Penobscot arc activity, but have extensional, within plate, geochemical signatures indicating they formed in a rift environment (Schulz et al., 2008). This rift has been suggested to potentially represent the original breakoff of Ganderia from Gondwana (Schulz et al., 2009) and would have been inboard of the Penobscot arc along the margin of Gondwana. If correlatives of the rift volcanic rocks of the Ellsworth terrane were ever present in SE New England they have since been lost through later faulting or subduction erosion. In any case, while of similar age, we do not see direct correlatives of the Ellsworth terrane volcanic rocks in the Nashoba terrane. However, we believe the
arc/back-arc volcanic rocks of the Nashoba terrane are general correlatives of those associated with Penobscot arc activity as seen in the Annidale and New River terranes.

Beginning in the mid-Silurian, the Nashoba terrane was being intruded by calc-alkaline dioritic, tonalitic and granitic magmas and was beginning to be deformed and metamorphosed to high grade. This period overlaps with the waning stages of the Salinic orogeny when Ganderia was consolidated with Laurentia (e.g., van Staal et al., 2009; Fyffe et al., 2011; Pollock et al., 2012). At this time Avalonia was still located some distance to the east (present day directions) and separated from the trailing edge of Ganderia by an expanse of oceanic crust (e.g., van Staal et al., 2009; Pollock et al., 2012). As Ganderia amalgamated with Laurentia, westward subduction of this oceanic crust initiated along the trailing edge of Ganderia. The results of this new arc volcanism are seen in the Silurian volcanic rocks of the Coastal Volcanic belt in eastern Maine and their southward continuation in the Newbury Volcanics of NE Massachusetts (Fig. 1) (Gates and Moench, 1981; Shride, 1976; Piñán Llamas and Hepburn, 2013). It is believed that the majority of the calc-alkaline tonalitic and dioritic plutons of the Nashoba terrane also formed as a result of this subduction and represent deep-seated plutons below the arc. The present Newbury Volcanics were somehow preserved in an upthrown fault block (Hon and Thirlwall, 1985). The intrusion of the intermediate-composition magmas brought heat into the crust of the Nashoba terrane, led to metamorphism and anatexis, and the formation of migmatites and granitic rocks (Wones and Goldsmith, 1991; Hepburn et al., 1995; Dabrowski, 2014). By the late Silurian or early Devonian the oceanic crust separating Avalon from Ganderia was entirely subducted and Avalon docked with and was thrust below the trailing margin of Ganderia, likely with a large sinistral oblique component of motion (Gerbi and West, 2007; van Staal et al., 2009; Fyffe et al., 2011; Pollock et al., 2012). This initiated the Acadian orogeny that gradually progressed westward across New England (e.g., Bradley et al., 2000, and references therein). In SE New England, the Nashoba terrane occupied the trailing margin of Ganderia by this time. The oblique thrusting of Avalon below the Nashoba terrane (Wintsch et al., 1992, 1993, 1995; Goldstein, 1989; Kohut and Hepburn, 2004) largely turned off the subduction magmatism, but a few intermediate-composition plutons such as the Assabet Quartz Diorite (385 Ma, called Straw Hollow Diorite, by Acaster and Bickford, 1999) were still being emplaced. Younger Devonian and Carboniferous pulses of metamorphism are likely related to the Neocadrian or Fammennian orogeny, (ca. 395-350 Ma; e.g., Robinson et al., 1998; van Staal et al., 2009; Hibbard et al., 2010, Pollock, et al., 2012) when the Meguma terrane joined the eastern margin of the now amalgamated Laurentia, as well as continuing younger movements as Gondwana moved toward Laurentia prior to or during the early phases of the Alleghanian orogeny.

Large faults with unknown displacements both within the Nashoba terrane and between it and the adjacent terranes have clearly disrupted the original order of the crustal segments. These faults have had a long and complex history of movement (e.g., Goldstein, 1989, 1992, 1994; Goldsmith, 1991a; Kohut and Hepburn, 2004), and the final positioning of the terranes, at least in eastern Massachusetts, is relatively late. The terrane boundary with the Avalon terrane of southeastern New England is marked by the Bloody Bluff fault zone in eastern Massachusetts [Stop 10]. This fault is a late, brittle feature thought to be a normal fault that may have had movement on it as late as Mesozoic (Kaye, 1983; Kohut and Hepburn, 2004). The Bloody Bluff fault zone overprints an older, more ductile shear zone, the Burlington Mylonite zone (Castle et al., 1976) that locally extends up to several kilometers east of the terrane boundary (Kohut and Hepburn, 2004 ). Petrofabric analysis of the Burlington Mylonite zone indicates the motion was largely sinistral transpression, with the Nashoba terrane moving south-southwest and over the Avalon terrane at a shallow to moderate angle (Goldstein, 1989, Kohut and Hepburn, 2004).

