THE AVALON AND NASHOBA TERRANES (EASTERN MARGIN OF THE APPALACHIAN OROGEN IN SOUTHEASTERN NEW ENGLAND)

by

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INTRODUCTION

The Boston area contains one of the best examples of "Avalonian" geology outside of the type area in eastern Newfoundland and the Boston-Avalon Terrane, together with the Nashoba Terrane to the northwest, make up the eastern margin of the Appalachian orogen in southeastern New England. The outboard Meguma Terrane of Nova Scotia presumably lies off shore but is not present on land at this latitude. This excursion is designed to show participants the important features of the Boston-Avalon and Nashoba Terranes and to visit many of the "classic" exposures. In addition, we will discuss new work on geochemistry, sedimentology and particularly exciting, new U-Pb isotopic age determinations that are leading to revised interpretations and models for the geological history of this area.

The Boston area and its rocks have been visited by geologists for nearly as long as geologists have existed in the New World (see Rodgers et al., 1989), so that even the hammer marks on the outcrops must bear a distinct chronology. Dozens of guidebooks and hundreds of articles have been written over the last two centuries, yet despite this long history and the many geologists who have worked here (or perhaps because of it) few exposures are entirely without controversy, as we shall see. Given the scope of this guidebook it is impossible to adequately credit or discuss all the work that has led to our current understanding of the Boston area, and we apologize to those whose work we are too constrained to credit. Recent field guides pertaining to eastern Massachusetts with more complete descriptions of many of the exposures we'll visit include several (in 1964, 1981, 1984 and 1986) put out by the New England Intercollegiate Geological Conference (NEIGC), an organization dedicated to field excursions that is nearly as old as the Geological Society of America itself, and one prepared for the 28th International Geological Conference (Zen, 1989). The Bedrock Geological Map of Massachusetts (Zen et al., 1983) is the most recent regional compilation of the geology. U.S.G.S Professional Paper #1366 E-J (Hatch, 1991) accompanies this map and contains a thorough summary of the areal geology and an extensive bibliography on eastern Massachusetts. Geological Society of America Special Paper #245 (Socci et al., 1990) provides recent summaries of some of the specific geologic problems we face in the Boston area.

BOSTON-AVALON TERRANE

Overview

The Boston-Avalon Terrane contains many features similar to the type Avalon of eastern Newfoundland including those critical for establishing it as a fragment of "Avalonia," a 590-630 Ma calc-alkaline plutonic-volcanic event and Cambrian platformal sedimentation with an Acado-Baltic fauna. However, the Boston area has been eroded to a somewhat deeper level than eastern Newfoundland. Indeed, at current levels of erosion the most widespread rocks are plutonic (Zen et al., 1983). Late Proterozoic sedimentary rocks are only exposed in the Boston Basin itself, and a thin vestige of the Cambrian sediments is all that remains of the early Paleozoic sequence.

The most abundant of the plutonic rocks (Figure 1) are those associated with the late Proterozoic (ca. 630-600 Ma, Zartman and Naylor, 1984) arc magmatism of the main pulse of Avalonian igneous activity (Figure 2). They are so abundant that we tend to relate all other events in the area to these rocks, as either "pre-" or "post-" this magmatism. These magmatic rocks include the calc-alkaline Dedham (Stop 1-4), Milford, Westwood (Stop 3-3) and associated granites, which together reach batholithic proportions. The Lynn, to the north of Boston (Stop 1-3), and the Mattapan Volcanics, to the south (Stop 3-4), are co-magmatic extrusive equivalents. A poorly preserved record of quartzitic sedimentation (Westboro Fm., Stops 1-5,1-6) and mafic volcanism that pre-date the late Proterozoic magmatism (Middlesex Fells Volcanics, Stop 3-1) are preserved largely as blocks and pendants in the plutons (Figure 3). Their age is not well constrained other than that they pre-date the Avalonian magmatism. Geochemistry

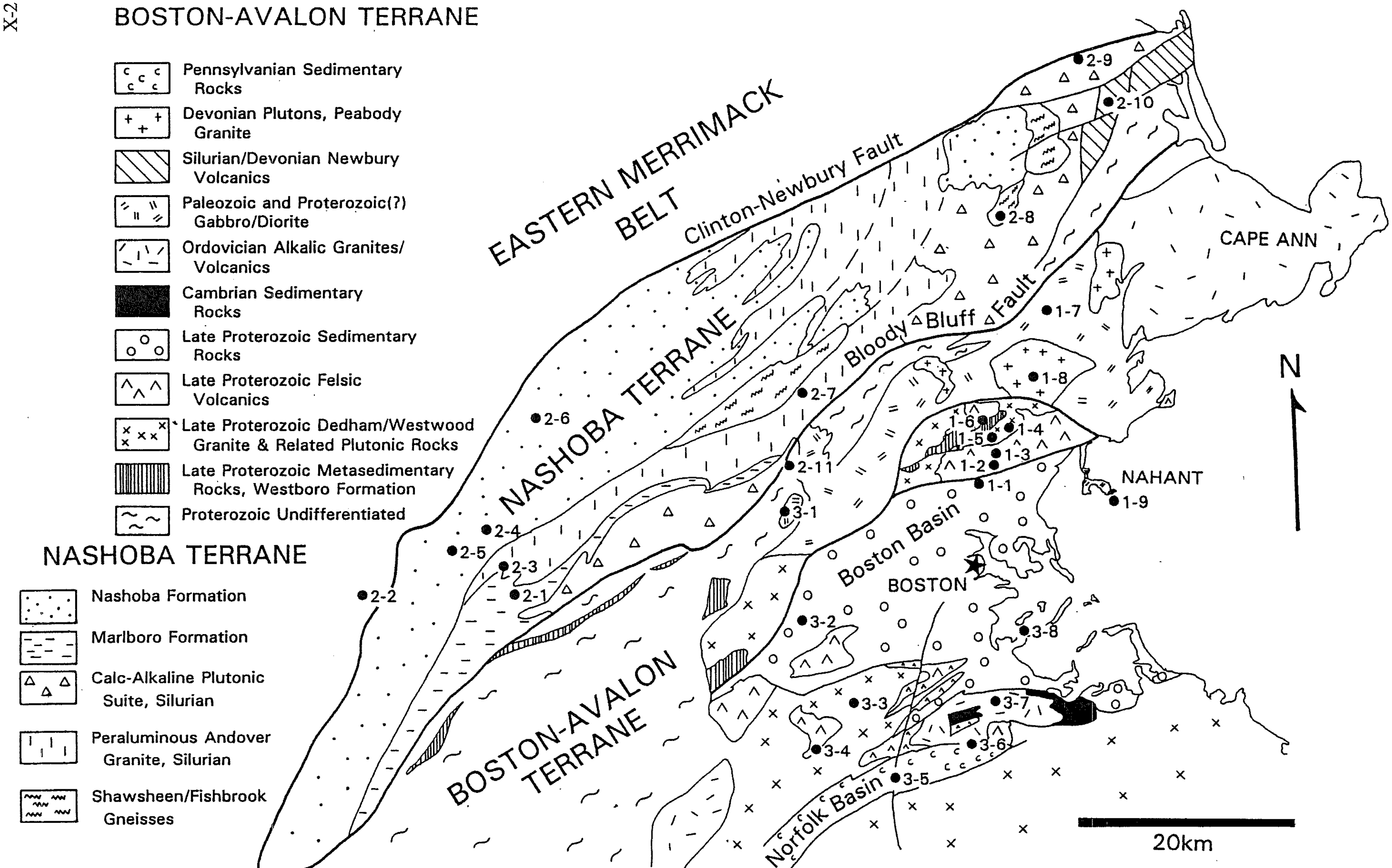

Figure 1. Geologic map of Boston - Avalon and Nashoba Terranes. Field trip stops are numbered dots.

indicates the Middlesex Fells Volcanics are alkalic (Cardoza et al., 1990) and likely formed in an extensional environment.

The Boston Basin developed as an intra-arc rift basin (Bailey, 1984; Nance, 1990; Socci and Smith, 1990) during the waning stages of the Avalonian arc magmatism. Acritarchs (Lenk et al., 1982) confirm the Late Proterozoic age of the Boston Bay Group sediments, which are of two principal types, conglomerates (Roxbury Fm., Stop 3-2) and shales (Cambridge Argillite, Stop 1-1). The depositional environment of the Boston Bay Group including the infamous Squantum Tillite or Tilloid (Stop 3-8) has long been debated. Terrestrial depositional models of glacial and/or fluviatile origin and those involving submarine mass-wasting are the leading contenders (Rehmer and Roy, 1976; Socci and Smith, 1990).

Following deposition of the Boston Bay Group, the area became a stable shelf or platform in the Early and Middle Cambrian (Figure 3) with deposition of the Weymouth (Stop 1-9) and Braintree Fms. (Stop 3-7). These units contain an Acado-Baltic trilobite fauna that allow correlation of the Boston area with the type Avalon and other Avalonian fragments (e.g., Rast and Skehan, 1983). There is no sedimentary record in the Boston-Avalon Terrane in Massachusetts with ages between Cambrian and Carboniferous (excepting for the Siluro-Devonian sediments within the Newbury Volcanic Complex; see below). During the Carboniferous, fossiliferous Pennsylvanian rocks (Stops 3-5, 3-6) formed as terrestrial deposits in rift basins.

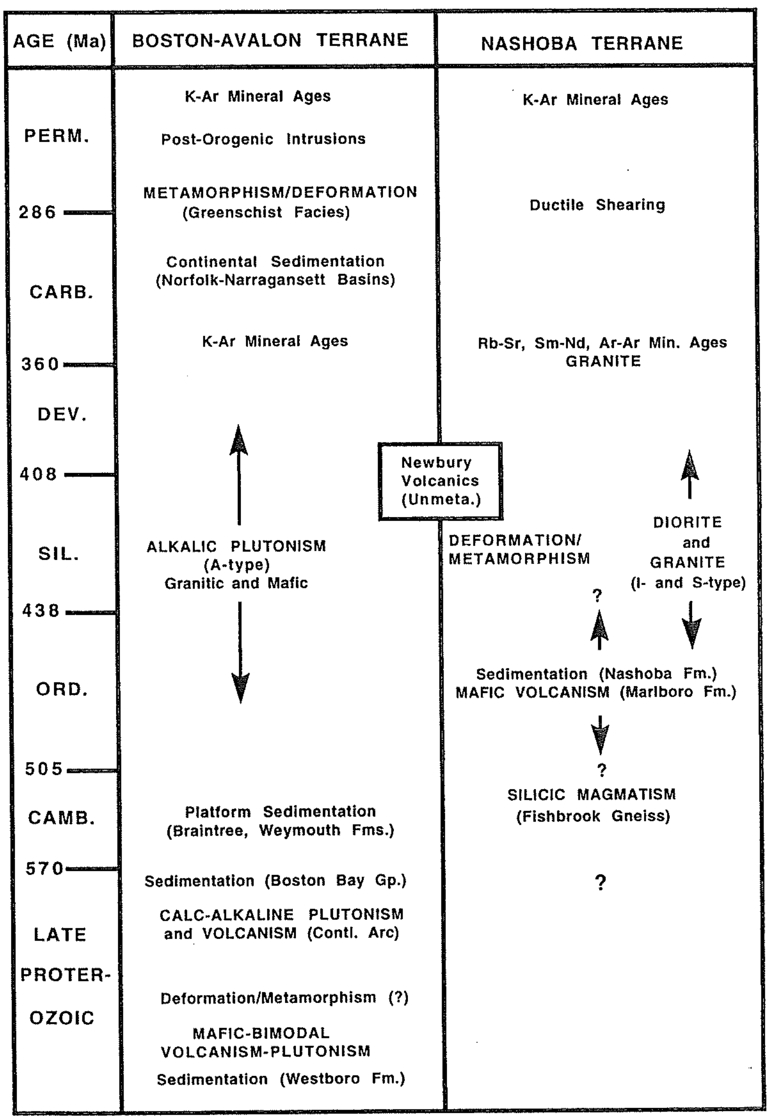

Figure 2. Comparisons of geologic events in the Boston-Avalon and Nashoba Terranes, Boston area, eastern Massachusetts.

From the Ordovician to the Devonian, the Boston-Avalon Terrane was broadly intruded by alkaline magmas quite different from the calc-alkaline ones associated with the earlier arc. These magmas, intruded in distinct pulses (Hermes and Zartman, 1985), include both granitic (Stop 1-8) and mafic plutons (Stops 1-7, 3-1) and local felsic volcanics (Hermes and Murray, 1990).

Metamorphism and Deformation

In the Boston area, the Boston-Avalon Terrane has experienced regional metamorphism no higher than the lower greenschist facies. Deformation, except along some of the major fault zones, is largely by brittle faulting. The metamorphism is generally thought to be largely Alleghanian in age. Alleghanian metamorphism clearly increases toward the south and the west. In southern Rhode Island, Pennsylvanian sediments in the Narragansett Basin are metamorphosed to upper amphibolite facies conditions (see Mosher et al., this volume, Chapt. BB). Evidence for Precambrian deformation and greenschist facies metamorphism preceding the Late Proterozoic arc magmatism is preserved in Rhode Island (Rast and Skehan, 1983; Skehan and Rast, 1983) but is difficult to decipher in the Boston area. Folded metasedimentary xenoliths found in the Dedham North Granite, north of Boston, are our best evidence for such an event.

Proterozoic and Paleozoic Sedimentary Rocks in the Boston-Avalon Terrane

Sedimentary rocks to be seen on this trip comprise the following four major depositional sequences:

1. Late Proterozoic Westboro Formation (Stops 1-5, 1-6)
2. Latest Proterozoic Boston Bay Group (Stops 1-1, 3-2, 3-8)
3. Early Cambrian Weymouth and Middle Cambrian Braintree Formations (Stops 1-9, 3-8)
4. Pennsylvanian Pondville and Wamsutta Formations (Stops 3-5,3-6)

Small amounts of fossiliferous Siluro-Devonian strata in the Newbury Volcanic Complex and areas of strongly deformed and metamorphosed Late Proterozoic metasedimentary rocks are also present but will not be examined on this trip.

Westboro Formation

Westboro strata are the oldest sedimentary rocks in the Boston-Avalon Terrane that have recognizable sedimentary structures and textures (Figure 3). The age of the Westboro is problematical, but must lie between 1500 Ma (the U-Pb age of contained detrital zircons, Olszewski, 1980) and the age of cross-cutting granitic plutons at 600 - 630 Ma (such as the Dedham North Granite at Stop 1-5). An age of 700 - 800 Ma is inferred for the Westboro based on possible correlations with better dated similar sequences in Newfoundland (O'Brien, et al., 1983). The Westboro is poorly exposed but is encountered as lenticular masses of quartzarenite, olistostromal mixtures of mudstone, quartzarenite and carbonate, quartzarenite turbidites and dark mudstones that generally have been subjected to no more than lower or middle greenschist facies metamorphism. Locally, these rocks are metamorphosed to the hornblende-hornfels facies immediately adjacent to plutons. Mafic Middlesex Fells Volcanics may be interstratified with the Westboro, but the relationship between these two formations is difficult to prove from field evidence. The Westboro has been interpreted as a platformal or cratonal sequence disrupted and subjected to gravity re-sedimentation during a ca. 750 Ma episode of ensialic rifting (Bailey et al., 1989).

