THE CAPE ANN PLUTONIC SUITE: A FIELD TRIP FOR PETROLOGY CLASSES

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 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,b), Hunt (1871), Wadsworth (1878, 1882a,b, 1885), McDaniel (1884), Sears (1888, 1889, 1890a, 1891a,b, 1893a,b, 1894a,b, 1895, 1898), Shaler (1889), Pearce (1893), Penfield and Forbes (1896), and Washington (1898a,b,c, 1899a,b,c,d). More recent studies of note include Wright (1900), Clapp (1921), Warren and McKinstry (1924), Bowen and Schairer (1935), Palache (1950), Toulmin (1964a,b), Dennen (1976, 1981, 1991a,b, 1992), Zen et al. (1983), Goldsmith (1991), Wones and Goldsmith (1991), Hon et al. (1993), Hepburn et al. (1993, 1998, 2004), and Hepburn and Bailey (1998). With this long history of study, Cape Ann offers an unusual wealth of data and opinion to match the extensive, interesting, and beautiful outcrops that occur there, making it a destination of choice for petrologists.

For many years, we have been jointly taking our 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 about Cape Ann, 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. Instead, it is a chance to look at some great rocks and to discuss the research that others have done in the region beginning in the mid-19th century.

GEOLOGIC SETTING

This field trip will be conducted wholly within the easternmost terrane of Massachusetts, the Boston-Avalon Terrane. This terrane is one of a series of late Proterozoic Avalonian island arcs originating off the coast of Africa that were accreted to North America during the Carboniferous Alleghenian orogeny (Wise and Francis, 2001). The calc-alkaline volcanic and plutonic arc rocks were intruded by Late Ordovician to Carboniferous A-type alkalic granites (Hermes and Zartman, 1992). These granites are associated spatially and temporally with mafic magmas (Hepburn et al., 1993) that may be related to continental extension. Some workers believe the extension resulted from back arc processes (Hepburn et al., 1993, 1998), whereas others (e.g. Hermes and Zartman, 1992; Wise and Francis, 2001) suggest that the extension is due to anorogenic processes associated with a stable platform. The crux of the issue seems to be when the Boston-Avalon Terrane is joined to the Nashoba Terrane. Hepburn et al. (1993, 1998) imply that this attachment is pre-Acadian, whereas Hermes and Zartmen (1992) explicitly argue for a post-Acadian suture during the Alleghenian orogeny.

The Bloody Bluff Fault (see Figure 1) separates the Boston-Avalon Terrane from the geologically distinct Nashoba terrane to the west. The Nashoba block is a Paleozoic metamorphic terrane consisting of upper amphibolite facies metamorphosed pelites, mafic volcanic rocks, and volcanoclastic rocks that have been intruded by I- and S-type granites to diorites (Hepburn et al., 1993). The late Ordovician to early Devonian age of these plutons overlaps the Silurian orgoenic event recorded in the metamorphic rocks. Indeed, Hepburn et al. (1993) suggest that the intrusion of the calc-alkaline magmas may have contributed heat for the production of the peraluminous to meta-aluminous granites from the metasediments. As developed by Hepburn et al. (1993), the Nashoba terrane formed in a lower Paleozoic arc or marginal basin. The Ordovician to Silurian calc-alkaline magmatism is related to an east-dipping subduction zone under the terrane. The Silurian deformation and metamorphism resulted from the oblique collision of the Nashoba block with the Merrimack Terrane to the west. This sequence of events marks the Acadian orogeny, which begins to the southeast in the late Silurian and continues to the northwest into the early to mid-Devonian. In this model, the Paleozoic alkaline plutons originated from the same east dipping Acadian subduction zone, perhaps in localized extensional-transtensional zones that formed in a setting analogous to SW Turkey today.

