SILURO-DEVONIAN IGNEOUS ROCKS OF THE EASTERNMOST THREE TERRANES IN SOUTHEASTERN NEW ENGLAND: EXAMPLES FROM NE MASSACHUSETTS AND SE NEW HAMPSHIRE

by
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INTRODUCTION

Siluro-Devonian igneous rocks in northeastern Massachusetts and adjacent southern New Hampshire have been the subject of mineralogical, petrological and geological studies for over 150 years (Rodgers *et al.,* 1989; Brady and Cheney, 2004), but only in recent times has it been recognized that these rocks lie in three distinct geological terranes. These rocks include a diverse variety of plutonic and volcanic rocks ranging in chemistry from peralkaline to calc-alkaline. Of particular note are the widely known mid-Paleozoic alkaline plutons that include the type localities of both the rock "essexite," nepheline monzogabbro to nepheline monzodiorite (Sears, 1891), and the mineral "annite," iron biotite (Dana, 1868). This field excursion is designed to demonstrate the diversity of the igneous rocks in the area and to visit (weather permitting) some of the classic localities. Throughout the excursion, the relationship of the timing and petrogenesis of the magmatism to the tectonics will be considered.

It is impossible to exhaustibly discuss or credit all the work that has led to our current understanding of the igneous rocks in this region. The list includes many petrologists such as H.S. Washington, N. S. Shaler, C. H. Clapp, N. L. Bowen, J. F. Schairer and C. Palache who worked on these rocks through the years, particularly the alkaline rocks of the Cape Ann Plutonic Complex (see listing in Brady and Cheney, 2004). More recent detailed studies include those of Toulmin (1964b) who mapped the Salem quadrangle in detail and Dennen (1991a, b, 1992) who mapped the Ipswich, Marblehead North, Gloucester and Rockport quadrangles and was able to subdivide the Cape Ann Complex on the basis of the quartz abundance in the rocks. More regional studies of the area of the field trip include those of Zen *et al.* (1983), Goldsmith (1991a,b), Wones and Goldsmith (1991) and Lyons *et al.* (1997). Numerous field excursions have traveled to the area. Recent trips from the New England Intercollegiate Geological Conference (NEIGC), the Geological Society of America and the 28th International Geological Congress include those by Toulmin (1964a), Dennen (1976), Shride (1971b), Hon *et al.* (1986, 1993), Zen (1989), Hepburn *et al.* (1993), Hussey and Bothner (1995), Hon and Hanson (2004), Hanson and Hon (2004), Brady and Cheney (2004), Ross (2004), Thompson *et al.* (2004) and Hepburn (2004). Brady and Cheney's trip (2004) shows that the Cape Ann Complex is an excellent suite of exposures to visit with petrology students. Today's excursion draws heavily on the material and stops in these guides and the participant is referred to these for more detailed descriptions of the rocks than space permits herein.

GEOLOGIC SETTING

The eastern margin of the Appalachian orogen in southeastern New England is underlain by three distinct geologic terranes. From east to west these are: the composite Avalon terrane of southeast New England, the Nashoba terrane and the Merrimack belt or Merrimack trough (Fig. 1). These terranes are fault-bounded and no units can be directly correlated between them. Current tectonic interpretations indicate that these terranes formed near the Gondwanan continental margin and then later interacted with and were accreted to terranes to the west adjacent to Laurentia during the mid-Paleozoic (e.g., Rast and Skehan, 1993; Rankin, 1994; van Staal *et al.*, 1998; Keppie *et al.*, 1998). Some combination of them likely served as the driving force for the Acadian Orogeny (L. Sil. - M. Dev.). However, later Paleozoic movements on the faults both within and between these terranes are undoubtedly present in the area and the amount of Alleghenian magmatism, deformation and metamorphism generally increases toward southern New England.

Composite Avalon Terrane of SE New England

The composite Avalon terrane of southeastern New England (herein abbreviated as the Avalon terrane) underlies the area east of the Bloody Bluff fault zone (Fig. 1). This terrane shares many features in common with the type Avalon of eastern Newfoundland including those critical for establishing it as a fragment of "Avalonia" such as a major ~585-630 Ma calc-alkaline magmatic event and Cambrian platformal sediments bearing an Acado-

Baltic fauna (e.g., O'Brien *et al.*, 1983; Rast and Skehan, 1983; Williams and Hatcher, 1983; Thompson *et al.*, 1996). In Massachusetts, the Avalon terrane has only been weakly regionally metamorphosed to the lower or middle greenschist facies and is essentially unaffected by Acadian deformation.

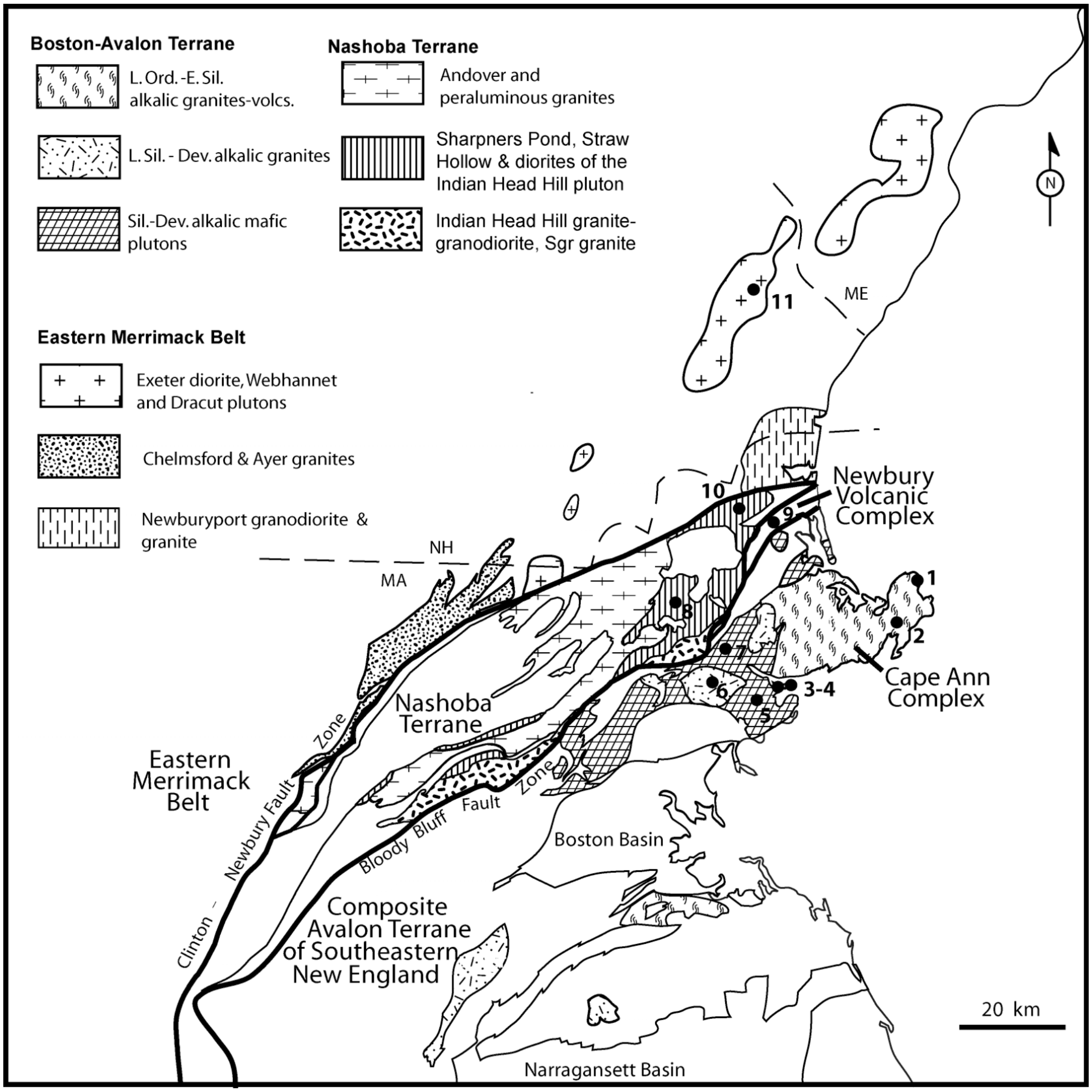


Figure 1. Location map with field trip stops. Base geologic map modified after Zen *et al.*, 1983.

The Avalonian Neoproterozoic calc-alkaline magmatism formed in a continental suprasubduction zone setting and batholiths of this age make up the bulk of the rocks exposed at current levels of erosion in the Avalon terrane in southeastern Massachusetts (Zen *et al.*, 1983; Wones and Goldsmith, 1991). These rocks form a typical I-type plutonic-volcanic magmatic association with the majority of the plutonic rocks ranging in composition from granodiorite to granite.

Following this Neoproterozoic arc magmatism, the Avalon terrane in Massachusetts was magmatically quiescent for ~100 my during which time the area was undergoing shallow water shelf sedimentation. When magmatism returned in the late Ordovician, it was of a very different type. From the late Ordovician through the mid-Devonian the Avalon terrane in Massachusetts was intruded by a bi-modal series of A-type alkaline granitoids and alkaline to transitional gabbros, diorites and related rocks (Hermes and Zartman, 1985, 1992; Zartman and

Marvin, 1991) (Fig. 2). These likely occurred in two general series. The older series, from late Ordovician to early Silurian predates metamorphism in the neighboring Nashoba terrane and volcanism within the adjacent Newbury Basin. The younger series, from late Silurian to middle Devonian postdates both events. However, many of these plutons were dated more than 25 years ago and some ages have relatively large errors (see summary in Zartman and Marvin, 1991).

