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THE CAPE ANN PLUTONIC SUITE: CLASSIC STOPS FOR TEACHING PETROLOGY ALONG THE NORTH SHORE

By

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INTRODUCTION

Cape Ann, because of its proximity to Boston and many universities, has long been a focus of geologic study. Nineteenth century papers we located that consider mineralogy or petrology of Cape Ann rocks include Prescott (1839), Nichols (1856), Kimball (1860), Gregory (1862), Mudge (1862), Balch (1864), Cooke (1866, 1867), Knowlton (1867), Hyatt (1869, 1871a, 1871b), Hunt (1871), Wadsworth (1878, 1882a, 1882b, 1885), Sears (1888, 1889a, 1889b, 1890a, 1890b, 1891a, 1891b, 1893, 1894, 1898), Shaler (1889), Pearce (1893), Penfield (1896), and Washington (1898, 1899a, 1899b, 1899c, 1899d). More recent studies of note include Wright (1900), Warren (1903) Clapp (1921), Warren and McKinstry (1924), Bowen (1935), Palache (1950), Toulmin (1964), Dennen (1976, 1991a, 1991b, 1992), Wones (1983), Hon et al. (1993), Hepburn et al. (1993), Bozhilov and Evans (2001), Thompson and Ramezani (2008), Rose et al. (2009), Thompson et al. (2010a), Thompson et al. (2010b), and Ross, M. (2014). With this long history of study, Cape Ann offers an unusual wealth of data and opinion that match the extensive, interesting, and beautiful outcrops that occur there, making it a destination of choice for petrologists.

For many years, Brady and Cheney have been jointly taking their petrology classes on a one-day field trip to the Cape Ann region to see and discuss igneous rocks in a spectacular setting. We have found this to be a very rewarding experience both for us and for our students. We offer this NEIGC trip to share with others what we think are the best teaching stops, some comments about teaching strategies, diagrams that may be useful for teaching, and our current understanding of the geologic history of the Cape Ann Plutonic Suite. This is not a trip about new research, although our students have collected data over the years that are included in some of the figures, and recently obtained U-Pb zircons dates are included that clarify the age of the Cape Ann suite. Instead, this trip is a chance to look at some great rocks, to discuss research that began in this area in the mid-19th century and to consider new questions about their origin and significance. This is a slightly modified and updated version of a similar NEIGC trip previously offered by Brady and Cheney (2004).

GEOLOGIC SETTING AND AGE RELATIONSHIPS

Eastern Massachusetts consists of two geologically distinct terranes that originated along the margin of Gondwana on the far side of seaways pre-dating the modern Atlantic. The Nashoba terrane lying between the Clinton-Newbury and Bloody Bluff faults (Fig. 1) contains Lower Paleozoic amphibolite grade pelites, mafic volcanic rocks and volcaniclastic strata that have been intruded by late Ordovician to early Devonian I- and S-type granites and diorites (Hepburn et al., 1993). The back-arc origin of these units on the trailing margin of the terrane called Ganderia for occurrences in Newfoundland's Gander Zone, as well as the timing of terrane accretion will be explored in trips B3 and C4 (Hepburn et al., this volume; Kuiper et al., this volume).

The trip today will visit locations east of the Bloody Bluff Fault in the terrane known as Avalonia that is underlain mainly by Ediacaran magmatic and sedimentary sequences with counterparts in the Avalon Peninsula of Newfoundland (Hibbard et al., 2006). Plutonic and volcanic members of this suite show calc-alkaline compositions and trace element signatures consistent with their origin in an island arc setting. U-Pb zircon dates for members of this suite fall between 610 Ma and 585 Ma, within the 630-580 Ma interval defining "younger Neoproterozoic magmatic arcs" of Hibbard and co-authors. Members of the arc complex exposed closest to Boston in the Avalonian sector shown in Figure 1 are listed at the bottom of Table 1 along with published U-Pb zircon geochronological constraints. Only dates in the left hand column would have been available in time for publication of the Bedrock

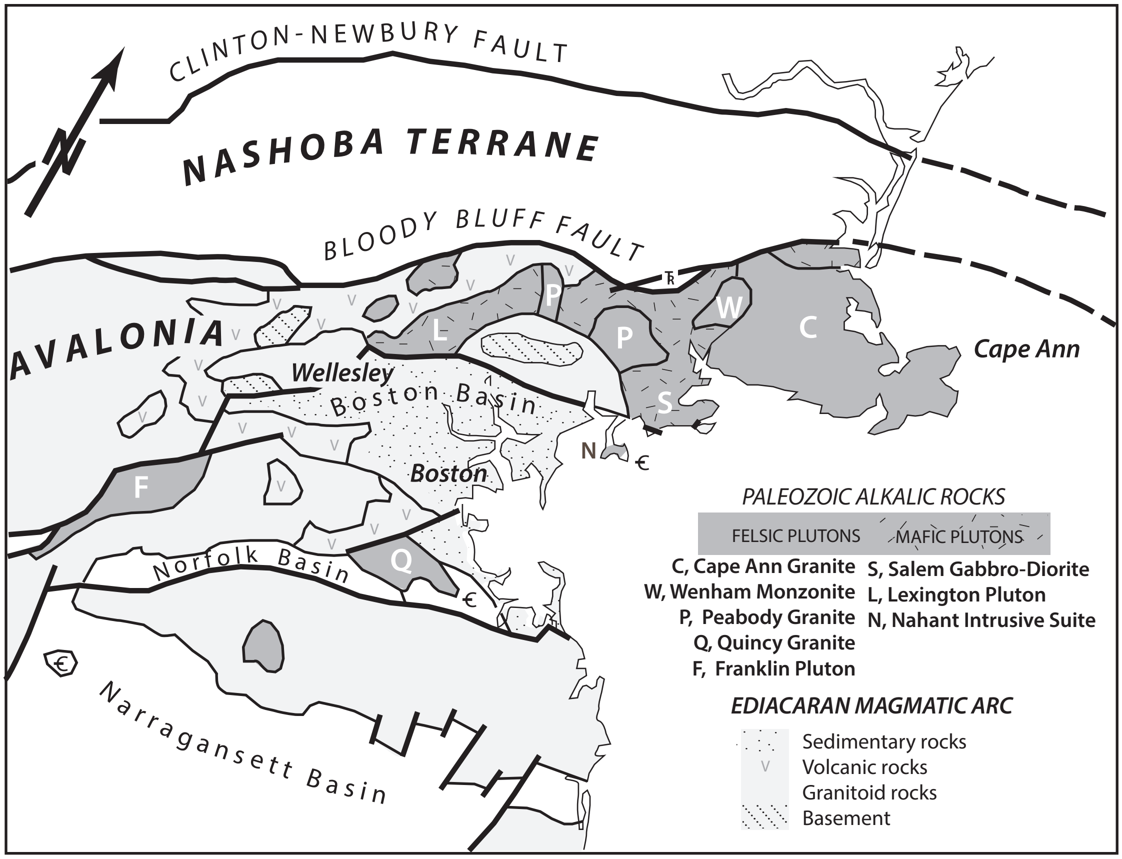


Figure 1. Slightly modified detail from Lithotectonic Map of the Appalachian Orogen showing Ediacaran arc-related granitoid and volcanic rocks and Paleozoic alkalic plutons that are the subject of this trip (units 19a and 30, respectively, of Hibbard et a. 2006). More detailed subdivisions of these rocks (albeit with much poorer age control) can be found in the Bedrock Geologic Map of Massachusetts (Zen, 1983) and accompanying text (chapters by Goldsmith, 1991 and Wones and Goldsmith, 1991)..

Geologic Map of Massachusetts (Zen, 1983), but these have now been superseded by more reliable results in right-hand columns (especially weighted mean ^{206}Pb/^{238}U dates on far right obtained by CA-TIMS methods (detailed discussion in Thompson et al., 2010a). Some of the arc-related units in Table 1 (and many others elsewhere in SE New England) were characterized—without any U-Pb isotopic constraints and before the Ediacaran Period was delineated—as Neoproterozoic Z in the 1983 map.

Most of today's stops will be in members of the Cape Ann pluton, the largest of various Paleozoic intrusions identified in Figure 1. As already pointed out, rocks comprising this body have been thoroughly documented during more than a century of investigation. The Cape Ann plutonic suite consists predominantly of felsic intrusives that range from granite to alkali granite through quartz syenite to syenite and finally to minor trachyte and sodalite-nepheline syenite (as late dike rocks). Less abundant mafic rocks include olivine gabbro, diorite, and diabase. Rocks of the Cape Ann suite are mildly alkaline in the sense of Peacock (1931). Nepheline monzo-gabbro/diorite in this suite was called essexite by Sears (1891a) and further discussed by Washington (1899a). Most of the mafic rocks contain titaniferous clinopyroxene. Felsic members of the association typically contain mafic minerals rich in alkalis and/or ferrous iron, whereas the calcium and magnesium contents are low to very low. The localized occurrences of mafic magmatic pillows, partially ingested enclaves, and segmented dikes in the felsic rocks establish the simultaneous existence of mafic and felsic magmas. These features are particularly well developed on Salem Neck, but also occur at other localities. The close temporal and spatial relationship between mafic and felsic melts provides an environment of possible fractionation and mixing that resulted in considerable complexity. Most of the granitoids contain at least some alkali-amphibole indicative of the slightly peralkaline nature of the felsic rocks. The Cape Ann plutonic series is similar to other bimodal anorogenic intrusive provinces such as the younger granites of Nigeria and Rapakivi massifs of southern Finland, i.e. iron-rich, normal to peralkaline alkali-rich granitic rocks

Table 1.
U-PB GEOCHRONOLOGICAL CONSTRAINTS FOR EDIACARAN ARC COMPLEX AND PALEOZOIC INTRUSIVES IN FIGURE 1

Dated unit	U-Pb Zircon Date (millions of years)[†]					
	Through 1985	Current Constraint				
		Lower intercept date	Upper intercept date	Weighted mean ^{207}Pb/^{206}Pb date	Weighted mean ^{206}Pb/^{238}U date	Source
Paleozoic intrusive rocks						
Gabbro-diorite, Waltham, MA			373 ± 4			1
Peabody Granite	380 ± 15[2]				378.08 ± 0.15	3
Gabbro pegmatite, Waltham (?), MA			392 ± 4			4
Wenham Monzonite	398 ± 10[§] 393 ± 5[§]					2
Cape Ann Granite	450 ± 25[5]				425.97 ± 0.11	3
Lexington Pluton (gabbro)				427 ± 1.5		6
Franklin Pluton (granite)			417 ± 6			7
Syenite pod, Danvers, MA		444 ± 3				1
Nahant Gabbro					488.53 ± 0.81	8
Ediacaran arc-related plutonic and volcanic rocks						
Brighton Igneous Suite					584.19 ± 0.70	9
					585.37 ± 0.72	9
Westwood quartz diorite			589 ± 2			10
Lynn Volcanic Complex					595.8 ± 1.2	11
			596 ± 3			1
Mattapan Volcanic Complex	602 ± 3[12]				593.2 ± 0.7	9
				597.4 ± 1.5		11
					596.0 ± 1.4	11
					595.7 ± 1.6	11
			596 ± 2			10
Westwood Granite			599 ± 1			10
Dedham Granite North of Boston		606 ± 3				1
		607 ± 4				1
		609 ± 4				1
Dedham Granite	630 ± 15[13]				608.9 ± 1.2	14
					609.1 ± 1.1	14
					609.5 ± 1.1	14

[†] All entries in table from Thermal Ionization Mass Spectroscopy [TIMS]; zircons pre-treated by chemical annealing [CA] for analyses in right hand column.

[§] ^{207}Pb/^{206}Pb dates from multi-zircon sieve fractions; other entries in this column are upper intercept U-Pb dates.