Boston Bay Group

The Boston Bay Group consists of over 5 km of immature clastic sedimentary rocks and interstratified mafic Brighton Volcanics that rest unconformably on the Dedham Granite and/or Mattapan Volcanics (Figure 3). Of the two main units, the coarser clastics of the Roxbury Formation dominate the southern half of the Boston Basin, and finer clastics of the Cambridge Formation comprise most of the northern portion of the basin. The lower Cambridge is coeval and interstratified with the Roxbury, while the upper Cambridge onlaps the Roxbury to the south (Billings, 1976). The Roxbury is a heterogenous mixture of conglomerates, sandstones, and mudstones, capped by a thick diamictite or sequence of diamictites. The Cambridge Formation contains acritarchs that assign a Late Proterozoic age to the Boston Basin sediments.

Sediment compositions, facies relationships, and indicators of paleocurrent and paleoslope demonstrate that a rugged, largely granitic and felsic source terrain formed the southern and western margin of the Boston Basin. Inferred depositional environments and transport mechanisms include braided streams and fan deltas, submarine slopes

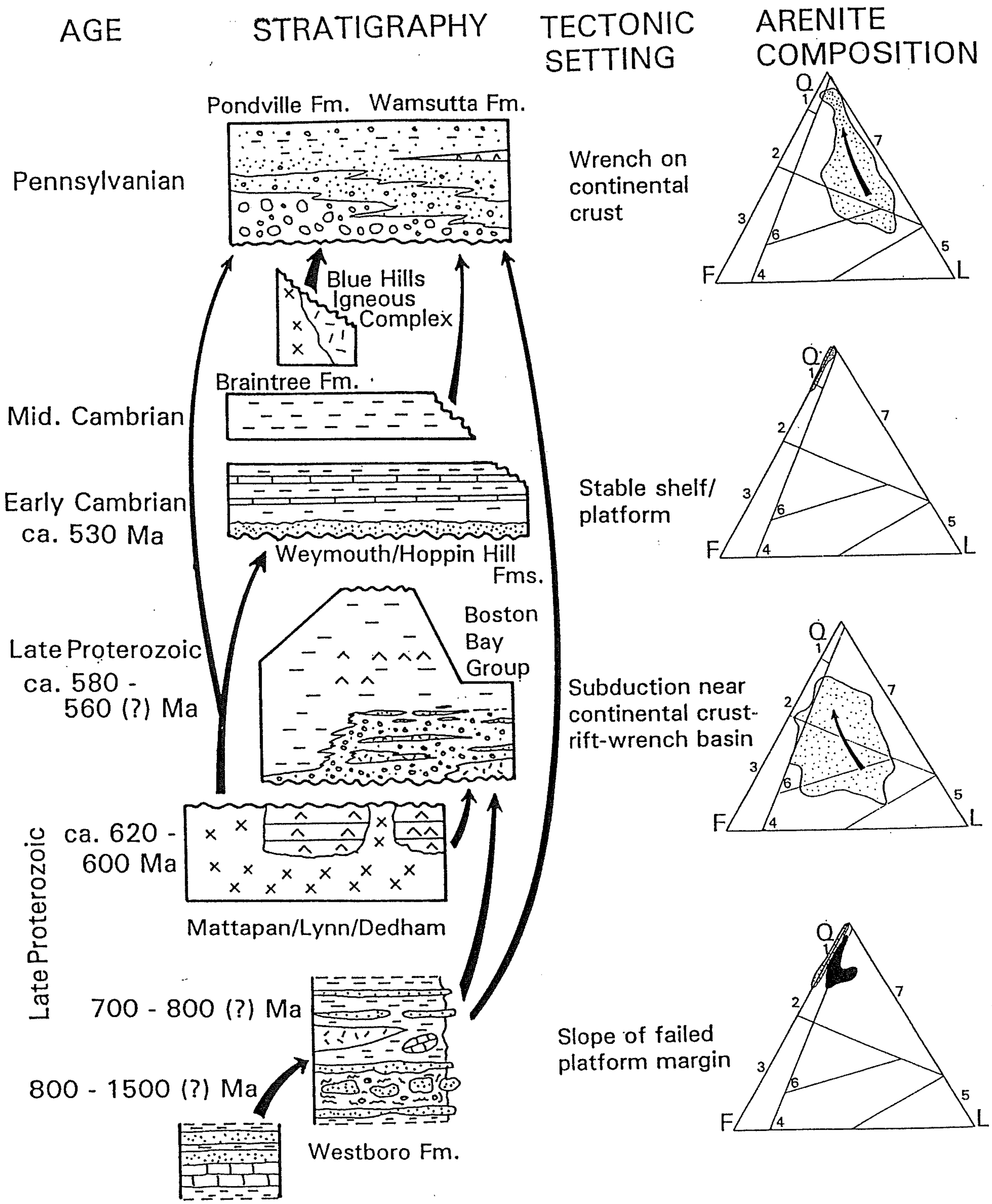

Figure 3. Summary of stratigraphy, tectonic setting, and sandstone composition of four sedimentary sequences in the northern part of the Boston-Avalon Terrane: Arrows link sedimentary sequences with primary source rocks. Q-F-L plots with tectonic discrimination fields, 1) craton interior, 2) transitional continental, 3) basement uplift, 4) transitional arc, 5) undissected arc, 6) dissected uplift, 7) recycled orogenic; black area in Westboro plot encloses Boston Bay Group quartzite cobbles; arrows show change in composition upsection.

and fans with debris and other sediment gravity flows, or a deep basin with distal turbidites. There is evidence that some facies may have formed on shallow shelves and glaciation may have played a role in the deposition of portions of the sequence. Geochemistry of the Brighton Volcanics (Cardoza et al., 1990) and compositions of detrital framework grains suggest that the Boston Bay Group formed in a tectonic regime where continental crust was involved with subduction (Figure 3). A fault bounded wrench or rift basin in a region of general crustal convergence would provide an appropriate depositional and tectonic setting for the Boston Bay Group.

Weymouth and Braintree Formations

The Early Cambrian Weymouth Formation consists of reddish to black thinly laminated mudstones, nodular mudstones, and reddish and white limestones. At the type area in Mill Cove, Quincy, MA, a mudstone and limestone interval with an Acado-Baltic small shelly fauna is overlain by mudstones bearing a *Callavia* zone trilobite fauna. Only the lower portion of the sequence is now exposed and the trilobite horizon has been covered for many years. Cambrian strata at East Point in Nahant, MA (Stop 1-9) correlate with the lower Weymouth of Mill Cove. At Nahant several 2 to 3 m thick limestones occur in at least 100 m of nodular, silty, trace fossil-bearing mudstone. Early Cambrian strata probably were deposited unconformably on the Boston Bay Group but are now isolated in structural blocks that were thrust over the Boston Basin. The Weymouth Formation and correlative fossiliferous strata at Hoppin Hill, North Attleboro, MA are shelf or platform facies deposited on stable crust. A more complete description and discussion of the Early Cambrian strata at Nahant, MA are given in Bailey and Ross in this volume (Chapt. Y).

The Middle Cambrian is represented by the gray mudstones of the Braintree Formation (Stop 3-7). The Braintree contains a low diversity trilobite assemblage including abundant specimens of the large species *Paradoxides harlani* (Green) and several species of inarticulate brachiopod and hyoliths. Middle Cambrian strata occur as roof pendants, xenoliths, and fault bounded blocks within or against the Quincy Granite.

Pondville and Wamsutta Formations

Pennsylvanian rocks of the Norfolk Basin (Figure 1) are an erosional outlier of the much more extensive Narragansett Basin in SE Massachusetts and Rhode Island. About 1500 m of strata are preserved in the Norfolk Basin in a tightly folded syncline. Along the NE margin of the basin, boulder conglomerates of the Pondville Formation (Stop 3-6) rest unconformably on the Blue Hills Igneous Complex or Mattapan Volcanics; but in most areas the basin is bounded by faults that juxtapose Pondville or Wamsutta Formations against older rocks (Figure 1). Plant fossil biostatigraphy suggests that deposition began in the early Middle Pennsylvanian (Westphalian B) in a local graben (preserved in part by the present Norfolk Basin) and extended south during the mid-Late Pennsylvanian (Stephanian) as the crust underwent further extension and general subsidence (Skehan et al., 1986; Mosher, 1983). Crustal extension and syntectonic deposition of immature clastics are attributed to wrenching along sinistral transcurrent faults that formed step-faulted pull-apart basins.

The Pondville Formation conglomerates and sandstones represent proximal to medial alluvial fan and braided stream deposits which intergrade upward into the reddish Wamsutta Formation sandstones and mudstones. The Wamsutta (Stop 3-5) is a sequence of fining upward braided channel cycles with intervals of red overbank mudstones. Abrupt crevasse splay deposits, broad gravel floored channels, abundant mudcracks, and poorly developed caliche nodule horizons suggest a monsoonal paleoclimate with a prolonged dry season.

Igneous Rocks of the Boston-Avalon Terrane

Most of the igneous rocks to be seen on this trip comprise two principal petrological suites that occur within three broad magmatic episodes:

1. Calc-alkaline arc magmatism associated with the late Proterozoic Avalonian event; 590 to 630 Ma: Dedham North Granodiorite/Granite (Stops 1-4; 1-5), Westwood Granite (Stop 3-3), Lynn (Stop 1-3) and Mattapan (Stop 3-4) Volcanics.

2a. Alkaline magmatism of the Late Ordovician (ca. 435 to 460 Ma) : Quincy Granite (Stop 3-7), diorite at Danvers (Stop 1-7).

2b. Alkaline magmatism of the Devonian (ca. 370 to 400 Ma): Peabody Granite (Stop 1-8); gabbro- diorite in Waltham (Stop 3-1)

Other plutonic episodes created the Cambro-Ordovician Nahant Gabbro (Stop 1-9) and the Jurassic Medford Dike north of Boston, while possibly other plutonic events remain to be identified.

Avalonian Calc-alkaline Magmatism

One of the defining criteria of the Avalon Terrane is the presence of extensive felsic volcano-plutonic complexes that yield emplacement ages between 590 and 630 Ma. Within the Boston-Avalon Terrane about a dozen or so separate plutonic bodies have been identified to date, and new ones are still being added to the list (Dillon and Hon, 1993; Hamidzada et al., 1993). Voluminous extrusive rocks are associated with this magmatism both north of the Boston Basin (Lynn Volcanics) and south of it (Mattapan Volcanics). These are co-magmatic or associated with the Dedham North (Smith and Hon, 1984) and Westwood granites (Kaye, 1984), respectively. The Brighton Volcanics (not visited on this trip) form flows and tuffs within the Boston Bay Group and likely represent the waning stages of arc magmatism (Cardoza et al., 1990).

Extensive calc-alkaline plutons both north and south of Boston have long been recognized and, although physically separated by the Boston Basin, have been commonly mapped together as the Dedham. We will be visiting only the Dedham north of Boston (Dedham North), a petrologically diverse suite that varies from granite to granodiorite, tonalite, and quartz diorite. An FMA plot and a Peacock diagram (Figure 4 A, B) illustrate the calc-alkaline nature of the rocks from the Dedham North suite. Chemical variations within the suite plot as a straight line (Figure 4 C, D) between felsic and mafic end members, implying a mixing of two magmas as the principal petrogenetic process. Fractionation would have produced a concave trend. Thus, the Dedham North formed largely by the mixing of two melts: (1) a leucogranitic magma formed by partial melting of Westboro Fm. sediments; and (2) an enigmatic mafic magma whose parental composition is not represented as part of the complex itself. Support for this model is seen in overlapping ages of the different rocks from this suite (see Figure 5) and the fact that inherited zircon components in the granite match detrital zircon ages in the Westboro (Olszewski, 1980). In addition, since the minimum granites cannot be the heat source for the anatexis of the sediments (because granites do not have high enough temperatures), the presence of a higher temperature mafic magma is required to drive the partial melting process. The mafic melt must have had a composition more mafic than that of the quartz diorite phase. It may be equivalent to some of the mafic dikes that cut the Dedham North (Stop 1-5) and that show "undulating" contacts, indicating both rocks were still liquid or partially so at the time of intrusion. These analyzed, apparently co-intrusive dikes tend to plot at the extrapolated end of variation diagrams (Figure 4 C, D). They have calc-alkaline geochemical signatures that suggest a convergent plate margin in continental arc or back arc setting.

Crystallization ages for the Dedham North suite fall between 606 and 609 Ma, while the geochemically similar dacites and rhyolites of the Lynn Volcanics are somewhat younger at 596 ± 3 Ma. Presumably the Lynn Volcanics formed a surficial cover over the slightly older volcano-plutonic suite, and most of the older volcanics were eroded away prior to the eruption of the somewhat younger Lynn. Away from the Northern Boundary Fault, where the Lynn Volcanics abuts abruptly against the Boston Basin (Figure 1) the Lynn goes from red into darker bluish and greenish shades and becomes a subvolcanic facies with a high (40-60%) phenocryst count. This suggests that a traverse away from the fault (Stops 1-3 to 1-2 to 1-4) is also a traverse deeper into the subvolcanic regime and eventually into the magma chamber itself.

Paleozoic Alkaline Magmatism

Granite Intrusions. There are two episodes of Paleozoic alkaline hypersolvus granitic intrusions into the Boston-Avalon Terrane (Hermes and Zartman, 1985): (1) in the Late Ordovician (Cape Ann Complex north of Boston; Quincy Granite/Blue Hills Complex south of it; and (2) in the Devonian. The Peabody Granite (Stop 1-6) belongs to this younger age and is one of several such plutons that approximately track the trend of the Bloody Bluff Fault north of Boston (Figure 1). Devonian granites also occur south of Boston (Hermes and Zartman, 1985; Wones and Goldsmith, 1991). Descriptions of the alkalic rocks we will see are given for the individual stops. Volcanics associated with the granites likely form part of the Blue Hills Igneous Complex (Wampatuck Volcanics; Billings, 1982) south of Boston (Hermes and Murray, 1990).