Alkaline Granitic Rocks – The Older Series. The Cape Ann Plutonic Complex (Fig. 1), along with the Quincy Granite and the associated Blue Hills Porphyry south of Boston are the principal components of the L. Ord.-E. Silurian alkaline granitoids. Zartman and Marvin (1991) assign an age of 450 ± 25 Ma to these rocks (Fig. 2). The first five stops on this field trip will be rock exposures within this series north of the Boston Basin.

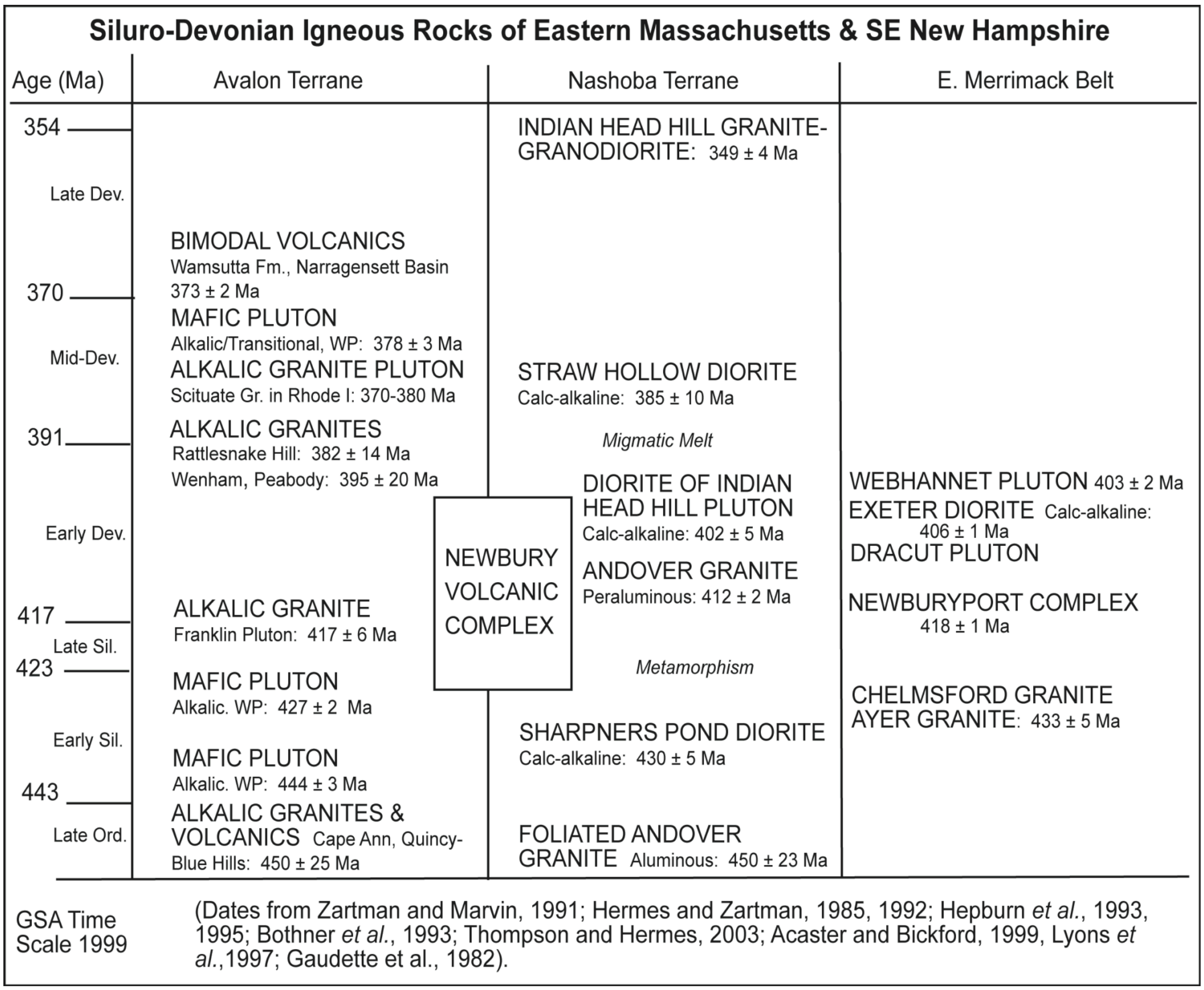


Figure 2. Siluro-Devonian Igneous Rocks in Eastern Massachusetts and Southeastern New Hampshire.

Cape Ann Plutonic Complex and Related Rocks. The Cape Ann Plutonic Complex (CAPC), of most interest for this field excursion, underlies some 385 km^2 of Cape Ann and adjacent areas (Wones and Goldsmith, 1991). It includes mainly felsic intrusives although bodies of alkaline diorite and gabbro, assumed to be co-genetic with the granites (Dennen, 1981; Wones and Goldsmith, 1991), are present in this section. The CAPC principally encompasses an area underlain by hypersolvus perthitic granites to quartz syenites (Cape Ann Granite), syenitic rocks (Beverly Syenite), and a small two feldspar intrusion (Squam Granite) completely surrounded by Cape Ann Granite. Aerially, the CAPC covers the entire Cape Ann peninsula plus an adjacent region that extends southwesterly to Salem, MA and northward to Ipswich, MA (Zen *et al.*, 1983). Mafic rocks, largely of alkali olivine affinities are commonly present and ubiquitous throughout the Complex observed as dikes, enclaves, and minor bodies intruding both the CAPC granites and the syenites. Near its western border, the CAPC rocks are intensely intermingled with mafic rocks that transition over a short distance into an area dominated by mafic intrusives with only a subordinate presence of felsic rocks. Both felsic and mafic suites are seen grading into each other, interacting as coexisting magmatic liquids, and on mixing, forming an intermediate suite of rocks. The mafic rocks were earlier mapped as the Proterozoic Salem Gabbrodiorite. Some of the rocks originally mapped as the Salem now should be considered part of a magmatic suite genetically related to the CAPC rocks (Dennen 1981).

Mineralogy and Petrology. The Cape Ann Granite consists of medium-grained perthitic alkali feldspar (60 to 65%), quartz (25 to 35%), and less than 10% of the mafic minerals ferrobiotite, ferrohastingsite, and riebeckite with traces of fayalitic olivine and aegirine. Zircon, apatite, fluorite, and opaques are accessory minerals. Chemical analyses are very low in MgO and CaO (0.3 to 1 wt%) and total Fe varies between 2 and 4 wt%. Na_2O and K_2O are present in near equal amounts (4 to 5 wt%). Presence of modal fayalite, quartz, and opaques are indicative of QFM buffer conditions and low oxygen fugacities. The Cape Ann Granite and associated pegmatitic pockets are the type locality for annite. The original description by Dana (1868) lists annite as ferric mica with comparable amounts of Fe^{2+} and Fe^{3+} in the octahedral layer. Winchell (1925) classifies annite as the Fe^{2+} end member of phlogopite. Dyar and Burns (1986) proved by Mössbauer spectral study that annite from Cape Ann contains both valence states in the octahedral layers.

Petrogenesis of Felsic Rocks. The close spatial and temporal relationship of felsic rocks from the CAPC with mafic rocks suggests a petrogenetic relation. Paige (1991) modeled CAPC rocks using selected trace elements from mafic, subsilicic, and silicic rocks and suggested that mafic magmas mixed with quartz saturated granitic magmas in various proportions and that fractional crystallization of subsilicic magmas further diversified the observed compositional range. The higher color index of rocks of the Beverly Syenite, along with the higher abundances of CaO and MgO, additionally supports the magma mixing model. Petrogenetic discrimination diagrams (Fig. 3; after Pearce, 1984) show the CAPC rocks as within plate granites or, by the definition of Loiselle and Wones (1979), as A-type magmas. Further subdivision of A-type magmas into A_1 and A_2 subcategories by Eby (1990, 1992) on the basis of Nb/Y ratios would associate the CAPC magmas with the A_1 subtypes, granitoids of rifts, plumes, and hotspots. Mineralogy, petrology, and geochemistry of the CAPC rocks is consistent with a petrogenetic model of generation from mafic magmas in a rifting environment and underplating the lower crust. Heat transfer from these magmas to dry rocks of the lower crust then results in dry partial melting under reducing conditions. Subsequent magma mixing, fractionation and crystallization in a shallow crustal setting is a proposed model that best fits the observed compositional range within the CAPC suite.

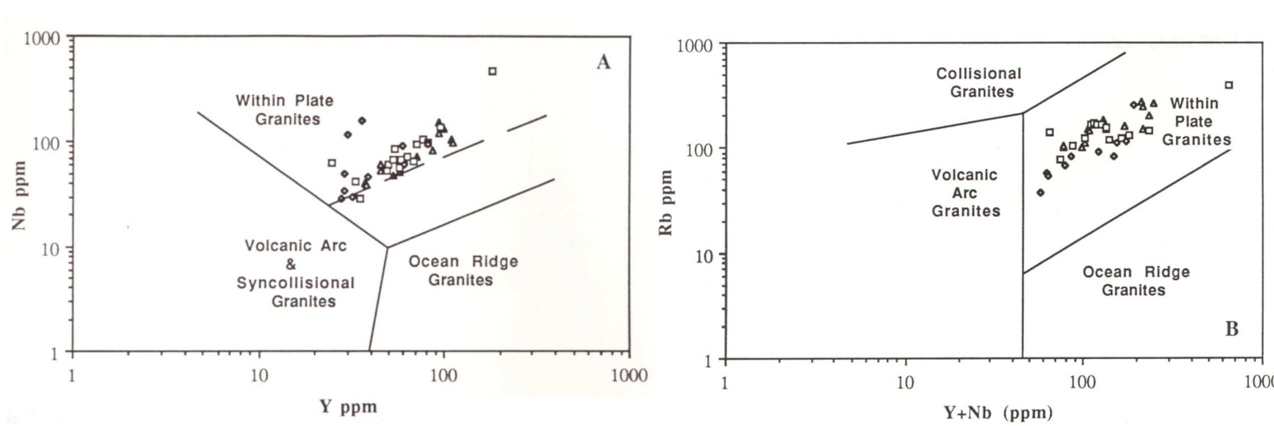


Figure 3. Petrogenetic plots for granites and syenites of the Cape Ann Plutonic Complex. (A) Nb vs. Y plot; (B) Rb vs. Y+Nb plot. Both plots after Pearce *et al.* (1984).