Sources of dates are: 1—Hepburn et al., 1993; 2—Zartman, 1977; 3—Thompson and Ramezani, 2008; 4—Acaster and Bickford, 1999; 5—Zartman and Marvin, 1971; 6—personal communication of G.R. Dunning regarding date in Hepburn et al., 1998; 7—Hermes and Zartman, 1992; 8—Thompson et al., 2010b; 9—Thompson and et al., 2014; 10—Thompson and others, 1996; 11—Thompson and others, 2007; 12— Kaye and Zartman, 1980; 13—Zartman and Naylor, 1984; 14—Thompson et al., 2010a.

that seem to be related to co-genetic mafic rocks. The Cape Ann suite contains a large pendant mapped as Salem Gabbro-diorite inside its northwestern border (Dennen, 1976 and 1981, Zen, 1983) but the only view of the contact zone between these units is at Salem Neck, MA (Toulmin, 1964b). The Salem Gabbro-diorite is part of an extensive map unit (Zdigb of Zen, 1983) for which several Paleozoic ages have more recently been determined (Danvers, Lexington and Waltham entries in Table 1). Xenoliths of undated metavolcanic units (Zv of Zen, 1983) are also reported (Dennen, 1981).

Establishing contemporaneity among apparently co-genetic members of the Cape Ann suite, however, has been hampered by shortcomings of available age constraints. The 450 ± 25 Ma date reported for the Cape Ann Granite (Zartman and Marvin, 1971) typifies results obtained during early phases of U-Pb geochronology. This and other entries in the left-hand column of Table 1 reflect analyses of sieve fractions of zircons that were neither hand-picked to avoid inherited components nor pre-treated to minimize Pb loss. Analyses from "batch" samples like these were commonly discordant, and the date was obtained by regressing a line through points representing several such analyses to its upper intercept with the concordia curve (for example, Figure 3 in Zartman and Marvin, 1971). The 450 ± 25 Ma upper intercept date is further complicated by the fact that several data points on the regression line were from analyses of the geographically removed Quincy Granite located south of Boston (Q in Fig. 1). This result translates into the "Lower Silurian or Upper Ordovician" age range for all of these rocks both in Zen's 1983 Massachusetts map and in Figure 1 from Hibbard et al.'s 2006 lithotectonic map. Accurate and precise U-Pb dates are also necessary to establish where the various Paleozoic alkalic plutons fit into the tectonic chronology of New England and to clarify whether they record pre-Acadian continental extension or back-arc activity (Hepburn et al., 1993 and 1998) or Alleghanian anorogenic activity in a post-Acadian stable platform (Hermes and Zartman, 1992). Emerging refinements to U-Pb zircon dates that are necessary for addressing the foregoing issues are included in Table 1 and discussed in the following descriptions of specific map units in the field trip area:

Paleozoic intrusive rocks

Cape Ann Granite. The Cape Ann Granite is typically a massive, medium- to coarse-grained leucocratic alkali granite to quartzose alkali syenite. The feldspar is primarily microperthitic alkali feldspar. Albitic plagioclase, quartz, hornblende, biotite, oxides (magnetite + ilmenite), and riebekitic amphibole, acmitic augite and fayalite all occur in various amounts. Dennen (1991a, 1991b, 1992) subdivided and mapped the Cape Ann Granite Complex based upon variation in quartz content. Specifically, as shown in Figure 2, Dennen (1991a, 1992; see also Washington 1899d) mapped granites with quartz contents >25% and 15-25% as the Granite facies, whereas he designated those rocks including the Beverly Syenite with 5-15% and 5% modal quartz as the Syenite facies. Dennen (1992) suggested that the variation in modal quartz was related to cumulate processes or perhaps "convective motions of the magma."

A sample collected from the Granite facies at Johnson's Quarry in Rockport, MA was dated in MIT's Radiogenic Isotope Lab using chemical abrasion-thermal ionization mass spectroscopy (CA-TIMS) methods. Full discussion of sample preparation and analytical methods can be found in Thompson et al. (2010a). Five single zircons from this sample yielded a weighted mean ^{206}Pb/^{238}U date of 425.97 ± 0.11 Ma (MSWD—mean square of weighted deviates = 0.34; uncertainty includes analytical error only; Thompson and Ramezani, 2008). Besides being more accurate than the 450 ± 25 Ma date of Zartman and Marvin (1971), the CA-TIMS date is also two orders of magnitude more precise. It lies outside the Upper Ordovician to Lower Silurian interval implied by the earlier result and is consistent with a mid-Silurian crystallization age.

Beverly Syenite. The Beverly Syenite commonly consists of massive, medium-grained syenite composed largely of microperthitic alkali feldspars (up to 90%) and variable mafic minerals including arfvedsonitic amphibole, biotite and augite containing some acmitic component. This group of nearly quartz-absent rocks consists of a wide variety of medium- to coarse-grained syenite and pegmatitic syenite dikes, including nepheline syenite pegmatites that intrude other rock types in the area. Hon et al. (1993) have argued that at least some of these syenites originated as liquid fractionates of the alkaline basaltic rocks based on their close spatial association with mafic rocks and on their geochemical nature. Dennen (1991a, 1992) identified as Beverly Syenite the syenites he mapped with <5% modal quartz, and he interpreted all of the syenites as part of a mineralogic continuum of the Cape Ann Granite. It is very possible that there are syenites of differing origins in this plutonic complex and that lumping all syenites together has obscured their differences. In the chemical data discussed below, there are both nepheline normative and quartz normative syenites.

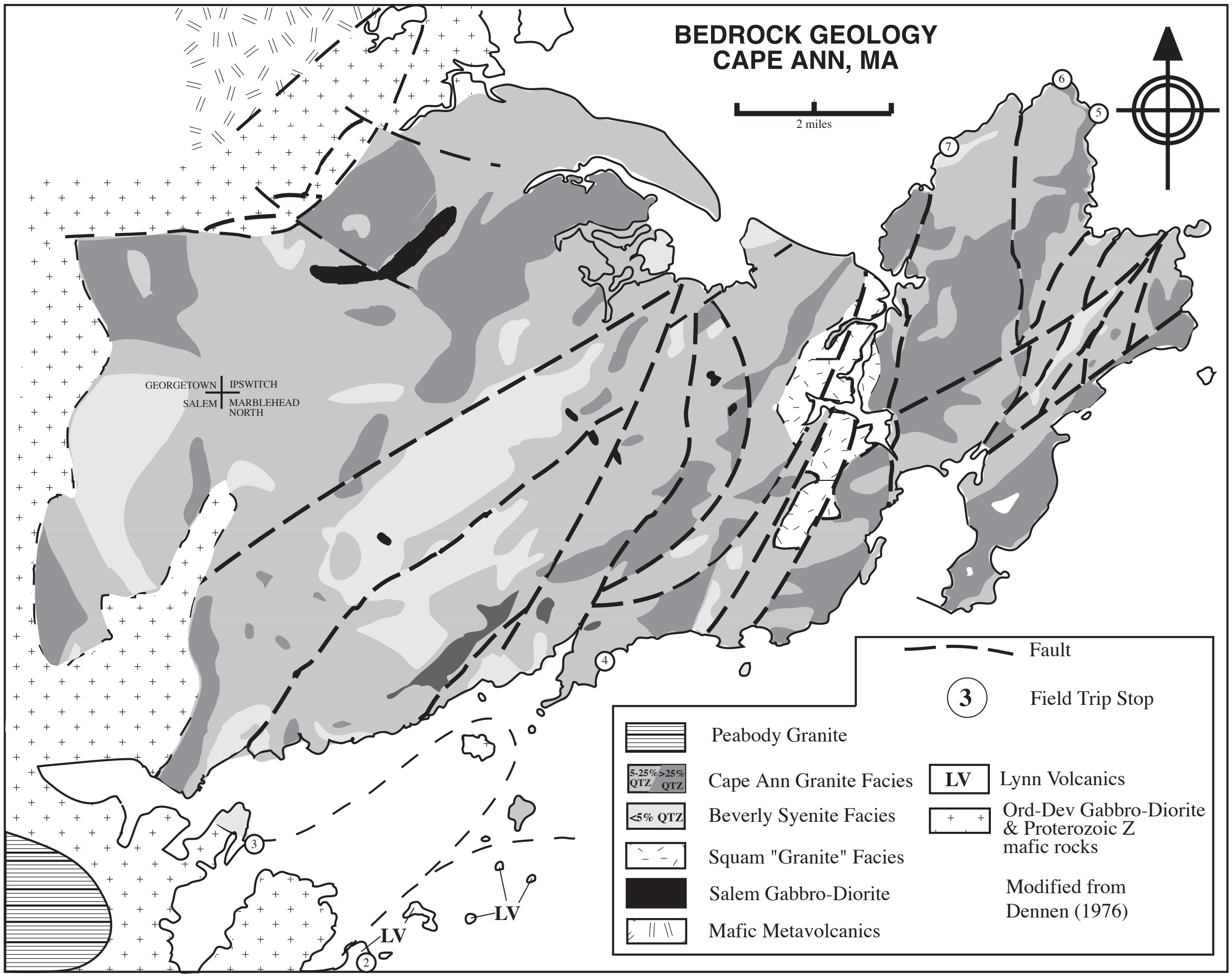


Figure 2. Geologic map of the Cape Ann Plutonic Complex and location of field trip stops. Modified from Dennen (1976) and Zen et al. (1983)..

Quartz normative syenite was collected for CA-TIMS U-Pb geochronology in the east wall of a quarry at the end of East Street leading to Cooney Field in Beverly, MA. The sample is medium- to coarse-grained syenite, locally containing pegmatitic stringers and segmented mafic dikes. This sample lies within a domain of "granitic and coarse-grained alkali-feldspar syenite containing <5% modal quartz" in the bedrock geologic map of the Salem Quadrangle (unit Ocg1 of Toulmin, 1964b), but it contains 12% modal quartz. Six zircons from this sample yielded concordant analyses with a range of mid-Silurian dates, the youngest of which overlaps the Cape Ann date within error (unpublished data of Thompson and Ramezani).

Squam Granite. The Squam Granite is a fine- to medium-grained gray granite. Quartz (15-30%) and sodic plagioclase (5-40%) occur with orthoclase, microcline or microperthitic microcline. Mafic minerals comprise from 5% to 50% of the rock. These include ferrohornblende, biotite and, less commonly, clinopyroxene. Common accessory minerals are apatite, zircon, "opaque minerals", titanite, allanite and monazite. Dennen (1991) considered this two-feldspar subsolvus granite as a facies of the Cape Ann Granite complex, and indeed four single zircons from a sample collected along Rust Island Road, Gloucester, MA yield a mid-Silurian weighted mean ^{206}Pb/^{238}U CA-TIMS date (unpublished data of Thompson and Ramezani) that is virtually identical to the Cape Ann result above.

Peabody Granite. The Peabody Granite is very similar to the Cape Ann Granite. It is a massive, medium- to coarse-grained granite composed of quartz (approximately 25%), microperthite (approximately 65%) and hornblende (approximately 5-10%) with minor amounts of clinopyroxene, biotite, riebeckitic amphibole, magnetite, ilmenite, titanite and zircon. This pluton was sampled in Emerson Park, Peabody, MA and yielded a 378.08 ± 0.15

Ma weighted mean $^{206}Pb/^{238}U$ CA-TIMS date based on five zircons (Thompson and Ramezani, 2008 reported here with analytical error only; MSWD = 1.3). This result supersedes the pre-1985 age estimate in Table 1 (complete discussion in Zartman, 1977, p. 270), and pinpoints a Late Devonian age for the larger, easterly body of Peabody Granite shown in Figure 1.