Diorite to Gabbro Intrusions. Northwest of the Dedham North Complex is a band of largely mafic rocks 5 to 10 miles wide and at least 50 miles long (Bell and Alvord, 1976; units "Zv" and "Zdigb" of Zen et al., 1983; subzone 2 of Hepburn et al., 1987a). Rocks within it have variously been assigned to the Precambrian, Cambrian, Ordovician or Silurian. While field evidence suggests several magmatic pulses of different ages, geochemistry has failed so far to distinguish any distinct magmatic fingerprints. All rocks so far analyzed geochemically fall between transitional continental tholeiites and alkali basalts. New dates on mafic samples from this belt (see below) give ages

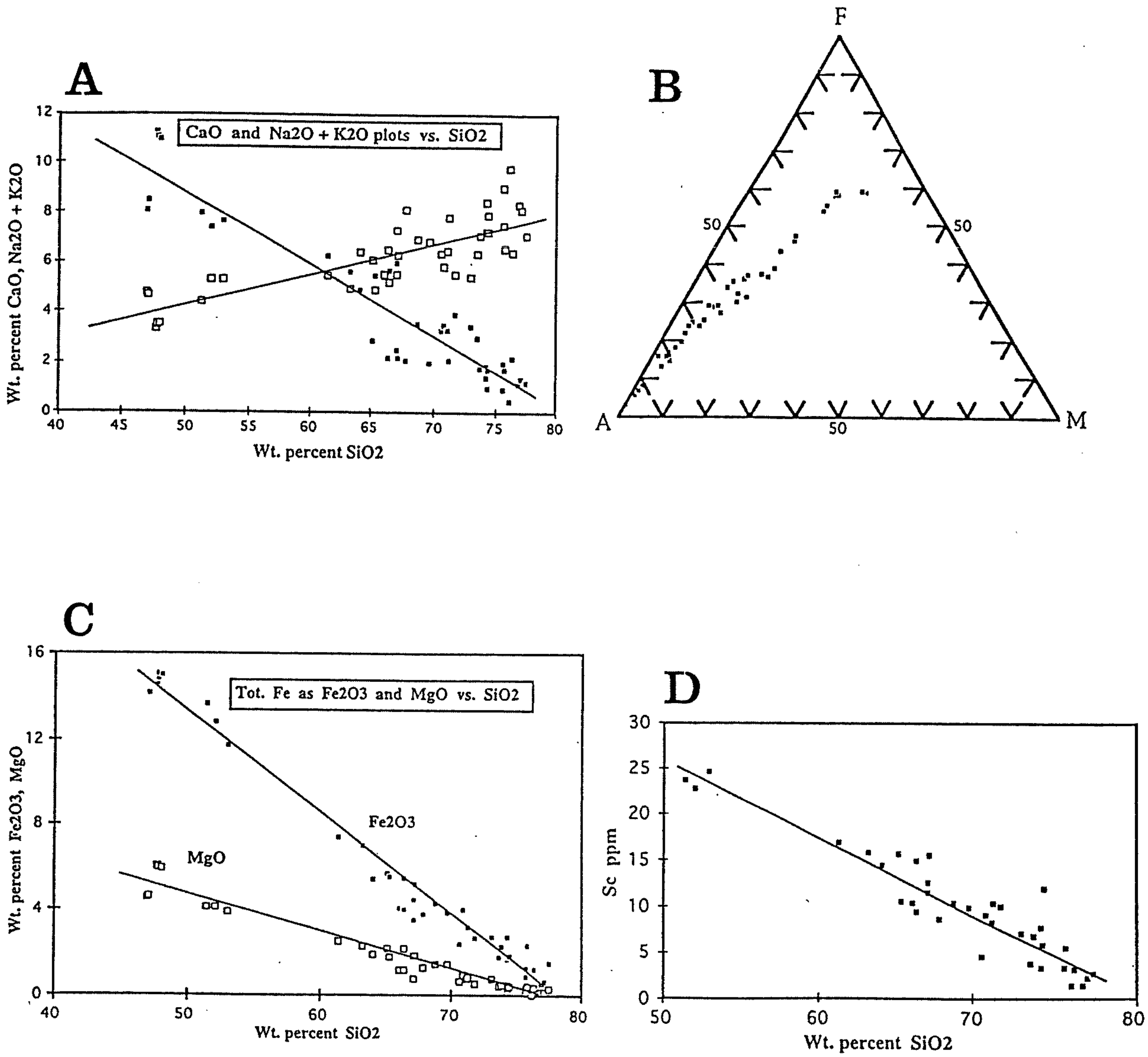

Figure 4. Harker variation diagrams and FMA plot for the Dedham North plutonic suite. Rocks with silica < 55% are mafic dikes.

A. CaO (solid squares) and $Na_2O + K_2O$ (open squares) vs. SiO_2 "standard" Peacock diagram, which defines calcic vs. alkalic affinity of a suite. The intercept at 62 wt.% SiO_2 is within the calc-alkaline domain.

B. FMA diagram. The distribution of rocks follows a calc-alkalic trend.

C, D. Geochemical plots suggest mixing (straight variation lines) between two end members (felsic and mafic) as opposed to concave trends (fractionation).

of 444 ± 3 and 373 ±4 Ma, indicating that extensive mafic magmatism was also present at the same time as the alkaline granitic plutonism. However, since field relations indicate that some of the mafic magmatism in this belt is related to the period of Dedham intrusion, younger ages cannot be uniformly extrapolated throughout it.

New U-Pb Geochronology of the Boston-Avalon Terrane

Six new U-Pb ages were determined by Dunning on rocks from the Boston-Avalon Terrane as part of our ongoing studies (Figure 5). (All these sample locations will be visited during the excursion). Four of the ages are from Late Proterozoic rocks associated with the main period of Avalonian magmatism: Lynn Volcanics, Dedham North Granodiorite, and the two samples from Sheffield Heights. These latter two samples are part of the Dedham North suite but reflect different compositional variations. The other two samples (Figure 5E-5F) are from the younger period of early to mid-Paleozoic alkaline magmatism.

Analytical Specifics

Samples were processed using the basic procedures as outlined by Dunning et al. (1990). All isotopic ratios were measured with a MAT 262 multicollector thermal ionization mass spectrometer, at Memorial University, operating in static multicollection mode with ^{204}Pb measured with an ion-counting secondary electron multiplier system. All error ellipses and uncertainties quoted on the ages are at the 2 sigma level. Linear regressions used the procedure of Davis (1982).

Lynn Volcanics. This rhyolite yielded abundant clear euhedral zircon. Three abraded fractions define a short mixing line anchored on concordia with a concordant fraction at 596.6 Ma. The regressed line yields a lower intercept age of eruption of 596 ± 3 Ma and a poorly defined upper intercept of 2672 +1700/-690 Ma (Figure 5A).

Dedham Granodiorite. This sample yielded both high quality euhedral zircon and titanite. Three abraded zircon fractions all clearly contain an inherited component and are not colinear, either due to Pb loss or variable ages of the inherited component. Two titanite fractions overlap with $^{206}Pb/^{238}U$ ages of 607 and 612 Ma. The regressed line through Z1, Z2 and T1 yields an intercept age of 607 ± 4 Ma, overlapping the titanite ages. The average age of the inherited zircon component is 1577 +130/-110 Ma (Figure 5B).

Sheffield Heights Diorite. This sample yielded abundant euhedral zircon and high quality titanite. Three fractions of abraded zircon prisms, and titanite concordant at 607 Ma, define a line that yields a lower intercept age of crystallization of 606 ± 3 Ma. The line gives an upper intercept average age of the inherited component of 1660 +150/-140 Ma (Figure 5C).

Sheffield Heights Granite. This granite yielded coarse euhedral to subhedral zircon. Four fractions of abraded euhedral grains show a minor but significant inherited older component. Fraction Z1 of lath-shaped grains touches the concordia curve with $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages of 608 and 617 Ma respectively. A regression line through all four fractions yields a lower intercept 609 ± 4 Ma age of crystallization with an average age of inherited zircon of 1780 +390/-260 Ma (Figure 5D).

Syenite Pod, Danvers. Three fractions of abraded clear coarse euhedral zircon from this rock define a mixing line with a lower intercept age of crystallization of 444 ± 3 Ma and a poorly constrained upper intercept of 2312 +1600/-570 Ma (Figure 5E).

Gabbro-Diorite, Waltham. This sample yielded high quality titanite and turbid high-U zircon. At the time of writing only one fraction of each has been analysed (Figure 5F). These yield an age of 373 ± 4 Ma from concordant titanite, supported by a $^{207}Pb/^{206}Pb$ age of 376 ± 3 Ma from 4% discordant, abraded zircon. Quite clearly, this is the age of igneous crystallization.

Interpretation

The 596 Ma date on the Lynn Volcanics finally ends the long standing debate about its age. Although, more recently a Precambrian age has been generally assumed for the Lynn because of its similar chemistry to the Dedham (Smith and Hon, 1984; Hermes and Murray, 1990), this marks the first time the Lynn has actually been dated. The date firmly establishes the Lynn as part of the Late Proterozoic Avalonian magmatic event in the Boston area.

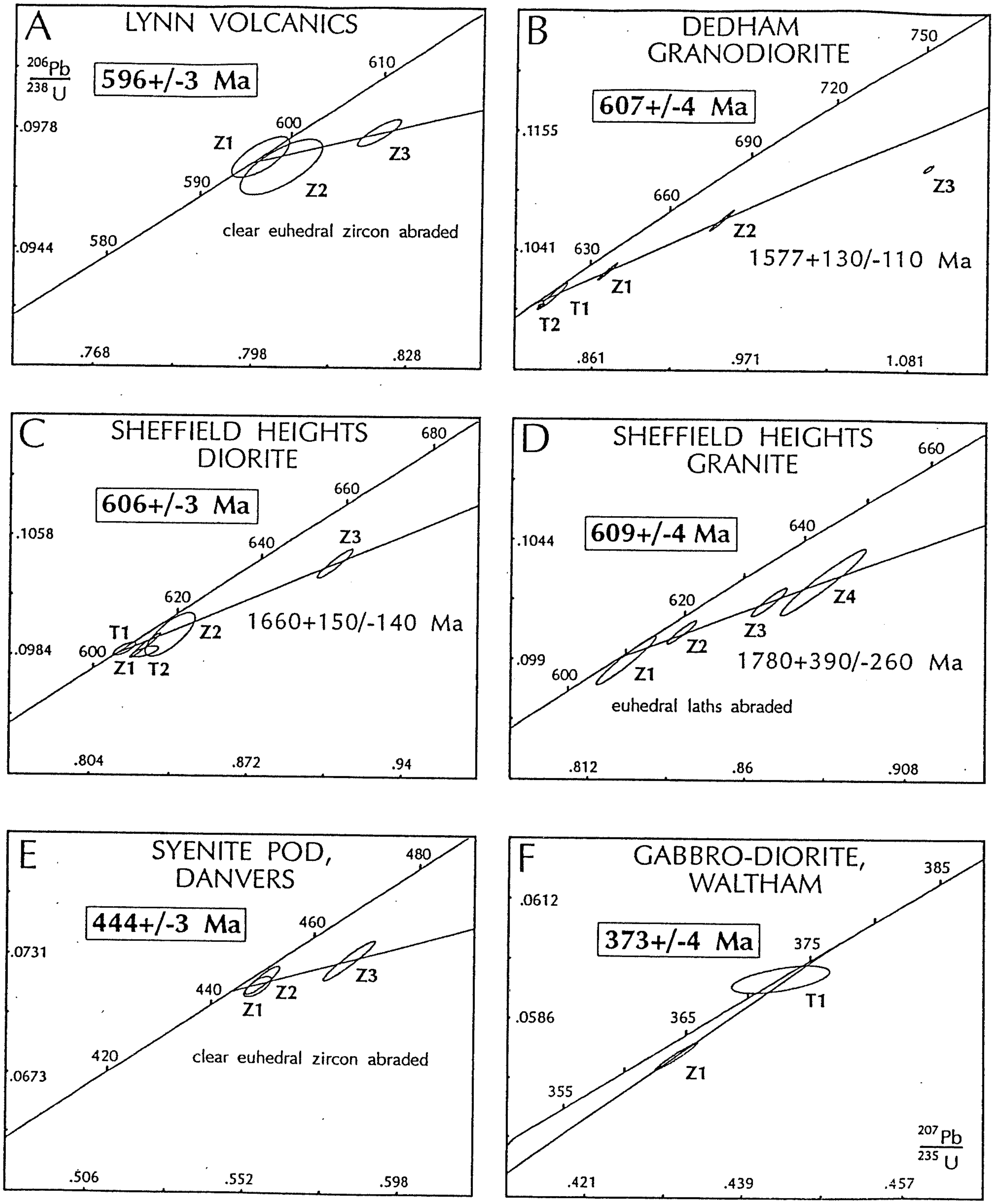

Figure 5. Concordia diagrams for new U-Pb data for rocks from the Boston-Avalon Terrane, eastern Massachusetts.

The Dedham Granodiorite north of Boston had not been dated previously by the U-Pb method (Zartman and Marvin, 1991). The 607 Ma age clearly indicates the Dedham North is part of the Late Proterozoic magmatic event, although it is somewhat younger than the 630 ± 15 Ma age obtained on the Dedham south and west of Boston (Zartman and Naylor, 1984). The dates on the two samples from Sheffield Heights indicate these samples are part of the Dedham North suite, despite their compositional variations and support the model for the origin of the Dedham North presented above and in the description for Stops 1-4 and 1-5. The age of the inherited zircon component in these plutonic samples is similar to that found by Olszewski (1980) for detrital zircons from the Westboro Fm.

The ages on the syenite pod from the gabbro-diorite in Danvers and from the gabbro-diorite in Waltham establish these rocks as having formed during the lower to mid-Paleozoic (Ordovician and Devonian) alkaline magmatism. They confirm that this event had a major mafic component in addition to the well known granitic magmatism of this period. It also means the ages of many of the mafic rocks in the western portion of the Boston-Avalon Terrane may need re-appraisal.

NASHOBA TERRANE

Overview

The Nashoba Terrane (Figure 1) lies west of the Boston-Avalon Terrane, across the prominent Bloody Bluff Fault Zone (Stop 2-11). It has a geological history distinct from that of the Boston-Avalon Terrane, and no geological units can be correlated between them. The stratigraphy of Nashoba Terrane (Figure 2) is dominated by a thick sequence of largely mafic volcanic rocks (Marlboro Fm., Stop 2-1) and volcanogenic sedimentary rocks (Nashoba Fm., Stops 2-4, 2-5, 2-6) of Ordovician age (which may also include some Cambrian or Early Silurian). These have been polydeformed and metamorphosed under sillimanite and sillimanite-K-feldspar zone conditions in the Silurian to amphibolites, various biotite-feldspar gneisses, schists and calc-silicate granulites (Bell and Alvord, 1976; Goldsmith, 1991a). Migmatites are developed in rocks of the appropriate compositions, particularly toward the northeast. Geochemistry of the Marlboro indicates the amphibolites were generally high-alumina basalts with trace element signatures compatible with an arc or marginal basin tectonic setting (DiNitto et al., 1984).

Dunning (Figure 6B) recently re-dated the Fish Brook Gneiss (Stop 2-8), a leucocratic feldspar-biotite gneiss once thought to represent Late Proterozoic basement for the terrane, on the basis of a 730 Ma date (Olszewski, 1980) and an unusual "swirled" foliation that suggested a possible earlier deformation (Bell and Alvord, 1976). The new date of 520 +14/-11 Ma establishes not only the age of this unit but constrains the age of the overlying Marlboro and Nashoba Fms. to the interval between 520 and 430 Ma, the younger age being that of the cross-cutting Sharpners Pond Diorite. The new date signifies that no Precambrian rocks have been found in the Nashoba Terrane. However, detrital zircons (Olszewski, 1980) and Nd isotopes in the Andover Granite (Hill et al., 1984) indicate the presence of Early Proterozoic crustal material in the terrane, at least as detritus.

The Nashoba Terrane experienced widespread plutonism from the mid-Ordovician through at least the Silurian (Figure 2) of contemporaneous calc-alkaline intermediate and granitic magmas (Zartman and Naylor, 1984; Hepburn et al., 1987a). The intermediate composition plutons, typified by the Straw Hollow Diorite (Stop 2-3) and the Sharpners Pond Diorite (Stop 2-9) are little deformed and range in composition from gabbroic cumulates to hornblende and hornblende-biotite diorites and tonalites that have sphene as a common accessory phase (Hill et al., 1984; Hon et al., 1986). The granites range in composition from metaluminous to peraluminous and vary from foliated biotite-muscovite granite to unfoliated garnet-bearing muscovite granite and pegmatite. They were likely intruded over at least a 50 Ma period (Zartman and Naylor, 1984; Hill et al., 1984). The Andover Granite (Figure 1, Stop 2-7) is thought to have been at least partially generated by anatexis of the Nashoba Fm. (Stop 2-6) during Silurian metamorphism. A new U-Pb date on the unfoliated, peraluminous younger phase of the Andover (Figure 6A) of 412 ± 2 Ma supports this conclusion. Magmatic pillows and other features (Stop 2-9; Hon et al., 1986; Hon et al., this volume, Chapt. Q) indicate the co-existence of at least some of the granitic and intermediate magmas. Geochemistry however, indicates they are not co-genetic. It is thought likely the intrusion of the calc-alkaline magmas contributed heat for the anatexis of the metasedimentary rocks that led to the granite formation.