Nashoba Terrane

The fault-bounded Nashoba terrane, with its distinct geological history, lies west and northwest of the composite Avalon terrane across the prominent Bloody Bluff fault zone (Fig. 1). This terrane is underlain by a thick sequence of deformed Cambro-Ordovician mafic and felsic volcanic rocks and volcanogenetic sediments that are now metamorphosed to the upper amphibolite facies, sillimanite and sillimanite-K-feldspar zones in a lower pressure-higher temperature facies series. Migmatites are common in rocks of the appropriate composition. Trace element signatures of the volcanic rocks indicate that they originated in an arc or marginal basin tectonic setting (DiNitto *et al*., 1984). The oldest rocks yet found in the terrane are from a felsic gneiss unit (Fish Brook Gneiss) dated as 499 +6/-3 Ma (Dunning, in Hepburn *et al*., 1995). A U-Pb monazite age of 425 ± 3 Ma (Dunning, in Hepburn *et al*., 1995) from the same Fish Brook Gneiss sample indicates a major metamorphic event in the mid-Silurian, although at least some migmatization occurred at ~395 Ma (Hepburn *et al*., 1995). Hornblende $^{40}Ar/^{39}Ar$ isotope correlation ages indicate the terrane cooled below ~500ºC during the interval between 354-325 Ma (Hepburn *et al*., 1987), thus escaping the effects of a major Permian (Alleghenian) thermal overprint.

Following the early Paleozoic arc magmatism, significant plutonism occurred in the Nashoba terrane from the Late Ordovician or Early Silurian to the Mississippian. The most widespread plutonism entailed the contemporaneous intrusion of calc-alkaline dioritic to tonalitic magmas and aluminous granites during the Late Ordovician or Early Silurian through the Devonian (Fig. 2) (Zartman and Naylor, 1984; Wones and Goldsmith, 1991; Hon *et al*., 1993; Hepburn *et al*., 1995; Acaster and Bickford, 1999). The Sharpners Pond Diorite (Stops 8,10) is typical of the intermediate composition intrusions and has been dated as 430 ± 5 Ma (U-Pb, Zartman and Naylor, 1984). These plutons are little deformed hornblende and hornblende-biotite diorites and tonalities that include minor gabboric cumulates or more granitic fractionates and have titanite as a common accessory phase. Geochemistry indicates these plutons are calc-alkaline and have both major and trace element abundances similar to those found in continental arcs (Fig. 4) (Hill *et al*., 1984a,b; Hon *et al*., 1986, 1993; Wones and Goldsmith, 1991; Hepburn *et al*., 1995). Wones and Goldsmith (1991) indicate the mineralogy of these plutons is characteristic of lower pressure I-type calc-alkaline intrusions. Thus, these plutons indicate a subduction related tectonic setting in the Silurian to mid-Devonian for the Nashoba terrane.

Granitic rocks underlie an appreciable portion of the Nashoba terrane in eastern Massachusetts. Most have been included in the Andover Granite (Zen *et al*., 1983; Wones and Goldsmith, 1991). The Andover includes a complex variety of granites that range in composition from metaluminous to peraluminous and vary from foliated biotite and two mica granites to unfoliated garnet-bearing muscovite granite and pegmatite. The older foliated granites have traditionally been interpreted to be pre-or syn-kinematic, while the unfoliated varieties are thought to be post-kinematic. However, the possibility exists that at least some of granites acquired their foliation through later ductile shearing in association with the numerous shear zones in the terrane. Never the less, it is clear that the granites included in the Andover represent more than a single intrusion and likely were intruded over an extended period. An age of 412 ± 2 Ma (Dunning, in Hepburn *et al*., 1995) provides a good age for the youngest, peraluminous unfoliated granites and pegmatites. However, the older foliated varieties have proven difficult to date because of included source rock zircons. Zartman and Marvin (1991) give an age of 450 ± 23 Ma for these rocks (see Hepburn *et al*., 1995 for more compete discussion of the age of these granites). It is clear that the intrusion of the granitic rocks included in the Andover Granite temporally overlapped the calc-alkaline dioritic and tonalitic intrusions (430-385 Ma). In places, particularly near the boundary of the Sharpners Pond Diorite, dioritic rocks are commingled with granitic rocks and locally form magmatic pillows (Hon *et al.,* 1986, 1993) indicating the coeval nature of at least some of these magmas. Trace element and isotopic chemistry indicate the granites are the result of crustal anatexis and not simply fractionates of the calc-alkaline magmas (Hill *et al*., 1984a; Hill 1985; Hon *et al*., 1986, 1993). However, it is thought likely that the intrusion of the diorites contributed heat to the crust for anatexis of medasedimentary rocks that in turn led to at least some of the granite formation.

Two younger granites, the Sgr granite of Zen *et al*. (1983) and the Indian Head Hill pluton are prominent along the eastern margin of the Nashoba terrane. The Sgr is a salmon-pink, unfoliated granite that remains undated (Wones and Goldsmith, 1991). The Indian Head Hill pluton includes both an older, Silurian dioritic phase, included in the discussions above, and Mississippian (349 ± 4 Ma, Dunning in Hepburn *et al*., 1995) biotite granite to granodiorite (Hepburn and DiNitto, 1978; DiNitto *et al*., 1984; Wones and Goldsmith, 1991). These rocks have now been subdivided into separate units in recent mapping (Kopera *et al*., 2006). The Indian Head Hill Granite is the youngest intrusive rock yet found in the Nashoba terrane and likely represents a separate magmatic event from the Siluro-Devonian granites.

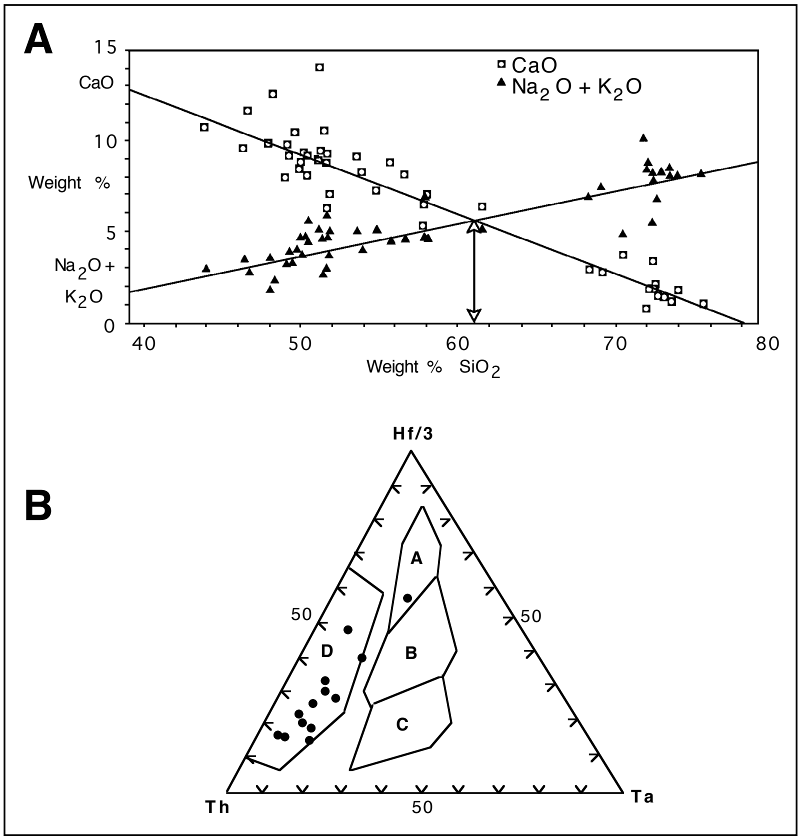


Figure 4. (A) Peacock plot for samples from the Sharpners Pond pluton with both CaO and $Na_2O + K_2O$ plotted against SiO_2. The intercept at 61wt. % SiO_2 indicates that the rocks are calc-alkaline (after Hon *et al.*, 1993). (B) Hf/3-Th-Ta tectonomagmatic discrimination diagram (after Wood *et al.*, 1979) shows mafic and intermediate rocks from the Sharpners Pond Diorite (modified after Hon *et al.*, 1993). Fields: A, N-MORB; B, P-MORB; C, within plate basalts; D, destructive plate margin basalts.