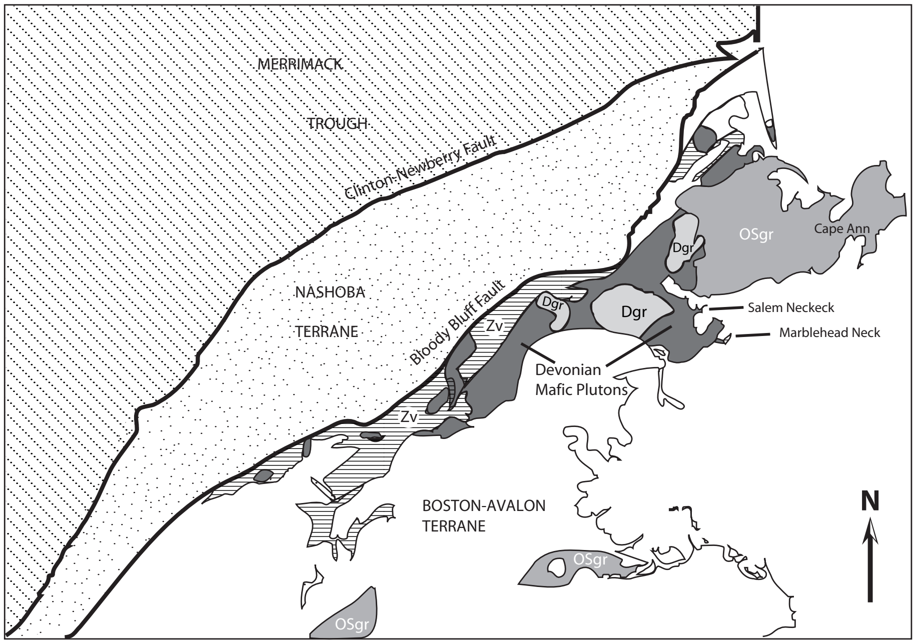

Figure 1. Generalized geology of the Boston-Avalon and Nashoba Terranes modified from Zen et al. (1983) and Hepburn et al. (1998). Dgr, Devonian granite. Osgr, Ordovician-Silurian granites. Zv, Proterozoic Z metamorphosed mafic to felsic volcanics, including some gabbro and diorite. Boston-Avalon Terrane in white includes the Dedham Batholith, Lynn Volcanics, and Boston Basin sediments.

PLUTONIC ROCKS OF NORTHEASTERN MASSACHUSETTS

Overview

The relationships among the plutonic rocks of the Boston-Avalon Terrane northeast of the Boston Basin (Figure 1) are complex in detail, resulting in continued controversy in spite of detailed study for more than 150 years. On the bedrock geology map of Massachusetts, Zen et al. (1983; also see Goldsmith, 1991; Wones and Goldsmith, 1991) have divided the various igneous rock types into groups that can be combined, based principally upon age, as follows:

(1) A group of pre-Paleozoic felsic igneous rocks. This group includes all Proterozoic Z granitic rocks in the area, including rocks mapped as the Dedham Granite/Granodiorite (Zdgr) and the Topsfield Granodiorite (Ztgd).
(2) A group of pre-Paleozoic mafic igneous rocks. This group includes diorites and gabbros such as those commonly referred to as the Salem Gabbro-Diorite (Zdigb) or the Newburyport Quartz Diorite (Zdi).
(3) A group of Devonian or Proterozoic felsic volcanic rocks. Northeast of Boston, these rocks are called the Lynn Volcanics (Dzl).
(4) A group of Ordovician to Devonian, sodium-rich plutons of hypersolvus granite to peralkaline granite to syenite comprising, among others, the Peabody, Squam, and Cape Ann (Socgr) Granites and the Beverly Syenite (Socb) that intrude the pre-Paleozoic plutonic rocks (Zen et al., 1983).

New data obtained since the state map was published, particularly radiometric ages and geochemical data, show that this grouping is too simple, and in some cases incorrect.

