THE AVALONIAN AND NASHOBA TERRANES, EASTERN MASSACHUSETTS, U.S.A.: AN OVERVIEW

J. Christopher Hepburn, Malcolm Hill**, and Rudolph Hon**

**Department of Geology and Geophysics, Boston College
Chestnut Hill, Massachusetts 02167*

***Department of Geology, 14 HO, Northeastern University
Boston, Massachusetts 02115*

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Three major fault-bounded terranes comprise the eastern margin of the Appalachian Orogen in the vicinity of Boston, Massachusetts. Each has a distinctive geological history. The easternmost, the Boston-Avalon Zone, contains features common to Avalonian terranes in the northern Appalachians. These include voluminous Late Proterozoic (650-600 Ma) calc-alkaline granitic to dioritic plutons and related volcanic rocks associated with the "main phase" of Avalonian thermal activity. These are covered by a thin veneer of Late Proterozoic to Early Paleozoic sedimentary rocks and fluviatile Carboniferous basin deposits. This terrane can be divided into three subzones on the basis of the igneous rocks present, metamorphic grade, and style of deformation. The metamorphism generally is no higher than the greenschist facies in the Boston area, but reaches the amphibolite facies to the south and west. The metamorphism is generally assigned an Alleghanian age although there is evidence for Late Precambrian deformation and metamorphism.

To the west, across the Bloody Bluff fault zone is the Nashoba Block, a terrane largely underlain by mafic volcanic rocks and volcanogenic sedimentary rocks. During the Ordovician-Silurian this terrane underwent upper amphibolite facies metamorphism and was intruded by calc-alkaline intermediate plutons and metaluminous to peraluminous granites.

West of the Nashoba Block, across the Clinton-Newbury fault zone, is the Merrimack Trough, underlain by a thick sequence of flysch and calcareous flysch. Crosscutting Ordovician plutons establish an upper age limit for these sedimentary rocks and the ages of deformation and metamorphism.

Because of differing Late Proterozoic - Early Paleozoic histories, it is unlikely that the Boston-Avalon Zone and Nashoba Block could have been juxtaposed prior to the Mid-Paleozoic. Whether the Nashoba Block and Merrimack Trough represent separate terranes, a composite terrane joined in the Late Precambrian or Early to Mid-Paleozoic, or faulted portions of a single terrane remains to be determined.

Aux alentours de Boston, au Massachusetts, la marge orientale de l'Orogène Appalachien comprend trois lanières majeures bordées par des failles. Chacune a son histoire géologique distincte. La plus orientale de celles-ci, la Zone de Boston-Avalon, possède des traits communs aux lanières avaloniennes du Nord-Est des Appalaches. Parmi ceux-ci, on peut mentionner de volumineux plutons calco-alcalins, granitiques à dioritiques, tardiprotérozoïques (650-600 Ma) ainsi que des volcanites, apparentées à ces derniers, qui sont associées avec la "phase principale" de l'activité thermique avalonienne. En général, le métamorphisme ne dépasse pas le faciès à schistes verts dans la région de Boston quoiqu'il atteigne le faciès à amphibolites au sud et à l'ouest. On attribue généralement un âge alléghanien au métamorphisme bien qu'il y ait preuve d'une déformation et d'un métamorphisme tardiprécambriens.

A l'ouest, de l'autre côté de la Zone de failles de Bloody Bluff, se trouve le Bloc de Nashoba, une lanière formée surtout de volcanites mafiques et de roches sédimentaires volcanogènes. Durant l'Ordovicien et le Silurien, cette lanière subit un métamorphisme au faciès à amphibolites supérieur ainsi qu'une intrusion de plutons neutres calco-alcalins et de granites métalumineux à péralumineux.

A l'ouest du Bloc de Nashoba, au-delà de la zone de failles de Clinton-Newbury, se trouve la Fosse de Merrimac qui renferme une puissante assise de flyschs et de flyschs calcaires. On établit la limite supérieure sur l'âge de ces roches sédimentaires ainsi que les âges de la déformation et du métamorphisme grâce aux plutons ordoviciens qui traversent celles-ci.

La juxtaposition de la Zone de Boston-Avalon et du Bloc de Nashoba avant le Paléozoïque moyen n'est guère vraisemblable en raison de leurs histoires différentes du Tardiprotérozoïque à l'Eopaléozoıque. Il reste encore à déterminer si le Bloc de Nashoba et la Fosse de Merrimac représentent des lanières séparées, une lanière composite assemblée lors du Tardiprécambrien ou de 1,Eo- au Médiopaléozoïque, ou bien des parties d'une seule et même lanière qui sont en rapport par failles.

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INTRODUCTION

The eastern margin of the Appalachian orogen in southeastern New England, east of the Siluro-Devonian rocks in the Kearsarge - Central Maine Synclinorium (Lyons *et al.*, 1982), can be divided into three fault-bounded tectonic terranes (Fig. 1) identified from east to west as the Boston-Avalon Zone, the Nashoba Block or Zone and the Merrimack Trough. As the name suggests, the easternmost of these has been correlated with other fragments of Avalonia around the Atlantic (e.g., Williams and Max, 1980; Rast and Skehan, 1983; O'Brien *et al.*, 1983). The relation of the Nashoba Block and

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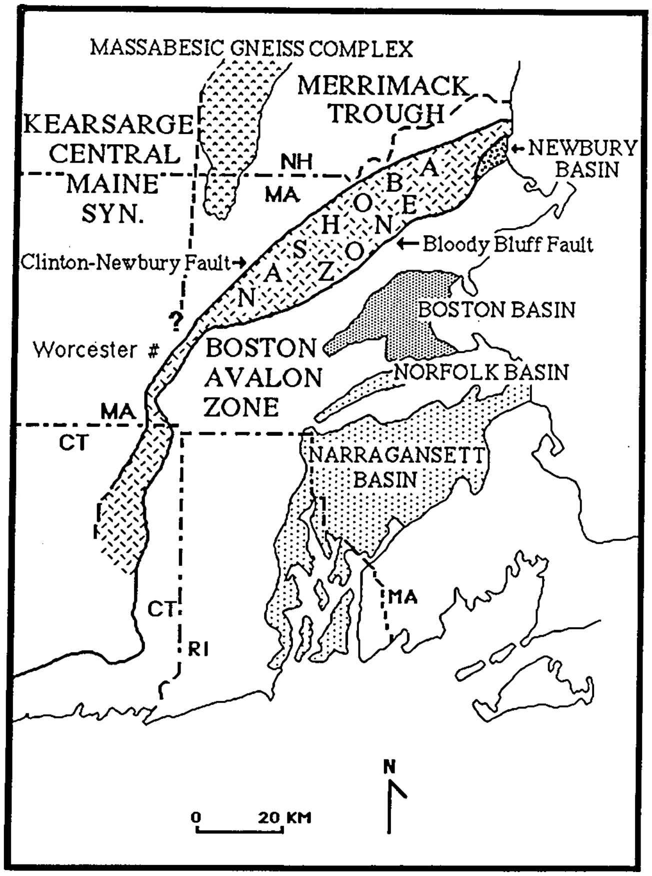

Fig. 1. Location map showing terranes of southeastern New England as used in this paper: Boston-Avalon Zone, Nashoba Block or Zone, Merrimack Trough, and Kearsarge-Central Maine Synclinorium. Sedimentary basins of the Boston-Avalon Zone include the Boston Basin (Late Proterozoic - Early Paleozoic), and the Norfolk and Narragansett Basins (Carboniferous).