Newbury Volcanic Complex

The Newbury Volcanic Complex (Stop 9) occurs in a fault-bounded basin directly between the Avalon and Nashoba terranes in northeastern Massachusetts (Fig. 1; Zen *et al.*, 1983) and it is not clear whether these rocks belong to either terrane. The Newbury volcanics are composed of a series of unmetamorphosed and non-penetratively deformed, although faulted and tilted, basaltic-andesite, andesite and rhyolitic volcanic rocks and shallow intrusions with interbedded sedimentary rocks that contain latest Silurian to Early Devonian fossils (Shride, 1976a). McKenna *et al.* (1993) show the Newbury igneous rocks are calc-alkaline with trace element signatures indicative of formation in a continental arc environment (Fig. 5). Similar volcanic rocks of the same age occur in the Coastal Volcanic Belt in easternmost Maine (Gates and Moench, 1981) and may have once been continuous with the Newbury. Hon and Thirlwall (1985) and Hon *et al.*, (1986) note the similarity in the composition of the Newbury volcanic rocks to the intermediate and granitic magmas of the Nashoba terrane and suggest that the Newbury may be the volcanic expression of these plutonic rocks preserved in a down-dropped fault block.

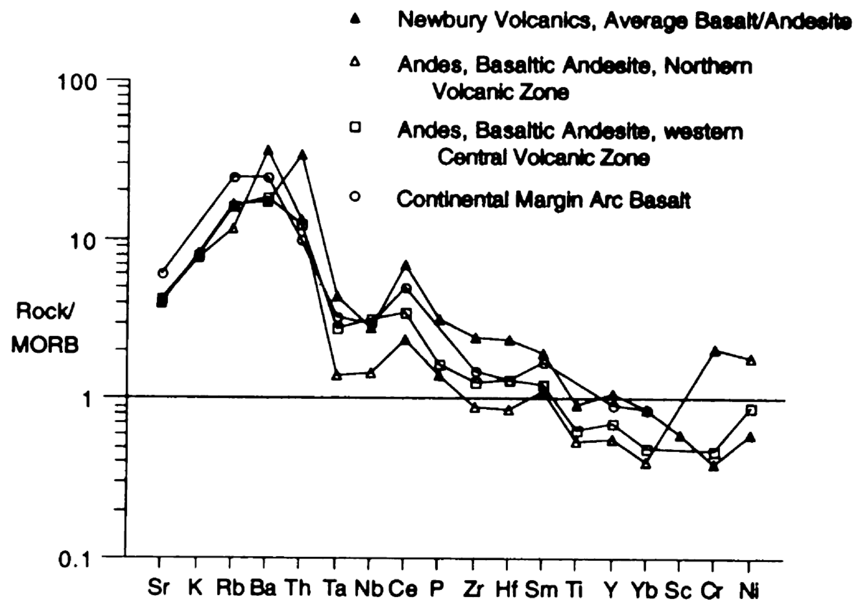


Figure 5. Multi-element variation diagram showing average of 10 basalt/andesite samples from the Newbury Volcanic Complex plotted against Andean basaltic andesites from the Northern Volcanic and western Central Volcanic zones (after Thorpe *et al.*, 1984) and Continental Margin Arc Basalt (after Condie, 1989 and BVTP, 1981). MORB normalization factors after Pearce, 1983. Newbury data after McKenna *et al.* (1993) and McKenna, unpublished data (1992). Diagram from Hepburn *et al.*, (1995).

Eastern Merrimack belt

The eastern portion of the Merrimack terrane lies west and northwest of the Nashoba terrane (Fig. 1). This area has been referred to as the Merrimack belt (Zen *et al.*, 1983; Robinson and Goldsmith, 1991; Watts *et al.*, 2000) and the Merrimack trough (Lyons *et al.*, 1997). Further, Robinson and Goldsmith (1991) place this area into their Rockingham sub-belt of the Merrimack belt. Regional syntheses generally correlate the eastern Merrimack terrane with the Gander Zone in Newfoundland (e.g., Williams and Hatcher, 1983; Rankin, 1993). The eastern portion of the Merrimack terrane is largely underlain by stratified rocks of the Merrimack Group, a thick sequence of metamorphosed calcareous turbidites, metasandstones and metapelites (e.g., Hussey and Bothner, 1995; Robinson and Goldsmith, 1991). While the age of these stratified rocks has been debated in the past because of differing dates on crosscutting plutons, it now appears that these rocks are Silurian or Ordovician and Silurian in age (Lyons *et al.*, 1997; Bothner *et al.*, 1993; Aleinikoff *et al.*, 1995).

A series of granitic and dioritic plutons ranging in age from Silurian to Early Devonian (Wones and Goldsmith, 1991; Zartman and Marvin, 1991) intrudes the eastern part of the Merrimack terrane (Fig. 1). Many of these plutons occur just west of the Clinton-Newbury fault zone that marks the western boundary of the Nashoba terrane. The granitic rocks include the Ayer, Chelmsford and Newburyport plutons. These form complex, variable intrusions that range in composition from granite through granodiorite to tonalite (Wones and Goldsmith, 1991; Gore, 1976). The Ayer and Chelmsford have been extensively sheared and foliated giving them a gneissic texture in many areas, particularly the Chelmsford Granite (the common curb stone used in the Boston area). These granites tend have a calc-alkaline chemistry (Wones and Goldsmith, 1991).

The Exeter pluton (Stop 11) is typical of the calc-alkaline intermediate composition intrusions in the eastern Merrimack terrane. Other such plutons in this zone, thought to be of the same age, include the Dracut and Webhannet (Fig. 1). The Dracut has been described as ranging in composition from gabbro to tonalite and includes a noritic phase with hypersthene, augite, hornblende and olivine (Dennen, 1943; Hon *et al.*, 1986). At one time the Dracut was mined for nickel. The Exeter is dominantly dioritic in composition although it ranges from gabbroic in the southwest to granodioritic toward the northern end (Watts *et al.*, 2000). The more granitic compositions occur where the Exeter intrudes metasediments of the Merrimack Group (Birch, 1979, fig.2). Texturally it is massive and medium- to coarse-grained. Portions of the pluton have been extensively altered. The Exeter is the best dated of these plutons with an age of 406 ± 1 Ma (Bothner *et al*., 1993). It intrudes metamorphosed and deformed sedimentary rocks and has formed a small contact metamorphic aureole thereby indicating that the major deformation and metamorphism pre-dates the intrusion and is thus early Acadian.

The tectonic relations of the eastern Merrimack terrane to the rocks on either side are still subject to ongoing debate (e.g., Hussey and Bothner, 1999; Watts *et al*., 2000; Robinson and Goldsmith, 1991). Regional metamorphism in this terrane is commonly no higher than the mid-greenschist facies on the eastern side of the zone adjacent to the Clinton-Newbury fault zone but increases to the west and northwest across the belt. General similarities in igneous rock history and composition with the Nashoba terrane to the east make it attractive to consider the eastern Merrimack rocks as part of this terrane. However, the stratigraphic rocks are different lithologically and appear to be of dissimilar ages. In addition, Watts *et al*. (2000) indicate that trace element abundances in the intermediate composition plutons of the Merrimack and Nashoba terranes are different enough so that and these plutons can not be genetically related. To the west, the eastern Merrimack rocks have similarities with those of the Central Maine terrane suggesting they were part of a single terrane or at least shared a common Siluro-Devonian history. Correlations depend upon detailed stratigraphic interpretations and age relations as well as the ages of crosscutting plutons (for summaries see Hussey and Bothner, 1995; Robinson and Goldsmith, 1991). Watts *et al*. (2000) indicate the similar nature of the early Devonian calc-alkaline plutons in the eastern Merrimack area and the New Hampshire Plutonic Series to the west and suggest that it is likely that both were produced in a single magmatic suite and emplaced within a common arc. If true, this would indicate that the eastern Merrimack terrane and the Central Maine terrane were adjacent by the early Devonian.

TECTONIC QUESTIONS

From the Late Ordovician through the Silurian, magmatism in the three easternmost terranes in northeastern Massachusetts and southeastern New Hampshire was of varying chemistry. The igneous rocks thus provide constraints for tectonic models. Calc-alkaline rocks in the Merrimack Belt, Nashoba terrane and Newbury Volcanics all indicate formation in a subduction related environment with the Newbury being a remnant of the arc preserved in a tectonic sliver. The alkaline rocks in the Avalon terrane indicate formation in an extensional or rifting environment. However, producing a unified tectonic model to explain these differences in chemistry and tectonic setting has proven difficult and is subject to much debate. One reason for this is that no consensus exists as to when and how these three terranes came together. Were some or all of them accreted to each other prior of their interaction with terranes to the west? Or did they arrive as separate terranes? One simple model would have an eastward dipping subduction zone (present coordinates) producing the calc-alkaline rocks in the Merrimack Belt, Nashoba terrane and Newbury Volcanics. In this model the Avalonian alkaline intrusions would form in a back-arc extensional environment. This implies that the terranes were all together as one block or at least in relatively close proximity to each other prior to the intrusion of the Cape Ann Plutonic Complex. It also implies a rather extended period of subduction with the terranes in this geometry. A second model would have the calc-alkaline rocks of the Merrimack Belt and Nashoba terrane being formed by westward dipping subduction, possibly by two separate subduction zones, one beneath each terrane. The Newbury Volcanics would lie upon Nashoba basement. In this scenario, the alkaline rocks of the Avalon terrane would be due to internal plate motions causing rifting and extension, possibly as a later arriving Avalon moved toward the subduction zone beneath the Nashoba terrane. Undoubtedly the actual tectonic picture is more complex than either of these models and awaits further study. We welcome your discussions of the tectonic setting during the trip.