Proterozoic Z Felsic Plutonic Rocks

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

Proterozoic Z Mafic Plutonic Rocks

These rocks are typically medium- to coarse-grained hornblende-augite-biotite diorites that contain variable yet minor amounts of Kspar and quartz. The plagioclase is either twinned andesine or oligoclase, or un-twinned albite or oligoclase. The rock is commonly brecciated and cut by salmon-pink felsic stringers. There are also true olivine-bearing gabbros, which in some cases are nepheline normative. Some of these mafic rocks are reported (in Goldsmith, 1991) to have been intruded by pre-Paleozoic granitoids. However, the ages for three of these mafic rocks have recently been determined by the U/Pb radiometric method as latest Ordovician to mid-Devonian by Hepburn et al. (1993). These dated rocks include the Lexington Pluton (427±2Ma), the Diorite at Waltham (378±3Ma), and the Gabbro-Diorite at Danvers, all of which are shown on the Massachusetts State Map as Proterozoic (Zdigb) by Zen et al. (1983). The occurrence of these mafic plutons along the northwestern boundary of the Boston-Avalon Terrane delineates a major mafic component of the early Paleozoic alkaline mafic magmatism in this area (Hepburn et al., 1998) and puts into question the assigned Proterozoic age for other mafic plutonic rocks in the Cape Ann Region.

Lynn Volcanics

The Lynn volcanic complex of Marblehead Neck and Salem Harbor consist of a series of felsic flows, agglomerates, and pyroclastic rocks. This volcanic series was formerly considered as a possible extrusive facies of the Cape Ann plutonic complex (Clapp, 1921; Dennen, 1991a). However, a Proterozoic age of 596±3Ma has been reported for the Lynn rocks, thus establishing the Lynn Volcanics as part of the Avalonian basement (Hepburn et al., 1993). 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).

Paleozoic Igneous Rocks

These rocks were once thought to be co-genetic and have been collectively called the “Cape Ann Plutonic Series” (Bell and Dennen, 1971). However, recent radiometric dates have “obscured” the genetic relationships among strikingly similar rocks that differ in age by as much as 70 Ma. The Paleozoic (middle Ordovician to Devonian) Cape Ann plutonic complex consists of mafic rocks (olivine gabbro, diorite, and diabase) and predominantly felsic plutonic rocks 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). These rocks are intrusive into greenschist (Zv), diorite, and gabbro (Zidgb) under probable anorogenic conditions. The rocks are mildly alkaline in the sense of Peacock (1931). Essexite, nepheline monzo-gabbro/diorite, was named for these rocks by Sears (1891a) and discussed by Washington (1899a). Most of the mafic rocks contain titaniferous clinopyroxene. The dominant 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 occurrence of mafic magmatic pillows, partially ingested enclaves, and segmented dikes in the felsic rocks establishes the simultaneous existence of mafic and felsic magmas. These features are particularly well-developed on Salem Neck, but also occur at other localities such as Stop 3 of this trip. 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. Thus, mineralogically and chemically, 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 that seem to be related to co-genetic mafic rocks.

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 riebeckitic amphibole, acmitic augite and fayalite all occur in variable amounts. Accessory minerals include titanite, zircon, apatite, fluorite, and allanite. Dennen (1991a, 1991b, 1992) subdivided and mapped the Cape Ann Granite Complex based upon variation in quartz content. Specifically, as shown on Figure 2, Dennen (1991a, 1992; see also Washington, 1899d) mapped granites with quartz contents >25% and 15-25% as the Granite facies, whereas those rocks with 5-15% and <5% modal quartz, including the Beverly Syenite have been designated as the Syenite facies on Dennen’s maps. Dennen (1992) suggested that the variation in modal quartz was related to cumulate process or perhaps “convective motions of the magma”. Zartman and Marvin (1971) found the Cape Ann Granite to be middle Ordovician (450±25 Ma).