ROAD LOG

Meeting Place
Meet in the designated parking lot at Wellesley College just east of the Science Center - see campus map at http://web.wellesley.edu/map/). We will car pool from here and leave at 8:00 AM. Please bring lunch; we will picnic at the outcrop. The trip will return here in time for the reception and dinner. UTM coordinates (WGS84) are given for parking areas at each stop. It will be difficult for a group of cars to stay together in urban traffic. PLEASE HAVE THE ROADLOG AVAILABLE AND A DESIGNATED PERSON FOLLOW IT IN EACH CAR as we will get separated!
Mileage Directions to Stop 1.
0.0 Exit parking lot, turn right and follow to College Road.
0.1 Turn right on College Road and follow through Wellesley College to Rt. 135.
0.7 At light, turn right onto Rt. 135 (Central St.).
1.2 Turn sharp left at first light onto Weston Rd.
2.2 After underpass turn right and enter Rt. 9 West (use caution entering Rt. 9).
11.4 Stay Right on Rt. 9 West—Do not go up ramp on the left.
15.3 Take ramp on right to I-495 North and continue north on I-495.
16.7 Crossing Bloody Bluff fault zone into the Nashoba terrane.
17.4 Take Exit 23C to Simarano Drive on right.
18.2 Turn left at light onto Simarano Dr.—marked “toward Southboro.”
18.5 At light, turn left onto Cedar Hill St.—which shortly changes to Northboro Rd. at town line.
19.0 Outcrop on left at the entrance to The 495 Technology Center, 153-155 Northboro Rd., Southborough. Park on right or reverse direction and park along the north side of the road off the pavement. Be careful crossing street; cars are coming fast here (UTM WGS84-19T 0288026 m E - 4687836 m N).

STOP 1. MARLBORO FORMATION, AMPHIBOLITE (25 minutes)

This outcrop is typical of amphibolites near the eastern boundary (base?) of the Marlboro Fm. and similar to those included in the Sandy Pond Mbr. of Bell and Alvord (1976). The rocks are generally fine-to medium-grained, well-foliated amphibolite containing both hornblende and biotite. A few more schistose layers can be found, as can small sheared granitic layers. The foliation dips steeply to the north and multiple lineations are present. Asymmetric folds plunge shallowly to the east and indicate top-to-the-north (normal) movement. Late carbonate coated joints and fractures are common here and in many areas near the Bloody Bluff and Assabet River fault zones.

0.0 Return to cars and head west on Northboro Rd.- Cedar Hill St. Roadlog is re-set to 0.0, as some maybe joining the trip here.
0.6 At light stay straight on Cedar Hill St.
1.5 T-intersection; turn right onto Bartlett St.
1.6 Turn left onto Hayes Memorial Drive.
2.4 Pull off and park along the right side of the road, about 0.1 miles south of Nickerson Rd. at the south end of the guard rail (19T 0285729 m E – 4689949 m N). Take care, cars are moving faster here than they should. Walk on small trail to the right to pavement outcrops.

STOP 2. MARLBORO FORMATION, METASEDIMENTARY ROCKS (25 minutes)

Even though the Marlboro Fm. is commonly thought of as being largely amphibolite, other rock types including schist and felsic gneiss are present. This exposure is in the Schist and Granulite Member of the Marlboro Formation (DiNitto et al., 1984; Kopera et al., 2006). (Granulite is used here as a textural term meaning of equal grain size and does not a refer to metamorphic grade.) These rocks continue eastward and are present along Main Street in downtown Marlborough, Emerson’s (1917) type locality for the Marlboro Formation. The town name, Marlborough, was apparently shortened to Marlboro by Emerson and other early workers when describing the rocks, thus resulting in the different spellings of the town and formation names.

Rocks exposed here consist of thin beds of interlayered light-gray weathering, fine- to medium-grained quartzofeldspathic granulite or impure quartzite and of gray, brown to rusty weathering mica schist. Conspicuous garnets, in places up to a couple of centimeters in diameter, occur in the schist. Black, fine- to medium-grained amphibolite is also present. Note the presence of folds and the sheared nature of the beds in the central portion of the exposure, as well as younger, more brittle, minor deformational features.