Salem Gabbro-Diorite. The Salem Gabbro-Diorite is a heterogeneous intrusive complex that borders the Cape Ann Granite on the northwest and occurs in scattered small outcrops as dikes and pods around the region, including Salem Neck. Mafic members of this suite are medium- to coarse-grained and consist primarily of plagioclase (labradorite to andesine), hornblende, clinopyroxene, biotite, and locally minor amounts of olivine. Included in this diverse group of rocks are those that form magmatic pillows and xenoliths in the felsic rocks. The mafic rocks at Cat Cove vary from fine-grained basalts to medium-coarse grained gabbro-diorite. The xenoliths or magmatic pillows that occur in localized fields within the Granite on Cape Ann are characterized by red-purple labradorite megacrysts up to 10 cm long that occur in gabbro porphyry and cumulate anorthosite (Paige, 1991). The rocks at Salem Neck are very similar to gabbro at Nahant, MA now precisely constrained by the 488.53 ± 0.81 Ma 206Pb/238U CA-TIMS date in Table 1 (details on this and closely comparable dates from more siliceous members of the Nahant suite in Thompson et al., 2010a). The Nahant assemblage has been inferred beneath gabbro-diorite in the vicinity of Salem, MA (Zdigb in cross section BB' of Zen et al., 1983) and may well give rise to gravity and magnetic mapped in the Cape Ann area (Bromery, 1967; USGS, 1970). Yet the cross section interpretation of the Nahant suite (with latest Cambrian crystallization ages in the geologic time scale of Gradstein et al., 2012) intruding Neoproterozoic gabbro-diorite is at odds with post-1983 U-Pb geochronology which has yet to provide any evidence of Neoproterozoic age. Available results (Table 1) include 373 ± 4 Ma gabbro-diorite in Waltham, MA, 427 ± 1.5 Ma pegmatitic gabbro in Lexington, MA and a 444 ± 3 Ma syenite pod in Danvers, MA (Hepburn et al., 1993 and personal communication of G.R. Dunning). Another gabbroic pegmatite from an ambiguous location in Waltham or Belmont, MA has also been reported as 392 ± 4 Ma (upper intercept date of Acaster and Bickford, 1999). The spread of these dates over 70 Ma indicates that these intrusrions should not be treated as products of a single magmatic episode

Ediacaran arc-related plutonic and volcanic rocks

Deadham Granite. Most pre-Paleozoic granitic rocks are mapped on the Zen et al. (1983) state map as the Dedham Batholith and are principally monzogranites with lesser granodiorite. These rocks are medium- to coarse-grained, light grey to pink, and commonly porphyritic. The principal mineral constituents are quartz, microcline and plagioclase, with lesser amounts of hornblende and biotite. Although these rocks were assigned a 630±15 Ma by Zartman and Naylor (1984), the Deadham Batholith is now known to have crystallized at 607±4 Ma (Hepburn et al., 1993).

Lynn Volcanics. The Lynn volcanic complex of Marblehead Neck and Salem Harbor consist of a series of felsic flows, agglomerates, and pyroclastics. This volcanic series was formerly considered as a possible extrusive facies of the Cape Ann plutonic complex (Clapp, 1921; Dennen, 1991a). However, an Ediacran age of 595.8 ± 1.2 Ma has been determined for the Lynn rocks, thus establishing the Lynn Volcanics as part of the Avalonian basement (Hepburn et al., 1993; Thompson et al., 2007). The similar age and composition of the Lynn Volcanics and the Dedham Granodiorite suggest a possible genetic relationship between these rocks (Hepburn et al., 1993).

WHOLE ROCK CHEMISTRY

Much of the difficulty in understanding the spatially-related rocks from Salem Neck to Beverly to Cape Ann derives from their mineralogical, and hence physical, similarity. It is now clear that there are hypersolvus syenogranites that differ in age by at least 70 Ma and that there are syenites of similar age, but of different origin. Chemical data from the Cape Ann rocks can be used to demonstrate nicely to students the power of geochemistry to solve problems in igneous petrology. Using various graphs, it is possible to test hypotheses regarding the petrologic history of these rocks. In this section, we use whole rock chemical analyses of major and trace elements to characterize and help understand the Cape Ann Granite and spatially-related rocks. The chemical data used here have been assembled from a variety of sources (see Figure 3 legend).

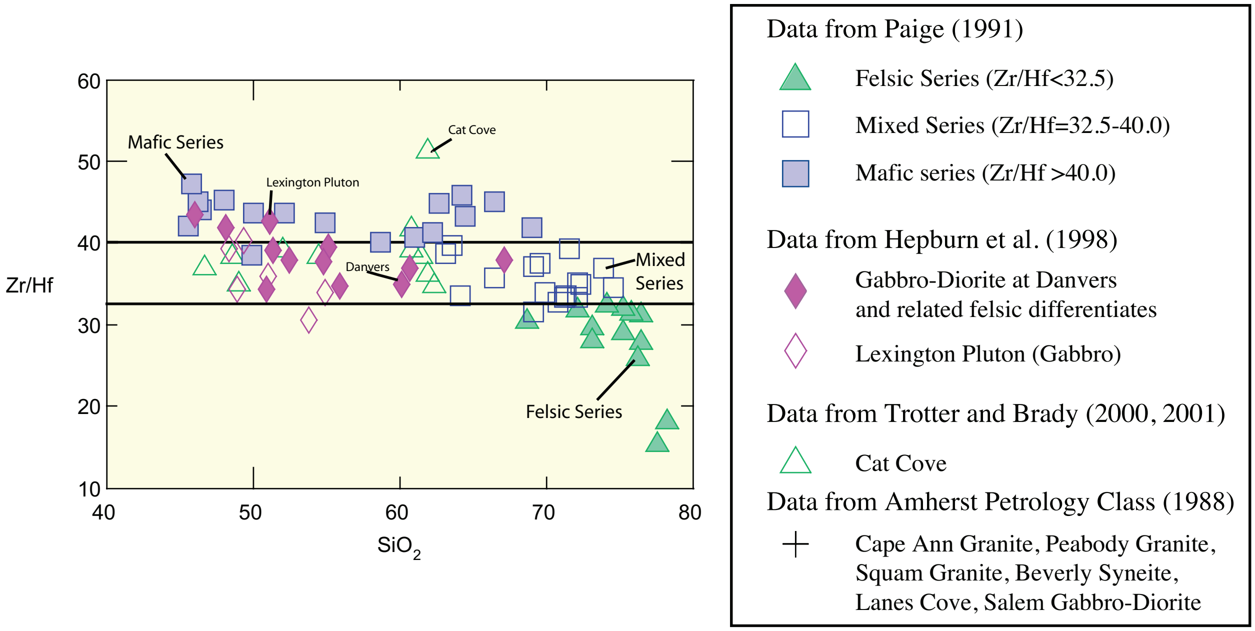


Figure 3. Plot of the Zt/Hf value versus weight percent silica showing the classification of Cape Ann rocks proposed by Paige (1991) and Hon et al. (1993). New data have been added as shown in the legend.

Figure 3 shows the distribution in Wt.% SiO_2 with change in the Zr/Hf value as used by Paige (1991) and Hon et al. (1993) to separate the Cape Ann rocks into three groups: a felsic series with low Zr/Hf (<32.5), likely derived from continental crust; a mafic series, with high Zr/Hf values (> 40), that includes its felsic differentiates and is likely mantle-derived; and a mixed series with Zr/Hf between 32.5 and 40 that can be derived by mixing of mafic and felsic series magmas. The systematic relationships found by Hon et al. (1993) seem less robust in Figure 3 with the addition of new data from Cat Cove (Trotter and Brady, 2000, 2001) and the mafic rocks from the gabbro-diorite and related rocks at Danvers and the Lexington pluton (Hepburn et al., 1993). Specifically, there is a much larger variation in the Zr/Hf value at lower Wt.% SiO_2, the basaltic composition range. The variation in Zr/Hf may be more complex if Zr and Hf are differentially incompatible or if the mafic sources are different or heterogeneous. The use of analyses from different labs may also affect the systematics.

There are clearly mafic rocks with low silica contents and felsic rocks with higher silica contents as shown on shown on Figure 4. The total alkalis vs. silica diagram provides a reference for the corresponding plutonic rock names in the terrane. All of the rocks are alkalic as shown on Figures 4 and 5a. The distribution of these rocks is shown on an AFM diagram in Figure 5b for completeness. Figure 6 shows that with increasing silica content some rocks (all with SiO_2>60 Wt.%) tend to be peralkaline, with (Na_2O+K_2O) > (Al_2O_3) on a mole basis. Whereas all the mafic rocks (SiO_2<57 Wt.%) are metaluminous in that (moles of Al_2O_3) > (moles of Na_2O+K_2O).

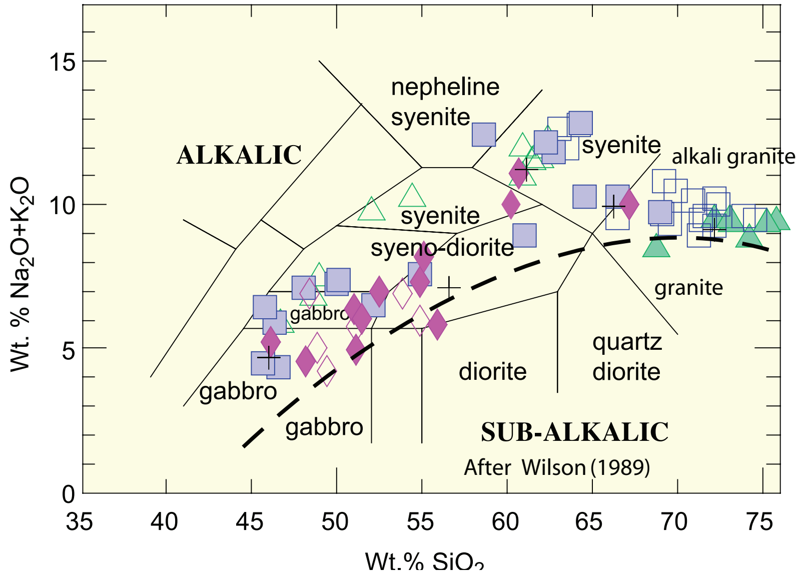


Figure 4. Nomenclature of plutonic rocks after Wilson (1989). The heavy dashed line separates alkalic and sub-alkalic rocks. Data symbols are the same as in Figure 3.

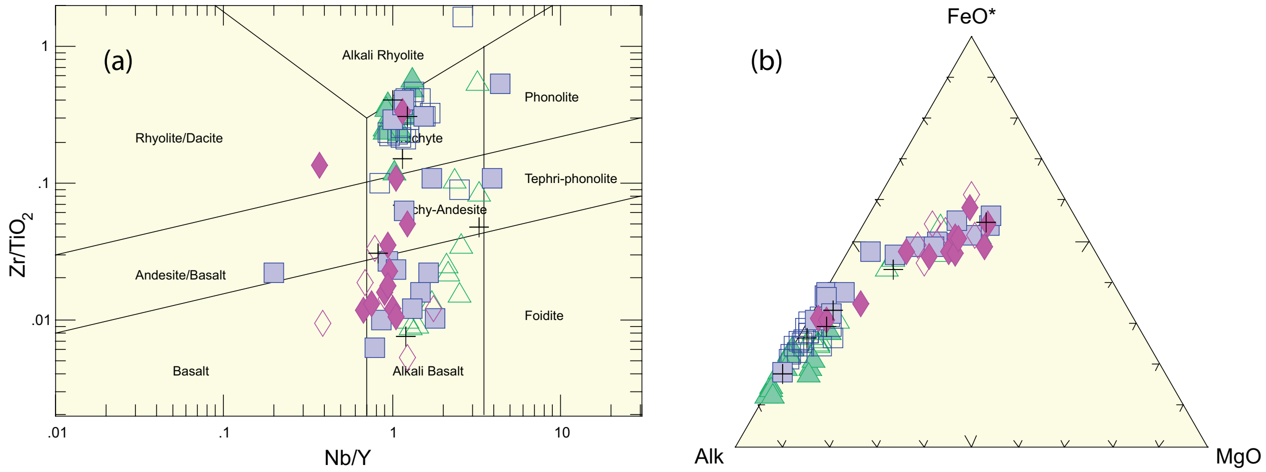


Figure 5. (a) Whole rock data plotted on a volcanic rock classification diagram (Pearce, 1996), based upon incompatible trace elements, which shows the alkaline nature of the Cape Ann Complex. (b) AFM diagram in weight percent of oxides. Alk = Na_2O+K_2O, FeO* is total iron as FeO. Data symbols are the same as in Figure 3.

Although there is some overlap, the rocks can be can be divided into three groups based upon their silica contents as shown in Figure 7. The low-silica gabbroic rock group consists of all but two of the samples with silica <57 Wt.% silica. This group generally corresponds to the high (>40) Zr/Hf value group of Hon et al. (1993). These rocks are alkalic and have alkaline basalt affinity, although some are quartz normative. Most of the granitc rocks have SiO_2 >67 Wt.%, are alkalic, and all are quartz normative. Most have Zr/Hf values <40 and this group includes the felsic and most of the mixed series rocks of Hon et al. (1993). A third group consists mostly of those samples that plot in the syenite field of Figure 4, but includes all of those rocks not in groups 1 and 2. This intermediate group tends to have between 57% and 67% SiO_2 by weight, is quite heterogeneous, and consists principally of higher total alkali rocks, many with Zr/Hf values >40. Most of these rocks are alkaline and several are nepheline normative. These are likely felsic differentiates of the mafic alkaline rocks as suggested by Hon et al. (1993) and Hepburn et al. (1998). All but two of the new Cat Cove analyses (Trotter and Brady, 2000, 2001) plot in this group.