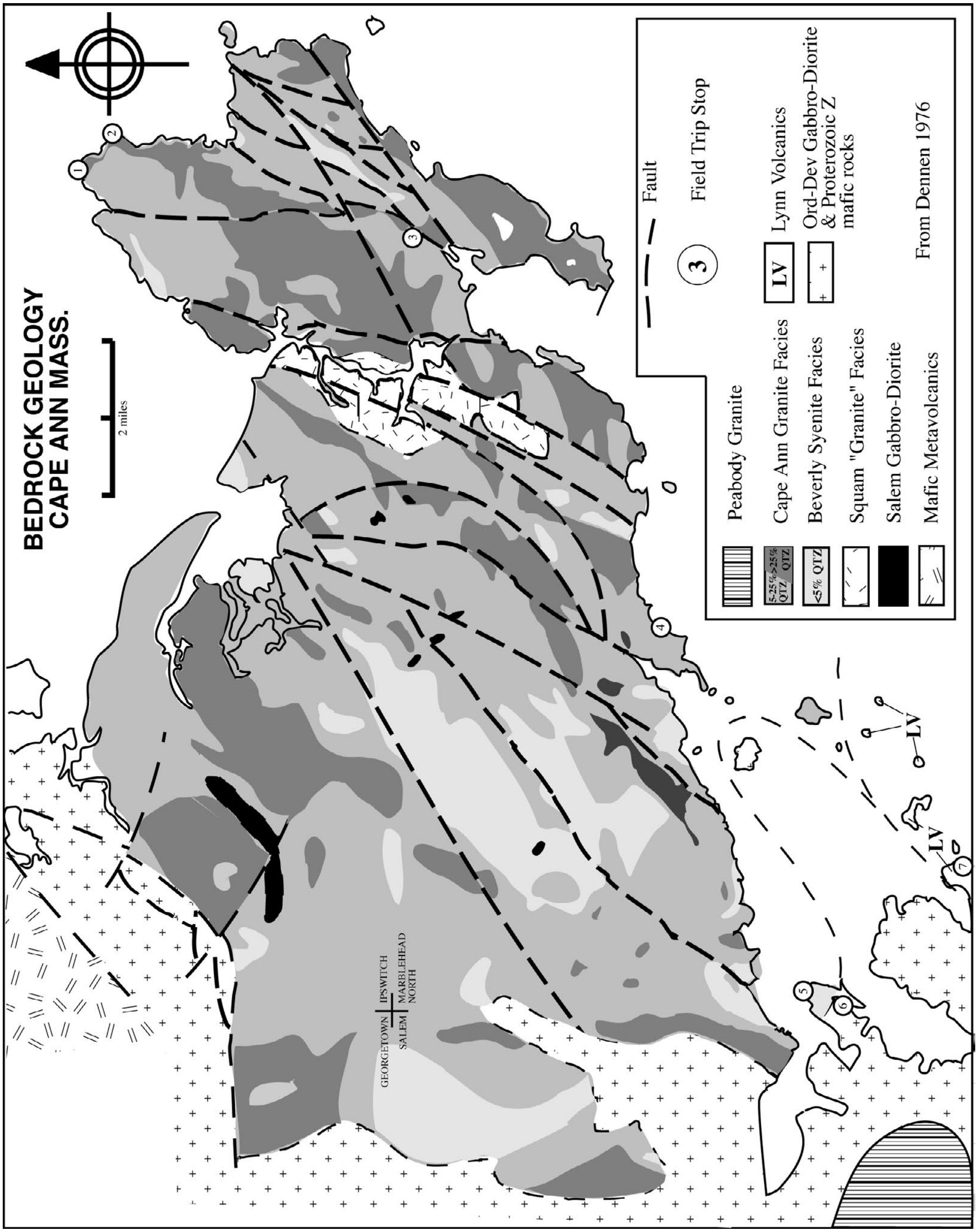

Figure 2. Geologic map of the Cape Ann Plutonic Complex and location of field trip stops. Modified from Dennnen (1976) and Zen et al. (1983).

The Beverly Syenite commonly consists of massive medium-grained syenite composed largely of microperthic alkali feldspars (up to 90%) and variable amounts of mafic minerals including arfvedsonitic amphibole, biotite, and augite containing some acmite 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 cut other rock types in the area. Hon et al. (1993) have argued that at least some these syenites originate 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 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 terrane 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. Zartman (1977) obtained a U-Pb age for this rock of 450±25 Ma.