ACKNOWLEDGEMENT

Our current understanding of magmatic rocks of the Siluro-Devonian interval in the northeastern corner of Massachusetts would not have been possible without contributions of many dissertation studies by students in the Department of Geology and Geophysics at Boston College. RH would like to acknowledge work of Garen Sahagian (1987), Christer Loftenius (1988), Stan Flagel (1988), and Matt Paige (1991) whose work spans all three tectonic terranes discussed in this field trip guide. Their effort in the field, sample collecting, and analytical laboratory work has been a major contributing factor for the advancement of our geologic understanding of these terranes. JCH acknowledges a similar contribution by Duff Collins (1987). However, the views expressed in this article are the sole responsibility of the authors.

ROAD LOG

Preface

Outcrops for this field trip have been described by many geologists for excursions through the years, please see a partial list in the introductory section of this write-up. The exposures are largely selected from field trips previously co-lead by the authors and presented in two separate guidebooks: (1) 1993 Boston GSA Field Trip Guidebook for the Northeastern United States (Chapters Q and X); and (2) 96th Annual NEIGC (2004) Guidebook to Field Trips (trips A2 and B4). In contrast to the above-mentioned guides, this field trip brings together exposures of only the intrusive and extrusive rocks that were emplaced within the three terranes that underlie the Appalachian easternmost margin in NE MA and SE NH during the period from the upper Ordovician to the mid-Devonian. The field trip is divided into three separate odometer logs each starting at 0.0 miles. The first log starts at the junction of Rt. 128 and Rt. 127 in Gloucester (exit 11 off Rt.128N – Grant Circle) and follows Rt. 127N circumnavigating Cape Ann, first along its western shoreline and then along the east facing shoreline after reaching the northernmost point at Halibut State Park. The second odometer sequence is reset to zero in Salem at the southern exit from Essex Bridge – Rt.1A (over the Danvers River). The last log navigates the trip from I-95N starting at the Hampton toll booths (exit 2) in New Hampshire. The first log includes Stop 1 and Stop 2, the second log is for Stops 3 through 10; and the third log is for Stop 11. Stop leaders: RH (Stop 1 through Stop 6); RH & JCH (Stop 7); JCH & RH (Stops 8, 9, and 10); and JL (Stop 11). Enjoy the trip!!

From Durham NH, take Rt. 4E and I-95S toward Rt.128 in MA. Once you reach Rt.128N north of Boston (after leaving I-95S) stay on Rt.128 until you reach exit 11 – Grant Circle. A full services rest area is located a short distance beyond exit 19 and we will likely make a quick stop here. Past exit 12 is the Annisquam River, a north-south passage along the western side of Cape Ann – Cape Ann is an artificial island. Reverend Blynman received in 1642 permission to dig a north-south channel connecting the Annisquam River to Gloucester Harbor. The canal bears his name: Blynman Canal.

Set odometer to 0.0 just after leaving Rt.128 at exit 11 (Grant Circle) as you enter Rt.127N, 3/4 way around traffic circle

Follow Rt.127N along the western shoreline of Cape Ann.

0.0 Rt.127N at the exit from Rt.128N
4.4 CAUTION: Sharp left and right turns
5.4 Gloucester – Rockport town line
5.9 Entrance to Halibut State Park. Site of former Babson Farm Quarry that was active between 1840s and 1929. This site, along with Rockport Quarries further south, yielded many outstanding mineral specimens of fayalite and annite. These quarries are noted as the type localities for annite and danalite, a ferrous beryllium member of the sodalite group.
6.3 Turn left onto Phillips Avenue
6.6 90 degree right turn in the road
6.8 Continue straight on Linwood Avenue
7.0 Turn right on Point De Chene Avenue. Park cars on right. Please, respect rights of the local residents. Proceed north on foot (opposite direction) across Linwood and Long Branch Aves. to exposures along the Atlantic Ocean shoreline on your right. On return we will follow a different path, one of several public access trails to the coastline.

STOP 1. ANDREWS POINT, ROCKPORT, MA. Cape Ann Granite, Pegmatites with Blue Quartz and Annite, Aplites, Mafic Dikes (45 minutes) (Previously described as Stop 1-13, Hon *et al.*, 1993; Stop 2, Brady and Cheney, 2004; Stop 10, Dennen, 1976; Stop 3, Ross, 2004)

We will traverse about 500 ft north-south along the coastline and leave toward Point De Chene Avenue using another local path visible on the orthomap in Figure 6a. The traverse follows approximately the map of Pelke, 1972, (after Wones and Goldsmith, 1991), shown in the Fig. 6b. Typical Cape Ann granite here is a hypersolvus granite consisting primarily of perthitic alkali feldspar (60 to 65 modal %), quartz (30 to 35 modal %) and usually less than 5 modal % of ferrobiotite and ferrohastingsite. It is of a interest to point out that the ferrous end member of the biotite solid solution, annite, is named after Cape Ann. The type locality is the local quarries were large books of annite were collected from pegmatitic pockets. The silica content of the Cape Ann granite is typically > 75 wt. % with subequal amounts of Na_2O and K_2O at 4 to 5 wt. %. CaO only rarely exceeds 0.5 wt. %. The granites are metaluminous and their agpaitic index varies from 0.93 to 1.05. Along the traverse we will cross exposures of remnant blocks of mafic dikes, once continuous and now pulled apart. The pull-apart dikes may be observed at a number of other localities throughout the Cape Ann Complex. They occur when very viscous solidifying felsic magmas are brittlely fractured, rapidly filled with a fluid basaltic magma and then quickly solidify into a basaltic sheet. A subsequent slow viscous flow of the felsic magma segments the dike sheet into a discontinuous series of

a.

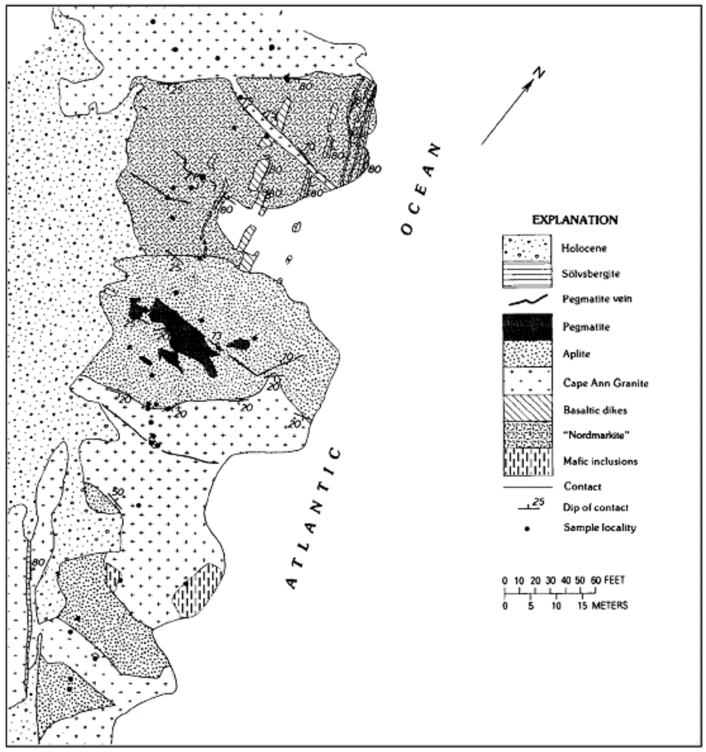


Figure 6a: Orthophoto map showing a detailed view of Andrews Point. The N-S trending street nearest the coastline is Point De Chene Avenue and the E-W trending street in the lower part of the map is Linwood Avenue; 6b. Geologic sketch of the coastline with locations of pegmatitic pockets and zones, aplites, and mafic dikes (After Pelke, 1972, reproduced from Wones and Goldsmith, 1991).

blocks. Infrequent in the Cape Ann Complex are large pockets of pegmatites and pegmatitic zones as seen well displayed here along the shore. The pegmatites contain large, 2 to 25 cm mega-crystals of blue quartz, alkali feldspars, books of iron-rich biotites, iron-rich amphiboles and iron oxides. The type annite was likely collected from one of these pegmatites in the local quarries. Close association of pegmatites with aplites at this locality may suggest a present day view into an escape system of hot supercritical fluids and their decomposition into an aplitic melt and volatile-rich phase during their decompression ascent.

Return to Point De Chene Avenue and walk back to cars.

	Continue south on Point De Chene Avenue
7.1	Merge into Phillips Ave
7.4	Merge with Ocean Ave, stay on Phillips Ave
7.45	Turn right on Cathedral Avenue; continue till end (1 block)
7.5	Turn left onto Rt.127S
8.4	Crossing over a narrow cut-through road leading into the main Rockport Quarries on your right
8.6	Stay right on Rt.127S, bypassing downtown Rockport, a popular art colony
9.2	Passing commuter rail line station
9.3	Turn right at the Stop sign. Follow Rt.127S (do not take Rt.127A going to downtown Rockport)
11.1	Rockport – Gloucester town line

12.2 Look for Harrison Ave on your right. It is easy to miss it. Watch for Dunkin Donuts on your left; Mobil gas station, small pond and Helen Way on your right. Harrison Avenue is the next right.

12.3 Just as you see Jct. warning sign on your right be prepared to turn right onto Harrison Ave. Park cars. Walk back to Rt.127 and proceeded toward Rt.128. Rt.128 ends here and we want to walk toward road cuts (partially overgrown) on the northern wall of Rt.128S.
CAUTION: Please, exercise care and be aware of traffic!!
A short distance beyond the turn at the intersection is a narrow sidewalk. As soon as you can cross over the guard rail and work your way to the exposures along the rock wall.