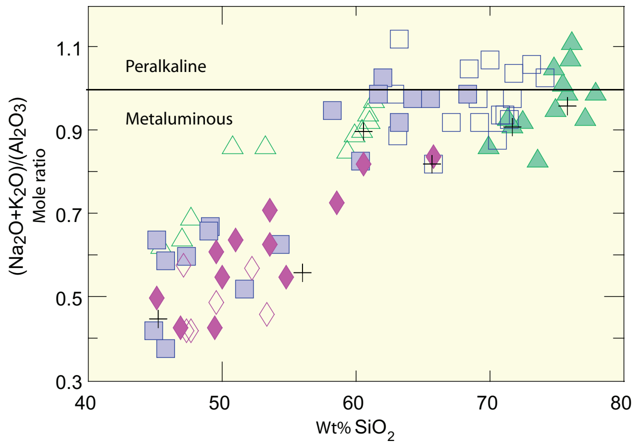


Figure 6. Aluminum saturation classification showing the mole ratio $(Na_2O + K_2O)/(Al_2O_3)$ plotted against weight percent silica. Although all mafic, low silica rocks have normal alumina contents, some of the higher silica granites are peralkaline. Data symbols are the same as in Figure 3.

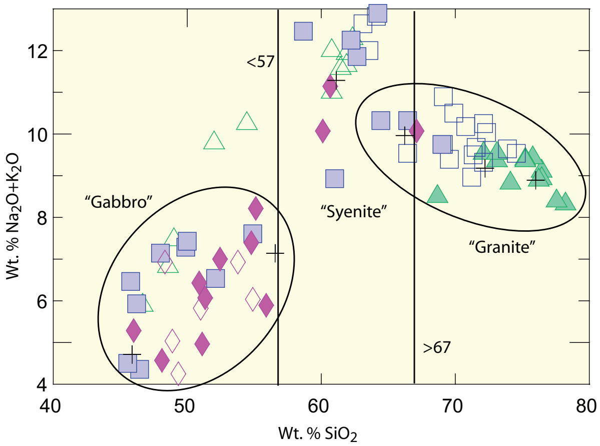


Figure 7. Total alkalis versus silica diagram. This diagram shows the relationship between weight percent silica and arbitrarily grouped rocks. Data symbols are the same as in Figure 3.

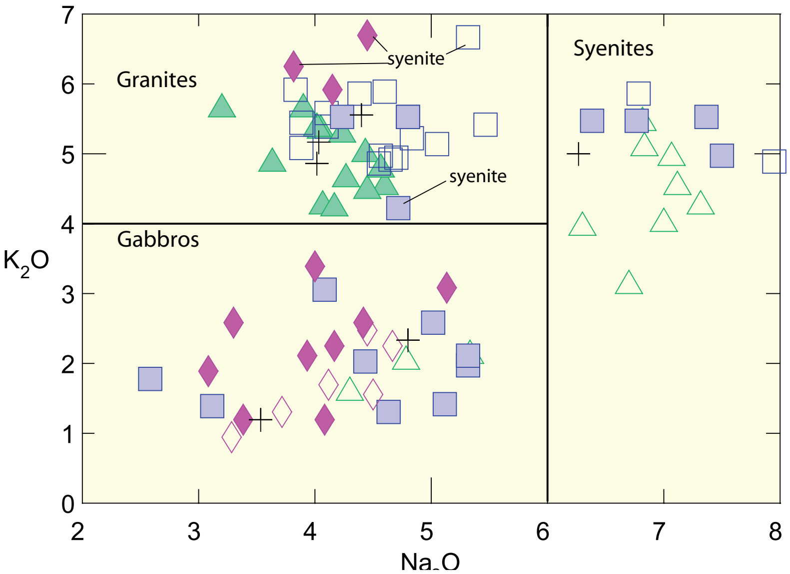


Figure 8. Weight percent Na_2O versus K_2O diagram showing the groups of rocks defined in Figure 7. The granites are K-rich relative to the gabbros, which are low in both Na_2O and K_2O. There are two types of syenites: those that are K-rich like the granites and those that are also Na-rich. Note that the trachytic syenite from Salem Willows (Stop 5) is shown as a cross in the K+Na-rich syenite field. Data symbols are the same as in Figure 3.

Figure 8 shows the distribution of the rocks delineated in Figure 7 as a function of sodium and potassium contents. Again the rocks tend to plot in discreet, but arbitrarily defined areas. Of interest is that the syenites of Figure 7 plot on different portions of the diagram, suggesting that there is more than one origin for these rocks. Some have sodium-rich compositions (e.g. >6 Wt.% Na_2O), which we believe results from their origin by fractionation of the mafic rocks. Others group with the granites, suggesting a common origin for some syenites and granites as proposed by Dennen (e.g.1991a, 1992). However, the origin of some intermediate rocks may have resulted from mixing as suggested by Hon et al. (1993).

Figures 9 and 10 are classic Harker variation diagrams for most of the major oxides and some representative trace elements. One interesting observation is that the intermediate silica content rocks are not simple linear mixtures of two end points. Moreover the diagrams can be interpreted to mean that multiple processes, including fraction and mixing, operated during the formation of these rocks as suggested by Hon et al. (1993).

Rare earth patterns for the three groups delineated in Figure 7 are shown on Figure 11. The mafic rocks are remarkably consistent and overlap, despite their slight differences from silica undersaturation (nepheline in the norm) through silica saturation (neither nepheline nor quartz in the norm) to silica oversaturation (quartz normative). The absence of negative Nb and Ta anomalies and their similarity to ocean island basalts (OIB) (Figure 11) are consistent with an alkaline olivine basalt parent in a continental or within-plate setting, as shown on Figure 12.

Similarly, the silica-rich (>67 Wt.%) granitic rocks also form consistent and overlapping REE patterns. The Spider diagram of Figure 11 shows an enrichment relative to model upper crust consistent with a crustal origin for this group of rocks. The characteristic negative Eu anomaly may result from residual feldspar in the source or feldspar fractionation or both. As shown on Figure 12, these granites have compositions that are typical of A-type, anorgenic, within-plate granitoids.

The intermediate silica group, as expected, overlaps the other two groups in concentration and some samples have pronounced positive Eu anomalies, whereas others have negative Eu anomalies. The magnitude of the Eu anomalies as a function of silica content is shown by their value of Eu/Eu* on Figure 11. Eu* is the expected Eu content in the absence of feldspar separation or accumulation. Some of the intermediate group clearly have REE patterns similar to the granites with strong negative Eu anomalies. Others in this syenite group, typically felsic differentiates of Hon et al. (1993), have positive Eu anomalies indicative of feldspar accumulation – again suggesting multiple origins for the syenite rocks. The syenites (<15% modal quartz) mapped by Dennen (1991a, 1992) are not well represented in this data set. The syenites grade into the quartz-richer granites in the field, and some of the syenites share common major and trace element chemistries with the granites, suggesting a common origin. Similarities of the high- and low-modal-quartz rocks are consistent with quartz variation by cumulate processes, as suggested by Dennen (1991a, 1992).

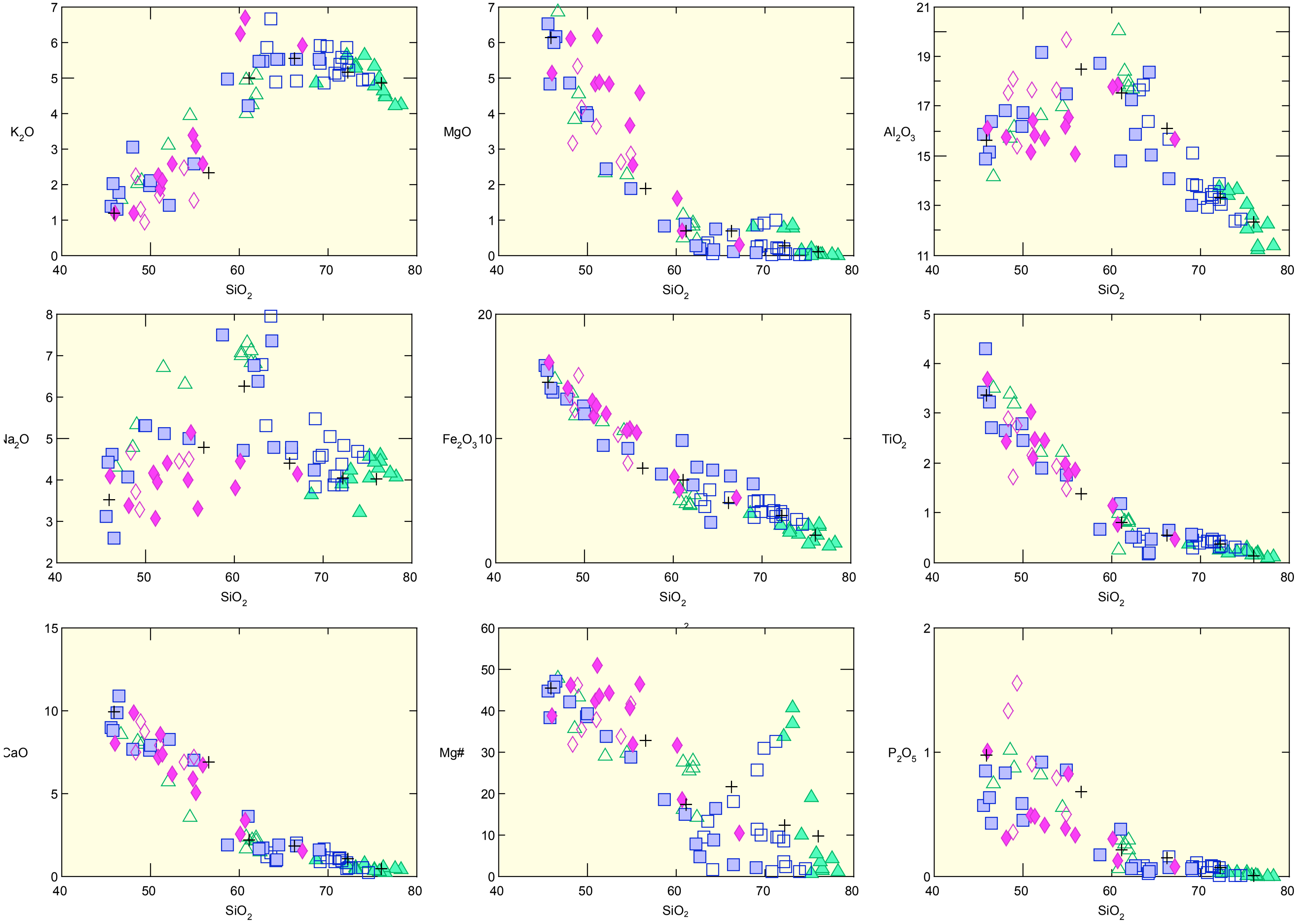


Figure 9. Harker diagrams in weight percent showing the variation in the major oxides with change of silica. Data symbols are the same as in Figure 3.