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 rocks. 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. The relationship between this relatively small but mineralogically distinct pluton and the hypersolvus granites of the Cape Ann complex remains unresolved (Hon et al., 1993).

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. However, with an age of 380±20 Ma (Zartman, 1977; Hermes and Zartman, 1985), it is much younger than the Cape Ann Granite, suggesting that the alkaline igneous activity was long-lived.

The Salem Gabbro-Diorite is a medium- to coarse-grained mafic rock that borders the Cape Ann Granite on the northwest and occurs in scattered small outcrops as dike and pods around the region, including Salem Neck. These heterogeneous rocks 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 the 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). Zartman and Marvin (1971) found the Salem Gabbro-Diorite to be middle Ordovician (460±15 Ma). The rocks at Salem Neck are very similar to the Ordovician Nahant Gabbro. The Nahant Gabbro is projected to lie at shallow depth under the Cape Ann Granite and may be the likely source of the anomalous high magnetic intensities and gravity values that are associated with the Cape Ann area. The mafic rocks at Salem Neck are also chemically and temporally similar to mafic rocks at Lexington and Waltham as discussed below.

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 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

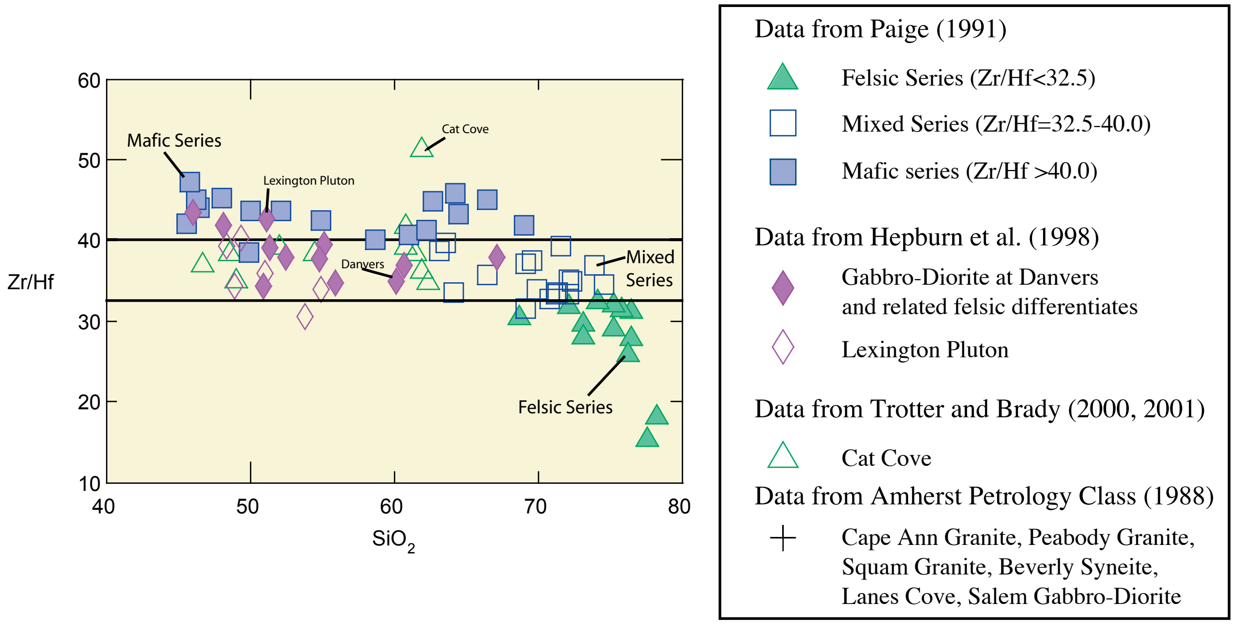

Figure 3. Plot of the Zt/Hf value versus weight percent silica showing the classification of Cape Ann rocks proposed by Paige (1991) and Hon et al. (1993). New data have been added as shown in the legend.

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).