STOP 2. NORTHERN TERMINUS OF RT. 128, GLOUCESTER, MA. Cape Ann Granite, Trains of Mafic Enclaves (20 minutes) (Previously described as Stop 1-10, Hon *et al.*, 1993; Stop 11, Dennen, 1976; Stop 3, Brady and Cheney, 2004)

Along the rock wall are exposures of numerous 10 to 30 cm enclaves freely suspended in a granitic matrix. The host Cape Ann Granite at this locality is less granitic and more syenitic, noted for a higher proportion of mafic minerals and lower quartz content. Some enclaves have a semispherical rounded shape, while others are multilobed, a typical shape for magmatic pillows. Margins are finer grained, "chilled," and often contain a single euhedral megacrystic plagioclase in the center. Grain size gradually increases toward the core of the enclave with a discernable fine-grained gabbroic texture. Megacrysts can occasionally reach a size in excess of 5 cm; other less frequent phenocrysts are mafic minerals. Another characteristic of the enclaves is their apparent spatial variation along the exposed section. Perhaps three or more different basaltic classes of enclaves can be observed: plagioclase megacrysts, aphyric, and phenocrysts of mafic minerals. The style and appearance of the enclaves suggests repeated propagating intrusions of very fluid mafic liquids into a highly viscous and cooler granitic host. Geochemistry of the enclaves suggests that the basalts can be classified as alkali basalts.

The first odometer log ends here. Navigate your vehicles onto Rt.128S past the enclaves outcrop. Pass through Blackburn and Grant Circles following Rt.128S signs. After approximately 10 miles, take exit 18 off Rt.128 toward Beverly and Salem staying on Rt. 22S. Follow 22S, now Essex Street. Cross Rt. 62 and follow Rt. 22S to its merger with Rt.1A and then follow Rt.1A south. The signs may at time appear inconsistent. In any instance, always follow signs toward Salem, eventually reaching Essex Bridge over the Danvers River. At the southern end of the bridge, after exiting the bridge road to your left, reset your odometer to 0.0.

0.0 Bridge Street in Salem at the southern exit point off Essex Bridge

0.5 At traffic lights turn left on Webb Street

0.9 Bear left after passing through traffic light toward Fort Avenue and Winter Island Road

1.5 Cat Cove on your right. Shoreline exposures here are the type locality for essexite (Ne normative alkalic gabbro)

1.6 Turn right on Winter Island Road. Proceed to the gatehouse and entrance to Winter Island Park

1.9 Enter the park and follow Waterfront signs; park cars facing a lighthouse to your left

STOP 3. WINTER ISLAND, SALEM, MA. Commingling and Magma Mixing of Mafic and Silicic Magmas. (35 minutes) (Previously described as Stop 1-3, Hon *et al.*, 1993; and Stop 1, Hon and Hanson, 2004; and Hanson and Hon, 2004)

This stop is a short walk counterclockwise circumnavigating a small promontory near the lighthouse. We will return to the parking lot along the same road that we drove in on earlier. Follow the shoreline toward the lighthouse and continue around the point until you reach a small bay and beach. Return to the road along the beach access path.

The shoreline exposures here afford spectacular views of various stages and modes of interaction between two co-existing magmatic liquids. These are excellent examples of commingling where mafic liquids are seen pillowing into the felsic magmas. The commingling subtypes clearly demonstrate the contemporaneous nature of the mafic and felsic magmatic liquids and support a close genetic relationship of the mafic and silicic magmas. The commingling is observed where a felsic host is intruded by mafic dikes as shown, for example, on photos in Figure 7. Geochemical trends suggest that Cape Ann granitic liquids are formed by dry melting of lower crustal rocks likely in response to added heat by mafic melts that underplate the crust at the mantle-crust interface. Hot and dry silicic liquids rise to the uppermost crust as A-type magmas (Loiselle and Wones, 1979). We recognize the A-type magmas in this area as the Cape Ann granites. Magma mixing and crystal fractionation of mafic liquids resulted in a wide variety of rock mineralogies from cumulitic gabbros to sub-silicic granites. A rock type dominated by alkali feldspars was described by Toulmin (1964b) as the Beverly Syenite (see Stop 4 below). The mafic magmas are classified as olivine and nepheline normative alkali basalts.

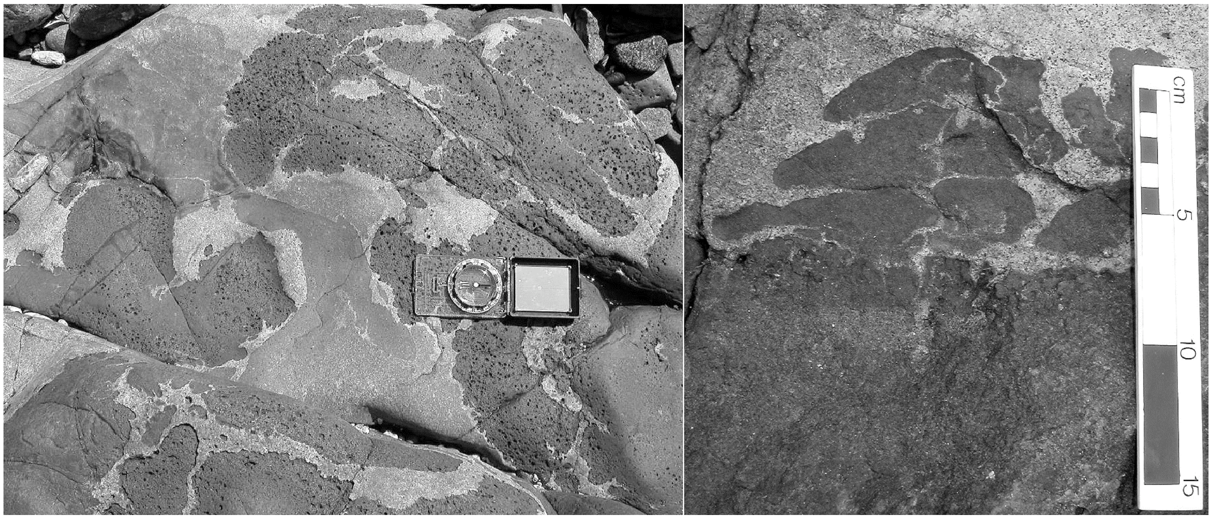


Figure 7. Magmatic pillows at Winter Island. Photo credit: Lindley Hanson

Reverse directions and proceed to Fort Avenue
2.2 Gatehouse
2.6 Turn right on Fort Avenue toward Salem Willows Park
3.0 Park on the right near the gate to Salem Willows Park

STOP 4. SALEM WILLOWS PARK, SALEM, MA. Beverly Syenite (20 minutes)
(Previously described as Stop 5, Hon and Hanson, 2004; and Hanson and Hon, 2004; Stop 5 Brady and Cheney, 2004)

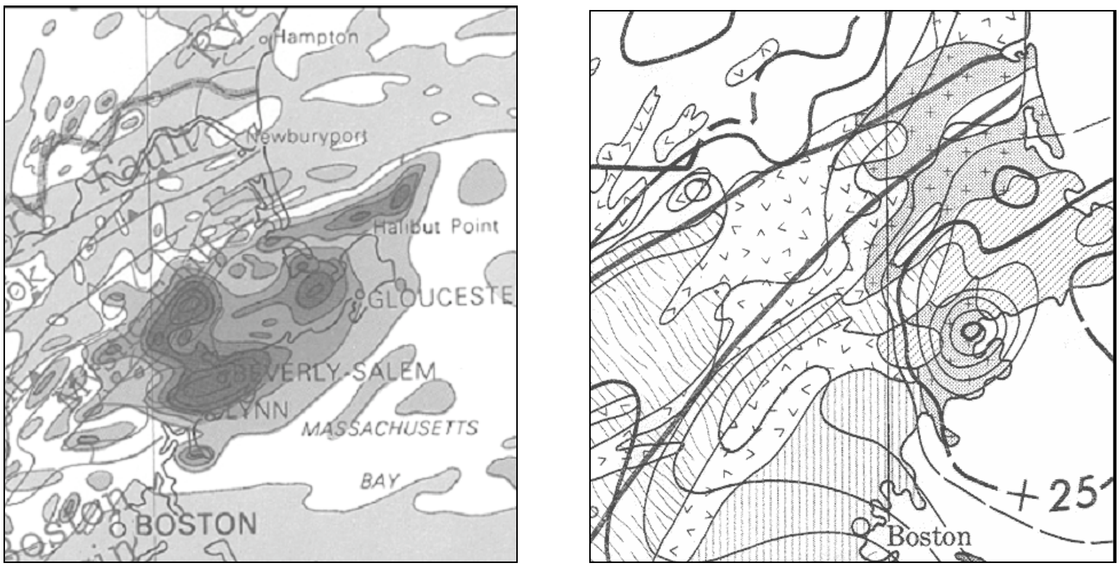
Enter park on foot and continue straight to the coastline. Rocky bluffs in front and on the other side of a small beach are rocks of the Beverly Syenite. The Beverly Syenite occurs here in two northeast trending alignments surrounded by mafic intrusives. A 120-meter-wide zone forms the cove containing the public beach on the northeast side of the Willows. Similar exposures are on both sides of Dead Horse beach, located on the northwest side of the amusement park. The mineralogical composition of the syenites is dominated by alkali feldspar, with zero, traces, or, at most, minor quartz. The color index varies from less than 5% to 10-15%. Geochemistry of the syenites suggests two modes of evolution: crystal fractionation and mixing with Cape Ann Granite magmas.