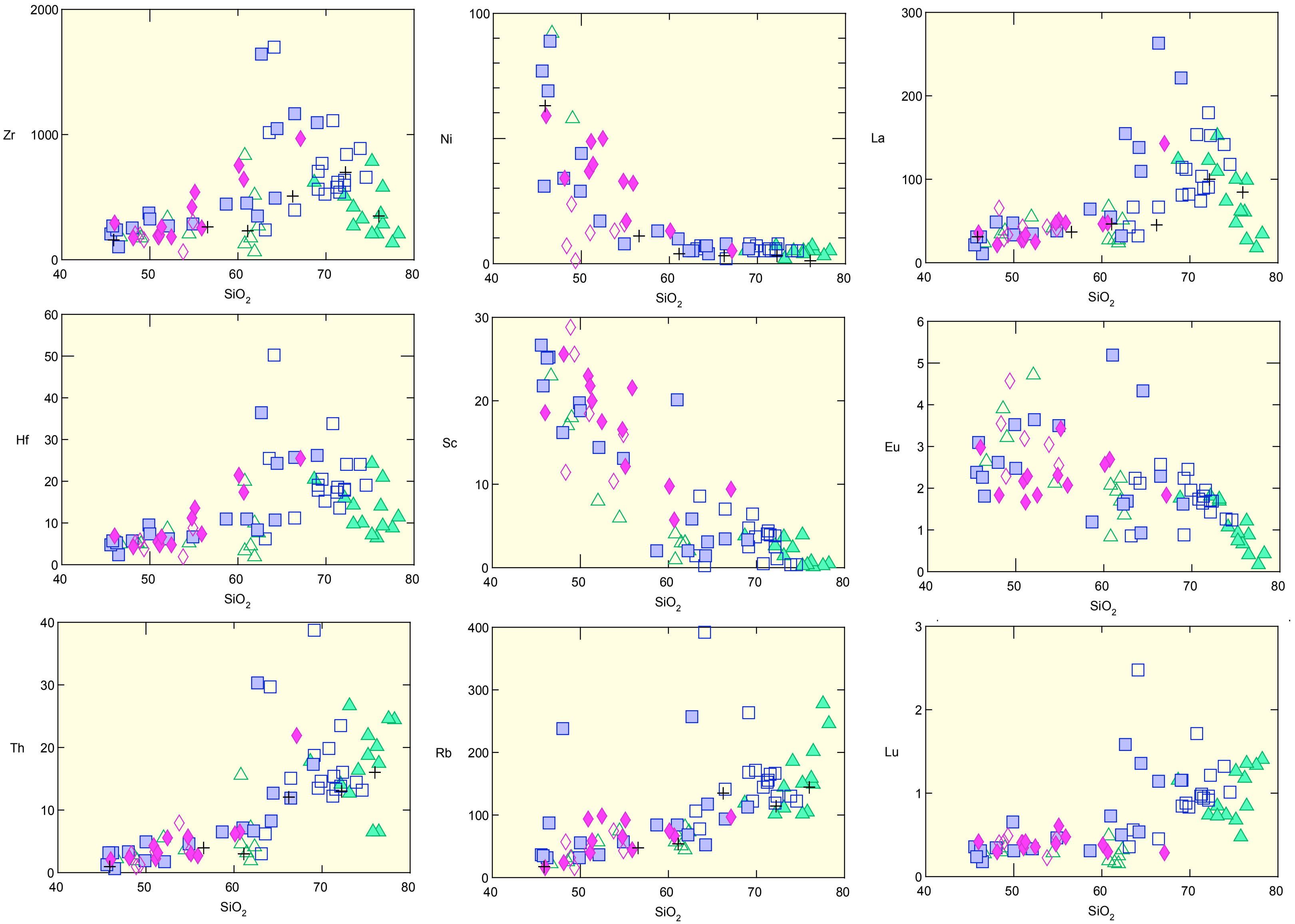


Figure 10. Harker diagrams showing the variation for representative trace elements in ppm with change of weight percent silica. *The Ni diagram is missing three anomalous samples with >150 ppm Ni at Wt.% SiO$_2$ of 60-65. Data symbols are the same as in Figure 3.

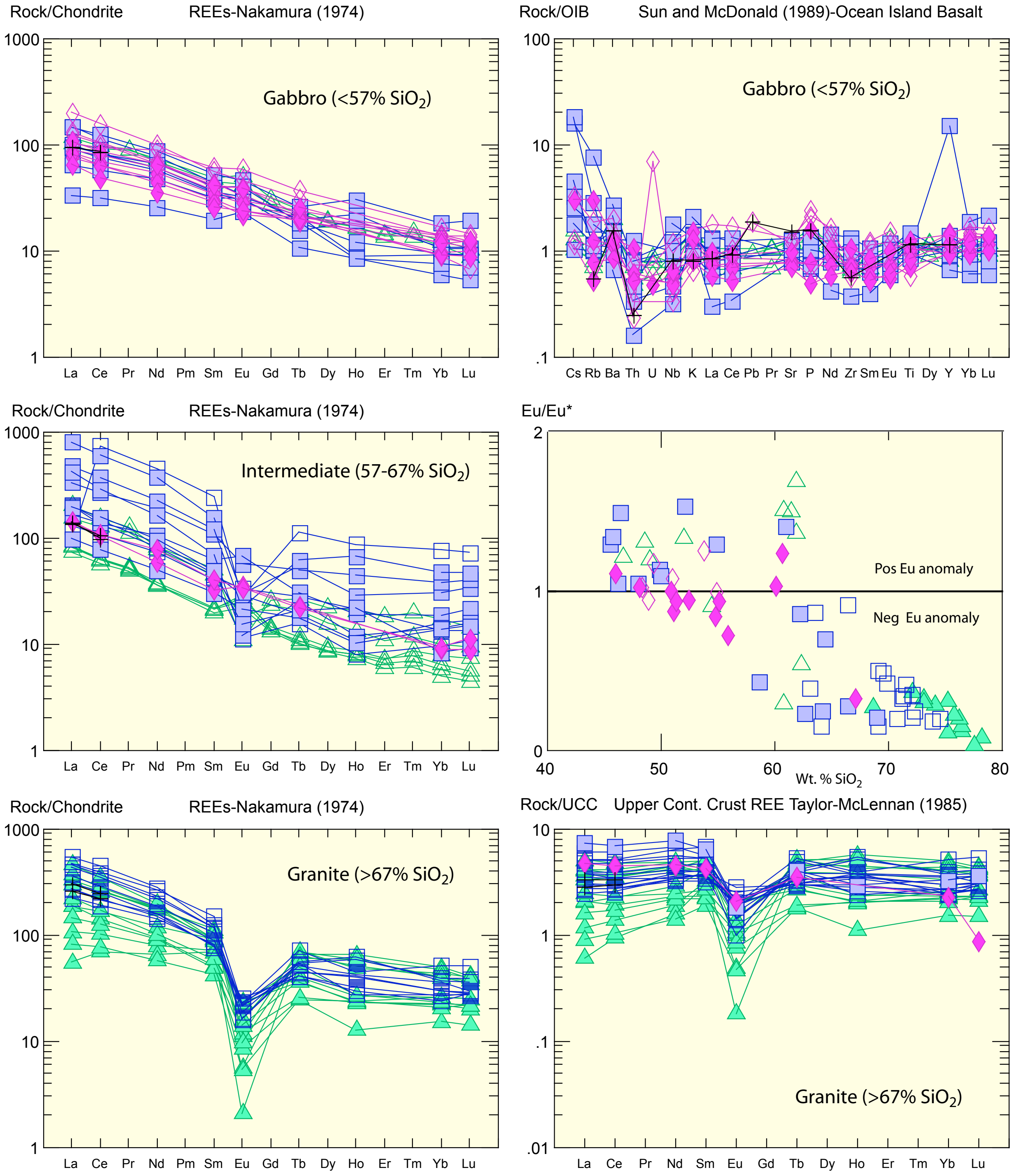


Figure 11. Chondrite-normalized rare earth diagrams on the left and Spider diagrams on the right. Note that the middle diagram on the right is a plot the Eu/Eu* ratio versus silica. Eu* is the predicted Eu content in the absence of feldspar accumulation or depletion and, thus, the ratio is a measure of the Eu anomaly as shown on the diagram. Data symbols are the same as in Figure 3.

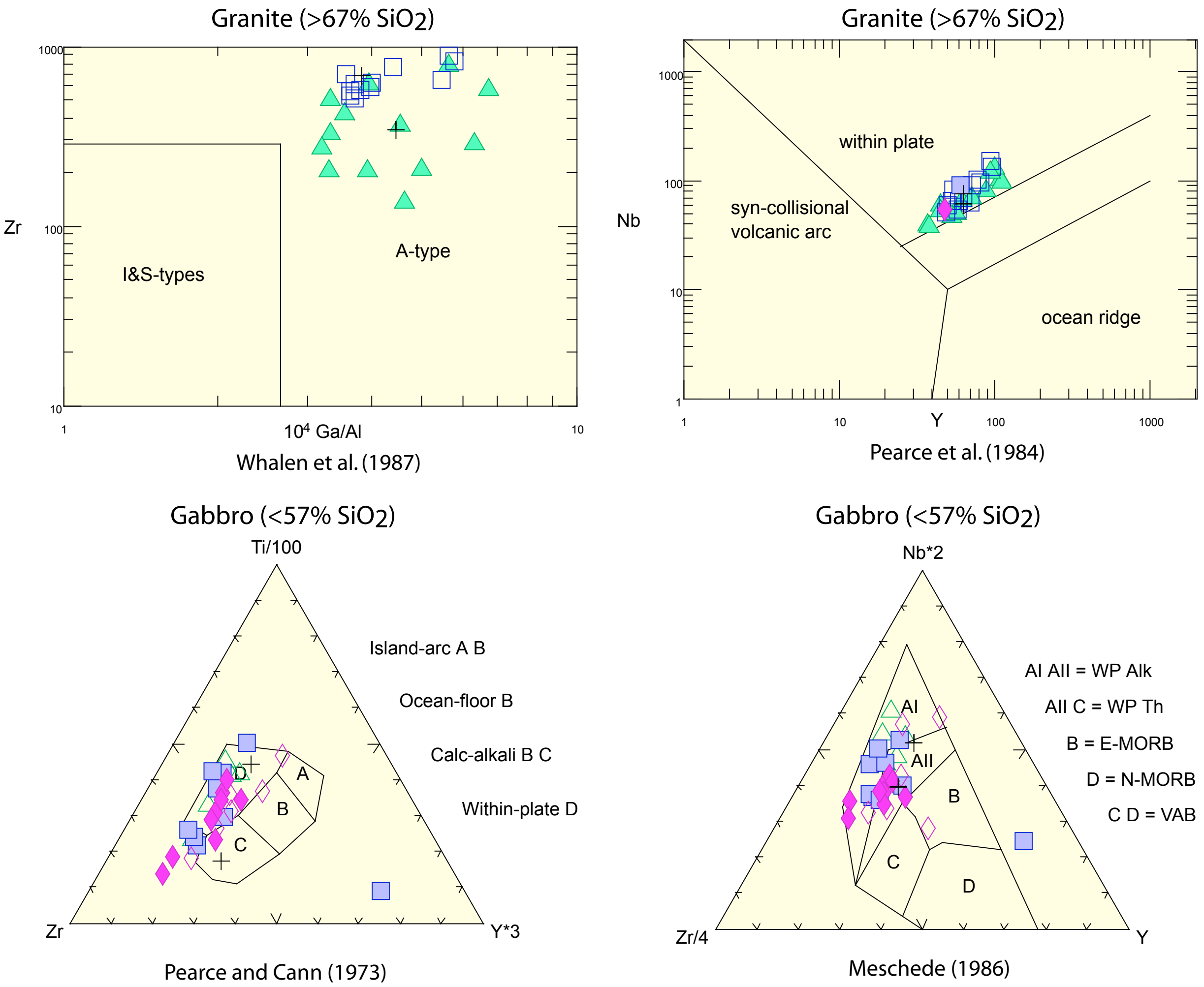


Figure 12. Discrimination diagrams commonly used to characterize the tectonic setting of igneous rocks. The gabbros have been plotted on diagrams typically used to classify basalts. WP alk = within plate alkaline. WP Th is within plate tholeiitic. VAB is volcanic arc basalt. Data symbols are the same as in Figure 3.

SUMMARY

The Cape Ann Plutonic Complex is a classic bimodal plutonic suite of gabbroic and granitic rocks similar to suites elsewhere that formed under anorogenic conditions. As proposed by Dennen (1991a, 1992) and by Hon et al. (1993), the mantle-derived alkaline, mafic magmas likely provided thermal energy that facilitated crustal melting. The existence of contemporaneous mafic and felsic magma is indicated by the occurrence of numerous mafic magmatic pillows and dikes that are enclosed and chilled against the cooler granite magma. The hypersolvus character of the granites suggests that the felsic magma was relatively dry and shallow. The variation in modal quartz remains enigmatic, but may involve cumulate processes (Dennen, 1991a, 1992), possibly related to venting brought on by the gradual buildup of water in the residual magma as originally proposed by Toulmin (1964). Other syenites, including the Beverly Syenite likely resulted from the fractionation of the mafic alkaline magmas. Some of the diversity of rocks in Cape Ann Plutonic Complex is probably due to the mixing of these differentiates with the granites as suggested by Hon et al. (1993).