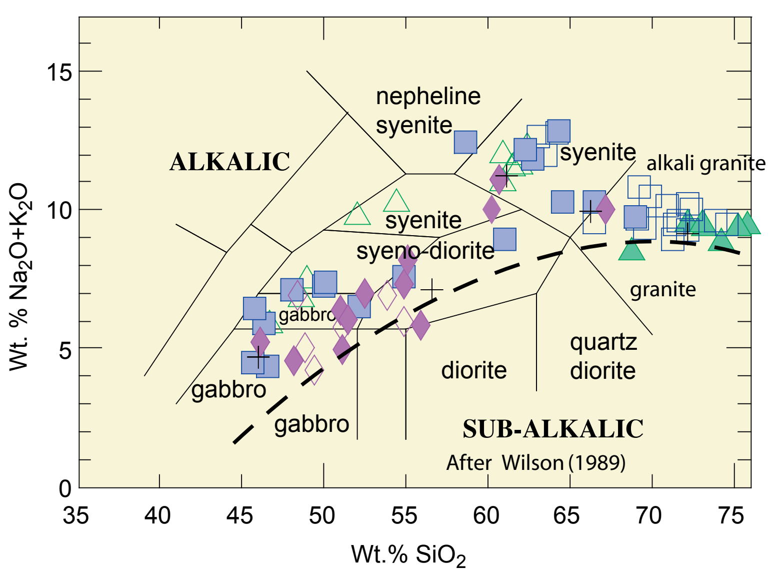

Figure 4. Nomenclature of plutonic rocks after Wilson (1989). The heavy dashed line separates alkalic and sub-alkalic rocks. Data symbols are the same as in Figure 3.

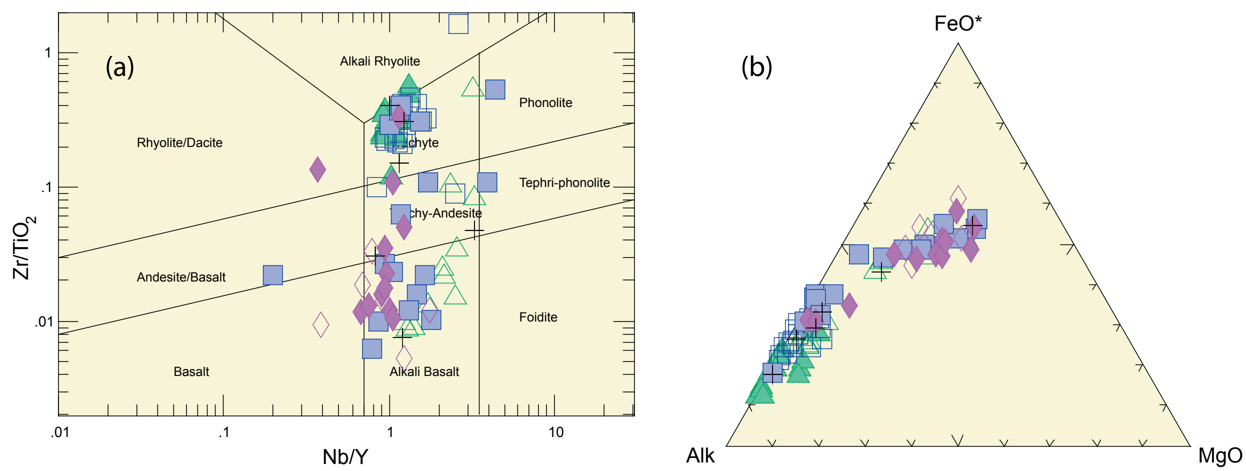

Figure 5. (a) Whole rock data plotted on a volcanic rock classification diagram (Pearce, 1996), based upon incompatible trace elements, which shows the alkaline nature of the Cape Ann Complex. (b) AFM diagram in weight percent of oxides. Alk = Na_2O+K_2O, FeO* is total iron as FeO. Data symbols are the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