Return to cars and proceed north on Hayes Memorial Drive.
and Hansen, 2014). In any case, it is likely that the dioritic rocks at this stop are among the dioritic rocks in this belt have been reassigned to the Assabet Quartz Diorite (Kopera et al., 2006; Kopera, 2014). The rock here is largely a well-foliated, medium-grained hornblende-plagioclase ± biotite amphibolite that likely was originally a plutonic rock. A few, more feldspathic layers are also present in the outcrop. Small pavement outcrops in the field to the east show some of the variation in the amphibolite and the folding present. Late brittle deformation features, some filled with feldspar or carbonate, crosscut the outcrop and are common throughout much of this area.

Return to cars. Since we will have varying mileages in the shopping mall, re-start log mileage at the exit from the R.K. Centre parking lot as you enter Rt. 20.

STOP 3. MARLBORO FORMATION, AMPHIBOLITE (25 minutes).

This relatively fresh exposure is another fairly typical amphibolite in the Marlboro Formation (Bell and Alvord, 1976; DiNitto et al., 1984; Kopera et al., 2006). The rock here is a medium-grained, well-foliated, garnet-bearing two mica granite with a few minor biotitic inclusions. This rock is interpreted to represent the oldest phase of the Andover Granite and a recent date from this exposure gave a CA-TIMS age of 419 Ma (Dabrowski et al., 2013, Dabrowski, 2014). This indicates the foliated Andover is Early Devonian and not Ordovician as thought previously (Zartman and Naylor, 1984).

Return to cars and return to Reed Rd.

STOP 4. ANDOVER GRANITE, FOLIATED (20 minutes)

The Andover Granite is a large composite intrusion in the Nashoba terrane and occurs in both foliated and unfoliated phases, see preceding discussion. This fresh exposure is typical of the foliated phase. Here it is a medium-grained, well-foliated, garnet-bearing two mica granite with a few minor biotitic inclusions. This rock is interpreted to represent the oldest phase of the Andover Granite and a recent date from this exposure gave a CA-TIMS age of 419 Ma (Dabrowski et al., 2013, Dabrowski, 2014). This indicates the foliated Andover is Early Devonian and not Ordovician as thought previously (Zartman and Naylor, 1984).

Return to cars and return to Reed Rd.

STOP 5. ASSABET QUARTZ DIORITE – (STRAW HOLLOW DIORITE) (15 minutes)

Scattered small exposures adjacent to the parking lot and across the street in the office park are a poor substitute for those we previously passed along Rt. 85, but we are unable to stop at those with a group. Exposures here are typical of the Assabet Quartz Diorite, one of the series of calc-alkaline Siluro-Devonian intermediate-composition diorite to tonalite plutons in the Nashoba terrane. Acaster and Bickford (1999) dated a diorite near here that they called the Straw Hollow Diorite (385 ± 10 Ma). However, since this time, the dioritic rocks in this belt have been reassigned to the Assabet Quartz Diorite (Kopera et al., 2006; Kopera and Hansen, 2014). In any case, it is likely that the dioritic rocks at this stop are among the youngest of the
calc-alkaline intermediate intrusions in the terrane. Intrusion of these plutons brought heat into the crust that aided metamorphism and migmatite formation. The Assabet Quartz Diorite is an unfoliated to weakly foliated biotite-hornblende tonalite to quartz diorite.

Return to cars. Continue straight ahead on Forestvale Rd.

5.8 Cross Broad St. and turn immediately right onto Rt. 85 North, Washington St. Continue north on Rt. 85.
6.8 In Hudson, turn left on Rt. 62 West, around the small circle rotary.
6.9 Stay left onto Rt. 62 West.
8.0 Stop light at Highland Commons Mall—stay straight.
8.3 2nd stop light at Highland Commons Mall—stay straight.
8.5 Turn left into small office park just before Gates Rd. - park at west end of lot away from buildings. Parking for Stop 6 (19T 0285755 m E – 4697066 m N). Walk ~ 150 meters ahead, west, along the road shoulder to exposures along the exit ramp from I-495. WATCH OUT FOR TRAFFIC AND STAY OFF OF THE EXIT RAMP HIGHWAY!