During the Silurian, the Nashoba Terrane was polydeformed and metamorphosed. The 425 ± 3 Ma U-Pb age on monazite (Figure 6B) from the Fish Brook Gneiss dates the metamorphism. The metamorphism is generally of a lower pressure-higher temperature andalusite-sillimanite type, although early kyanite pseudomorphs replaced by sillimanite have been found in a few locations (Stop 2-3; Bober, 1989).

$^{40}Ar/^{39}Ar$ ages on hornblendes from amphibolites of the Nashoba Terrane give an age range of 354-325 Ma, and an Ar plateau age on biotite gives 308 Ma (Hepburn et al., 1987b). These indicate the time of uplift and cooling of the terrane. They also indicate the Nashoba Terrane in Massachusetts did not experience an Alleghanian thermal event sufficient to affect the Ar/Ar systematics of hornblende or biotite.

New U-Pb Geochronology of the Nashoba Terrane

Samples of the Nashoba Terrane were analyzed for U-Pb geochronology using the same procedures as noted previously for the Boston-Avalon Terrane samples, after the method of Dunning et al. (1990). Three geologically important ages were determined from the samples of the Andover Granite and Fish Brook Gneiss (Figure 6).

Analytical Specifics

Andover Granite. This coarse grained to pegmatitic muscovite-bearing S-type granite yielded zircon of a variety of morphologies and grain size and monazite. Much of the zircon is interpreted to be inherited from the source rocks, and the monazite is interpreted to be igneous, as is common in S-type granites. Three fractions of monazite analysed plot slightly above concordia with $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ages of 412- 413 Ma and 410-411 Ma respectively. They indicate an age of 412 ± 2 Ma for this rock (Figure 6A).

Fishbrook Gneiss. The Fishbrook Gneiss yielded a large amount of zircon, much of which is virtually opaque, turbid and brown in color. There is also a significant amount of clear euhedral prism zircon and fine grained monazite. Three fractions of zircon and two of monazite have been analysed. Two abraded fractions of the clearest zircon have normal U concentrations of 150 - 200 ppm and plot near concordia with $^{207}Pb/^{206}Pb$ ages of 499 and 502 Ma, within error of each other, and one overlaps concordia. From these data, the igneous age of this rock could be 500 ± 5 Ma. The third fraction of abraded brown zircon contains 2000 ppm U and is very discordant. A line regressed through the three zircon fractions has an upper intercept age of 520 +14/-11 Ma and a lower intercept of 286 Ma (Figure 6B).

This 520 +14/ -11 Ma age would best represent the time of igneous crystallization if the low U clear zircons were affected by the disturbance (Alleghanian) that caused Pb loss in the high-U grains. But this need not be the case. If not, 500 ± 5 Ma is the better age. This will be resolved with further analyses underway at the time of writing.

Monazite yielded a reproduced unambiguous age of 425 ± 3 Ma, which is interpreted to represent a metamorphic event.

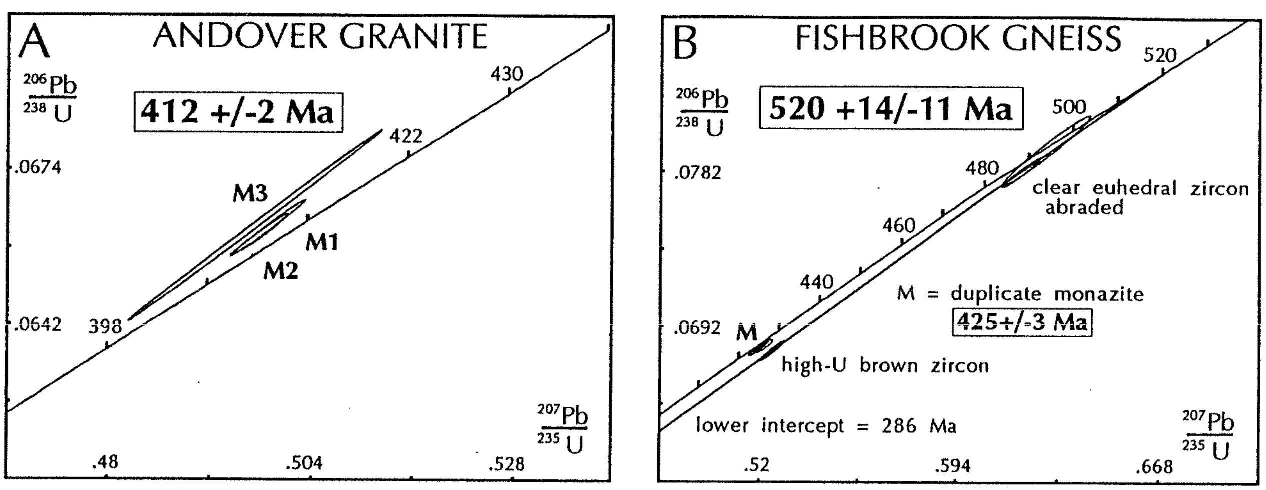

Figure 6. Concordia diagrams for new U-Pb data for rocks from the Nashoba Terrane, eastern Massachusetts.

Interpretation

The 520 Ma igneous crystallization age on the Fish Brook Gneiss establishes that this unit is Paleozoic and not Precambrian as previously thought (Olszewski, 1980). Two conclusions from this fact result: (1) the terrane has no (as yet) identified Precambrian basement, which supports the idea that it originated as an early Paleozoic arc, and (2) this age greatly restricts the possible age range of the overlying stratified rocks in this terrane (Marlboro Volcanics and Nashoba Fm.) to the interval between 520-430 Ma. Previously they were only known to be pre-430 Ma.

The date of 425 Ma on the monazite from the Fish Brook Gneiss clearly establishes the timing of the metamorphism in the Nashoba Terrane. Previously, this was only very approximately known through a series of, perhaps circular, arguments concerning the ages of poorly dated foliated plutons thought to have experienced the deformation and metamorphism vs. unfoliated plutons thought to post-date the metamorphism (Hepburn et al., 1987a). This date is of considerable importance for tectonic interpretations.

The date on the Andover Granite finally establishes the age for the younger phase of this complex pluton that has proved exceedingly difficult to date in the past (Zartman and Naylor, 1984; Hill et al., 1984). This age further confirms the timing of the deformation and metamorphism in the terrane as Silurian and supports the idea that the peraluminous Andover was at least partially generated by anatexis of sediments during the metamorphism.

EASTERN MERRIMACK BELT

Northwest of the Nashoba Block across the Clinton-Newbury Fault Zone is another potential terrane, the Merrimack Trough or Eastern Merrimack Belt (Figure 1). Since we will only be visiting one exposure in this terrane, it is beyond the scope of this guidebook to describe it in detail, particularly since the age of the rocks and their deformation are presently controversial. For detailed descriptions of these rocks refer to Lyons et al. (1982) and Robinson and Goldsmith (1991).

The rocks in this belt between the Clinton-Newbury Fault and approximately the Fitchburg Pluton (Zen et al., 1983) include a sequence of calcareous metasiltstones (Stop 2-2), pelites and impure quartzites. The metamorphic grade varies from lower greenschist facies near the Clinton-Newbury Fault Zone to the upper amphibolite facies westward in the belt. The rocks are either (1) Ordovician-Silurian in age (as shown by Zen et al., 1983) based on correlation with fossiliferous strata in Maine (Robinson and Goldsmith, 1991) or (2) pre-Middle Ordovician based on the ages of cross-cutting plutons (Lyons et al., 1982; Gaudette et al., 1984 ; Bothner et al., 1984; Hon et al., 1986). The age of the deformation and metamorphism in this belt depends to some extent upon the age assignment of the rocks and is either Acadian or from an earlier event.

NEWBURY VOLCANIC COMPLEX

The Newbury Volcanic Complex (Stop 2-10) occurs only within fault-bounded slivers (Figure 1) directly between the Boston-Avalon and Nashoba Terranes. It is not clear that it belongs to either of these terranes. For example, Zen (1989) included them within a separate terrane (Atlantica II) within his Atlantica Composite Terrane. The Newbury is composed of a series of andesitic and rhyolitic volcanics, shallow intrusions and interbedded sedimentary rocks that contain latest Silurian to Early Devonian fossils (Shride, 1976a). The rocks are essentially unmetamorphosed and, although tilted, not penetratively deformed. McKenna et al. (1993) indicate these rocks are calc-alkaline with trace element geochemical signatures indicative of formation in a continental arc environment. Hon and Thirlwall (1985) and Hon et al. (1986) note the similarity in the composition of the Newbury Volcanics to the intermediate and granitic magmas of the Nashoba Terrane and suggest that the Newbury may be the volcanic expression of this terrane preserved in a down-dropped fault block. Volcanic rocks similar in both composition and age also occur in the coastal volcanic belt in eastern Maine and may have once been continuous with the Newbury (Gates and Moench, 1981).

TECTONIC DISCUSSION

Differences in the geological history of the Boston-Avalon and Nashoba Terranes are shown in Figure 2. The Boston-Avalon Terrane was part of a continental arc during the Late Proterozoic, but by the early Paleozoic arc magmatism ceased and the area became a stable shelf or platform. It remained largely tectonically stable throughout the lower and middle Paleozoic, experiencing only intrusions by alkaline granitic and mafic magmas. In contrast, the Nashoba Terrane is interpreted to have formed in an arc or marginal basin setting in the Lower Paleozoic. Intruded extensively by calc-alkaline intermediate and granitic magmas during the Ordovician-Silurian it was deformed and metamorphosed to high grade during the Silurian. We interpret the Ordovician-Silurian calc-alkaline plutonism in the Nashoba and Eastern Merrimack Belt to be related to an east-dipping subduction zone beneath these terranes. The Newbury Volcanics may be preserved remnants of this magmatism. As the leading edge of the eastern terranes (Nashoba Terrane) impinged upon the Merrimack Belt (the whole Merrimack Belt of Zen et al., 1983, and not just the eastern portion described above) to the west during the Silurian, perhaps obliquely, it was deformed and metamorphosed. This initiated the final closure of the eastern terranes with those to the west. Thus, the Acadian orogenic cycle (if something at 425 Ma can be called Acadian) started earlier on the southeastern side of the belt and telescoped northwestward and westward during the late Silurian and early to mid-Devonian. In this interpretation, the rather extensive Ordovician to Devonian alkaline magmatism in the Boston-Avalon Terrane represents behind-the-arc magmas originating from the same east-dipping subduction zone and interacting with the mature crust of Avalonia (Paige and Hon, 1988; Hon et al., this volume, Chapt. Q). The Mississippian $^{40}Ar/^{39}Ar$ ages from the Nashoba Terrane represent the time of its final uplift and cooling in post-Acadian times.

The large faults within and between these terranes have clearly disrupted the original order of the crustal segments by foreshortening and strike-slip displacements of unknown magnitude. They have had a long and complex history of movement ranging from Precambrian to Mesozoic that is only now beginning to be understood (e.g., Skehan and Rast, 1991; Goldstein, 1992; Goldsmith, 1991b; Rast et al., this volume, Chapt. S).

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ROAD LOG - DAY 1
BOSTON-AVALON TERRANE

STOP 1-1. CAMBRIDGE FM., LATE PROTEROZOIC, BOSTON BAY GROUP (Malden, MA; 30 minutes). From Boston proceed north on Rt. 1 to exit for Rt. 60 and Malden, follow signs for Rt. 60 west (Eastern Ave.) and proceed west for about 1.5 mi., left on Faulkner St., left on Lyme St., and park just before the next intersection. Climb to crest of hill to NE (Figure 7); hill is Tartikoff Park immediately to SW of former Daniels School (now Daniels Apartments) .

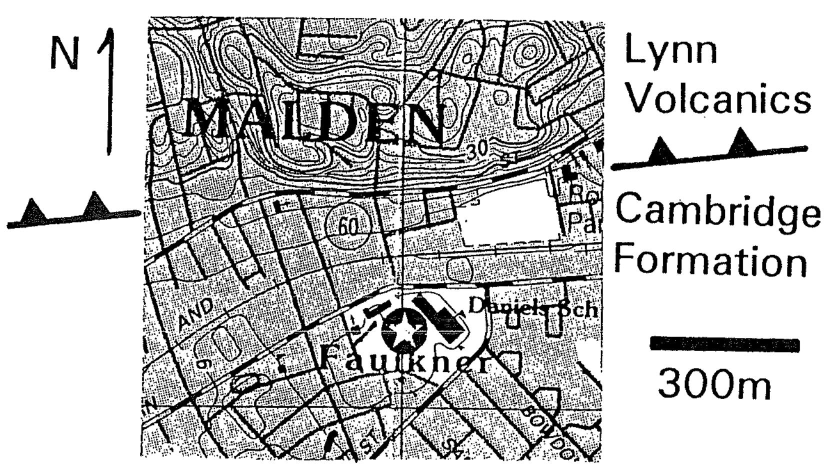

Figure 7. Location of the Cambridge Fm. about 0.7 km E of Malden Square, MA; USGS Boston North Quad. Cambridge outcrops occur on the hill (shown by star) SW of Daniels Apts. The position of the Northern Boundary Fault, inferred by topography and from strike projected from the Malden Tunnel data, is indicated along the sides of the figure.

This is the northernmost outcrop of the Cambridge Fm. in the Boston Basin; in fact, the Northern Boundary Fault of the Boston Basin is only about 300 m due north from the crest of the hill in the park (Figure 7). Hills to the north form a fault line scarp resulting from the differential resistance to erosion of the Lynn Volcanics relative to the softer sediments of the Boston Basin. The Cambridge at this locality strikes 230^o and dips 78^o to 82^o to the north. Graded beds of very fine feldspathic sandstone and scour structures indicate that the beds are overturned and young to the south. The gray mudstone is thinly laminated and contains many soft sediment deformation structures including slump folds, load structures, pinch and swell bedding, and intrastratal microfaults. The outcrop north of the fence and above the church parking lot exposes many detailed sedimentary structures and 0.6 to 1.0 cm diameter ring-like structures (fossils?) on the soles of beds. A 4 m wide dolerite dike, striking 280^o, cuts the Cambridge (cross-section is exposed north of the fence) and has been sheared parallel to strike. Much of the mudstone has also been tectonized.

The 1.6 km long Malden Tunnel, about 1.4 km to the west of this outcrop, crossed from the steeply dipping Cambridge to the Lynn Volcanics that form the upland topography to the north of the Boston Basin. Billings and Rahm (1966) described the fault in the tunnel as "knife-sharp and tight" and dipping 55^o to the north. There is no doubt that the boundary fault in this area is a thrust as a borehole drilled during the tunnel project penetrated about 25 m of Lynn felsite along the edge of the thrust sheet before entering underlying Cambridge mudstones (Billings and Rahm, 1966). Projection from tunnel data suggests that the Tartikoff Park outcrop is probably the oldest exposed Cambridge and is about 300 m above the lowest Cambridge beds in the Malden Tunnel.

STOP 1-2. DEDHAM NORTH GRANITE, LATE PROTEROZOIC, SUBVOLCANIC - SHALLOW INTRUSIVE FACIES (Malden, MA; 20 minutes). From the Daniels Apartments (Stop 1-1) turn right onto Rt. 60 east (Eastern Ave.) for 0.8 mi toward an intersection with Rt. 99 north. Take left turn on Rt. 99 north (Broadway St.) and proceed for approx. 0.8 mi. At the intersection with Central St. to your right and Elwell St. to your left, turn left on Elwell St. Immediately behind the MOOSE club house at the corner of Elwell St. and Rt. 99 enter the parking lot on your left side. Exposures are on the sloping incline at the far right corner of the parking lot. NOTE: Eastern Ave. is parallel to and about 300 meters south of the Northern Boundary Fault. Rt. 99 then follows one of the younger faults that transects and offsets the Boundary Fault.