Reverse direction. Return on Fort Avenue
3.5 Salem Harbor Power station on your left
4.1 Turn left onto Essex Street. CAUTION: We will be passing through Salem Center with many one-way streets and narrow roads
4.5 Turn left to Hawthorne Blvd
4.6 Turn right on Derby Street
4.8 Pass through traffic lights. Continue straight across
4.9 Washington Street intersection. Continue straight ahead
5.1 You are now on Norman Street. Turn left on Summer Street
5.15 Turn right to Broad Street
5.6 As we approach Rt.107 at the next intersection, we need to zigzag left and right to enter Jackson Street, the next street on your left. No left turn is allowed from Broad Street onto Rt. 107S.
5.6 At the lights on Jackson Street, turn left onto Highland Avenue, Rt.107S
6.8 Traffic light. Go straight to the next set of lights
6.9 Turn left at traffic lights and enter Shaw's Plaza. TriCity store on your right

7.0 Turn right at Eastern Bank branch office (2 Traders Way) and park against the rock wall cut in the back of the building

<u>STOP 5</u>. TRADERS WAY STREET, SALEM, MA. Salem Highland Pluton, Multiple intrusions of Mafic Magmas (20 minutes) (Previously described as Stop 2, Hon and Hanson, 2004; and Hanson and Hon, 2004)

The Salem Highland pluton is roughly 6 square-miles in area and is composed of multiple intrusive pulses of mafic magma. Intrusions composing the main body are typically several meters thick and commonly exhibit diffuse indistinguishable borders giving it its characteristic massive appearance. The body is cut by late stage basaltic dikes and discontinuous granitic and syenitic dikelets, possibly fractionated melt filling contractional fractures. Pegmatitic dikes contain visible orthoclase, quartz, calcite, and biotite. In the Aggregate Industries quarry located within the



a. b.

Figure 8a. Map of aeromagnetic anomalies stretching from Salem to Cape Ann (Zeitz *et al.,* 1979).
Figure 8b. Gravity anomaly map of NE Massachusetts (Kane *et al*., 1972). Note a pronounced gravity high at the location of Salem Highland pluton.

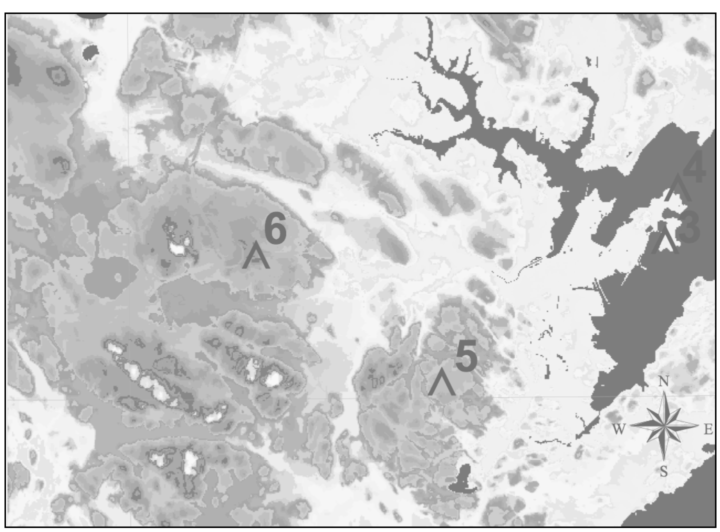


Figure 9. Digital Elevation Model with prominent outlines of the Salem Highland (Stop 5) and Peabody Granite plutons (Stop 6). Both plutons show no penetrative deformations.

pluton, along the Salem-Swampscott town line, the pluton is also cut by 0.5-to-2 meter thick, subhorizontal, porphyritic felsite dikes that may be related to intrusions of the felsic magmas seen elsewhere on this trip.
The Salem Highland pluton underlies a dissected upland that is clearly visible on the DEM (Fig. 9). It is also noted as a pronounced positive gravity anomaly (Fig. 8b) and as an area with strong aeromagnetic signatures (Fig. 8a). Zartman and Marvin (1971) obtained 452±12 Ma (K-Ar on Biotite) and 450±12 Ma (Rb-Sr on Biotite) age dates from rocks taken 0.3 miles southwest of this location. By comparison, Dunning obtained an age of 444+/-3 Ma (U/Pb zircon) from a syenitic pod within alkali gabbros collected at our Stop 7 (Fig. 1; see Stop 7 description). The Salem Highland pluton is largely undeformed consisting of massive fine- to medium-grained gabbro and forms a prominent topographic feature that resists weathering and erosion (Fig. 9)

Return to Traders Way road and head back toward the Rt.107 intersection at the traffic lights
7.3 Cross Highland Avenue (Rt.107) and continue straight on Marlborough Road. As the road descends toward lowlands, the traverse crosses the periphery of the Salem Highland pluton as is well seen on the DEM image (Fig. 9)
7.65 Salem – Peabody town line. Marlborough Road becomes Sutton Street and later Aborn Street
8.8 Turn left onto Washington Street
9.8 Turn slight right onto Lynnfield Street. Lynnfield Street follows an east trending valley cutting into the core of the Peabody Granite pluton (Fig. 9)
10.1 Crossing County Street / Summit Street intersection
11.2 Turn diagonally right onto First Avenue
11.5 Cross Centennial Drive intersection
11.6 Turn right and follow Jubilee Drive toward Pratville Machine building
11.9 Turn left into Pratvilllle Machine shipping / receiving parking lot. Park in spaces on right side. Proceed to the exposed rock ledges. During working hours, ask permission to look at the rocks.

<u>STOP 6</u>. JUBILEE DRIVE, PEABODY, MA. Peabody Granite, Hypersolvus Alkali Granite (20 minutes)
(Previously described as Stop 1, Hon and Hanson, 2004; and Hanson and Hon, 2004)

The Peabody Granite is a semicircular intrusion well outlined on images of the digital elevation model (Fig. 9) of approximately 15 square miles (Toumlin, 1964). We are located in the middle of the northern half of the pluton and on the backside of the exfoliation dome dissected by Rt.128 between the Forest Street and Rt. I-95 exits.

The granite is a massive, homogenous, alkali granite, containing coarse (1-2 cm) subhedral greenish-gray alkali feldspar (microperthite), smokey-gray anhedral quartz and approximately 10% mafics (ferro-hornblende and subordinate pyroxene (Toulmin, 1964b). In contrast to the mafic mid-Paleozoic intrusives in the area there are no observed dikes cutting the Peabody. However, the Peabody contains numerous dark inclusions exhibiting both phaneritic and fine-grained porphyritic textures. These inclusions were interpreted by Toulmin (1964b) as possible xenoliths of the mafic earlier Paleozoic intrusives. The inclusions exhibit gradational borders and could also be interpreted as detached blocks of the chilled marginal facies or cumulate lenses formed within the granite. The young Devonian age of the Peabody (395±20 Ma, Zartman and Marvin, 1991) is reflected by its relative lack of deformation. This site was once an old quarry as evidenced by the vertical columns of short horizontal drill holes seen on the eastern side of the wall. In general, the Peabody stock forms a topographic high. Valleys cutting the pluton are in part structurally controlled and glacially modified through erosion and later deposition.

12.1 From the parking lot turn right onto Jubilee Drive
12.4 Pass First Avenue and continue straight on Jubilee Drive
12.8 Overpass over I-95 / Rt.128. Jubilee Drive becomes Farm Avenue
12.9 Turn left on Dearborn Street also marked as Intercontinental Way
13.7 Turn right onto Rt.1 at Wendy's on your right side
14.7 Stay left and follow Rt.1N. Pass entrance ramp to I-95N
16.0 Pass exit to Rt.114. Stay on Rt.1N
16.8 Take exit ramp to Centre Street, Danvers. Proceed slowly to the next intersection
17.1 Turn right, pass slowly through the intersection, and park cars off the road surface along the right edge of the road before the underpass. Proceed on foot toward road cuts along both sides of the exit ramp to I-95S **<u>CAUTION:</u>** Exercise caution when crossing Center Street – watch for oncoming traffic from <u>all</u> directions.

<u>STOP 7</u>. CENTER STREET, DANVERS, MA. Danvers Alkali Gabbro and Cumulitic Syenites (25 minutes) (Modified from Stop 1-7, Hepburn *et al*., 1993)

The principal rock type here 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). The rocks at these exposures were previously mapped as Proterozoic (Zen *et al*. 1983) but a U/Pb date on a zircon sample from one of the syenitic pods at this outcrop yielded an age of 444 ± 3 Ma (Dunning in Hepburn *et al*., 1993, 1995). This age is similar to the emplacement age of the Cape Ann Granite suggesting close ties between the Cape Ann Granite Complex and the 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^{o} to 50^{o} E and dipping 60^{o} NW), indicating post-Ordovician deformation.