STOP 6. NASHOBA FORMATION, SCHISTS AND MIGMATITIC GNEISSES (45 minutes, BE AWARE OF POISON IVY)

These exposures show some of the diversity within the gneisses and schists of the Nashoba Formation. The outcrops around this intersection are dominated by biotite-muscovite-sillimanite-magnetite-K-feldspar-quartz-plagioclase migmatitic gneisses. Mineral modal abundances are highly variable throughout the outcrop and depend on bulk composition. Garnet is present in the more schistose beds. Muscovite is present within foliation planes and a second generation occurs as large unoriented flakes that are likely retrograde. Minor amphibolite, calc-silicate gneiss and pre-metamorphic intrusions are present in this outcrop, as is a younger cross-cutting granite. Upper amphibolite facies metamorphic conditions prevailed here, and granitic “sweats” are ubiquitous. The amount of preserved migmatitic leucosome generally increases toward the northeast in the Nashoba terrane (as we will see at Stop 8), but rock composition also plays an important role in the distribution of migmatite.

The style of deformation is variable throughout this heterogenous outcrop due to rheological competency contrasts, but several general trends exist. The dominant foliation dips moderately to steeply to the northwest and is either defined by stromatic migmatitic foliation or gneissic fabrics. Outcrop-scale isoclinal folds with parasitic folds are present in the outcrop, though difficult to see. Smaller intra-layer isoclinal folds can be distinguished. These isoclinal folds are folded by a generation of top-down-to-the-northwest asymmetric folds. The axial planes to these asymmetric folds are parallel to the dominant foliation and fold hinges plunge gently to the NNE. The migmatitic and gneissic fabrics are cut by northwest-side-down subvertical shear zones. Ultra-cataclasites (1-5cm thick) are planar to and locally cut these normal shear zones.

Return to cars. Upon exiting the parking lot it is one-way to the east. Thus, we’ll exit east and almost immediately turn around in the Holiday Inn parking lot. USE CAUTION.

8.6 Exit parking lot and turn right, (east) onto Rt. 62, but get into left lane and be ready to turn left.
8.65 Turn left into Holiday Inn Express parking lot and reverse direction; enter Rt. 62 West.
8.9 Proceed under I-495 overpass.
10.8 Village of Berlin. Don’t speed!
11.0 At blinking light on curve, make a sharp left onto Linden St., USE CAUTION!
11.5 Follow Linden St. to the RR track crossing. Park on right just before the RR tracks.
(19T 0282105 m E – 4694991 m N)

Walk north along the path beside the RR tracks—this is an active train line. Follow path until you can cross the small stream on the right. Then climb the Army Corp of Engineers flood control earthen dam over North Brook. Walk across the top of the dam to exposures across the spillway at the eastern end of the dam.
STOP 7. NASHOBA FORMATION, CALC-SILICATE (60 minutes).

Calc-silicate granulite, gneiss and marble occur at several horizons in the Nashoba Fm. (Bell and Alvord, 1976). The calc-silicate rocks in this outcrop contain diopside, actinolite, phlogopitic biotite, plagioclase, tourmaline and opaques. Garnet-bearing schistose rocks, amphibolites, and sillimanite-bearing rusty schist are also present at the outcrop. The outcrop is folded into a tight gently north-plunging upright synform that can be recognized by the repetition of these units and parasitic folds. Most of the eastern side of the synform is preserved in outcrops along the treeline stretching some 150 meters south along the spillway. The northwestern limb of the synform is northeast-striking and sub-vertical while the southeastern limb dips moderately to the northwest. The deformation has been largely accomodated by flow and recrystallization involving the more calcareous layers. Tectonic “fish” of the less ductile, originally more dolomitic or shaley layers are readily observed “swimming” in the marbles (Hepburn and Munn, 1984). These less ductile layers provide great markers for recording parasitic folds. In the higher portions of the outcrop where weathering has removed much of the carbonate material, the folds within the more resistant layers are easy to observe. Throughout the outcrop thin quartz stringers are isoclinally folded, but the orientation of these folds is unclear. In the western steeper limb of the fold shear fabrics are preserved, especially in the garnet-bearing schistose unit. The relative timing between these shear fabrics and the outcrop scale folding is unclear.

Note the broken rocks flooring the spillway that are in large part from the adjoining terranes. These include quartzite from the Westboro Fm. of the Avalon terrane of southeastern New England, with many showing excellent examples of brittle fault brecciation and calcareous fracture fillings. Granitic rocks in the spillway include those of the Chelmsford Granite of the eastern Merrimack belt to the northwest, which is a commonly used highway curbing stone in the Boston area.