ACKNOWLEDGEMENTS

We thank our many teachers, colleagues, and students who have taught us about these rocks. Special thanks belong to Chris Heburn, Rudi Hon, Pete Robinson, Jim Thompson, and Amanda Trotter. Mark Frigeau of the Northeast Massachusetts Aquiculture Center at Cat Cove has been especially welcoming and helpful to us and to our students.

ROAD LOG

This is a NO HAMMERS trip. Geologists have been visiting these locations for over 100 years. We hope to preserve the best outcrops for future generations of geologists. Please bring your camera instead of your hammer. The trip will assemble on Friday at 8:30 am in the parking lot of the Square One Mall, 1201 Broadway, Saugus, MA 01906. The Square One Mall is on Route 1 (and Route 129), 4 miles south of I-95. Look for the outcrops in the mall parking lot NE of Macys.

STOP 1. SQUARE ONE MALL PARKING LOT. DEADHAM GRANITE. (40 MINUTES) Low, glacially-polished exposures in the parking lot provide good gathering spots for small groups. Larger, blasted cliff exposures are also available behind the mall. The rock is typical gray- to salmon-colored Deadham monzogranite with at lease as much plagioclase as alakli feldspar. On weathered surfaces, the distinction between gray quartz and chalky white weathered feldspar is easily visible to students. The dark minerals are biotite and hornblende than can be distinguished if the sun is shining. So can resinous sphenoidal crystals of titanite (sphene!). The Deadham is higly altered in places, giving it a green color due to epidote and chlorite. The outcrop is crossed by epidote-green, hydrothermal veins in many orientations. Some of the plagioclase grains have green cores that reflect the compositional zoning of the plagioclase and the similarity of the composition of epidote/clinozoisite (Czo) to anorthite (An). Neglecting the iron, Czo = 3 An + $Ca(OH)_2$. Jim Thompson would always make this point when bringing students to Deadham outcrops near here. He would also powder the altered hornblende and apply diflute HCl to demonstrate that dolomite was produced as part of the hydrothermal alteration.

In our petrology classes, we like to use Shand's (1927) chemical classification for felsic igneous rocks: peralkaline [(Al2O3) < (Na2O+K2O)], metaluminous [(Na2O+K2O) < (Al2O3) < (CaO+Na2O+K2O)], and peraluminous [(CaO+Na2O+K2O) < (Al2O3)]. This classification is typically reflected in the mineralogy of a granitic rock with peralkine rocks having one (alkali) feldspar and unusual mafic minerals (aegirine and arfvedsonite), peraluminous rocks having two feldspars with muscovite and biotite, and metaluminous (=subalkline) rocks having two feldspars and either hornblende or biotite or both (and no muscovite or aegirine). Furthermore, this classification also typically reflects the tectonic setting of the felsic igneous rock with peralkaline implying an anorogenic setting, metaluminous implying an arc settting, and peraluminous implying a sediment-melting, continent-continent collision setting. There are, of course, many exceptions to this generalization, but it works well in a majority of cases, including this field trip where it helps students think about the Deadham Granite in contrast to the Cape Ann Granite.

In the outcrops at this stop, there are several examples of basalt dikes cross-cutting the Deadham Granite. The mineralogy of the fine-grained, dark basalt is challenging for a student with a hand lens, but white plagioclase crystals are evident. In some places, students can see that the crystals are smaller near the margins of the dike. The dikes provide a good chance to discuss relative ages and to note that basalt dikes of Mesozoic age are common in New England.

Observations to make:

(1) What minerals are visible in these rocks? What features can be used to identify these minerals?
(2) What minerals give the rock it's color and how do these colors vary across the outcrop?
(3) Are there any outcrop scale features associated with the color variations?
(4) Is there more than one type of rock here?

Discussion questions:

(1) Based on the mineralogy, what is the appropriate name for this rock?
(2) What tectonic setting might have produced these rocks?
(3) Why might there be so much alteration in this plutonic rock?

Mileage

0.0 Exit the Square One Mall to the northwest, turning right at the light onto Main St. Follow Main St, east over Rt. 1 and then right for the onramp to Rt. 1 north.
0.5 Follow Rt. 1 north for 4.3 miles.

4.8 Take the I-95/128N ramp following the signs to Gloucester. Keep left at the fork.
9.4 Take exit 25A toward MA-114 and Salem. Follow MA-114 as it twists and turns through Salem until you reach Ocean Avenue at a light with a fire station on the corner.
16.6 End of Route 114. Turn right at light onto Ocean Avenue.
17.0 Causeway to Marblehead Neck (see Figure 13).
17.4 Bear right with Ocean Avenue.
17.7 Park on right at the entrance to Castle Rock. Walk southeast to the shore on the public path.

STOP 2. CASTLE ROCK, MARBLEHEAD NECK. LYNN VOLCANICS. (40 MINUTES) Skehan (1977) has described this outcrop in some detail and we draw heavily from his work. These rocks were mapped as Lynn volcanics by Zen et al. (1983) and Dennen (1991b). Castle Rock consists of a complex assembly of felsic volcanic rocks that includes light-colored agglomerates and pyroclastic rocks, and dark-colored vitrophyres (now devitrified). The dark purple to black vitrophyres have white andesine phenocrysts. Chemically the rocks are rhyolite (68-76 wt.% SiO_2) (Dennen, 1991b). The agglomerates include a high proportion (>50%) of fragments of the vitrophyres and other rocks in a slightly greenish aphanitic matrix (see Figure 13). In some places, the two rock types are interlayered in bands that are contorted and steeply dipping. There is a circular structure that some have suggested is a remnant of a vertical pipe or vent. A basalt dike of probable Mesozoic age, less resistant to erosion, cuts the volcanic sequence on the north side of Castle Rock.

Unfortunately, there are no field relations at Castle Rock to identify its age relative to the Cape Ann Plutonic Complex. Goldsmith (1983) describes field relations of the Lynn and similar Mattapan volcanic rocks in eastern Massachusetts that are somewhat contradictory, probably resulting from the assignment of all felsic volcanic rocks to the Lynn or Mattapan. However, recent dating (Hepburn et al., 1993; Thompson et al., 2007) indicates an age of 596 Ma for the Lynn Volcanics, consistent with the observation of LaForge (1932 cited by Goldsmith, 1983) of Lynn volcanics lying nonconformably on weathered, Deadham granodiorite (607 Ma). Therefore, there is little relationship except physical proximity between the volcanic rocks at Castle Rock and the Cape Ann Plutonic Series. Nevertheless, this locality is one of the few places in Massachusetts for students to observe felsic volcanic rocks in the field.

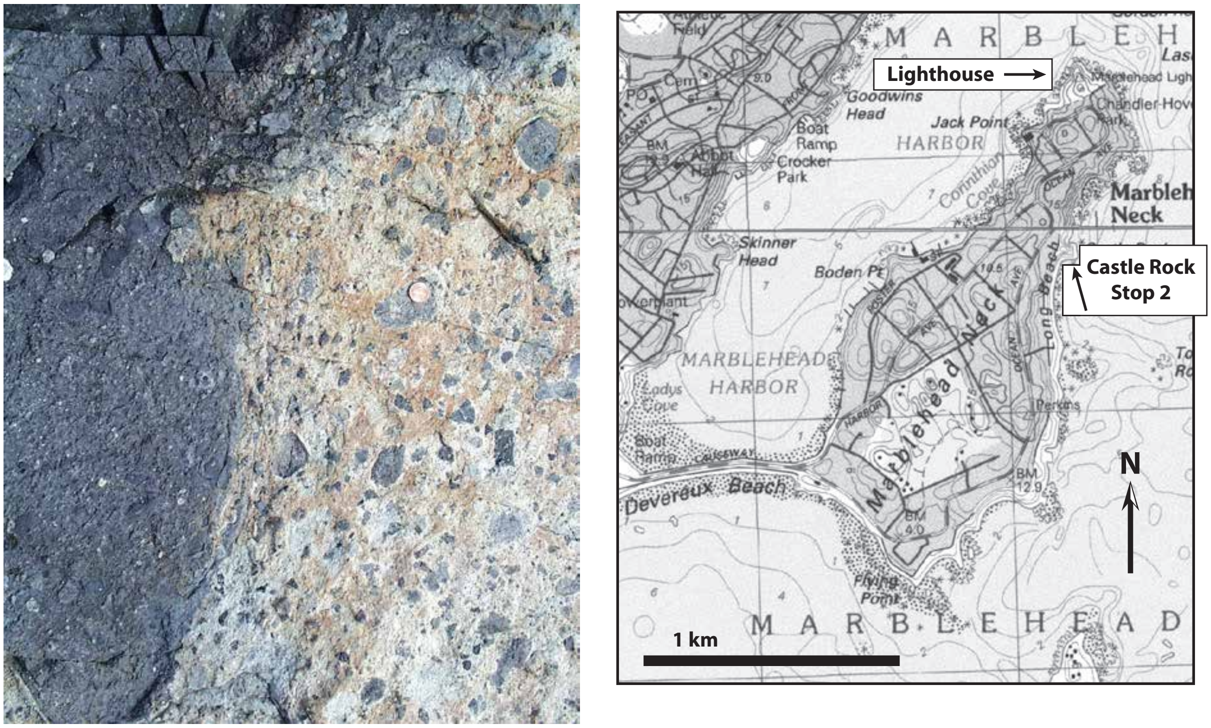


Figure 13. On the left is an outcrop photograph of dark, plagioclase-phyric vitrophyre and light agglomerate (with dark vitrophyre clasts) at Castle Rock. A penny is visible for scale. On the right is a location map for Marblehead Neck from the Marblehead North and Marblehead South 7.5-minute quadrangles.

Observations to make:

(1) Place the rocks that occur here into similar groups. How many groups are needed and what are their characteristics?
(2) What are the relative ages of the rock groups?
(3) Observe the geometric relationships among the mafic and felsic rocks.
(4) Look for minerals that can be identified.

Discussion questions:

(1) Are these igneous, sedimentary, or metamorphic rocks? How can we tell?
(2) What tectonic environment might have produced these rocks?
(3) What are the possible petrologic relationships between these rocks and those seen previously today? What data are needed to choose among them?

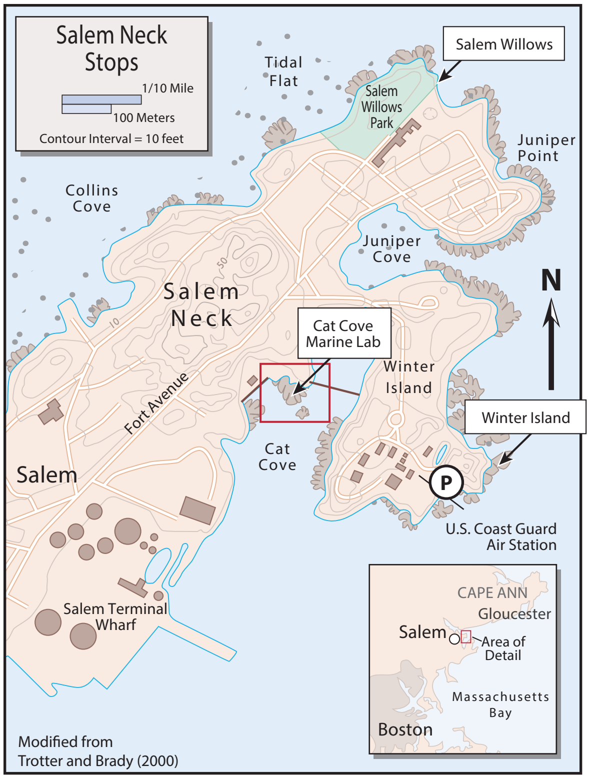
Optional Mileage

0.0 If you would like to see more felsic volcanic rocks, continue northeast on Ocean Avenue, bearing right at all intersections.
0.4 Lighthouse park. The rocks around the lighthouse are similar to those at Castle rock. Flow-banding is more evident here as well as flow-folding of the bands (see Figure 14). To see folding look at the outcrops close to the flagpole. The bands are fairly distinctive on the weathered surfaces of the vitrophyres, and virtually invisible on fresh surfaces and in thin section.