Merrimack Trough to Avalonia, however, is more problematic. In this paper, we discuss the geologic features that distinguish the Boston-Avalon Zone and the Nashoba Block in the vicinity of Boston, Massachusetts. A summary of the salient features of the Merrimack Trough has been described recently by Lyons *et al*. (1982) and we present here only a short summary of this terrane.

BOSTON-AVALON ZONE

Late Proterozoic igneous rocks (650 - 600 Ma) are areally the most important feature observed at current levels of erosion in the Boston-Avalon Zone in eastern Massachusetts (Fig. 2) and represent the main phase of Avalonian thermal activity. The geological record prior to this igneous activity is scanty, but blocks and roof pendants within the plutonic rocks record bimodal volcanism and quartz-rich sedimentation. Following the main phase of Avalonian igneous activity, magmatism ceased rather abruptly and the area became a stable shelf in the Early Paleozoic.

It is possible to subdivide the geology of the Boston-Avalon Zone into three fault-bounded subdivisions (inset, Fig. 2), which we refer to as Subzones 1, 2, and 3. Each subzone reflects a different character of the igneous rocks present, the degree of metamorphism, or the intensity and style of deformation. Subzones similar to ours were also noted by Zen (1983a), on the tectonic map that accompanied the Massachusetts state geologic map. While there may be disagreement over the boundaries of these subdivisions, there are significant differences in the geology between the subzones that are worth highlighting. The significance of these subdivisions is, however, not yet fully understood. They may simply represent fragments of a single terrane, reshuffled by faulting, or they may indicate that portions of the Boston-Avalon Zone had separate origins and thus that this zone is itself a composite terrane. The idea that Avalonia possibly represents a composite terrane has been expressed by many authors (e.g., Williams and Hatcher, 1982, 1983; Zen, 1983b; Rast and Skehan, 1983; Keppie, 1985).

Subzone 1

Subzone 1 contains relatively few of the mafic igneous rocks that typify Subzone 2, and it lacks the intensely deformed granitic gneisses which are common in Subzone 3. We further distinguish three distinct regions within this Subzone: 1A, 1B, and 1C (Fig. 2). Subzones 1A and 1C are underlain principally by Late Proterozoic plutonic rocks (Dedham and Westwood Granites) and coeval volcanic rocks (Lynn and Mattapan Volcanics) associated with the main Avalonian magmatic phase. Subzone 1B includes the Late Proterozoic sedimentary and volcanic rocks of the Boston Basin (Fig. 3). All of the geologic elements that have been used to correlate the Boston-Avalon Zone with other Avalonian terranes are located within Subzone 1.

The Dedham Granite and contemporaneous pyroclastic rhyolite-dacite of the Lynn and Mattapan Volcanics are the chief products of the main phase of Avalonian magmatic activity (650-600 Ma) in Subzone 1 (Kaye and Zartman, 1980; Smith and Hon, 1984; Zartman and Naylor, 1984; Hon *et al*., 1984; Thompson, 1985). North of Boston, the Dedham is a fine- to coarse-grained hornblende- and biotite-bearing calc-alkaline intrusion, ranging from tonalite to granite in composition, with 57 - 72% SiO_2 (Smith and Hon, 1984). The Lynn Volcanics are cogenetic with the Dedham: complete textural gradations occur between the two units as well as complete overlap in major and trace element abundances and Nd isotope ratios (Smith and Hon, 1984). Similar gradational textural relations have been reported between the Dedham and portions of the Mattapan Volcanics south of Boston (Kaye and Zartman, 1980).

While the main phase of Avalonian magmatic activity was calc-alkaline, that which preceded it was of a more alkaline nature (Smith and Hon, 1984). The Middlesex Fells Volcanics occur as blocks and pendants in the Dedham Granite north of Boston (Bell and Alvord, 1976). They are bimodal and include both felsites and transitional alkali olivine basalts (Smith and Hon, 1984). The Middlesex Fells Volcanics have not been radiometrically dated, hence we cannot be sure by how much they preceded the main phase of Avalonian magmatism.

The oldest stratified rocks that occur as inclusions in the Dedham Granite are quartz-rich sedimentary rocks of the Westboro Formation (Bell