The Dedham North Granite is located north of the Boston Basin in contrast to the main body of Dedham Granite located to the south of the basin. Both plutons appear to have similar mineralogical and petrological characteristics, inspiring early workers to lump most of the eastern Massachusetts intrusives under one designation. The Dedham North intrusives are covered by the Lynn Volcanics on the south side and grade into more mafic compositions to the north.

This locality is only a few dozen yards away from a fault contact with the Lynn Volcanics, and the rocks exposed here are of a chilled, near contact facies. The rock is composed of 30 to 60% micrographic (granophyric) matrix and 1 to 5 mm phenocrysts of plagioclase (zoned andesine-oligoclase), quartz, hornblende, and biotite. The alkali feldspar-quartz micrographic matrix is colored pink; the euhedral plagioclase is white; quartz is transparent glassy; and hornblende and biotite are dark. Approx. half way up the outcrop is a 2 ft. wide greenish colored dike of rhyodacite that is compositionally similar to the Dedham North suite. The present day erosional levels at this locality are near the upper contact of the pluton.

STOP 1-3. LYNN VOLCANICS, LATE PROTEROZOIC, EXTRUSIVE FACIES (Saugus, MA; 25 minutes). Return to Rt. 99 (Broadway St.), turn left on Rt. 99 north, and continue north for approx. 0.5 mi. Immediately past the Malden-Saugus town line make a left turn into the entrance of TRIMOUNT quarry. Stop at the office on your left and ask for permission to enter the quarry area.

The quarry offers an amphitheater view of several members of the volcanic sequence, intruded by stoping pockets of the Dedham North or compositionally alike magmas, all cut by a prominent set of younger mafic dikes. Three different types of the Lynn Volcanics are represented here: (1) reddish colored, (2) dark bluish or greenish colored, and (3) a resurgent dome-like facies with up to 50% phenocrysts in the very fine-grained matrix.

The red colored facies occurs only in the regions immediately adjacent to the Northern Boundary Fault. It has been informally suggested that the reddish color of the volcanics is a result of intense surficial oxidation/weathering during the late Precambrian, shortly after their deposition. A sample of the reddish colored facies, collected at this locality, was dated by the zircon U-Pb method at 596 ± 3 Ma (Figure 5A). This is about 10 million years younger than the age of the underlying Dedham North intrusives. Similarity of geochemical composition and the presence of an older zircon population in both suites suggests a similar mode of origin. At present there is no geochronological evidence for volcanics exactly coeval with the Dedham North. However, field evidence suggests otherwise for some of the volcanics. Perhaps the reddish member seen here is a distal facies from a different caldera system.

STOP 1-4. DEDHAM NORTH GRANITE, LATE PROTEROZOIC, GRANODIORITIC FACIES (Saugus, MA; 15 minutes). Re-enter Rt. 99 north (Broadway St.) and continue north for approx. 0.5 mi. At this point Rt. 99 north will end by merging with Rt. 1 north. Proceed approx. 0.9 mi on Rt. 1 north passing Essex St. and Main St. exits. After the Main St. overpass and Grossman store on your right, enter the large parking area of the Kowloon Restaurant, just before Rt. 1 reaches the crest of the road. Exposures are at the far end of the parking lot.

This locality is very near a temporary blasting site from which we collected a sample for age determination. Based on data obtained from titanites and zircons (Figure 5B), the age is 607 ± 4 Ma. The age is approx. 10 million years older than the age of the Lynn Volcanics. A strong zircon inheritance component is present in this sample, pointing to an averaged age population of 1577 +130/-110 Ma. Similar inheritance is also seen in leucogranitic and quartz dioritic compositions within the Dedham North.

The Dedham North Granite has a compositionally highly variable suite ranging from leucogranites to granodiorites, tonalites, and quartz diorite. Mineralogy varies correspondingly from that of a minimum granite composition of 30 to 35% quartz, 25 to 30% plagioclase, 30 to 35% alkali feldspar, and 2 to 8% biotite to a quartz diorite modal composition of 10 to 15% quartz, 35 to 40% plagioclase, 10 to 15% alkali feldspar, and up to 25% hornblende and biotite. At this location the Dedham is of the typical granodiorite variety with partially saussuritized plagioclases of greenish white color, pinkish alkali feldspar, quartz, and partially chloritized biotite and hornblende.

Geochemical and isotopic evidence (Hill, pers. comm.; Figure 4) supports the conclusions that the Dedham North igneous suite is largely a result of mixing between a mafic magma not represented in the complex and an anatectic crustal melt, along with a smaller degree of concurrent fractional differentiation. The origin of the anatectic melt will be examined and discussed at the next stop (Stop 1-5).

STOP 1-5. DEDHAM NORTH GRANITE, LEUCOGRANITIC FACIES AND PARTIALLY MELTED WESTBORO FM. (Saugus, MA; 45 minutes). After returning to Rt. 1 north continue for approx. 1 mi. and take the first exit, the Lynn Fells Parkway. You will loop over Rt. 1. After making a left turn on the Lynn Fells Parkway south, continue for approx. 1.2 mi., crossing Main St. at 0.9 mi. Watch on your left side for the entrance with a guard house to Sheffield Heights Condominiums and turn left. Follow Lewis O. Gray Drive uphill. On your right you will pass exposures of the quartz diorite facies, the zircon dated locality (Figure 5C). As you reach the ridge line, turn left on Sheffield Way and continue all the way to the end. Turn around at the cul-de-sac and park on your left. Exposures are a ridge that forms a median between Sheffield Heights and Hammersmith Village developments. Please, be careful when crossing the landscaping, this is private property!!!

We are standing at the northeast tip of a large pendant consisting of gneisses and quartzites of the Westboro Formation. Entirely engulfed within the Dedham North suite, this pendant is approx. 900 ft. long and 200 to 300 ft. wide and is aligned in a northeasterly direction, which is also the direction of the foliation. The exposures show extensive migmatization of the pendant by partial melting of layers with a suitable geochemical composition. Geochemistry of the melts that surround the pendant are minimum granites, but a short distance from the pendant the composition rapidly changes to granodiorite, tonalite and quartz diorite. A sample of the "leucosome" leucogranite taken from this exposure was dated by zircon U-Pb and yielded an age of 609 ± 4 Ma (Figure 5D). A sample of the quartz diorite only 800 ft. to the north from this locality gave an age of crystallization at 606 ± 3 Ma (Figure 5C). Both samples contain a similar inheritance with the upper intercept of the concordia plot at 1780 +390/-260 Ma and 1660 +150/-140 Ma, respectively. These ages are statistically the same and show similar inheritance as in the sample of the Dedham North granodiorite taken at Stop 1-4.

In summary, the Dedham North suite consists of granites and rocks of intermediate compositions. The granites originated by partial melting of a sedimentary protolith, while the intermediate members show a mixing between this granitic magma, as evidenced by the zircon inheritance, and a mafic magma. In addition, since the granites cannot be the heat source, the presence of a mafic magma is required as a heat source to drive the partial melting process. The mafic melt that contributed to the Dedham North Complex presumably may be equivalent in composition to some of the mafic dikes at this exposure that show "undulating" (mafic magma intruding felsic magma) contacts. The geochemical character of these dikes suggests a convergent plate margin setting, although not the main arc environment. Perhaps, they reflect a setting transitional between the main arc and back-arc(?).

STOP 1-6. WESTBORO FM., LATE PROTEROZOIC (Saugus, MA; 45 minutes). North on Rt. 1; exit onto Lynn Fells Parkway and follow the parkway about 1 mile to intersection with Main St., turn right on Main and proceed about 1.2 miles to point where powerline crosses Main St. Park under powerline and take dirt road on northwest side of powerline to the south about 1.2 km. Hike over hill and down to the point where the road turns sharply left and descends a rocky scarp. Stop here and walk back through the section to the north (Figure 8).

This is the only known outcrop of the Westboro Fm. that displays common primary sedimentary structures and has a relatively unmodified sedimentary texture. These are low grade metamorphic rocks with metamudstones and muddy meta-arenites rich in chlorite, actinolite, epidote and quartz. Quartz-rich meta-arenites contain muscovite but are often not very recrystallized. Locally higher grade metamorphic mineral assemblages developed adjacent to the

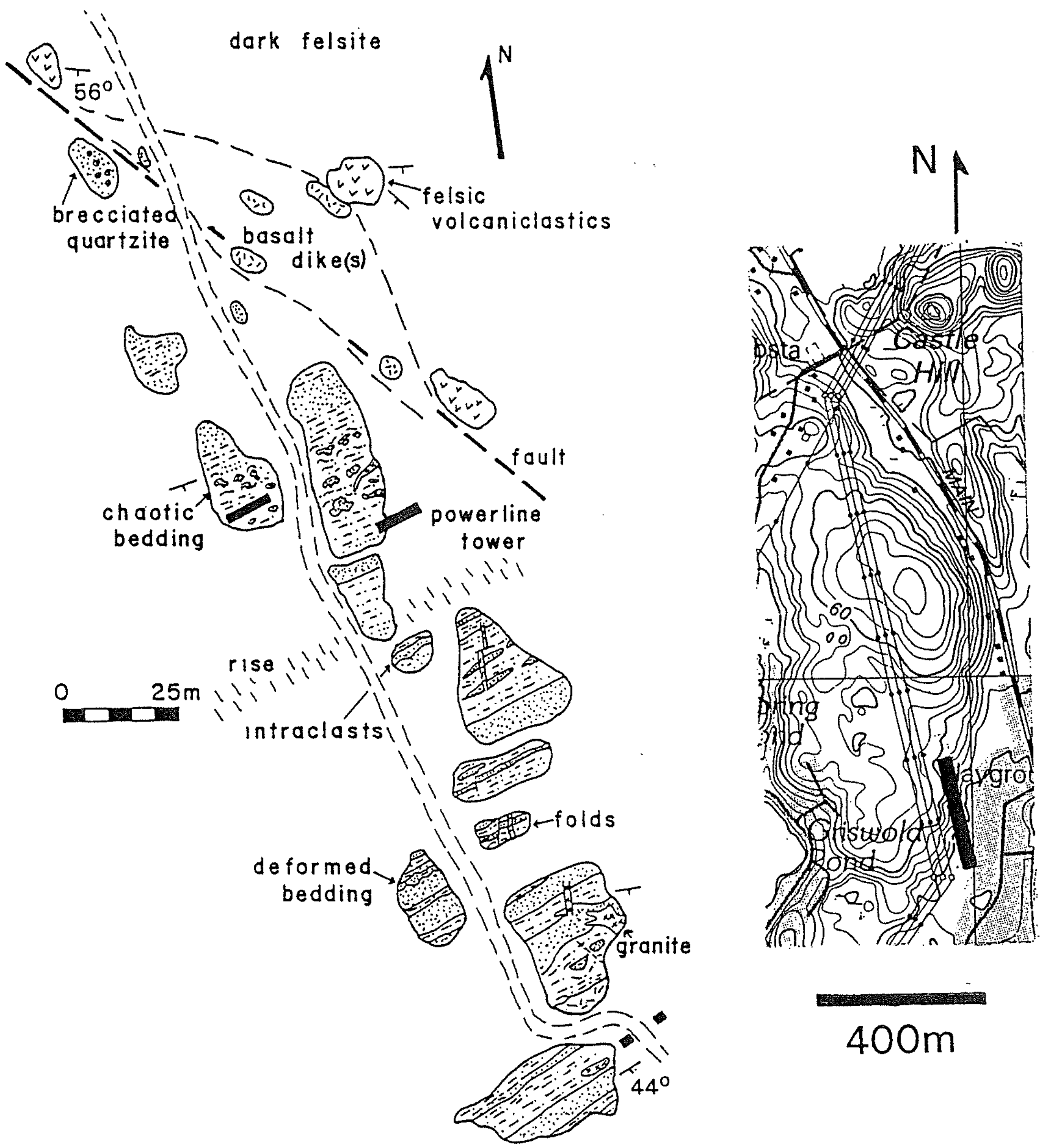

Figure 8. Location map (inset) and generalized sketch map of Westboro Fm. at Stop 1-6. Heavy bar on inset topographic map shows interval represented in detailed map.

Dedham intrusives. In the following discussion sedimentary protolith terms are used. Dark reddish brown siltstones and mudstones are interbedded with gray fine sandstones and 0.3 to 2 m thick beds of white quartzarenite. The sequence dips about 45° to the south and on the basis of load structures and cross-lamination is right-side up. Several arenite beds grade from medium sand upward to very fine sandstone and siltstone. Many of these arenites contain rounded, highly deformed or intricately embayed siltstone, mudstone and sandstone intraclasts. The uppermost portion of one graded bed has ripple cross-lamination and several beds have irregular, scoured and loaded lower contacts. These sandstones are interpreted as turbidites formed by a highly concentrated, cohesionless, sandy gravity flows.

Some of the beds are lenticular and deformed, and there is a 14 m thick interval (beneath the powerline towers) of highly irregular sandstone and mudstone intraclasts in a dark brown mudstone matrix. In thin section some of the sandstone masses have diffuse margins with escaping quartz grains and mudstone embayments. The megascopic features and microscopic texture suggests that this material was mixed together while soft. Bailey et al. . (1989) interpreted this and similar outcrops as olistostromes.

Dedham North Granite forms the first knob to the south of the sedimentary section, and veins and pods of presumably Dedham North intrude parts of the Westboro. A pegmatitic vein occurs in the road where it descends the rocky scarp. North and east of the sedimentary sequence are outcrops of crystal/lithic/vitric felsic tuff. Brecciated quartzites along the contact and the strike of the Westboro into the volcanics suggest that a fault separates the metasediments from the volcanics (Figure 8). As you hike back across the hill to the vehicles you pass through outcrops of dark to light gray recrystalllized felsite, and on the SW flank of the hill to the NE of the powerline, a diorite intrusion cuts the felsite.

STOP 1-7. DANVERS ALKALI GABBRO AND SYENITIC CUMULATES, ORDOVICIAN (Danvers, MA; 25 minutes). Retrace your way back to Rt. 1 north and continue north for approx. 7 mi. passing along the way exits to Rt. 129, Rt. 128, and Interstate 95 north. 0.8 mi. north of the Rt. 114 exit, follow the exit ramp to Centre St. CAUTION. This interchange serves Rt. 1, Centre St., and I-95 S and is somewhat disorienting! (Figure 9). On the completion of the ramp loop, turn right onto Centre St. and go under Rt. 1. At the T intersection turn left, and then left again into the parking area of a strip mall along Rt.1 south. Walk back under Rt. 1 and proceed to exposures on both sides of the ramp to Rt. 1 N and I-95 S from Centre St.