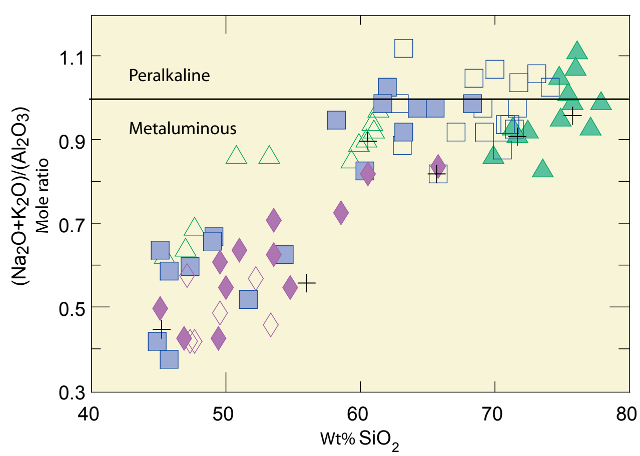

Figure 6. Aluminum saturation classification showing the mole ratio (Na_2O + K_2O)/(Al_2O_3) plotted against weight percent silica. Although all mafic, low silica rocks have normal alumina contents, some of the higher silica granites are peralkaline. Data symbols are the same as in Figure 3.

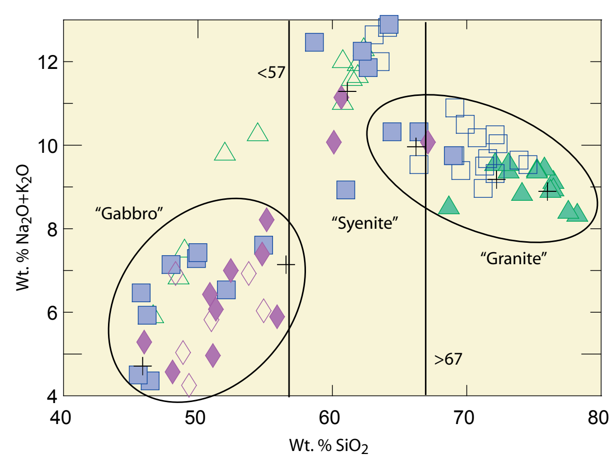

Figure 7. Total alkalis versus silica diagram. This diagram shows the relationship between weight percent silica and arbitrarily grouped rocks. Data symbols are the same as in Figure 3.

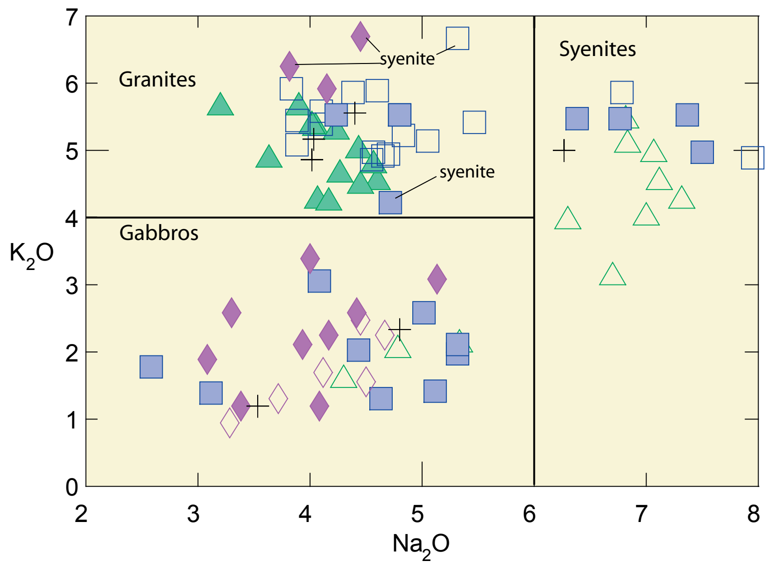

Figure 8. Weight percent Na_2O versus K_2O diagram showing the groups of rocks defined in Figure 7. The granites are K-rich relative to the gabbros, which are low in both Na_2O and K_2O. There are two types of syenites: those that are K-rich like the granites and those that are also Na-rich. Note that 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).