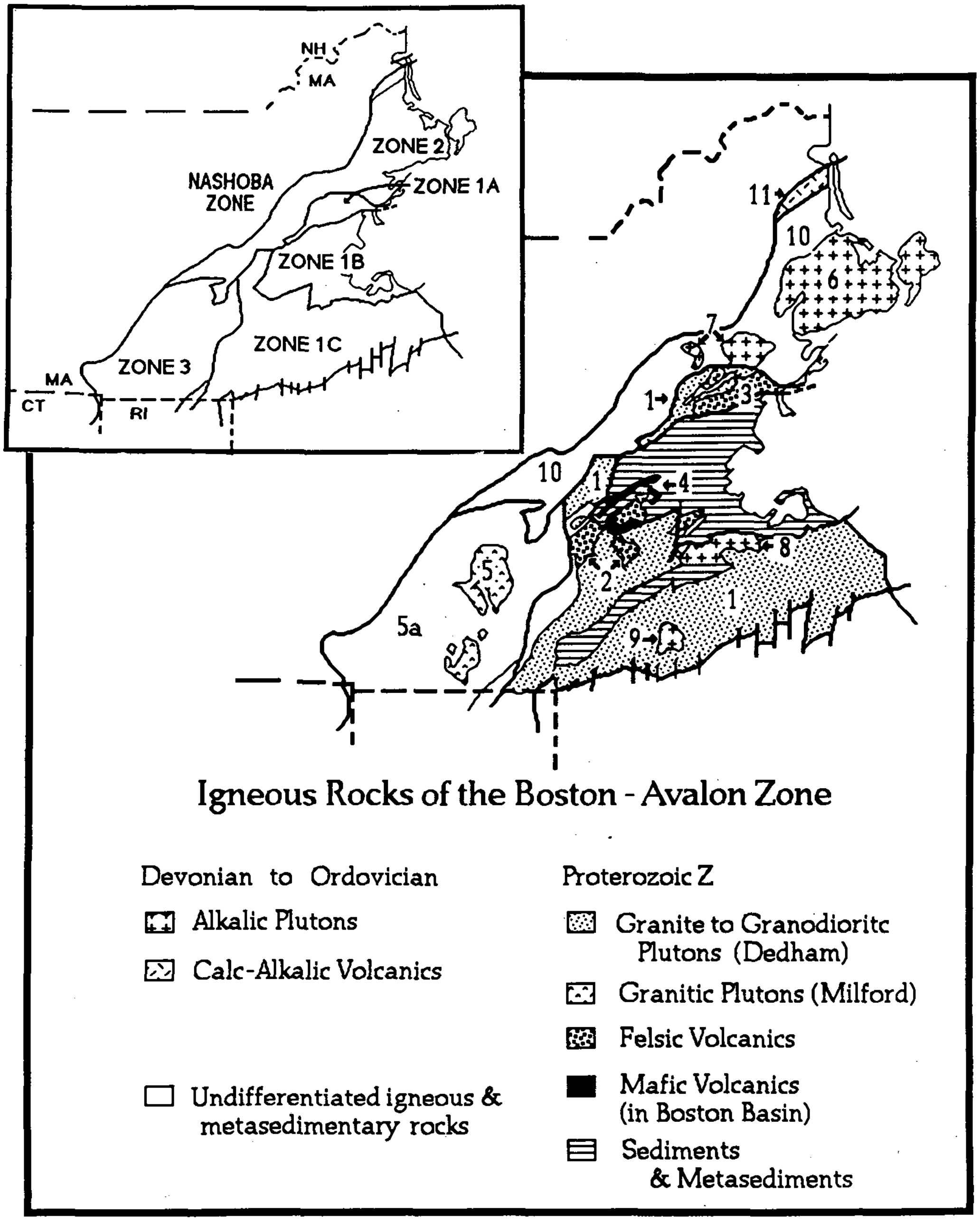

Fig. 2. Generalized geologic map of the major igneous rocks of the Boston-Avalon Zone and fault sliver containing the Newbury Volcanics (modified after Zen, 1983a). Numbered units are: 1. Dedham Granite; 2. Mattapan Volcanics; 3. Lynn Volcanics; 4. Brighton Volcanics; 5. Milford Granite; 5a. Leucocratic granitic gneisses, Late Precambrian; 6. Cape Ann Granite; 7. Peabody Granite; 8. Quincy Granite; 9. Rattlesnake Hill Pluton; 10. Mafic plutonic and volcanic rocks; 11. Newbury Volcanics. Inset: Subzones of the Boston-Avalon Zone; see text.

and Alvord, 1976; Bailey, 1984). Bailey (1984) and Bailey *et al.* (1987) suggested that the Westboro formed as olistostromal deposits on a lower slope or upper submarine fan by the rifting and collapse of a craton margin. Similar rocks that may correlate with the Westboro Formation occur in the "Avalonian Zone" in Rhode Island in the Blackstone Group and possibly also in the Newport Formation (Bell and Alvord, 1976; Bailey, 1984; Skehan *et al.*, 1985; Bailey *et al.*, 1987). Older plutonic rocks have been recognized as xenoliths in the Dedham granite as well (Smith and Hon, 1984).

The geologic record following the peak of Avalonian magmatic activity is preserved either within structural basins (Boston Basin) or as a thin veneer of sedimentary rocks locally overlying the magmatic rocks. Sedimentary rocks in the Boston Basin (Boston Bay Group) are largely conglomerates and shales that have been dated as Late Proterozoic on the basis of acritarchs (Lenk *et al.*, 1982). Included within the Boston Bay Group is the Squantum Tillite or Tilloid (see Rehmer and Roy, 1976; and Rehmer, 1980 for discussion) and thin volcanic flows and

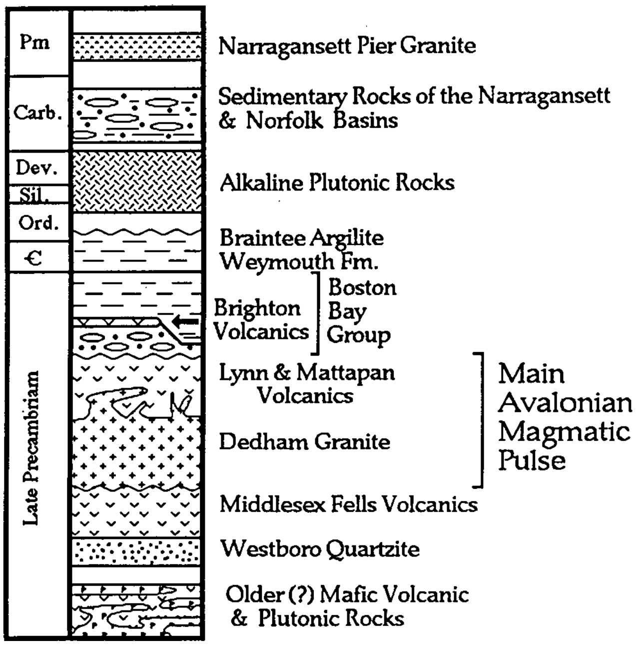

Fig. 3. Simplified stratigraphic column for Subzones 1 and 2 of the Boston-Avalon Zone, eastern Massachusetts. Narragansett Pier Granite from southern Rhode Island is projected onto the column for completeness.

agglomerates of the Brighton Volcanics. These basaltic to intermediate volcanic rocks represent the last episode of Precambrian (Avalonian) magmatism in the Boston area (Durfee Cardoza *et al.*, 1987). Subsequently, the Boston area became a stable shelf for the next 100 - 150 Ma with no recorded magmatic activity. Cambrian platformal sedimentary rocks contain an Acado-Baltic trilobite fauna and allow the correlation of this area with other fragments of Avalonia (e.g., Rast and Skehan, 1983).

When magmatism resumed in the Early to Middle Paleozoic, a distinctly different suite of magmas was present than in the Late Proterozoic, indicating a changed tectonic environment. From the Late Ordovician through the Devonian, sporadic peralkaline plutonism and local felsic volcanism occurred within this terrane in Massachusetts and Rhode Island (Zartman and Marvin, 1971; Naylor and Sayer, 1976; Zartman, 1977; Zartman and Naylor, 1984; Hermes and Zartman, 1985). The peralkaline intrusions are largely granitic but include some gabbro. Rocks of similar alkaline compositions have been interpreted as forming in anorogenic settings (Pitcher, 1982). The development of an early Paleozoic stable cratonal shelf and the lack of evidence for Ordovician-Devonian deformation throughout the Boston-Avalon Zone are consistent with this interpretation.

Finally, Carboniferous fluviatile rocks in the Norfolk and Narragansett Basins record the youngest Paleozoic sedimentary history in the Boston-Avalon Zone and serve as important guides for differentiating Alleghanian metamorphic and structural events. In southernmost Rhode Island, the peraluminous Narragansett Pier Granite (272 Ma, Hermes *et al.*, 1981) closes out the Paleozoic magmatic history of this terrane.