Mileage

0.0 Follow Ocean Avenue 0.1 mile to its junction with Harbor Avenue. Turn left and head southwest, crossing the causeway back to the T-intersection with MA-114.
1.9 Turn left onto MA-114 and follow it back to the ceter of Salem, keeping straight with MA-1A (leaving MA-114, which bears left at Lafayette Park).
4.9 Turn right onto Derby St. with MA-1A at a traffic light. Follow Derby St. straight (leaving MA-1A, which turns left) past the Salem Maritime National Historic Site (good toilets here), and past The House of the Seven Gables to Fort Avenue.
5.8 Bear right at the stop sign onto Fort Avenue.
6.5 Bear right past the Cat Cove Marine Lab of Salem State College onto Winter Island Road. Follow the road 0.5 miles to its end at a parking area on the SE shore of Winter Island.

Figure 14 (above). Photograph of dark, banded, and flow-folded vitrophyre near the flagpole adjacent to the Marblehead Neck lighthouse. A penny is included for scale.



Modified from Trotter and Brady (2000)

Figure 15 (right). Location map for stops on Salem Neck.

Figure 16. Photographs of outcrops at Stop 3. On the left is an outcrop photo showing the shapes and close proximity of the mafic pillows(?), surrounded by syenite. On the right is a different, more angular assmblage of mafic xenoliths(?) in syenite. Both images are about 30 cm across.

STOP 3. WINTER ISLAND LIGHTHOUSE. SALEM GABBRO-DIORITE, BEVERLY SYENIITE, AND RELATED ROCKS (40 MINUTES) This stop is an always-accessible substitute for the Cat Cove Marine Lab site described in the 2004 version of this trip. We prefer the Cat Cove site, but permission to access Cat Cove must be obtained in advance from the director of the Northeastern Massachusetts Aquiculture Center (NEMAC). Rocks and field relations similar to those at Cat Cove are well-exposed along the shore near the lighthouse. This area was described by Toulmin (1964a, Stop 8) and Hon et al. (1993, Stop 1-4). It is one of a series of localities on Salem Neck that were mapped as the "Beverly Syenite contact zone" by Toulmin (1964b). These outcrops contain a complex mixture of mafic rocks, typically in elliptical to ovoid pods, and felsic syenite in a variety of textual relations (see Figure 16). In these features, Hon et al. (1993) see "magmatic pillows in a syentic host." Toulmin (1964a) notes that, "The youngest dike rock is the nepheline-sodalite syenite, a blue-gray rock in which a greasy-looking feldspathoid is apparent in hand specimen. What looks like a single mineral is actually both a nepheline and a sodalite that fluoresces bright orange in long-wavelength ultraviolet light…." Fine-grained to very coarse (pegmatitic) varieties of syenite can be observed. A vareity of mafic rocks are found, although none as coarse as those that to the west at Cat Cove. There, a black, medium to coarse-grained rock has been described by Sears (1891a) and Washington (1899a) as essexite: a nepheline-normative olivine-bearing alkali gabbro that contains no feldspathoid. In thin section, the coarser-grained mafic rocks show peritectic textures of amphibole growing around pyroxene (see Figure 17).

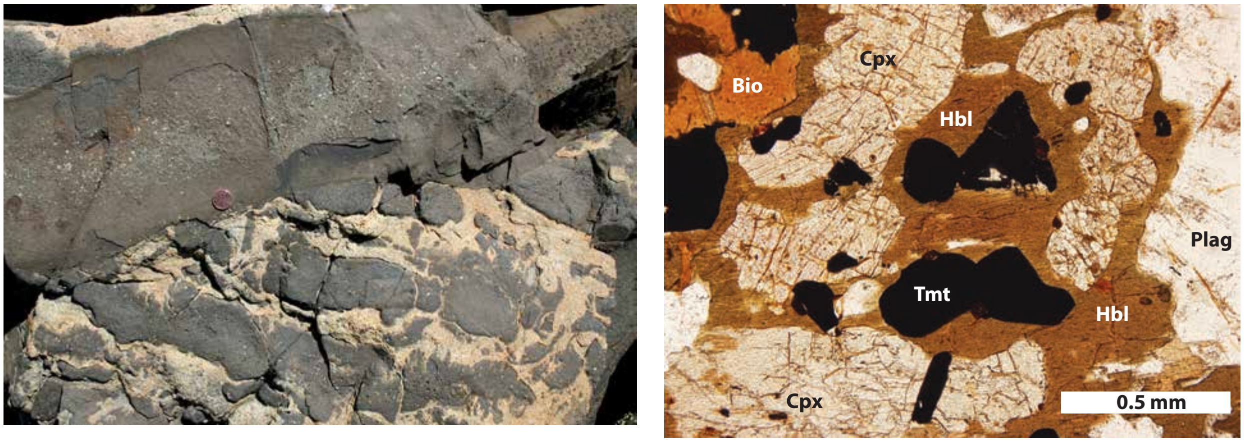


Figure 17. Photographs of Cat Cove rocks. On the left is an outcrop showing basalt pillows(?) in a syenite matrix. These features are crosscut by a basalt dike with chilled margins. A penny is shown for scale. On the right is a photomicrograph of a coarse-grained mafic rock (essexite) showing peritectic growth of amphibole (Hbl) around both clinopyroxene (Cpx) and titanomagnetite (Tmt).

Observations to make:

1. (1) Place the rocks that occur here into similar groups. How many groups are needed and what are their characteristics?
2. (2) What are the relative ages of the rock groups?
3. (3) Observe the geometric relationships among the mafic and felsic rocks.

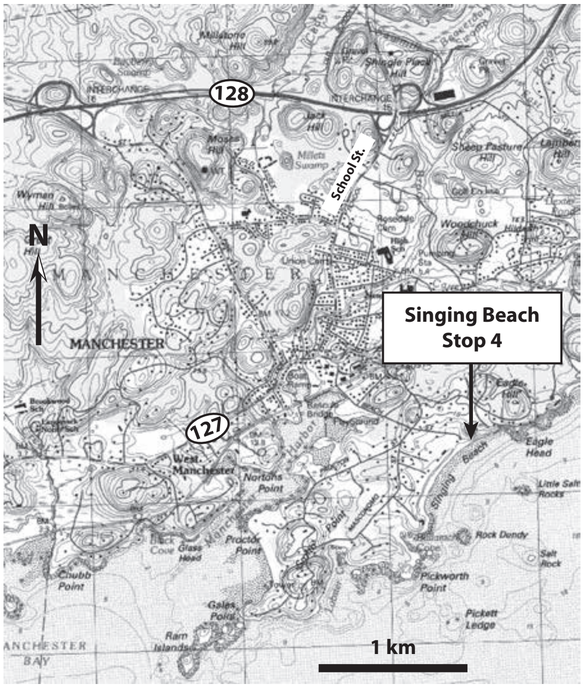
Discussion questions:

- (1) Are the ellipsoidal mafic rock masses magmatic pillow structures? How can we tell?
- (2) Some of the syenites that occur here contain nepheline? What does the presence of nepheline say about the origin of the syenites?
- (3) What igneous processes lead to syenites? Why are syenites less common than granites?
- (3) What are the possible relationships between this rock and the Cape Ann Granites that occur across the bay to the northeast? How could the various possibilities be distinguished by additional data?

If you have time, another good stop nearby is at Salem Willows on the northeast end of Salem Neck (see Figure 15). The rocks between the beach and the pier to the north at Salem Willows are Beverly Syenite with a trachytic texture. Dennen (1991) has mapped these trachytic rocks only on the north end of Salem Neck. Woodbury Point, another Beverly Syenite locality, is visible across the water to the north, although the rocks there have a coarser texture with little alignment. Toulmin (1964a, p.68) argues, "The textures of many of the trachytic syenite dikes imply that they have crystallized from a liquid of essentially the same composition as that of the rock." Is the origin of this syenite the same as that of the other low-quartz felsic rocks on Cape Ann?

Mileage

0.0	Follow Winter Island Road back to its junction with Fort Avenue.
0.5	Turn left onto Fort Avenue.
1.2	Continue onto Webb Street (no turn) to a T-intersection with MA-1A (Bridge St.).
2.6	Turn right onto MA-1A and follow it for one mile across the high bridge over North River.
3.6	Bear slightly right onto MA-22 (Cabot St.) and follow MA-22 to MA-128.
6.1	Turn left onto the onramp for MA-128 north towards Gloucester.
11.4	Take exit 15 right for School St. and Manchester.
12.6	T-intersection. Turn left onto MA-127.
12.7	Turn right on Beach Street (with Route 127).
12.8	Continue straight on Beach St. (Route 127 turns left.)
13.3	Continue straight on Beach Street at stop sign.
13.5	Singing Beach. Park in the lot on the right (unless it is summer when a resident's sticker is required). Walk to the beach and follow the coast northeast ~50m to the outcrops along the sand.



STOP 4. SINGING BEACH, MANCHESTER BY THE SEA. CAPE ANN GRANITE. (40 MINUTES) Dennen (1991) mapped this locality as alkali feldspar granite having greater than 25 percent modal quartz. Weathering of the rocks in outcrop is evident when contrasted with the freshly-quarried Cape Ann granite used as riprap blocks nearby. A basalt dike with 1-3 cm plagioclase phenocrysts is nicely exposed here. The dike margins are fine-grained and largely devoid of the phenocrysts. Basalt dikes occur in many places on Cape Ann (see Ross, 1984, 1990, 2004, 2014). Singing Beach is one of the best locations to view and discuss these dikes. Singing Beach is so named because of the "musical sand" that occurs there and was among the first sound-producing sands described in the scientific literature (Julien and Bolton, 1883). According to Lindsay et al. (1976), the best squeaking sands are well-sorted and largely made of well-rounded and highly-spherical quartz grains that squeak best when dry. "Booming sands" were also described, but these occur largely in desert dunes or the beach dunes

Figure 18. Another interesting feature of Singing Beach sand is its annual winnowing and deposition to create pronounced “winter “and “summer” beaches. Shown below are photos of Singing Beach on 26 March 2000 and on 1 April 2001. The level of the sand is at least one meter lower in 2001 than in 2000 leading to a pronounced difference in the beach appearance as granite boulders are exposed by the removal of sand.

of very dry climates. Singing beaches produce higher frequency (500-2500 Hz) sounds than booming sands (50-80 Hz).

Observations to make:

(1) Is this the same rock that occurs at Winter Island? How much modal quartz does it have?
(2) What is the distribution of phenocrysts in the mafic dike?
(3) How do the riprap rocks differ from the outcrop rocks?
(4) What parts of the beach “sing” when you walk upon them? What is their mineralogy?

Discussion questions:

(1) What is the age of the mafic dike relative to the felsic host?
(2) Was the felsic host a liquid when the mafic dike was intruded?
(3) What igneous processes could produce the observed distribution of phenocrysts in the dike?

Mileage

0.0	Retracing your route to MA-128, follow Beach St. to MA-127.
0.7	Turn left onto MA-127 south and then take the first right onto School St.
1.8	Turn left for the onramp to MA-128 north toward Gloucester.
7.5	Traffic circle. Continue straight with MA-128.
8.3	Traffic circle. Continue straight with MA-128.
9.4	Turn left onto MA-127 (Eastern Ave.) toward Pigeon Cove.
14.4	Turn right onto Phillips Ave., then immediately left with Phillips Ave., then bear right with Phillips Ave.
14.9	Continue straight onto Point De Chene Ave.
15.1	T-intersection. Park along Longbranch Avenue. Parking in the summer is not possible here (permit required), although you may be able to park here in the off season. We will park along Phillips Ave. past the turn to Point De Chene Ave.