Continue on Center Street through the underpass under Rt.1
17.2 Turn right on Armory Road
17.3 Turn right on Dayton Street. Follow signs to Rt.1S
17.35 Turn right onto Rt.1S
17.8 Follow the exit ramp to Rt.114W on your right
18.0 Merge left onto Rt.114W. Stay on Rt.114W for next 4 miles
19.1 Middleton town line. Crossing Ipswich River, small Triassic Basin fault sliver, and Bloody Bluff fault
20.8 Rt. 62 intersection in downtown Middleton. Bear slightly left and continue on Rt.114W at the intersection
22.3 Turn right into Hillcrest Estate Townhouses parking lot
Park cars and proceed to rock exposures along the entrance road

<u>STOP 8</u>. RT. 114, HILLCREST ESTATE TOWNHOUSES, MIDDLETON, MA. Sharpners Pond Diorite, Nashoba Terrane (20 minutes) (From Stop 11, alternate 1, Hepburn, 2004)

The Sharpners Pond pluton (approximately 150 sq. miles; Wones and Goldsmith, 1991) is the largest of the intermediate composition calc-alkaline plutons in the Nashoba terrane. It consists largely of quartz-bearing hornblende diorite, hornblende-biotite tonalite and biotite tonalite, but it also contains minor, more mafic gabbroic cumulates and feldspathic differentiates (Castle, 1964, 1965; Hon *et al*., 1986). While much of the Sharpners Pond is rather homogeneous, textural differences are common at the outcrop scale in many localities and can be seen in this exposure. Titanite is a characteristic accessory phase throughout the Sharpners Pond. The Sharpners Pond is essentially unfoliated. Zartman and Naylor (1984) dated the Sharpners Pond as 430 ± 5 Ma by U/Pb on zircons. Near its eastern boundary the Sharpners Pond diorites and tonalites exhibit a variety of complex structures with adjacent granites, including magmatic pillows of the more mafic rocks surrounded by granite (Hon *et al*., 1986) that we will see at Stop 10. These indicate that both the intermediate composition and granitic magmas co-existed. Geochemically, the granites and diorites and tonalities are not co-genetic (Hill *et al*., 1984a; Hill, 1985). Thus, it is likely that the granitic rocks represent anatectic melts formed in response to higher temperatures brought about by the intrusion of the more mafic magmas.

Return to the entry way to the Hillcrest Estates
22.5 Turn left onto Rt. 114E, reversing direction
23.9 Downtown Middleton. Turn left onto Rt. 62E. Follow signs, this is a busy and confusing intersection
25.8 Danvers town line
26.7 Pass under Rt.1
26.8 Follow exit to Rt.1 / I-95N
27.0 Merge left onto Rt.1N
27.8 I-95N entrance ramp on left. Continue toward I-95N
28.45 Merge with I-95N. Stay on I-95 for approximately 7 miles
35.7 Follow Exit 54A to Rt.133 E, Haverhill Street, and Rowley
39.0 Turn left onto Rt.1N at lights at Kent Corner intersection
40.5 Intersection with Wethersfield Street. Continue straight

41.1 Turn right at blinking lights onto Central Street toward Rt.1A
41.3 Turn left into Rowley Water Department yard and park cars here
Walk back to exposures near Rt.1 of andesites of the Newbury Volcanic Complex
CAUTION: BE CAREFUL. THIS ROAD HAS MORE TRAFFIC THAN ONE WOULD EXPECT!

STOP 9A. CENTRAL STREET AT INTERSECTION WITH RT. 1, ROWLEY, MA. Newbury Volcanic Complex, Porphyritic Andesite (20 minutes) (Modified from Stop 13A, Hepburn, 2004; Previously described as Stop 2-1A, Hon *et al*., 1993; Stop 2-10, Hepburn *et al*., 1993)

The Newbury Volcanic Complex consists of a series of basaltic andesite, andesite and rhyolitic volcanic rocks and associated sediments that lie entirely within fault slivers directly between the Nashoba and Avalon terranes (Fig. 1; Zen *et al*., 1983). The complex is well dated on the basis of shelly fossils (some found very close to this exposure, but now paved over) as latest Silurian or Early Devonian (Shride, 1976a,b). The exposures here are intercalated flows and tuffs of the porphyritic andesite member (Shride, 1976a,b; Member 7) that have been overturned. The top of each flow is recognizable by the presence of a vesicular band. Note the differences in the phenocryst content of the different flows. The andesites and basaltic andesites of the Newbury are high-alumina calc-alkaline rocks with trace element signatures indicative of formation in a continental arc (McKenna *et al*., 1993). The Newbury Volcanic Complex is similar in both age and composition to volcanic rocks in the Coastal Volcanic Belt in easternmost Maine (Gates and Moench, 1981).

Notice the undeformed nature of both the amygdule fillings and the plagioclase phenocrysts in this exposure. The Newbury, while tilted (overturned), is important because it demonstrates the lack of penetrative deformation and metamorphism no higher than the lowermost greenschist facies during the Acadian or subsequent orogenies.

Return to cars. Reverse direction and return to junction with Rt. 1.
41.4 Turn right at the light onto Rt.1N
41.8 Newbury town line
42.1 At blinking lights turn left onto Elm Street toward Governor's Academy (formerly Governor Dummer Academy) and almost immediately pull over adjacent to small road exposures on right of purplish rhyolites of the Newbury Volcanic Complex

STOP 9B. ELM STREET NEAR INTERSECTION WITH RT. 1, NEWBURY, MA. Newbury Volcanic Complex, Rhyolite (15 minutes) (From Stop 13B, Hepburn, 2004; Previously described as Stop 2-1B, Hon *et al*., 1993; Stop 2-10A, Hepburn *et al*., 1993)

The rocks in the two small exposures here are good examples of purplish, flow-banded rhyolite in the Newbury Volcanic Complex (Member 6 of Shride 1976a,b). Note the preservation of the fine textures in these rocks. This again indicates that they have not been deformed tectonically since being deposited.

42.1 Continue west on Elm Street
42.3 Governor's Academy on right. This is an independent school (ca. 370 students) for 9 to 12 grades.
43.5 Keep right at the intersection. Stay on School Street
43.9 Merge with Central Street
44.9 Take I-95N ramp on right
45.1 Merge with I-95N
46.5 Follow I-95N to exit 56, Scotland Road
47.0 At end of down-ramp, turn left onto South Street. Scotland Road is the road to the right
47.1 Turn right into Turkey Hill Road, make a U-turn, and re-enter South Street heading east toward the direction of the interstate highway.
47.2 Park on the right before the entrance ramp to I-95S. We will visit a small road cut adjacent to the ramp leading to I-95S. Proceed on foot alongside the I-95S ramp. Road log 2 ends.

STOP 10. SOUTH STREET/SCOTLAND ROAD TO I-95S ONRAMP-INTERCHANGE 56, NEWBURY, MA. Sharpners Pond Quartz Diorite, Intermingling of Felsic and Mafic Magmas, Nashoba Terrane. (20 minutes) (From Stop 2-4, Hon *et al*., 1993 and Stop 2-9, Hepburn *et al*., 1993)

The Sharpners Pond pluton 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, 1964, 1965). Much of the pluton is rather homogeneous with these rock types grading gradually into one another. Titanite is a characteristic accessory phase. Near its eastern border, as seen here along the ramp to I-95 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).

Another large outcrop of Sharpners Pond Quartz Diorite is located along the east side of the northbound onramp from Scotland Road to I-95N. We will visit if time permits. This is another complex outcrop that is typical for exposures along the eastern side of the Sharpners Pond pluton. Several types of igneous rocks have been intruded into each other at different times. The oldest intrusive types consist of a fine-grained gabbro to diorite intermingled with a light medium-grained biotite granite. Approximately 10 % of this outcrop consists of granite. The younger intrusive types consist of a homogenous, medium-grained quartz diorite and the youngest intrusive types crosscutting other rocks are represented by infrequent aplitic dikes. Northeast-striking, steeply dipping younger diabase dikes can be observed sharply cutting rocks of the Sharpners Pond pluton. These dikes differ from the rocks of Sharpners Pond pluton; the diabase has an alkaline affinity, compared to the calc-alkaline character of the Sharpners Pond pluton.

Enter I-95N and continue north past the Hampton, NH tollbooths at exit 2.

Outcrops 3-4 miles north of the toll both are in the Rye Complex. This belt of high grade mylonitic gneiss is east of, and in fault contact with, the younger and lower grade metasedimentary rocks (Merrimack Group) into which the Exeter pluton intrudes.

Exit I-95 at the Portsmouth interchange and take the Spaulding Turnpike, Route 16 north.
From Route 16 going north take the exit to Route 4, Durham, UNH. This is marked as the last exit before the toll. Bear right toward Durham.

0.0 Cross Scammel Bridge across Bellamy River. <u>Reset odometer</u>
Proceed through stoplight. Little Bay and the Great Bay estuary are to your left (west).
3.0 From Route 4 take the exit to Route 108, Durham/UNH and Dover. Slow down, outcrop is just ahead
3.1 STOP at the well-jointed outcrop on the right. PARK WELL OFF THE ROAD AND BEWARE OF TRAFFIC.

STOP 11. EXIT RAMP OFF RT. 4W TO RT. 108 (DOVER ROAD), DURHAM, NH. Exeter Pluton, Quartz Diorite of the Eastern Merrimack Belt (30 minutes)

Quartz diorite to granodorite of the Exeter pluton. This medium to coarse-grained, salt-and-pepper rock is typical of the calc-alkaline Exeter pluton near its contact with metasediments of the Merrimack Group. Both plagioclase and alkali feldspar may be identified in thin section. Plagioclase phenocrysts are zoned and sericitized. The major mafic mineral in hand specimen is biotite. Green hornblende is identified in thin section. Accessory minerals include titanite, apatite and zircon. Rutile shows sagenitic texture in biotite. When the rocks are altered, which is common on the UNH campus, the hornblende and included pyroxene(s) react to form actinolite + chlotite + green biotite + epidote. Zircon from this outcrop dated by S. Bowring gives a concordant age of 406 +/- 1 Ma (Bothner *et al*., 1993; Lyons *et al*., 1997, loc. 128).

End of Trip. Return to the cars.
Turn left on Route 108 towards Durham. The Holiday Express hotel is on your right just before the stoplight. The Holloway Commons is in town (see map for meeting).

At the stoplight turn left onto Madbury road. At the stop sign in 0.6 mile turn right onto Edgewood Rd. You will first come to the New England Center turn (left; see sign or note that there is a parking lot on your right) and then parking lot H (a total of a half mile). If all else fails turn left on Main street past parking lot H and you will find Holloway Commons at the east end of campus.

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