Subzone 2

Subzone 2 of the Boston-Avalon Zone (inset, Fig. 2) occurs to the northwest, between Subzone 1 and the Bloody Bluff Fault Zone. It is underlain largely by a complex of mafic plutonic and volcanic rocks (Bell and Alvord, 1976; Hurley and Shearer, 1981; units "Zv" and "Zdigb" of Zen, 1983a) that are generally more highly deformed than those in Subzone 1, particularly as the Bloody Bluff Fault is approached. Field evidence indicates that the majority of these mafic rocks likely predate the main phase of Avalonian magmatism, since some have been intruded by granites believed related to the Dedham or Milford (Barosh *et al.*, 1977; Hepburn and DiNitto, 1978). However, younger gabbros and other rocks related to the peralkaline Ordovician to Devonian period of intrusion also are present in this zone, especially toward the northeast near the Cape Ann Complex (Fig. 2).

Whether the Precambrian mafic igneous rocks in Subzone 2 are approximately contemporaneous with the main phase of Avalonian magmatism in Subzone 1 is unclear. Rb-Sr and K-Ar isotopic systems generally have been disturbed by younger events (Zartman *et al.*, 1970; Schutts *et al.*, 1976; Hurley and Shearer, 1981; Zartman and Naylor, 1984). Zartman and Naylor (1984) reported a single K-Ar date of 886 $\pm$ 22 Ma on a hornblende from a gabbroic pegmatite in this zone. However, because they were unable to rule out the possibility of excess radiogenic argon in this sample, the significance of the age remains uncertain.

Subzone 3

Subzone 3 is separated everywhere by faults from Subzones 1 and 2, and is characterized by Late Proterozoic leucocratic granitic gneisses and a generally higher metamorphic grade (amphibolite facies) than is found in Subzones 1 and 2. Ductile deformation is common, particularly near the borders of this subzone where foliation is more intense, especially near the Bloody Bluff Fault Zone. Locally, metasedimentary and metavolcanic rocks are present in Subzone 3 (Zen, 1983a). The Milford Granite (630 $\pm$ 15 Ma) intrudes the gneissic units near the center of this subzone (Zartman and Naylor, 1984) (Fig. 2) and includes both a granitic and a granodioritic phase (Zen, 1983a; Sheridan *et al.*, 1987). Both these phases are largely unfoliated and have escaped most of the later deformation which affected this subzone. The granitic phase is characteristically a salmon-pink biotite granite with garnet as a common accessory. While there is an overlap in the ranges of most major element concentrations between the Milford Granite and the Dedham Granite of Subzone 1, on average the Milford is slightly more aluminous. Garnet is common in the Milford Granite whereas garnet is absent from the Dedham Granite (Sheridan *et al.*, 1987). Some of the granitic gneisses of Subzone 3 are also garnet-bearing, particulary the Hope Valley Alaskite. The relationship of the more gneissic units with the Milford Granite is not yet well understood. Recently O'Hara and Gromet (1985) have argued that at least some of these gneisses belong to a separate Late Precambrian Avalonian terrane (their Hope Valley terrane).

Metamorphism and Deformation of the Boston-Avalon Zone

In the Boston area, most of the Boston-Avalon Zone (Subzones 1 and 2) has been metamorphosed no higher than the lower greenschist facies, with brittle faulting being the most common type of deformation observed (Zen, 1983a). Late Proterozoic and Early Paleozoic sedimentary rocks in the Boston area have open folds (Billings, 1976), with the development of cleavage in the more argillaceous rocks. Metamorphism increases to the amphibolite facies to the south and west of the Boston area in Subzones 2 and 3, where deformation and ductile shearing are more intense.

The Carboniferous sedimentary rocks of the Norfolk and Narragansett Basins south of Boston have been metamorphosed during the Alleghanian Orogeny with the grade of metamorphism increasing to the south (Hepburn and Rehmer, 1981). Temperatures exceeded 600°C in a Barrovian-type sequence in southern Rhode Island (Grew and Day, 1972). Based on this regional evidence, the metamorphism of Subzone 1 is largely ascribed to the Alleghanian. Evidence for Alleghanian metamorphism has been presented by O'Hara and Gromet (1983) for high-grade metamorphism along the Honey Hill fault in Connecticut and by Dallmeyer (1982) for gneisses in southern Rhode Island, likely correlative with those in Subzone 3. This supports, but does not prove, the idea that the higher grades of metamorphism and ductile deformation in our Subzones 2 and 3 are also likely, at least in part, Alleghanian in age. Zartman *et al*. (1970) described disturbed K-Ar ages over a widespread area of eastern New England, including the Boston-Avalon Zone, which they attributed to a regional Alleghanian thermal event.

While it is well established that the Boston-Avalon Zone experienced Alleghanian metamorphism and deformation, details of prior events are not as well understood. During the Early to Mid-Paleozoic, contact metamorphsim occurred adjacent to the Ordovician-Devonian peralkaline plutons. Schutts *et al*. (1976) reported a thermal and metasomatic event at about 370 Ma which affected some whole rock and mineral Rb-Sr ages and K-Ar mineral ages in the area of our Subzone 2. They interpreted this event as being caused by hydrothermal activity associated with intrusion of the peralkaline plutons in this area. (Below, we suggest that this event might mark the time of juxtaposition of the Boston-Avalon Zone and the Nashoba Block.)

The Boston-Avalon Zone in Massachusetts also experienced a Precambrian deformation. Sedimentary xenoliths enclosed in the 630 Ma Dedham Granite north of Boston are folded. However, definitive evidence for a Precambrian metamorphism has not been found in the Boston area. In Rhode Island, Precambrian sedimentary and volcanic rocks experienced deformation and lower greenschist facies metamorphism prior to the intrusion of a 595 Ma granite (Rast and Skehan, 1981, 1983; Skehan and Rast, 1983). Dreier (1983) described evidence for Precambrian low-grade metamorphism of the Blackstone Series in Rhode Island. Thus, it is likely that the Boston area also experienced a similar low grade metamorphism prior to the main phase of Avalonian magmatism.

NASHOBA BLOCK

Northwest of the Boston-Avalon Zone, across the prominent Bloody Bluff Fault is the Nashoba Block, a distinctly different terrane (Fig. 1). A thick pile of mafic volcanic rocks and volcanogenic sedimentary rocks of Ordovician or older age, now metamorphosed and migmatized under upper amphibolite facies conditions to amphibolite, biotite gneiss and schist, underlies this terrane. Peraluminous granite and contemporaneous Ordovician-Silurian calc-alkaline plutons of intermediate composition (Fig. 4) are also of major importance in the development of the Nashoba Block.

The oldest rock unit yet dated in this terrane is the leucocratic Fish Brook Gneiss, which Olszewski (1980) determined to be 730 Ma based on U/Pb studies of zircons with volcanic morphology. However, the contact relationships between the Fish Brook Gneiss where dated and other units in the Nashoba Block are not firmly established. The distinctive "swirled foliation" of parts of the Fish Brook Gneiss (Bell and Alvord, 1976) suggests that the Fish Brook may be more highly deformed than other rocks in this terrane, possibly indicating a period of deformation and metamorphism (Late Precambrian?) prior to deposition of the other units.