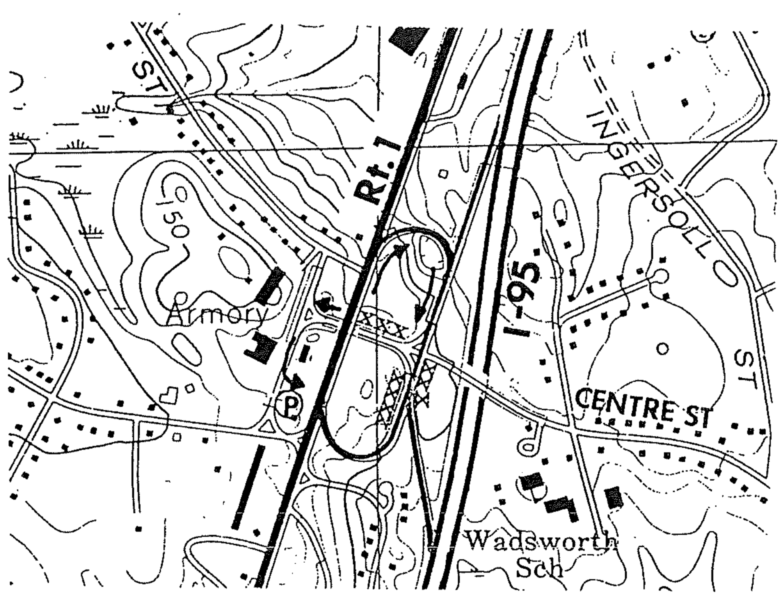

Figure 9. Location for Stop 1-7. Follow arrows to parking (P). The location of exposures is shown by strings of x's. Enlargement from U.S. Geol. Survey Topographical Map of the Salem Quadrangle, 1:24,000.

The rocks at these exposures prove both the presence of Late Ordovician mafic magmatism within the Boston-Avalon Terrane and a younger tectonic deformation. The principal rock type is a mildly alkalic gabbro (Ne normative) with phenocrysts of alkali feldspar. These phenocrysts are typically 0.5 to 2 cm in size and occasionally form pods and layers of syenite by accumulation of alkali feldspar (flotation and/or flow fractionation). A sample from one of these syenitic pods was dated by the zircon U-Pb technique and yielded an age of 444 ± 3 Ma (Figure 5E). This age is similar to the emplacement age of Cape Ann Granite (452 ± 10 and 446 ± 15; Zartman and

Marvin, 1971, and Zartman, 1977, respectively) suggesting that the origin of the Cape Ann Granite Complex is related to mafic alkali basalt magmatism.

Walk back toward the Rt. 1 overpass and examine the exposure on the north side of Centre St. just before the Rt. 1 overpass. The same rocks here are sheared and mylonitized (striking 45° to 50° E and dipping 60° NW), indicating post-Ordovician deformation.

STOP 1-8. PEABODY GRANITE, DEVONIAN (Peabody, MA; 15 minutes). Return to Centre St., proceed under Rt. 1, and take the exit ramp on your right to I-95 S to Boston. After the turn onto the exit ramp bear left at the fork and follow I-95 S toward Waltham for approx. 2.5 miles. Take Exit #45 to Rt. 128 north toward Gloucester. After 1.2 mi leave Rt. 128 N via Exit #28 to Centennial Drive. At the end of the exit ramp turn right on the cross road and immediately right again on Centennial Drive. Proceed 0.1 mi and turn left, crossing Centennial Drive into the parking lot of Hyde Opportunity manufacturing facilities. Exposures are at the far end on your right.

Throughout the Boston-Avalon Terrane are occurrences of mid-Paleozoic intrusions (Figure 1) of undeformed hypersolvus granites that belong to one of two discrete age groups: an Ordovician group of plutons emplaced during the 450 to 460 Ma interval, and Devonian plutons crystallized around 380 ± 20 Ma (Zartman, 1977; Hermes and Zartman, 1985). The chemical composition of both sets of plutons ranges between metaluminous to mildly alkaline granites with the corresponding agpaitic indices ranging from 0.85 to 1.15. Mineralogy in general is dominated by perthitic alkali feldspars, quartz, ferrous micas, ferrous amphiboles and pyroxenes.

Here, the Peabody granite is a homogenous, medium- to coarse-grained, hypersolvus granite with 20 to 30% quartz, 65 to 75% perthitic alkali feldspar, 5 to 10% ferrohastingsite and common accessories. Grain size is typically 5 to 10 mm, somewhat finer near the contacts. At these exposures we can observe common mafic enclaves that are virtually absent elsewhere in the pluton.

STOP 1-9. WEYMOUTH FM., LOWER CAMBRIAN (Nahant, MA; 60 minutes). From Rts. 1 or 128, or I-95, proceed south on Rt. 129 to Lynn Shore Drive, then south on Lynn Shore Drive to a rotary. From the rotary proceed south down the causeway on Nahant Rd. and follow Nahant Rd. to the gate at Northeastern University Marine Science Center at East Point. Proceed through the gate and park in front of MSC. You must obtain permission from the director of the Marine Science Center before your visit. From Boston or points south proceed north on Rt. 1A to rotary, then follow directions above.

In the rugged sea cliffs around East Point Early Cambrian nodule-bearing mudstones and limestones dip about 40° to the northwest. The limestones contain a diagnostic upper Placentian Series, Acado-Baltic small shelly fauna, but no trilobites. Cambrian strata are intruded by the Ordovician Nahant Gabbro and by numerous mafic dikes and sills. Details of igneous petrology, stratigraphy, and paleontology are given in Bailey and Ross, this volume, Chapt. Y. Please refer to this description for completeness.

ROAD LOG - DAY 2
NASHOBA TERRANE, EASTERN MERRIMACK BELT, BOSTON-AVALON TERRANE

STOP 2-1. MARLBORO FM., ORDOVICIAN?, NASHOBA TERRANE (Marlborough, MA; 20 minutes). Exit I-495 to Rt. 20 west, immediately turn right onto Felton St. toward the Radisson Inn. In 0.1 mi., turn left on Landry St. and follow (0.2 mi.) to junction with Rt. 20. Turn left (east) onto Rt. 20. In 0.1 mi. turn right into the parking lot of the DBM Corporation (just beyond gas station) and park. Walk SE to exposures along the entrance ramp from Rt. 20 to I-495 South and to exposures along Rt. 20 just west of the gas station by the "blue building." Beware of poison ivy and traffic!

Exposures here are typical amphibolites in the Sandy Pond Mbr. of the Marlboro Fm. (Bell and Alvord, 1976; DiNitto et al., 1984). Cross-cutting granitic dikes are tentatively assigned to the Andover Granite. The amphibolites are fine to medium-grained, massive to foliated hornblende-plagioclase ± quartz, biotite or epidote amphibolites and layered amphibolites. The metamorphic grade here is the sillimanite zone.

The Marlboro Fm. forms the major stratified unit on the eastern side of the Nashoba Terrane and consists of amphibolites, felsic gneisses and interbedded schists. It has generally been interpreted as a metamorphosed volcanic complex. Geochemistry on the amphibolites indicates that they were originally basalts and include high-alumina types with trace element signatures consistent with formation at a convergent plate margin or in a marginal basin setting (DiNitto et al., 1984).

STOP 2-2. OAKDALE FM., EASTERN MERRIMACK BELT (Boylston, MA; 20 minutes). From junction I-290 and Rt. 140 in Shrewsbury, proceed north on Rt. 140, 1.7 mi. to junction of Rts. 140 & 70. Continue NW on Rt. 140 for 0.3 mi. to outcrops on both sides of the road. Pull off on right and park.

The purpose of this stop is to examine exposures typical of the sedimentary sequence in the eastern part of the Merrimack Belt (Figure 1; Zen et al., 1983) and to contrast them with the Nashoba Terrane just to the east. The region immediately west of the Clinton-Newbury Fault Zone is characterized by a variety of calcareous metasiltstones, impure quartzites and pelitic rocks metamorphosed to only the lower greenschist facies, quite different from the high grade schists and gneisses in the Nashoba Terrane just to the east. The grade of metamorphism in the Merrimack Belt rises gradually westward. The age of the rocks and of the metamorphism and deformation in the eastern part of the Merrimack Belt is controversial. The rocks are either Siluro-Devonian as shown by Zen et al. (1983) and the deformation Acadian; or the rocks are pre-Middle Ordovician the the deformation possibly as old as Precambrian (Bothner et al., 1984)

The Oakdale Fm., here near its type locality, is typical of the rocks in this belt. It consists of light-gray to purplish-weathering calcareous metasiltstone and interbedded gray to gray-green phyllite. The siltstone beds range in thickness up to about 10 cm and are separated by thin partings of micaceous phyllite, or else they are interlaminated with paper-thin phyllite partings on a scale of a few mm. Ankerite causes the characteristic purplish-brown weathering spots (Hepburn, 1976). The beds dip moderately to the NW and are folded by small, tight folds with axial surfaces approximately parallel to bedding.

STOP 2-3. STRAW HOLLOW DIORITE & ANDOVER GRANITE, SILURIAN, NASHOBA TERRANE (Marlborough, MA; 40 minutes). From interchange of I-495, I-290 and "To 85" continue on "To 85" just beyond (east of) the point where the ramp from I-495 North joins it. Park with care on the right shoulder, past the electrical box. Or continue on "To 85" to the first intersection, turn around and retrace the route until just east of the cloverleaf and park on the shoulder.

We could spend hours at this series of exposures, but since time is limited we will restrict ourselves to three main features. First, proceed to exposures on the south side of "To 85" just east of junction with ramp from I-495 North along the south side of the cloverleaf. Here blastomylonite associated with a splay of the Assabet River Fault Zone is exposed. Later faulting at shallower depths produced fault breccia with a carbonate matrix, visible near the west end of the cloverleaf.

Next proceed with caution to the north side of the ramp from "To 85" to I-495 West, the center ramp in the interchange. Exposed along the north side of this ramp are examples of the two principal plutonic rock types in the Nashoba Terrane: intermediate composition diorites and peraluminous granites. The Straw Hollow Diorite is typical of the calc-alkaline dioritic to tonalitic bodies in the terrane. Most are hornblende or hornblende-biotite bearing and have sphene as an accessory mineral. The Straw Hollow contains at least two phases; a finer grained, more foliated phase has been intruded by a coarser grained, lighter colored, less foliated rock (Hill et al., 1984). The Straw Hollow is assumed to be similar in age to the Sharpners Pond Diorite to the northeast, dated at 430 Ma by Zartman and Naylor (1984). Granitic rocks in the Nashoba Terrane vary from two-mica foliated granites to unfoliated, garnet-bearing muscovite granites and pegmatites. Here, a coarse-grained phase of the Andover Granite is seen intruding the diorite. It has been sheared and deformed, likely at the same time that the blastomylonite seen on the other side of the cut was created. Note the Andover here for comparison with that we will see at Stop 2-7. At the east end of the outcrop, the Straw Hollow intrudes high grade pelitic schists containing kyanite pseudomorphs that have been replaced by sillimanite. (Please do not hammer on these.) Return to bus with care.

STOP 2-4. NASHOBA FM., ORDOVICIAN?, GNEISSES AND SCHIST, NASHOBA TERRANE (Berlin, MA; optional, 30 minutes). From Stop 2-3 proceed north on I-495. Exit at Rt. 62. Park along Rt. 62 at the bottom of the ramp from I-495 N. Examine the exposures along the east side of this ramp. <u>Beware of poison ivy!</u>

These exposures show some of the diversity within the Nashoba Fm., particularly among the gneisses. The gneisses commonly consist of biotite, quartz and plagioclase with varying percentages of these minerals in the different layers. K-feldspar may be an additional phase. More schistose beds may contain local garnet and/or sillimanite. Large muscovite flakes are likely retrograde. Minor amphibolite, calc-silicate granulite and dioritic sills are also present. Upper amphibolite facies metamorphic conditions prevail with granitic "sweats" starting to appear. The percentage of migmatitic melt generally increases to the NE in the Nashoba Terrane, as we will see at Stop 2-6. Note the multiple fold generations.

STOP 2-5. NASHOBA FM., ORDOVICIAN?, CALC-SILICATE GRANULITE AND AMPHIBOLITE (Berlin, MA; 50 minutes). From Stop 2-4 continue west on Rt. 62 for 2.1 mi. to flashing light in Berlin. Turn left onto Linden St. and continue for 0.5 mi. Park just before railroad tracks on the north side of the road. Walk north along dirt path adjacent to RR tracks and across the Corp of Engineers Flood Control Dam over North Brook, proceeding to the spillway at east end of the dam.

Calc-silicate granulite and marble occur at several horizons in the Nashoba Fm. This outcrop is likely correlative with calc-silicates in either the Beaver Brook or the Fort Pond Member of the Nashoba Fm. (Bell & Alvord, 1976). The calc-silicate granulites here contain diopside, actinolite, phlogopitic biotite, plagioclase, tourmaline and opaques. The deformation has been largely by flow in the more calcareous layers, and tectonic "fish" of originally more dolomitic or shaly layers (Hepburn and Munn, 1984) are readily observed . Garnet-bearing schistose rocks and amphibolites are present at the north end of the cut, and garnet-bearing amphibolites are present in outcrops 150 meters south along the spillway.

Return to I-495 and proceed north. Note large exposures of biotite gneiss and schist of the Nashoba Fm. along I-495 between Rt. 62 and Exit #28.

STOP 2-6. NASHOBA FM., ORDOVICIAN?, MIGMATITES (Harvard, MA; 30 minutes). Leave I-495 at Exit #28, Rt. 111 West. Turn right (west), cross over I-495 on Rt. 111 and stop 0.1 mi. beyond the bridge adjacent to large exposures on the right (north), opposite the entrance to I-495 South.

This large outcrop contains an excellent example of the migmatized Nashoba. Here biotite gneisses are interlayered with migmatitic gneisses and pegmatites. Sillimanite is commonly present with biotite in selvages along the rims of melted material. Muscovite is present in large, retrograded? flakes. Two generations of pegmatites are present here, the earlier having been deformed. It is believed that most of the pegmatite and granite in this outcrop is locally generated by anatexis of layers with the appropriate composition. Observe how the percentage of melt changes with the composition of the original layer. It is believed, although not yet firmly established, that when melting in the Nashoba reached sufficient proportions for the magma to coalesce and move, it formed the younger phases of the Andover Granite (Hepburn and Munn, 1984). Late brittle faults with gouge cut the outcrop.

LUNCH STOP. NORTH BRIDGE OVER THE CONCORD RIVER, MINUTE MAN NATIONAL HIST. PARK, CONCORD, MA. (40 minutes). Site of "the shot heard 'round the world" where the colonists first fired upon the British troops, April 19, 1775, starting the American Revolution.

STOP 2-7. ANDOVER GRANITE, SILURIAN, NASHOBA TERRANE (Bedford, MA; 25 minutes). From Concord continue on Rt. 62 east until junction with Rt. 3 in Bedford. Park on south side of Rt. 62 and examine exposures along the east side of the entrance ramp from Rt. 62 to Rt. 3 South.

The characteristic pink to white, unfoliated, muscovite-rich granite and granitic pegmatites of the Andover Granite are exposed here. This is the location from which the sample dated by Dunning gave the 412 ± 2 Ma age (Figure 6A). The dated rock represents the youngest granite in the outcrop and is believed to be one of the youngest phases in the Andover complex. It cross-cuts, or contains within it fragments to blocks of foliated Andover Granite, a more mafic granodiorite or diorite, and biotite gneiss of the Nashoba Fm.

STOP 2-8. FISH BROOK GNEISS, CAMBRIAN, NASHOBA TERRANE (North Andover, MA; 45 minutes). From junction of Rt. 114 and 62 in Middleton, proceed west on Rt. 114 approx. 4 mi. to the North Andover town line. In 0.2 mi. turn right onto Sharpners Pond Rd. and go straight to the end (approx. 1 3/4 mi.) to the entrance of Boxford State Forest. Park at the guard rails blocking the continuation of the road and walk the dirt path straight ahead for approx. 1/4 mi. to a large, semi-cleared area to the right of a small pond.