Return to cars.

11.6 Turn around and head back east on Linden St., we will retrace our route to I-495.
12.0 Turn right onto Rt. 62 East.
13.8 Pass under I-495 overpass and turn right onto ramp to I-495 North.
13.9 Turn right and enter ramp to I-495 North – continue on I-495 N.
16.1 Outcrops of Nashoba Fm. along here.
21.6 Bear right and take Exit #28, Rt. 111, Boxboro-Harvard.
21.8 Turn right onto Rt. 111 North/West, toward Harvard- cross over I-495.
22.0 Stop light, note large Nashoba Fm. exposure of migmatite on the right.
22.1 At 2nd light, turn left onto Codman Hill Rd.
22.3 Take 2nd left, turn left into driveway of #60-70 Codman Hill Rd.
22.4 Turn left into the parking area for #60-70 Codman Hill Rd. Outcrops are straight ahead at edge of parking lot and by field to the left. Park away from buildings. (19T 0290580m E – 4706891m N).

STOP 8. NASHOBA FORMATION, GNEISS AND MIGMATITE (45 minutes).

The exposures here and those we just passed at the I-495-Rt.111 interchange (see Kuiper et al., this volume) are good examples of the polydeformed and migmatized Nashoba Fm. Biotite gneisses are interlayered with migmatitic gneiss, pegmatites, and occasional calc-silicate gneisses. At least two generations of pegmatites are present. The metamorphic grade is sillimanite –K-feldspar and sillimanite is commonly present with biotite in the selvages at the edges of the migmatitic melted material. Muscovite is present in large, retrograded flakes. It is believed that at least some of the pegmatite and granite in these outcrops was locally generated by anatexis of layers with the appropriate composition. Observe how the proportion of melt changes with the composition of the original layer. Duplicate U-Pb monazite analyses from a medium- to coarse grained muscovite-and biotite-bearing granitic leucosome (at the exposure along Rt. 111) give a crystallization age of 395 ± 2 Ma (Hepburn et al., 1995).

The structural history displayed here is similar to Stop 6, except at this location very little evidence for outcrop-scale folding can be observed. The migmatitic and gneissic fabrics are northeast striking and generally subvertical in this outcrop. Intrafolial isoclinal folds are present, indicating that the package has
been folded. These intrafolial isoclinal folds are folded by another generation of top-down-to-the-northwest asymmetric folds.

Return to cars. Retrace route to Codman Hill Rd.

22.6 Turn left at light onto Rt. 111 North.
22.8 Enter Harvard MA.
23.0 Turn right onto Littleton County Rd., and then stay left on Littleton County Rd.
23.5 Stay right on Littleton County Rd.
24.5 Sharp left onto Old School House Rd.—proceed uphill.
24.8 Bear right onto Old Littleton Rd.
26.1 Overpass over Rt. 2.
26.6 Cross Littleton town line – road becomes Oak Hill Rd.
26.8 Park on right shoulder of the road - Stop 9 is across the street (19T 0292207m E – 4711605m N).

STOP 9. TADMUCK BROOK SCHIST (20 minutes).

The Tadmuck Brook Schist is a rusty-weathering schist to phyllite that marks the western boundary of the Nashoba terrane in northeastern Massachusetts (Figure 1) (Zen et al., 1983) and closely follows the terrane bounding Clinton-Newbury fault zone. This exposure is fairly typical of the formation in the sillimanite zone. The rock here is a sillimanite-bearing sulfidic mica schist that contains a few, thin, quartzite layers, but original bedding can be difficult to find. The amount of sulfide, usually fine-grained pyrrhotite, causes the rock to weather rapidly to a deep rusty-brown. The Tadmuck Brook is an interesting rock unit since it is always in the sillimanite zone on its southeastern side adjacent to the Nashoba Fm., but drops in grade to the northwest, reaching the lower to middle greenschist facies adjacent to rocks in the Merrimack belt. In at least some areas, the Tadmuck Brook Schist may include phyllonite. Is the sulfidic nature of the rock due to its original composition or the result of fluids introduced along the terrane bounding Clinton-Newbury fault zone?

Return to cars and continue north on Oak Hill Rd.