Mafic volcanic rocks (Marlboro Formation) and volcanogenic sedimentary rocks with minor carbonates (Nashoba Formation) were deposited in the Nashoba Block prior to the intrusion of the Andover Granite. Direct dating of the Marlboro amphibolites has been unsuccessful. However, Nd model ages calculated against typical depleted mantle model sources suggest a pre-450 Ma age for these rocks (DiNitto *et al*., 1984). The Marlboro volcanics are basalts including some high alumina types, with trace element signatures (low Ta and Nb contents compared with Ce and Th - see DiNitto *et al*., 1984) most compatible with an arc or marginal basin tectonic setting.

The Nashoba Block experienced widespread plutonism from the mid-Ordovician through the Silurian (approximately 450 - 400 Ma), with intrusion of peraluminous granites (Andover Granite; "Sgr" of Zen, 1983a; granitic phase of the Indian Head Hill Pluton) being broadly contemporaneous with that of calc-alkaline intermediate composition magmas (Sharpners Pond Diorite; dioritic phase of the Indian Head Hill Pluton; Assabet Quartz Diorite; Straw Hollow Diorite). The intermediate plutons are little deformed and range in composition from gabbroic cumulates to hornblende- and biotite-bearing diorites and tonalites with sphene as a nearly ubiquitous accessory phase (Castle, 1964; Hill *et al*., 1984a,b; Hon *et al*., 1986). Zartman and Naylor (1984) determined a 430 ± 5 Ma age from zircon in the Sharpners Pond Diorite; Hill *et al*. (1984a) reported a 402 ± 5 Ma Rb-Sr whole rock age for the older, dioritic phase of the Indian Head Hill Pluton, which is cut by the younger granitic phase. Hill *et al*. (1984a,b) noted the similarity of rare earth and other trace element distributions between the calc-alkaline plutons of the Nashoba Block and plutons of similar mineralogy developed at convergent plate boundaries (e.g., Sierra Nevada batholith, Noyes *et al*., 1983a,b).

Peraluminous granitic intrusions in the Nashoba

Block are more extensive than the intermediate plutons, particularly towards the northeast (Fig. 4). Many of these intrusions have been grouped together into the Andover Granite, although it has long been recognized that the Andover includes a number of different varieties of granite, some foliated and some not (Castle, 1964; Zartman and Naylor, 1984). Hill *et al*. (1984a) suggested that the Andover could be subdivided into at least two major units: a more foliated, biotite- and muscovite granite having a moderately steep rare earth element pattern; and a less foliated, biotite-poor, muscovite-rich and garnet-bearing granite having quite flat rare earth element patterns. More detailed mapping and analytical studies are in progress on the Andover. The Andover Granite has yet to be dated satisfactorily. Zartman and Naylor (1984) reported Rb-Sr whole rock data that indicated an age of 446 ± 32 Ma (without aplites) or 408 ± 22 Ma (including aplites, associated with the pegmatitic phase). Handford (1965) reported a Rb-Sr whole rock age of 450 ± 22 Ma for the Andover Granite.

If the ca. 450 Ma "ages" for the Andover Granite are approximately correct, then granitic plutonism in the Nashoba Block spanned some 50 Ma. There is ample evidence for the coexistance of granitic and intermediate to mafic magmas in the Sharpners Pond Diorite and within the un-named "Sgr" intrusive unit of Zen (1983a) (magmatic pillows, gradational contacts, etc.; Castle, 1964; Hon *et al*., 1986) and it is likely that both granite and diorite were intruded in several pulses. Trace element and isotope chemistry indicates that the granites are not fractionates of the calc-alkalic magmas, but resulted from anatexis of a crustal source (Hill, 1985; Hon *et al*., 1986).

Metamorphism and Deformation

The sedimentary and volcanic rocks in the Nashoba Block have been polydeformed and polymetamorphosed to the sillimanite and second sillimanite zones in an andalusite-sillimanite facies series. Temperatures in the western Nashoba Block exceeded 600° C. (Abu-moustafa and Skehan, 1976; Hepburn and Munn, 1984) and migmatites are common in the Nashoba Formation. Zones of ductile shearing and mylonitization are also widely developed associated with the numerous faults within this terrane. These generally have been mapped and interpreted as thrust faults (Skehan, 1968; Bell and Alvord, 1976; Skehan and Abu-moustafa, 1976; Barosh *et al*., 1977; Hepburn and Munn, 1984).

The age of metamorphism and deformation in the Nashoba Block is generally thought to be Ordovician to Silurian by comparison with dated igneous rocks (Hall and Robinson, 1982; Robinson, 1983; Hepburn and Munn, 1984; Zartman and Naylor, 1984). The Sharpners Pond Diorite is the key to this interpretation as it is essentially unaltered and undeformed and its age of 430 Ma is thought to establish the minimum time for the principal deformation and metamorphism. As noted above, the Andover Granite contains both foliated and unfoliated varieties and may therefore overlap the end of the deformation. Its metaluminous to peraluminous nature suggests that it formed by anatexis of a sedimentary source. The association of pegmatitic phases of the Andover with the Nashoba Formation has long been recognized and migmatites within the Nashoba generally increase as the Andover is approached. Castle and Theodore (1972) estimated P-T conditions for a pegmatitic phase of the Andover as 650°C at 5 kb, close to the