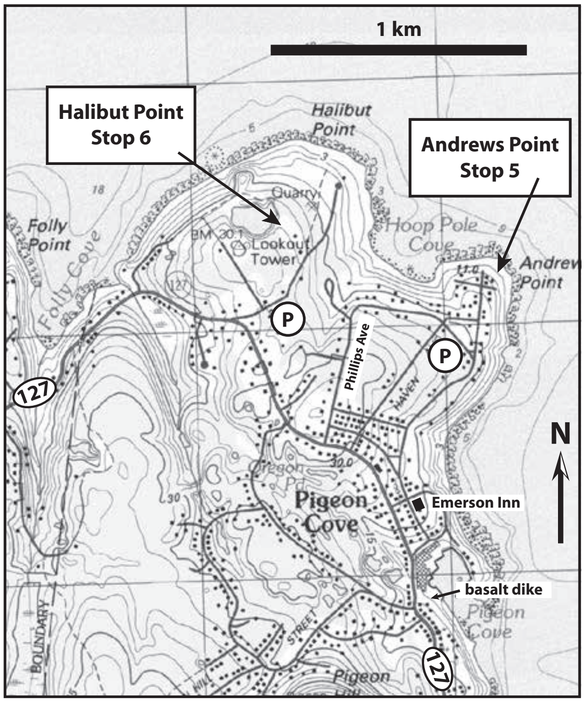


Figure 19. Photographs of pegmatites on Andrews Point. On the left are very large, darker (blue) quartz crystals in a lighter feldspar matrix. The whole pegmatite is surrounded by aplite. On the right is a closeup view of a euhedral quartz crystal with a 9-cm-long pocket knife for scale.

STOP 5. ANDREWS POINT, ROCKPORT. GRANITE, PEGMATITE, APLITE, ANNITE. (40 MINUTES) This stop was described by Dennen (1976, Stop 10) and Hon et al. (1993, Stop 1-13). Dennen (1992) mapped this locality as alkali feldspar granite having greater than 25 percent modal quartz. Although some of this locality is similar to Stop 4, small pegmatites can be found here containing blue quartz and other interesting minerals (see Figure 19). Very coarse-grained (>5cm) books of iron-rich biotite can be found in these pegmatites, close in composition to ideal annite, named for Cape Ann (Dana, 1868), but with quite a bit of Fe^{+3} (Wones et al., 1977). There are also very coarse-grained intergrowths of magnetite and grunerite that may be replacements of fayalite. Indeed, the pegmatite here is similar to that described by Palache (1950) from Halibut Point that contained fayalite crystals. Note also the co-occurrence of aplite and pegmatite within the Cape Ann Granite. The fenitized dike of Martin (1977) outcrops near where the beach path reaches the granite outcrop. An outcrop map of Adrews Point from Wones (1983) is reproduced as Figure 20.

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Observations to make:

(1) What are the coarse blue crystals? What features are used to identify them?
(2) What other minerals can be identified here? What features are used to identify them?

Discussion questions:

(1) What determines the size of crystals in an igneous rock?
(2) Although there are some very large crystals here, very fine-grained crystals occur in adjacent rocks (aplite). What igneous processes might produce both large and small crystals at the same locality?
(3) This is the type locality of annite, $KFe_3(AlSi_3O_{10})(OH)_2$, the iron endmember of biotite. What igneous processes might lead to such iron-rich rocks?
(4) Fayalite, Fe_2SiO_4, the iron end-member of olivine has been reported from this locality (and Stop 6). How can fayalite occur with quartz here whereas forsterite and most other olivines never occur with quartz?

Mileage

0.0	Return to Phillips Ave. Turn right and follow it to MA-127.
0.7	Turn right onto MA-127 north and then take the first right onto School St.
1.1	Turn right onto Gott Ave. A parking area is on the right. A pit toilet is available here.

STOP 6. HALIBUT POINT STATE PARK. CAPE ANN GRANITE. (40 MINUTES) Great exposures of typical quartz-rich Cape Ann Granite in an old quarry provide a sense of rock type variation and scale. Granite blocks were removed here from the "Babson Farm Quarry" starting in the 1840's and continuing until 1929 when the Rockport Granite Company went out of business. Palache (1910, 1950) describes collecting a large fayalite sample (about 20 pounds of fayalite) from a pegmatitie here around 1908, which can found today in the Harvard

Mineralogical Museum. His description of the pegmatite suggests that it was similar to the pegmatite that we saw at Andrews Point (Stop 5).

Observations to make:

1. What minerals are visible in this granite? What features are used to identify them?
2. In his bedrock geology map of the Gloucester and Rockport quadrangles, Dennen, (1992) separated the granite exposures on Cape Ann on the basis of modal quartz content. He mapped the south end of the main quarry pond as having 15-25 modal percent quartz. He mapped the granite north and east of the pond (to the coast) as having greater than 25 modal percent quartz. Can you tell the difference?

Discussion questions:

1. This granite has a high modal proportion of alkali felspar (microperthite - see Figure 21) and most

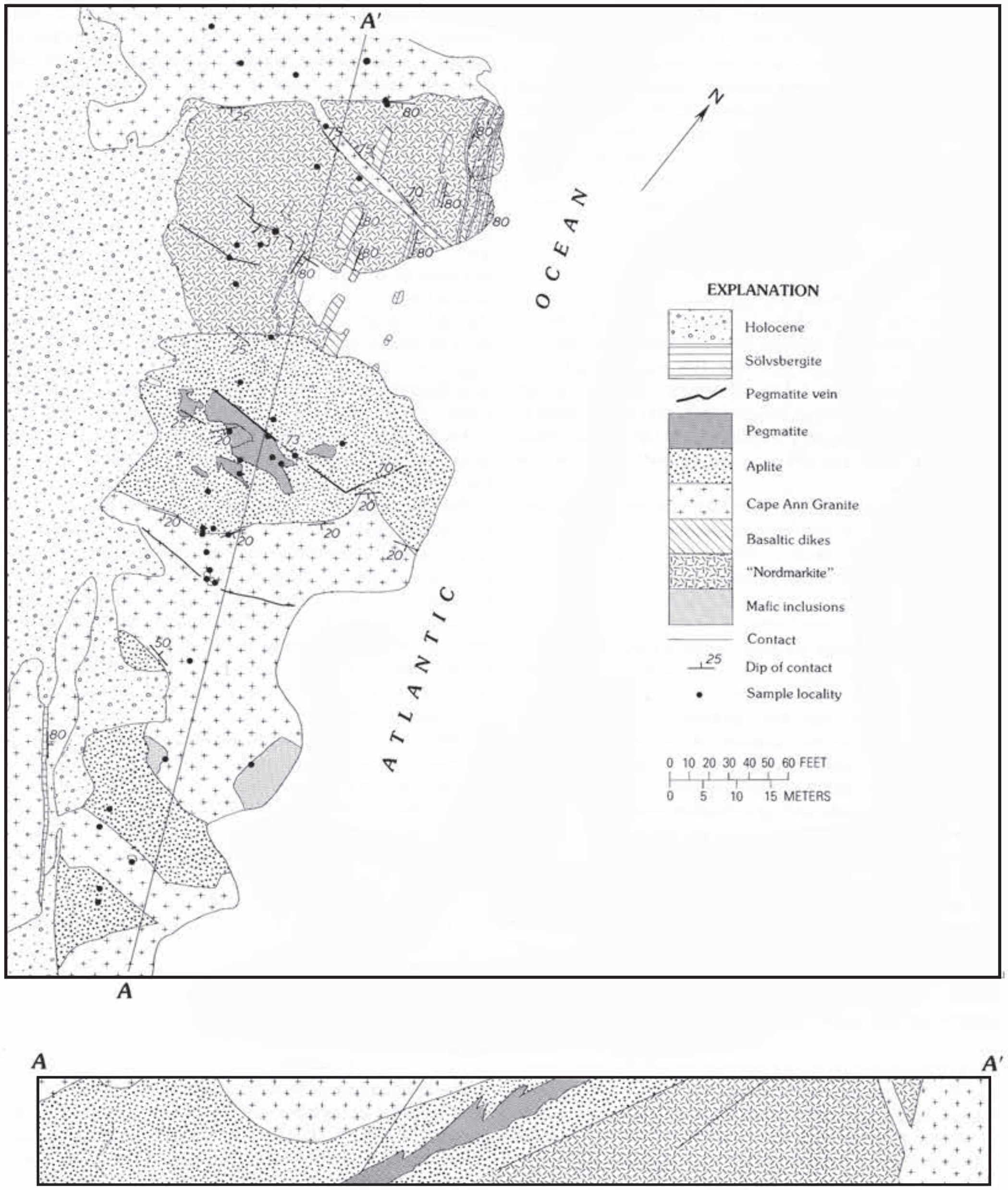

Figure 20. An outcrop map and cross section of Andrews Point modified from Wones (1983) and Pelke (1972). The public path to the shore is just off the top of the map.

samples have very little plagioclase feldspar, if any. One-feldspar granites have been described as "hypersolvus" granites in some texts. What does this mean for the crystallization history of Cape Ann granite?

(2) Chemically, these rocks are alkaline, and in some cases peralkaline. What are the possible tectonic settings for their origin?

(3) Dennen (1992) also mapped Cape Ann regions with 5-15 modal percent quartz and regions with less than five modal percent quartz. What igneous processes could lead to different modal proportions of quartz in these rocks?

Mileage

0.0	Return to MA 127 and turn right, northwest.
1.6	Turn right onto Dudley St. and drive slowly (rough road downhill and park to the left of the harbor. There may be many lobster pots stored here that should not be disturbed. Walk southwest along a shore path to smooth outcrops by the water.

STOP 7. LANES COVE. (40 MINUTES) This stop provides a good opportunity to review the rocks of the Cape Ann area and to discuss the possible origin of the Granite complex. The outcrop has both granite and syenite that are similar in color, but distinguishable based on the quartz contents. There are also fine-grained black rocks (basalt) that contain xenoliths of pink anorthositic gabbro and individual xenocrysts of plagioclase. The relative ages of granite, syenite, basalt, and anorthositic gabbro are constrained by the field relations (see Figure 22). However, careful examination will reveal some counter examples, leading to good discussion. If indeed, some of the syenite of Cape Ann is the result of fractional crystallization of basalt, then seeing other evidence of crystal sorting (anorthosite) can be used to support this theory.

Figure 21. A photomicrograph of the Cape Ann granite in crossed-polarized light showing the microperthite texture. Quartz (Qz) and aegirine-augite (Cpx) are also visible.

Figure 22. Outcrop at Lanes Cove showing field relations of granite (lower left), syenite (right) and xenolith-bearing basalt. The field of view is approximately 20 cm across.

Observations to make:

(1) How many rock types are present and what are their characteristic features?
(2) What evidence is present to constrain the relative ages of the different rocks observed?

Discussion questions:

(1) What are the relative ages of the rocks present?
(2) Why are the plagioclase crystals so large in some parts of the outcrop?
(3) What do the field relations tell us about the origin of the Cape Ann Granite?
(4) What is the meaning of the contradictory cross-cutting relations observable here?

Mileage

0.0 Return to MA-127 and turn right. Follow MA-127 to MA 128.
4.6 Traffic circle. Follow MA-128 from the traffic circle toward Boston.
23.5 Merge onto I-95 south. Follow I-95 south to the Wellesley exit.
49.2 Take exit 21B-22 from I-95, keeping left with exit 21B to MA-16 toward Wellesley. Wellesley College is aboout 4 miles from the exit.

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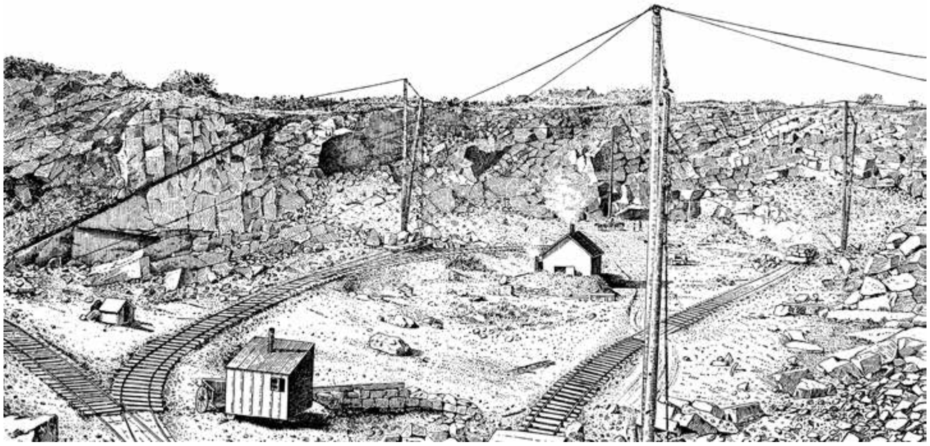

Rockport Granite Company's quarry at Halibut Point, looking west. Modified from Plate LXV of Shaler (1889).