The Fish Brook Gneiss is a gray, fine- to medium-grained biotite-bearing felsic gneiss with a particular "swirled" foliation (Bell and Alvord, 1976). Biotite schist, biotite gneiss and amphibolite are present in minor amounts as inclusions. Granitic and pegmatitic dikes cutting the Fish Brook are believed related to the Andover Granite.

The origin of the Fish Brook Gneiss and particularly its unusual foliation have been variously interpreted. Is the foliation an original, perhaps volcanic, feature enhanced by tectonism? Or has this unit experienced greater deformation (and an additional deformational event?) compared to the rest of the Nashoba Terrane, indicating that it is an older basement? Bell and Alvord (1976) included the Fish Brook as part of the stratigraphic sequence of the Nashoba Terrane and interpreted its origin as a waterlaid tuff. Olszewski (1980) obtained zircons from this and other Fish Brook localities which yielded a zircon Pb-U upper intercept age of 730 ± 26 Ma, which he interpreted to represent a crystallization age of an original volcanic protolith. New analyses from rocks at this site gave the concordia plot shown in Figure 6B and an age of 520 +14/-11 Ma for the original crystallization of the Fish Brook. This makes the Fish Brook Gneiss early Paleozoic, not Precambrian basement. Consequently, it is unlikely that it was separated from the other stratified units of the Nashoba Terrane by a major unconformity. The 425 ± 3 Ma age on monazite (Figure 6B) from this exposure is interpreted to represent the time of metamorphism for the Nashoba Terrane.

STOP 2-9. SHARPNERS POND QUARTZ DIORITE, SILURIAN, NASHOBA TERRANE (Newbury, MA; 30 minutes). Exit from I-495 N at Exit #56, Scotland Rd., Newbury-Newburyport. At the end of the exit ramp turn left, pass under I-495 and park on right shoulder. Walk to exposures on the north side of Scotland Rd., just west of I-495, and along the entrance ramp to I-495 South, near where it joins I-495.

The Sharpners Pond Pluton (approx. 60 sq. mi.; Hon et al., 1986) is the largest of the intermediate calc-alkaline plutons in the Nashoba Terrane. It is dated at 430 ± 5 Ma from zircons (Zartman and Naylor, 1984) and consists largely of hornblende diorite, hornblende-biotite tonalite and biotite tonalite (Castle, 1965). Much of the pluton is rather homogeneous with these rock types grading gradually into one another. Sphene is a characteristic accessory phase. Near its eastern border, as seen here along the ramp to I-495 S, the Sharpners Pond Pluton exhibits complex brecciation, "pillowing" and magma mixing of the more mafic rocks within a granitic matrix. Geochemical study indicates that the granite and the mafic to intermediate rocks are not co-genetic. The granitic rocks likely represent anatectic melts formed in response to higher temperatures that resulted from the intrusion of the more mafic magmas. These two magmas interact to form a variety of structures, as shown in these exposures (Hon et al., 1986).

Turn around, follow Scotland Rd. east to Park St. and Rt. 1 in Newbury. Go south on Rt. 1.

STOP 2-10. NEWBURY VOLCANIC COMPLEX, LATE SILURIAN-EARLY DEVONIAN, PORPHYRITIC ANDESITE (Rowley, MA; 25 minutes) From Newbury continue south on Rt. 1, crossing the Parker River. 1.5 mi. south of the river turn left (east) onto Central St. and park along the road as soon as possible. Outcrops are on both sides of Central St. near the intersection with Rt. 1.

The Newbury Volcanic Complex consists of a series of andesitic and rhyolitic volcanic rocks and associated sediments that lie entirely within fault slivers along the Bloody Bluff Fault Zone, directly between the Boston-Avalon and Nashoba Terranes (Figure 1). It is well dated as latest Silurian to possibly Early Devonian on the basis of shelly fossils found in associated sediments at this locality (but hidden beneath the pavement today) as well as other nearby sites (Shride, 1976b). The exposures here, at the so-called Glen Mills site, are tuffs and flows of the porphyritic andesite member (Shride, 1976a, b). The top of each flow is recognizable by the presence of a vesicular band. Note the differences in the phenocryst content between the flows.

Tectonically the Newbury, while tilted, is important because it demonstrates the lack of penetrative deformation and metamorphism higher than the lowermost greenschist facies during the Acadian or subsequent orogenies. Notice the undeformed nature of the plagioclase phenocrysts and the filled amygdules in the outcrop. (Contrast this to the Silurian deformation seen earlier in the adjacent Nashoba Terrane).

Geochemically the Newbury Volcanic Complex consists of a volcanic suite of andesites and rhyolites (Shride, 1976a). The andesites are high-alumina calc-alkaline rocks with trace element signatures indicative of formation on a continental margin above a subduction zone (McKenna et al., 1993). The Newbury Volcanic Complex is similar in age and overall composition to volcanic rocks in the Coastal Volcanic Belt of eastern Maine (Gates and Moench, 1981). Hon et al. (1986) suggested that the similarity in the chemistry between the Newbury and the plutonic rocks of the Nashoba Terrane could indicate the Newbury are preserved volcanic remnants of this terrane.

STOP 2-10A. NEWBURY VOLCANIC COMPLEX, RHYOLITE (Newbury, MA; optional, 20 minutes). From Stop 10 turn around, then turn right onto Rt. 1 and proceed north 0.9 mi. Turn left onto Elm St. (toward Governor Drummer Academy). Almost immediately pull off and park by a small outcrop on the right. The rock is a purplish flow-banded rhyolite in the Newbury (Member 6 of Shride, 1976 a, b).

STOP 2-11. BLOODY BLUFF FAULT ZONE, NEAR THE BOUNDARY BETWEEN BOSTON-AVALON AND NASHOBA TERRANES (Minute Man Natl. Hist. Park, Lexington, MA; optional, 30 minutes). From Stop 10 return to Rt. 1 south, follow to Rt. 133 west and take I-95 south and west to junction of Rt. 2A in Lexington, Exit #30B. Exit on 2A west, toward Concord. At the end of the exit ramp turn right and proceed 0.2 mi. to Massachusetts Ave. (just past the hotel entrance on right, opposite the road to Minuteman Tech. on the left). Turn right onto Mass. Ave. Proceed 0.2 mi. to curve at the south end of Fiske Hill. Park along the right side of the road. Walk across the road to the lighter colored outcrops. No hammers. This is a National Park.

Exposures along the north side of the road consist of mylonitized granite (Dedham Granite?) and mafic rocks within the Bloody Bluff Fault Zone in its type area. The Bloody Bluff Fault Zone separates the Nashoba Terrane on the west from the Boston-Avalon Zone on the east and has had a long and complex history of movement. See Nelson (1987) for a more complete description of this exposure. The fault zone here is on the order of a kilometer wide. The rocks have a well-developed mylonitic foliation dipping to the northwest. Differences in the response of the granitic and mafic rocks to the shearing are evident here.

Continue on Mass. Ave. for another 0.1 mi. until the intersection with the first road on left (Do not cross over I-95). Turn left onto Wood St., proceed 0.1 mi. and turn left onto Old Mass. Ave. Follow this for 0.5 mi. to junction with Rt. 2A. Park in the lot at left and walk to the outcrop to the right of the road junction. The small rusty-weathered exposure is "the" Bloody Bluff. The rock is an altered and shattered granite (again, likely Dedham). Bloody Bluff and Fiske Hill were sites of skirmishes between the colonists and the retreating British troops on April 19, 1775, following the outbreak of hostilities at North Bridge earlier that day. Due to casualties (and not the rusty coloration), the rock and consequently the fault zone received its sanguine name.

Follow Rt. 2A east to I-95, then back to the hotel.

ROAD LOG - DAY 3
BOSTON-AVALON TERRANE

STOP 3-1. IGNEOUS COMPLEX, WESTERN BOSTON-AVALON TERRANE (Waltham, MA; 30 minutes). From the hotel proceed north on I-95 to exit for Wyman St.-Winter St., Waltham. At end of exit ramp (0.3 mi), turn right. In 0.2 mi. turn right again and follow Winter St. west across I-95. In 0.4 mi. stay straight and follow Winter St. around the Cambridge Reservoir. In 1.2 mi. turn left into the Bay Colony Corp. Center. Follow road uphill past outcrops for 0.25 mi. Park in the turnout opposite the entrance to 950 Winter St. and walk back along entrance road to outcrops.

The westernmost portion of the Boston-Avalon Zone, to the west and north of Boston, is underlain by a complex series of largely mafic plutonic and volcanic rocks shown on the Massachusetts Geologic Map as Zdigb and Zv (Zen et al., 1983). Clearly, several ages of plutonic rocks are present in this area (subzone 2 of Hepburn et al., 1987a) but few details on their ages or chemistries have yet been firmly established. The purpose of visiting this locality is to demonstrate the complexity of the igneous rocks found throughout this belt, as well as to see the diorite recently dated as Devonian (373 ± 4 Ma; Figure 5F). Compare this rock with the gabbro-diorite seen further north in this belt (Stop 1-7) from which the syenitic pod yielded the 444 Ma date. These dates indicate that the Boston-Avalon Terrane experienced a major, prolonged period of mafic magmatism spanning the Ordovician to Devonian, in addition to the well recognized peralkaline granitic plutonism of the same time period (Cape Ann, Peabody, Quincy, etc.).

The rocks seen here include xenolithic blocks of pre-630 Ma Westboro Fm. (quartzite) and Middlesex Fells Volcanics (fine-grained epidotitized mafic rocks), the dated medium-grained diorite, finer grained gabbro-diorites and several generations of granitic dikes. One granitic dike contains spectacular, elongated, magmatic pillows of diorite.

STOP 3-2. ROXBURY FM., LATE PROTEROZOIC, BOSTON BAY GROUP (Wellesley, MA; 30 minutes). South on I-95 (Rt. 128), take exit #20 for Rt. 9 east. After about 0.25 miles bear right onto 1st exit road. Park beside old stone building, an 18th century nail factory, on the right (south) just before crossing the Charles River. Take trail on west side of the river to Hemlock Gorge and outcrops along river. You can continue up the trail to the top of the gorge where Echo Bridge, designed by Boston's famous 19th century architect H.R. Richardson, carries a water aqueduct across the river. Turn right (west) to see outcrops along the grade of the aqueduct. You can return to vehicles by the same trail or by crossing the aqueduct and descending stairs at east end of bridge. The latter will give you a chance to try out your echo.

The polymictic clast-supported conglomerates in the outcrops near the Charles River are typical of the Brookline Mbr. of the Roxbury Fm. Dominant clast lithologies are felsites, granites, and well rounded to subrounded quartzites (similar to the Westboro seen at Stop 1-6). Conglomerate matrix and interbedded sandstones are feldspathic litharenites; silicified felsite fragments are the dominant detrital framework sand grains (Figure 3). Most outcrops of Roxbury are apparently homogeneous. At some localities where sandstone and siltstone interbeds are common, large conglomerate-filled channels may be discerned. This lack of sedimentary structures within most of the Roxbury makes it difficult to infer mechanisms of transport and environments of deposition. Some outcrops have bedding characteristics and structures indicative of braided streams and fan deltas, while other outcrops are best explained by subaqueous gravity flow processes. It is possible that the unit was deposited in a variety of basin marginal environments.

STOP 3-3. WESTWOOD GRANITE, LATE PROTEROZOIC (Dedham, MA; optional, 30 minutes). From Stop 3-2 proceed south on I-95 and exit at Rt. 109, Westwood. At end of ramp turn left (east) on Rt. 109, cross I-95 and park opposite the entrance ramps to the northbound lane of I-95. Walk north, along the curved exit ramp from I-95 N to Rt. 109.

The Westwood Granite intrudes the Dedham Granite and is likely co-magmatic with the Mattapan Volcanics (Stop 3-4) (Wones and Goldsmith, 1991). The 603 ± 3 Ma U-Pb zircon date on the Mattapan (Kaye and Zartman, 1980) likely gives the best age estimate for the Westwood. The Westwood is characteristically light-colored, often pink to salmon weathering, notably finer grained than the Dedham, lacks hornblende and has a lower color index (Wones and Goldsmith, 1991). Also present in this exposure are a number of mafic dikes, as well as various intermediate to mafic inclusions.

STOP 3-4. MATTAPAN VOLCANICS, LATE PROTEROZOIC, BRECCIA (Westwood, MA; 25 minutes). From Stop 3-3, turn around and head SW on Rt. 109 to Westwood. At junction of Hartford St. in Westwod Center, stay to the left on Rt. 109, note the mileage. Continue on Rt. 109, 0.8 mi. to exposures on the right (north) side of Rt 109 (High St.) opposite the junction of Lake Shore Drive and the Westwood Veterans Memorial.

The Mattapan Volcanic Complex likely formed a co-magmatic volcanic-plutonic complex with the Westwood Granite, similar in many ways to that seen on Day 1 between the Lynn Volcanics and Dedham North Granite (Kaye, 1984). The Mattapan is thought to be the source of many of the felsic pebbles in conglomerates of the Boston Basin. Here, a volcanic breccia in the Mattapan is exposed. Most of the fragments in the breccia are felsite from the Mattapan itself or pieces of Dedham Granodiorite (Chute, 1964). Thompson and Hermes (1990) have interpreted this breccia as originating during collapse of a caldera.

STOP 3-5. WAMSUTTA FM., PENNSYLVANIAN, NORFOLK BASIN (Canton, MA; 30 minutes). South on I-95, take Exit #62 onto University Ave. Proceed for about 1 mi. and turn left at stop sign onto Dedham St. Proceed for about 0.7 mi. and turn right just beyond interstate overpass into Shawmut Industrial Park. Follow Shawmut Rd. to SW corner of park and turn right (toward railroad tracks) at back end of warehouses. Outcrop is a blasted face adjacent to tracks and a series of natural exposures to north. Danger - these tracks are heavily travelled by high speed commuter trains - keep off tracks.