27.8 Bear left at stop sign.
27.9 At stop sign turn right onto Taylor St. just before railroad track.
28.9 Cross over Rt. 2.
29.1 Take ramp on right to Rt. 2 East. Stay on Rt. 2 East; do not get on I-495.
36.5 Concord rotary-continue 180º (2nd exit) and stay on Rt. 2 East.
40.5 Move into left lane and prepare to exit on Rt. 2A.
41.0 At light stay straight on Rt. 2A East.
41.6 Enter Minute Man National Historical Park. You will be following the route of Paul Revere, parts of the battle of Concord and Lexington, and there are many historical locations, some marked.
43.6 Minute Man Natl. Park Visitor Center on the left.
43.9 View of Bloody Bluff ahead on the left.
44.0 Turn left into Old Mass. Ave. & almost immediately turn right into small parking lot and park. Parking for Stop 10 (19T 0313831 m E – 4701937 m N). Walk across Old Mass. Ave. and proceed back a short distance west along the path beside the road to the exposures under the high power line. You are walking a short distance along the route that Paul Revere took on his famous ride in April, 1775.

STOP 10. BLOODY BLUFF FAULT ZONE - TYPE AREA (15 minutes).

NO HAMMERS! LEAVE HAMMERS IN THE CAR since this is part of the National Historical Park and you can get arrested if you have a hammer. Watch out for Poison Ivy!

The small hill or bluff under the edge of the power line right-of-way is Bloody Bluff, where a skirmish took place on April 19, 1775 as the British were retreating to Boston following the outbreak of hostilities at North Bridge in Concord earlier that day (note the tablet at the base of the outcrop). The outcrop contains
brittly deformed, rusty-weathering, altered and shattered granite. The granite here is a dark phase of the Sgr granite of Zen et al. (1983) or the Sudbury granite of Kohut (1999) and Dabrowski (2014). This granite was recently dated as 420 Ma a few miles to the south (zircon, U-Pb CA-TIMS; Dabrowski, 2014; Dabrowski et al., 2013). Movement direction indicators for the Bloody Bluff fault zone are rare and equivocal. The Bloody Bluff fault zone marks the present terrane boundary between the Avalon and Nashoba terranes of southeastern New England (e.g., Rast et al., 1993; Rast and Skehan, 1995; Skehan et al., 1998; Kohut and Hepburn, 2004). It is the youngest major fault zone in the area, may have had movement as young as Mesozoic, and overprints earlier, more ductile mylonites in the Burlington Mylonite zone to the east. (For more detail and references, see Kohut and Hepburn, 2004.) In this area, the Bloody Bluff fault zone is a region up to nearly a kilometer wide of closely spaced faults and cataclastic rocks. The westernmost of these faults is the Avalon-Nashoba terrane boundary (not exposed here) that runs along the depression just to the west of this exposure. Stop 11 is on the hill to the SE by the parking lot under the powerline.

Return to cars. Exit parking lot and turn left on Old Mass. Ave.

44.2 Turn left, East on Rt. 2A
44.4 At light, turn right into Minuteman Vocational Tech School.
44.5 Turn left at first opportunity into #1 Cranberry Hill Rd.
44.6 Turn right into Parking Lot C and follow through the lot until you can turn left.
44.65 Turn left into small parking lot by the rock outcrop under the powerline and park.
Stop 11, Lexington (19T 0313705 m E – 4701497 m N).

STOP 11. (optional) BURLINGTON MYLONITE ZONE (15 minutes)

We have now crossed the terrane boundary onto the Avalon terrane of SE New England (Fig. 1). The Burlington Mylonite zone (Castle et al., 1976) contains ductilely deformed rocks that here form the western edge of the Avalon terrane. The Bloody Bluff fault zone overprints these higher temperature mylonites and the purpose of this short stop is to contrast the differences of the rocks at this exposure with those at Bloody Bluff just a short distance away. While the Burlington Mylonite zone is likely composite, the earlier, highest temperature rocks show sinistral transpressive motion of the Nashoba terrane moving south-southwest over the Avalon terrane (Goldstein, 1989, 1992; Goldsmith, 1991a; Kohut and Hepburn, 2004). The rock here (although badly covered with lichen) is a biotite granite gneiss of the Avalon terrane with both quartz and feldspars showing spectacular high temperature ductile deformation. (Take home a sample to cut and polish.) Work is currently in progress to date and better refine the movement direction of this rock.

End of trip. Return to Rt. 2A and take I-95 South to Rt. 9 West to Wellesley.

44.8 Turn right onto Rt. 2A
45.1 Turn right at ramp to I-95 South, and proceed on I-95 South approximately 11 miles to Rt. 9W (Exit 20B). Follow Rt. 9 west and return to Wellesley College.

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