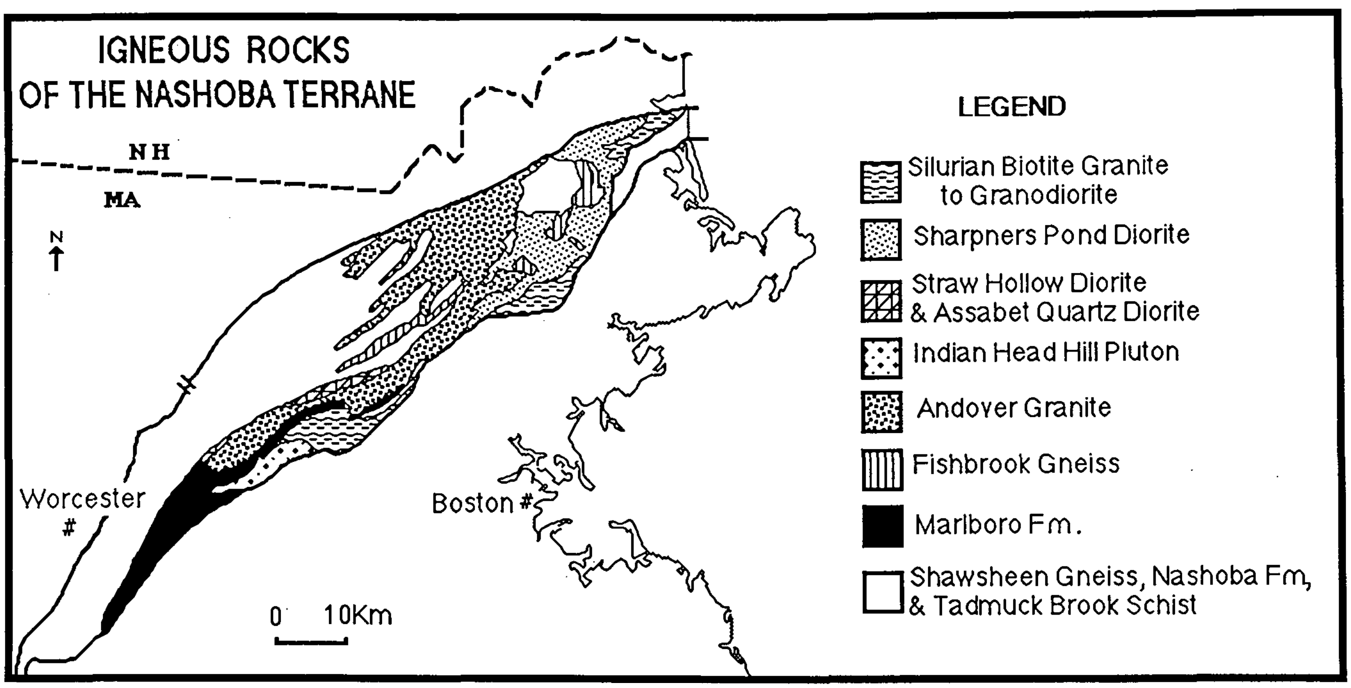

Fig. 4. Igneous rocks of the Nashoba Block or Terrane, eastern Massachusetts.

temperature estimates for metamorphism in the Nashoba. Thus, it seems likely that at least portions of the Andover were produced by anatexis of Nashoba rocks during the peak of metamorphism and that the metamorphism occurred in the range of 450-430 Ma, if the 450 Ma date on the Andover is correct. However, the date of 408 ± 22 Ma that is largely influenced by the aplitic phases associated with the Andover pegmatites (Zartman and Naylor, 1984) may indicate a somewhat younger minimum age for the metamorphism. Possible further support for an Ordovician age for the metamorphsim comes from Olszewski's (1980) Rb-Sr whole rock analyses of a number of metasedimentary and metavolcanic rocks from the Nashoba Block and surrounding areas which, although somewhat scattered, indicated a period of isotopic resetting and metamorphism at about 450 Ma.

Isotopic systems in the Nashoba Block also record evidence of younger closing times. $^{40}Ar/^{39}Ar$ ages for hornblende from amphibolites in the Marlboro and Nashoba Formations give Mississippian cooling ages ranging from 354 - 325 Ma, and Sm-Nd and Rb-Sr mineral isochrons from the Straw Hollow Diorite record cooling ages between 342-299 Ma (Hepburn *et al.*, 1987). Zartman *et al.* (1970) indicated that K-Ar ages on micas reflect Permian cooling or disturbance.

Newbury Volcanic Complex

The Newbury Volcanic Complex occurs in a small fault-bounded sliver between the Boston-Avalon Zone and the Nashoba Block (Fig. 1 and Fig. 2, #11). These rocks are essentially unmetamorphosed basaltic, andesitic and rhyolitic volcanics with interbedded sedimentary rocks containing Silurian to Early Devonian fossils (Shride, 1976). Citing geochemical evidence, Hon and Thirlwall (1985) suggested the Newbury Volcanics formed in a subduction zone environment. Volcanic rocks similar in both composition and age to the Newbury are found in the coastal volcanic belt in Maine (Gates and Moench, 1981).

MERRIMACK TROUGH

Northwest of the Nashoba Block (Fig. 1), across the Clinton-Newbury fault zone, is another potential terrane, the Merrimack Trough, with different geological characteristics (Lyons *et al.*, 1982; Olszewski *et al.*, 1984). The rocks of the Merrimack Trough previously were thought to be Siluro-Devonian (see Lyons *et al.*, 1982) and were included in the regionally extensive Merrimack Synclinorium. However, recent dating of cross-cutting plutons (Gaudette *et al.*, 1984; Zartman and Naylor, 1984; Hon *et al.*, 1986) indicates that the sedimentary rocks of the Merrimack Trough are pre-Middle Ordovician. The exact boundary of this terrane on the north and west is not yet clearly differentiated, particularly in Massachusetts, because of uncertainties in the age and correlation of various metasedimentary units. Lyons *et al.* (1982) have shown that the Massabesic Gneiss Complex of southern New Hampshire and north-central Massachusetts (Fig. 1) is associated with the Merrimack Trough and Olszewski *et al.* (1984) included it as part of this terrane. This complex contains two ages of orthogneiss and older paragneiss; the orthogneisses have been dated as 650 Ma and 475 Ma (Besancon *et al.*, 1977; Aleinikoff *et al.*, 1979; Kelly *et al.*, 1980).

The Merrimack Trough is underlain largely by the Merrimack Group of metasedimentary rocks, a thick sequence of flysch and calcareous flysch. These rocks are polymetamorphosed and deformed. The grade of metamorphism generally increases westward, from the greenschist facies along the Clinton-Newbury fault zone in the east, to the sillimanite and second sillimanite zones adjacent to the Massabesic Gneiss in the west (Bothner *et al.*, 1984). The metasedimentary rocks of the Merrimack Group are cut by the Newburyport Quartz Diorite (450 Ma, Zartman and Naylor, 1984) and the Exeter Diorite (473 Ma, Gaudette *et al.*, 1984; Hon *et al.*, 1986), hence the Merrimack Group is pre-Middle Ordovician in age. Bothner *et al.* (1984) suggested that the paragneiss in the Massabesic Gneiss Complex that is cut by the 650 Ma old orthogneiss is a high-grade equivalent of the Berwick Formation, part of the Merrimack Group metasedimentary rocks. If this is correct, then the sedimentary rocks in the Merrimack Trough are Precambrian. As the Exeter Diorite is undeformed and cuts deformed and metamorphosed rocks and has a contact aureole developed adjacent to the pluton (Bothner *et al.*, 1984; Hon *et al.*, 1986), the metamorphism and deformation must also be pre-Middle Ordovician.

DISCUSSION

Boston-Avalon Zone

Figure 5 summarizes the igneous, sedimentary, metamorphic and deformational histories of the Boston-Avalon Zone, the Nashoba Block, and the Merrimack Trough. The history for the Boston-Avalon Zone represents that for Subzones 1 and 2. Many authors have suggested that the Avalonian terrane is composite (e.g., Williams and Hatcher, 1982, 1983; Zen, 1983b; Rast and Skehan, 1983; Keppie, 1985) and was assembled during the Late Precambrian (Williams and Hatcher, 1983; Keppie, 1985) prior to deposition of overlapping Cambrian strata. Differences between the subzones of the Boston-Avalon Zone in the Boston area are consistent with this interpretation, but proof of their separate evolution has not been established. Particularly noteworthy is the contrast between Subzone 2, largely underlain by mafic rocks, and the more granitic Subzones 1 and 3. If the subzones of the Boston-Avalon Zone did originate as separate terranes, it is likely that they were joined by the Late Precambrian. Recognized Cambrian strata are restricted to Subzone 1; none overlaps onto Subzones 2 or 3. However, if the abundant granitic dikes and stringers in portions of Subzone 2 are related to the Dedham Granite, they indicate its proximity to the other subzones at the time of the 600 Ma Avalonian magmatism. Bell and Alvord (1976), however, noted the apparent lack of granitic dikes related to the Dedham Granite in the most northwesterly portions of what is our Subzone 2.