About 90 m of Pennsylvanian strata form a large scale, upward coarsening sequence that lies approximately 940 m above the basal unconformity (Stop 3- 6). The lower portion of the section consists of black and red shale with dark interbedded feldspathic litharenites (Figure 10). A caliche horizon of small carbonate nodules occurs in one

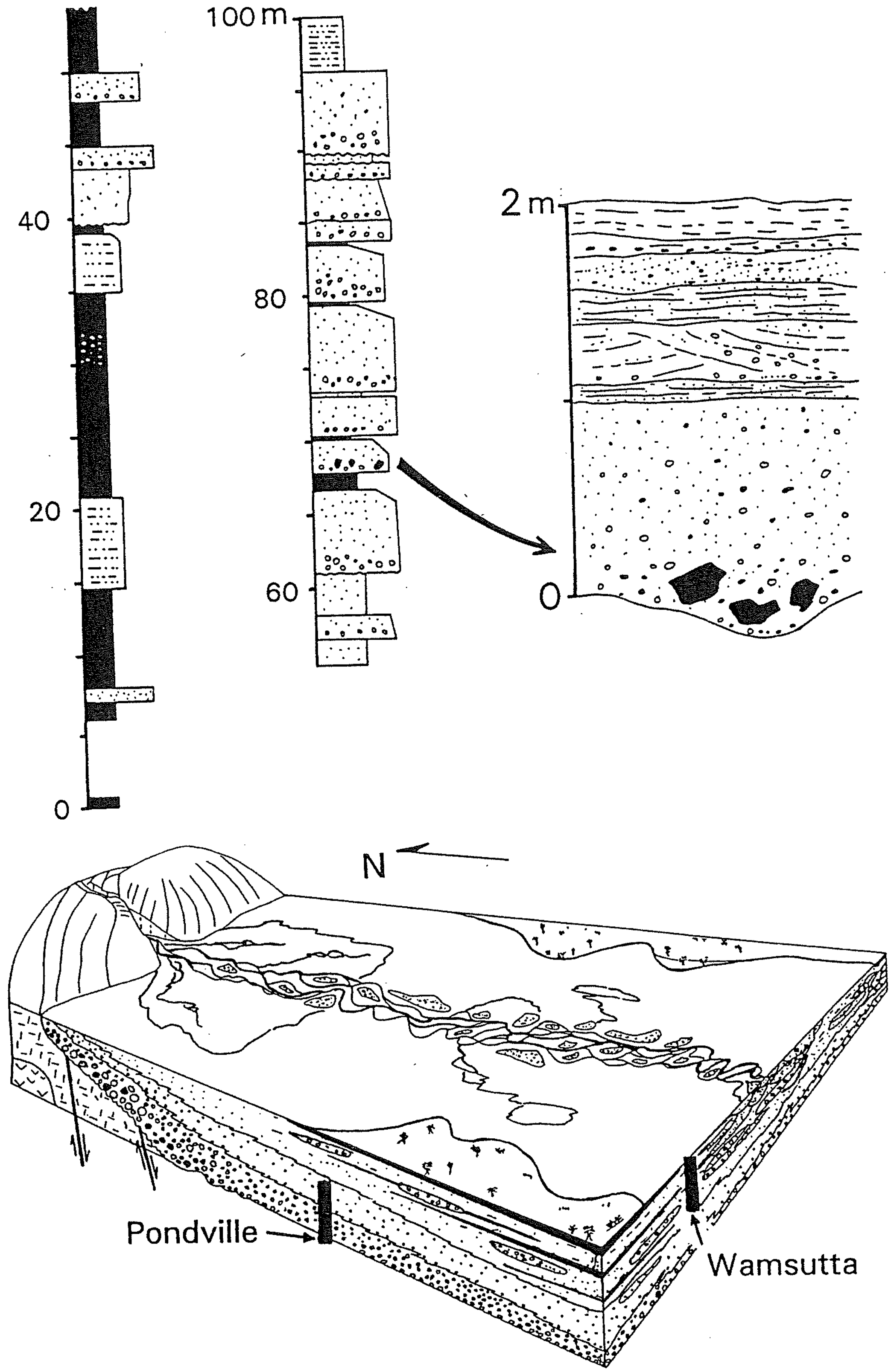

Figure 10. Stratigraphic section of Wamsutta Formation at Shawmut Industrial Park, Stop 3-5. Small inset section shows detail in one fining upward cycle. Block diagram shows facies relations and paleoenvironmental setting of the northern margin of the Norfolk Basin.

sequence of red mudstones (Figure 10), and portions of the black shales are carbonaceous. The upper part of the section is a sequence of polymictic conglomerates, sandstones, thin mud drapes and thin interbeds of dark mudstone organized in fining upward cycles. This part of the section may be interpreted as a series of flood cycles in a broad, shallow, braided stream system. The abrupt occurrence of mudstones beneath the conglomerate floored channels and large angular mudstone intraclasts in these conglomerates probably resulted from channel avulsion and lateral migration of the braided stream onto overbank deposits. Planar bedded and trough cross-bedded sandstones were probably deposited on tops of longitudinal bars migrating downstream. The lower portion of the section represents overbank environments or possibly large muddy intrachannel islands. Sandstones in this lower sequence probably represent tributary channel or channel avulsion deposits.

This outcrop is unusual because it has both the highest proportion of mudstone and the coarsest conglomerates of any measured Wamsutta section in the Norfolk Basin. This textural paradox might be the result of tectonic rejuvenation or wet climatic cycles that increased the competence of rivers.

The Alleghanian deformation in the Boston area is demonstrated by this exposure. It has folded these strata into vertical to slightly overturned beds, introduced a well-developed fracture cleavage into the mudstones and produced tension gashes filled with quartz, carbonate or chlorite. However, the rocks in this part of the Norfolk Basin are still submetamorphic (diagenetic zone; based on illite crystallinity from this exposure, Hepburn and Rehmer, 1981).

STOP 3-6. UNCONFORMITY AT BASE OF PENNSYLVANIAN PONDVILLE FM. AND PONDVILLE - WAMSUTTA TRANSITION (Quincy and Randolph, MA; 45 minutes). South on I-95. Take exit for Rt. 28 north, proceed north under I-95, make U-turn and park on the west side of Rt. 28 in a small pull-off that is just before the on-ramp for the northbound lane of I-95. Walk down the on-ramp toward the northbound lane of I-95 and cross over to large roadcut. Watch for speeding vehicles on roadway. To see the transition of the lower and upper members of Pondville walk back around on-ramp and south under I-95, enter gate between north and south bound lanes and walk down old road for about 100 m. To see the transition of the upper member of Pondville with overlying Wamsutta walk or drive to off-ramp of south bound lane of I-95. Pondville/Wamsutta transition is at north end of the cut along the off-ramp.

This spectacular roadcut exposes the southerly dipping (about 70^{o}) nonconformity between the Ordovician Blue Hills Igneous Complex (Blue Hills Porphyry) and the lower member of the Pondville Formation. Starting from the unconformity, about 94 m of the Pondville boulder conglomerate (lower member) is overlain by 91 m of pebbly granule and coarse sandstone (upper member),which grades upward into 45 m of Wamsutta red sandstones and mudstones. Moving northward from the nonconformity and into the Blue Hills Complex there is a thin zone of dense reddish aphanitic material with quartz phenocrysts. This is underlain by an interval of greenish porphyry spheroids (10 to 30 cm in diameter) in a phenocryst-bearing aphanitic groundmass. Below this the porphyry has been fractured, but the blocks have not been transported; and this zone grades into more typical homogeneous porphyry with quartz and microperthite phenocrysts.

A great deal of entertaining debate has focused on the origin of the "spheroidal zone" below the unconformity. A popular early interpretation was that the spheroids represent a Pennsylvanian paleosol developed on the exposed Blue Hills Igneous Complex. Other explanations have utilized magmatic and/or volcanic processes. The mineralogy and geochemistry of the spheroidal zone is a very close match with that of the rest of the Blue Hills Porphyry, which is co-magmatic with the Quincy Granite, so we do have some constraints on our speculation. Entertain us with your hypotheses.

The environment of deposition of the Pondville boulder conglomerate is intriguing. A likely geomorphic setting for such a coarse deposit could be the bedrock-floored mouth of a canyon at the apex of an alluvial fan. This extremely coarse conglomerate is restricted to a region less than 1 km broad along the northern margin of the Norfolk Basin. Clasts in the Pondville are mostly from the Blue Hills Igneous Complex; but curiously, typical Quincy Granite is very rare or not present. It is possible that during the Pennsylvanian the deeper portion of the igneous complex was still not exposed by erosion. Slate, basalt, and quartzite clasts are also present.

The Wamsutta outcrop south of I-95 is a sequence of upward-fining sandstone-mudstone fluvial cycles that exhibits an overall upward-fining megacycle. Sandstone beds are typically capped by a zone of mud cracks or mud curls. The entire I-95/Rt. 28 outcrop belt is a retrogradational "gigacycle" deposited in environments of diminishing transport energy. As the early rift topography was subdued by erosion more sluggish braided streams buried the source terrain. This retrogradation of sediments over a bedrock surface is reminiscent of pediment formation and burial in modern dry climates. Stream gradients would be re-established with subsequent tectonism and basin margin uplift (Cazier, 1987).

STOP 3-7. QUINCY GRANITE (ORDOVICIAN) AND BRAINTREE ARGILLITE (MIDDLE CAMBRIAN), IN THE QUINCY QUARRIES (Quincy, MA; 45 minutes). Take I-95 south to Rt. 3 north, exit for Furnace Brook Parkway but stay on ramp (rotary) to north and exit right onto Willard St., if you miss the turn go around the rotary and try again. Proceed north on Willard St. and turn left at stop sign. Go under Rt. 3 overpass and turn right onto Ricciuti Dr. at "Mr. Tux." Proceed about 0.5 mi. and park at sign indicating the trail to Quincy Quarries.

Quincy Granite. The Quincy Granite is characteristic of the early to mid-Paleozoic peralkaline intrusions into the Boston-Avalon Terrane (recall also the Peabody Granite, Stop 1-8) and forms the Blue Hills Igneous Complex along with the Blue Hills Porphyry. The Wampatuck Volcanics of the Blue Hills (Billings, 1982) may be an extrusive phase (Hermes and Murray, 1990). The Quincy Granite intrudes the Middle Cambrian Braintree Argillite, and although difficult to date (Naylor and Sayer, 1976) it has yielded a 450 ± 25 Ma (Ordovician) date by U-Pb methods (Zartman and Marvin, 1991). Typically the rock is a dark gray to green-gray, medium-grained, hypersolvus microperthitic granite with hypidomorphic texture. Riebeckitic amphiboles and acmitic pyroxenes are present (Wones and Goldsmith, 1991). While difficult to see from our stop at the top of the quarries, riebeckite can be found coating joints and slickenside surfaces (Wones and Goldsmith, 1991).

The Blue Hills Porphyry (not present at this stop) contains microperthite and quartz phenocrysts in an aphanitic matrix. Major and trace element chemistry indicate that the Blue Hills Porphyry and Quincy Granite are likely co-magmatic. Coarse-grained phenocryst-rich phases of the porphyry grade into true Quincy granite, and in some cases it is difficult to distinguish between the two. It is likely the Blue Hills Porphyry represents a hypabyssal, chilled border phase of the Quincy (Naylor and Sayer, 1976). At Stop 3-6 we saw a very fine-grained, matrix-rich version of the porphyry that might represent quenched magma at or near the margin of the pluton.

As evidenced by these large, abandoned quarries, the Quincy Granite has been used extensively as a building stone in the Boston area (e.g., Quincy Market) and elsewhere. The rock takes a good polish and has a distinctive gray to dark gray-green color. Quarrying began in 1815 but did not become extensive until the building of the Bunker Hill Monument. The first commercial narrow-gauge railroad in the United States was built to haul granite from Quincy to the monument's site in Charlestown (Skehan, 1975). Since there is no longer any commercial quarrying, many of the quarries have been preserved as public parks and reservations (to the delight of geologists, rock climbers and graffiti artists).

Braintree Argillite. A small pile of spoil excavated at or very near the original site of the famous Hayward Creek "trilobite" quarry in the Braintree Formation is about 5 m into the woods on the south side of the road, and about 50 m west down Ricciuti Dr. from the quarry trail parking area.

This spoil was produced when a drydock that now occupies a perfectly good trilobite locality was enlarged in the early 1970's. There are no extant collecting localities in the Braintree so the shipyard company dumped some of the spoil here for collecting. (When was the last time you searched for trilobites in a granite quarry?) The material in this pile is fresher and much more fossiliferous than any natural exposures that can be seen at present. The rock is a gray, brittle, silicified mudstone or argillite. Disseminated pyrite and small vugs filled with euhedral pyrite are commonly associated with the black trilobites. Bedding is obscure except where it is defined by fossils. There is no shortage of pieces of *Paradoxides* in the pile, but with individual trilobites up to 45 cm long, you are unlikely to recover more than a pygidium, a genal spine, or a piece of a cephalon. Correlative Middle Cambrian strata in Newfoundland were deposited on a deep water muddy shelf, and the Braintree Fm. probably accumulated in a similar environment.

STOP 3-8. SQUANTUM "TILLITE" MBR. OF THE ROXBURY FM., LATE PROTEROZOIC, BOSTON BAY GROUP (Squaw Rock Park, Quincy (Squantum) MA; 45 minutes). Go north on Rt. 3, exit at Granite Ave. Proceed north on Granite Ave. to intersection with Gallivan Blvd. Turn right on Gallivan Blvd. and proceed to Neponset Circle (intersection with Rt. 3). Follow signs for Rt. 3A to Quincy, stay in left lane and bear left onto Quincy Shore Drive after crossing Neponset River. Proceed on Quincy Shore Drive for 0.9 mi. and turn left at light onto Squantum St. Proceed on Squantum St. and bear left, following shoreline, onto Dorchester St. Just before causeway, turn left into parking area for VFW post. Follow trails to north then west along shoreline to outcrop A (Figure 11).

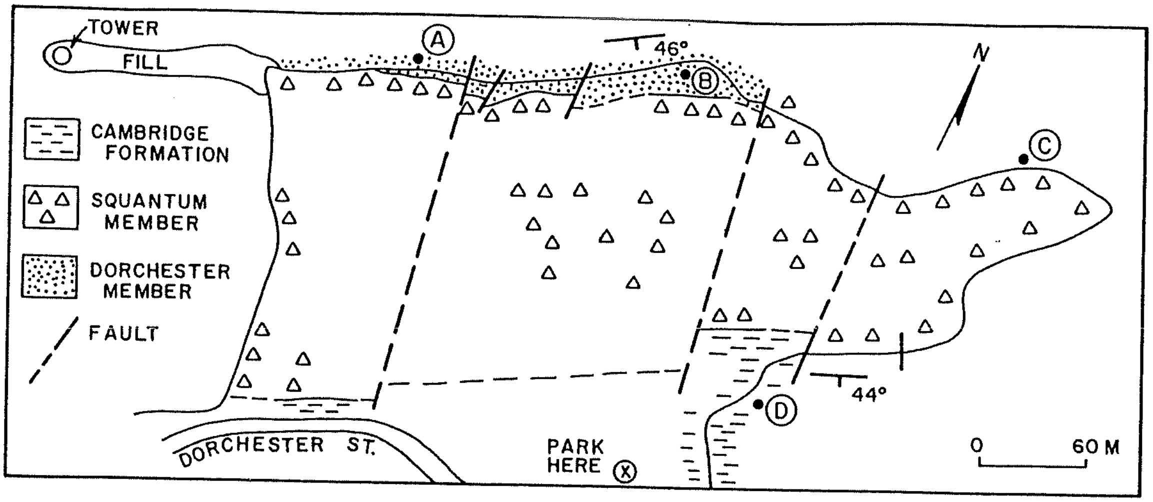

Figure 11. Simplified geologic map of Squantum Head, Squaw Rock Park, Quincy MA.

A 130 m sequence of polymictic diamictite beds, sandstones, and conglomerates comprise the heterogeneous unit mapped as the Squantum "tillite" or Squantum Member. The rocky headland known as Squaw Rock has the best and most extensive exposure of the Squantum in the Boston Basin. A unit of thinly laminated gray sandstones with graded beds and several scales of slump folds (mapped as the Dorchester Member of the Roxbury Fm.) underlies the diamictite sequence . Purple to gray mudstones with extensively deformed beds and pods of pebbly and granule sandstone overlie the diamictite (mapped as the Cambridge Argillite). The interbedded contacts of all units are fully exposed.

The base of the diamictite sequence is a chaotic interval of cobbles and boulders and intraclasts up to 2 m long in a purple-gray muddy matrix. Clasts in the diamictite are predominantly felsites and granites with some well rounded pebbles and cobbles of quartzite. This heterogeneous interval resulted from a spectrum of gravity mass transport processes ranging from low density cohesionless flow to high density plastic flow. See Bailey, in Newman et al., this volume, Chapt. U, for more details on the question of glaciation during the deposition of the Boston Bay Group.

Numerous faults cut the headland and offset the stratigraphy. Fine sandstones and mudstones have a strong cleavage that strikes nearly parallel to bedding and dips to the north at 60^{o} to 70^{o} degrees. This cleavage is also well expressed in the mudstone matrix of the diamictites but is deflected around clasts in the matrix.

End of Field Excursion

Return to Rt. 3 North and proceed to Logan Airport.

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