Sedimentary and volcanic xenoliths and roof pendants (Westboro Formation, Middlesex Fells Volcanics) in the calc-alkaline plutons of the Boston-Avalon Zone record events which pre-date the

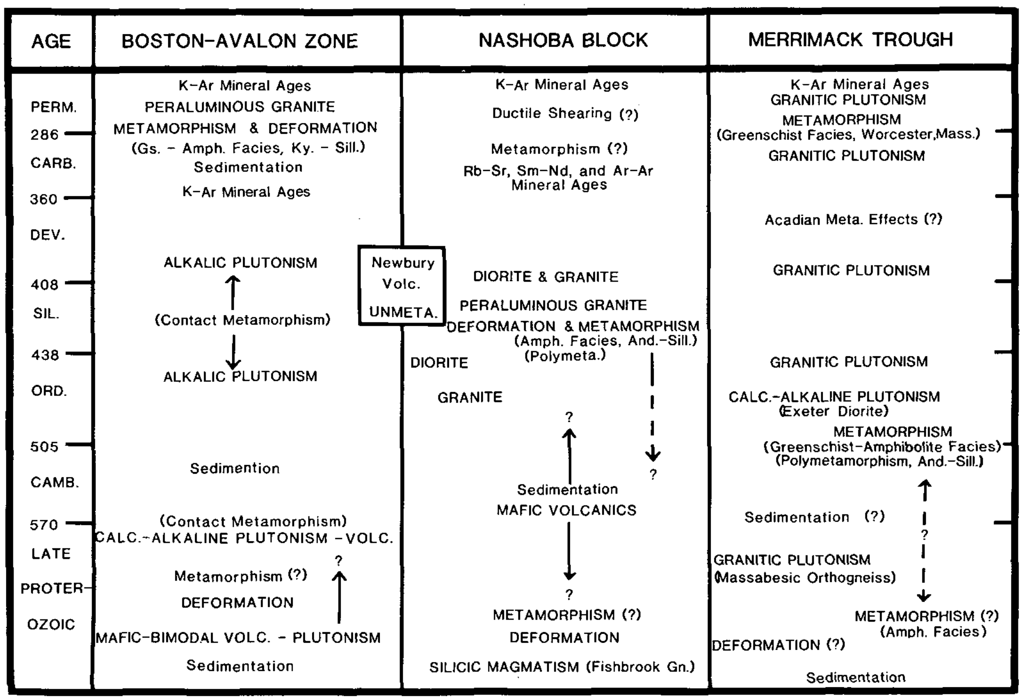

Fig. 5. Comparison of geologic events in the terranes in eastern Massachusetts and adjacent areas.

main phase of Avalonian magmatic activity. Evidence suggests that the Boston area was undergoing rifting or crustal extension prior to 650-600 Ma. Bailey *et al.* (1987) summarized structural and sedimentologic evidence that the Westboro Formation, north of Boston (Fig. 3) and other pre-main phase sedimentary rocks were deposited in a cratonal rift environment. The Middlesex Fells Volcanics are bimodal and contain both rhyolites and alkali basalts (Smith and Hon, 1984). These features are also compatible with a rift environment. Furthermore, preliminary work on the abundant mafic igneous rocks of Subzone 2 indicates that at least some are alkaline (Sahagian and Hon, 1985). Present geochronological data are too sparse to permit accurate dating of this extensional event in the Boston area. A pre-700 Ma age would be indicated if these alkali basalts correlate with those in the basal part of the 760 Ma Burin Group in Newfoundland, which was deposited in an extensional environment (O'Brien *et al.*, 1983) (see also, discussion in Bailey *et al.*, 1987).

In the Boston-Avalon Zone, the rifting stage was followed by the voluminous calc-alkaline magmatism in the period 650-600 Ma. By itself, this observation is consistent with either of two tectonic environments. Modern calc-alkaline rocks of similar composition occur at continental margins above subduction zones (e.g., Sierra Nevada, Noyes *et al.*, 1983a,b). Some modern continental rifts (e.g., Rio Grande Rift, Gardner *et al.*, 1986) also contain calc-alkaline suites similar to the Dedham-Lynn complex. Parenthetically, we note that the batholithic mass of the calc-alkaline Dedham-Lynn suite contrasts with the relatively low volume of exposed calc-alkaline rocks in the Rio Grande Rift, (Gardner *et al.*, 1986).

While the Avalon Peninsula in Newfoundland experienced some calc-alkaline magmatism in this period (O'Brien *et al.*, 1983), the volume of these magmas in the Boston-Avalon Zone appears to be much greater and is a distinctive feature of the Avalonian terrane in eastern Massachusetts. However, our results for the Boston-Avalon Zone are consistent with the general pattern of tectonism (rifting followed by convergence) proposed for Newfoundland by Strong *et al.* (1978) and by O'Brien *et al.* (1983) and for Avalon generally by Rast and Skehan (1983).

Nashoba Block and Newbury Volcanics

Metabasalts in the Marlboro Formation have trace element signatures of an arc or marginal basin setting (DiNitto *et al.*, 1984). It is interesting that the Chopawamsic Volcanics (Pavlides, 1981) in Virginia occur in this same time interval and are compositionally similar to the Marlboro metavolcanic rocks. Williams and Hatcher (1983) placed the Chopawamsic Volcanics in a separate terrane to the west of the Avalon terrane, a tectonic position similar to that of the Nashoba Block. We suggest a possible correlation between the Marlboro and Chopawamsic Volcanics.

Between 430 Ma and 402 Ma the deformed and metamorphosed metasediments and metavolcanics of the Nashoba Block were intruded by calc-alkaline intermediate magmas (Fig. 5). These intrusions overlap temporally with peraluminous to metaluminous granites of unrelated magmatic lineage. The calc-alkaline plutons likely represent subduction-related magmas (Hill *et al.*, 1984a; Hon *et al.*, 1986). When the age of the Andover Granite is resolved, it will be possible to better determine whether the calc-alkaline plutons acted as a thermal trigger to initiate melting of metasedimentary rocks in the Nashoba Block, or whether the granites formed in response to structural events (over-thrusting?), as in the case of the Manaslu Granite in the Himalaya (Le Fort, 1981).

The Newbury Volcanics (Fig. 5) are essentially contemporaneous with and are of similar composition to the intermediate and granitic plutons in the Nashoba Block (Hon and Thirlwall, 1985). Previously, the unmetamorphosed condition of the Newbury Volcanics led to the suggestion that they were related to the the Boston-Avalon Zone (Shride, 1976). Because of the similarities in age and chemistry between the Newbury and the plutons of the Nashoba Block, we argue that the Newbury Volcanics represent downfaulted remnants of cover once present above the Nashoba Block, an interpretation first suggested by Hall and Robinson (1982). If the interpretation of Hon and Thirlwall (1985) is correct, the Newbury Volcanics formed at a convergent plate boundary in the Silurian to Early Devonian. This implies subduction just prior to the Acadian Orogeny (Hon *et al.*, 1986). However, there is no evidence in the Newbury Volcanics for Acadian metamorphic or deformational effects.

Timing of Tectonic Events

Some constraints can be placed on the time of joining of the Nashoba Block and the Boston-Avalon Zone (see also discussion by Zartman and Naylor, 1984). Both terranes contain Late Proterozoic rocks: pre-630 Ma for the Boston-Avalon Zone (xenoliths and pendants in plutons) and dated 730 Ma gneiss in the Nashoba Block. However, the large-scale Late Proterozoic main phase Avalonian magmatism of the Boston-Avalon Zone is not found in the Nashoba Block. Similarly, between approximately 450-400 Ma, the Nashoba Block experienced intense regional metamorphism and deformation, as well as the emplacement of calc-alkaline intermediate plutons and the extensive formation of migmatites and anatectic granite. None of this activity is found across the Bloody Bluff fault zone in the Boston-Avalon Zone. Instead, in this time interval the Boston-Avalon Zone was intruded by distinctly different, peralkaline plutons, which in turn are absent from the Nashoba Block (Zartman and Naylor, 1984). Thus, the different Late Proterozoic and Early Paleozoic histories of the two terranes make it difficult to assemble them in their current positions prior to the mid-Paleozoic. The ca. 370 Ma Rb-Sr ages from the Boston-Avalon Zone and the Mississippian $^{40}Ar/^{39}Ar$ cooling ages from the Nashoba Block (Fig. 5) may reflect the time of juxtaposition (collision-related uplift and unroofing) of these terranes.

A mid-Paleozoic time of accretion of the Boston-Avalon Zone and the Nashoba Block is consistent with other evidence for the time of welding of Avalon to terranes to the west in the northern Appalachians (see more complete discussions in Coleman-Sadd, 1980; Zen, 1983b; Williams and Hatcher, 1983; Keppie, 1985). This is exemplified by the Ackley City Granite (350-355 Ma, Bell *et al.*, 1977; Dallmeyer *et al.*, 1980) which seals the Hermitage Bay fault along the boundary between the Avalon and Gander zones in eastern Newfoundland. On the other hand, O'Hara and Gromet (1983) presented evidence that their Hope Valley Shear Zone is Alleghanian in age and suggested that this shear zone is continuous with the Bloody Bluff fault zone, implying that accretion of the Boston-Avalon Zone with North America took place in the Permian. To date, there is no direct evidence in the Boston area to differentiate between Mid-Paleozoic vs. Late Paleozoic emplacement of the Boston-Avalon Zone in the Boston area. However, the fact that metamorphic hornblendes from the Nashoba Block record pre-Alleghanian $^{40}Ar/^{39}Ar$ ages in the range 354-325 Ma (Hepburn *et al.*, 1987) indicates that this terrane cooled through approximately 480°C by this time. This is in marked contrast to southern Rhode Island and south-central Connecticut where Wintsch and Sutter (1986) reported $^{40}Ar/^{39}Ar$ hornblende ages that are 75-100 Ma younger than the Nashoba cooling ages. Hence, any Alleghanian thermal effects within the Nashoba Block were insufficient to affect the Ar/Ar systematics, which is consistent with the interpretation of Wintsch and Sutter (1986) that Alleghanian effects diminish rapidly to the north away from southern Rhode Island and Connecticut.

Both the Boston-Avalon Zone and the Nashoba Block have isotopic evidence for a crustal component markedly older than any of the rocks now exposed at the surface. Olszewski (1980) dated 1511 Ma detrital zircons from the Westboro Formation, sedimentary rocks of the Boston-Avalon Zone which pre-date the main phase of Avalonian magmatism. Hill and Ross (1983) indicated that granulite facies crustal xenoliths from a Mesozoic dike near Boston have Nd model ages in excess of 800 Ma. In the Nashoba Block, Olszewski (1980) also identified detrital zircons from a metasedimentary gneiss (Shawsheen Gneiss) that give an upper concordia intercept of 2042 Ma. Hill *et al.* (1984a) interpreted Nd isotope data to indicate that the source(s) for the Andover Granite contain a significant component of Proterozoic material. Thus, while the terranes appear not to have docked until the Mid-Paleozoic, both appear to contain or to have developed in proximity to an older crustal source. An Archean zircon component in the Permian Narragansett Pier Granite reported by Zartman and Hermes (1984) may have been derived from beneath the Boston-Avalon Zone as a result of the Alleghanian convergence between Africa and North America (Hermes, 1986).

Merrimack Trough

Although the metamorphic grade drops abruptly west of the Clinton-Newbury fault zone, differences between the Merrimack Trough and the Nashoba Block are not as dramatic as those between the Nashoba Block and the Boston-Avalon Zone. There are a number of general similarities between the metamorphic and plutonic histories of the former pair (Fig. 5). For instance, both experienced major, Middle Ordovician or older andalusite-sillimanite type polymetamorphism (Hepburn *et al.*, 1985) and both contain similar intermediate to mafic calc-alkaline plutons of Ordovician-Silurian age (Hon *et al.*, 1986). Current uncertainties in the ages of the metamorphism in each region permit them to be of the same age, but their contemporaneity remains unproven. The plutons may be slightly older in the Merrimack Trough (473 Ma, Exeter Diorite, Gaudete *et al.*, 1984; 450 Ma, Newburyport Complex, Zartman and Naylor, 1984) than in the Nashoba Block (430 Ma, Sharpners Pond Diorite, Zartman and Naylor, 1984; 402 Ma, Indian Head Hill Pluton, Hill *et al.*, 1984a), but have similar compositions (Hon *et al.*, 1986). Thus, both areas may have been in a similar tectonic setting in the Ordovician-Silurian. It is not clear whether the Nashoba Block and Merrimack Trough represent a single terrane which has been disrupted along the Clinton-Newbury Fault, or whether they were separate terranes joined in the Late Proterozoic or Early to Mid-Paleozoic. Additional constraints on the depositional age of the sediments in both blocks and on the times of metamorphism and plutonism are needed to help resolve this question.

Concluding Remarks

The recognition of "Avalonian" terrane fragments in North America rests in large part upon distinctive Early Paleozoic fossil assemblages in essentially unmetamorphosed sedimentary rocks and on recognition of Late Proterozoic magmatism (e.g., Rast and Skehan, 1983). The Boston-Avalon Zone (at least Subzones 1 and 3) clearly record these features. However, Late Proterozoic rocks have been recognized to the west of the Boston-Avalon Zone in the Nashoba Block, Merrimack Trough and beyond (i.e., Dry Hill Gneiss, central Massachusetts, Zartman and Naylor, 1984). Whether these Proterozoic ages imply a genetic affinity between Avalon and some or any of the blocks west of the Bloody Bluff Fault is a major unresolved question in the region.

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