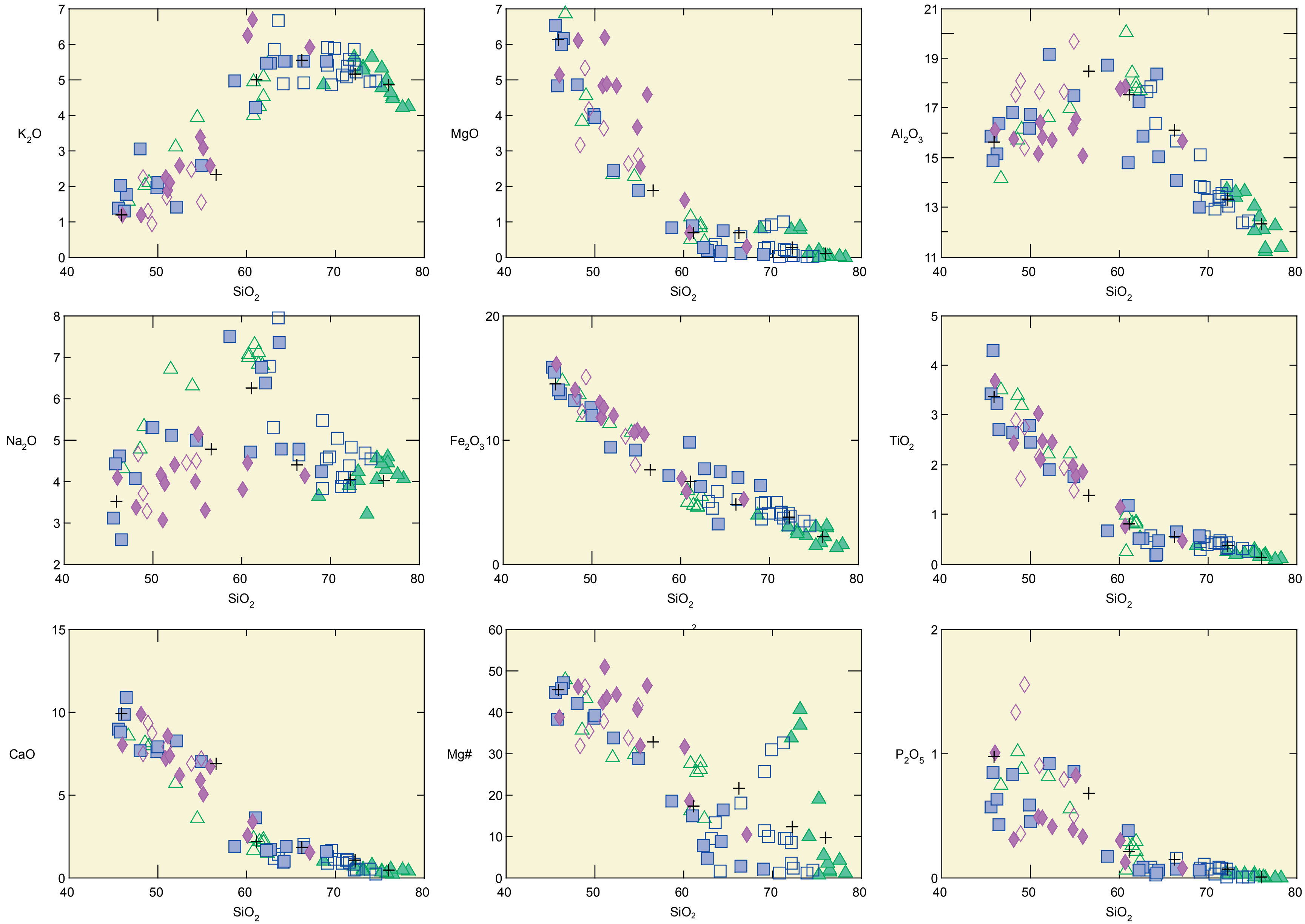

Figure 9. Harker diagrams in weight percent showing the variation in the major oxides with change of silica. Data symbols are the same as in Figure 3.

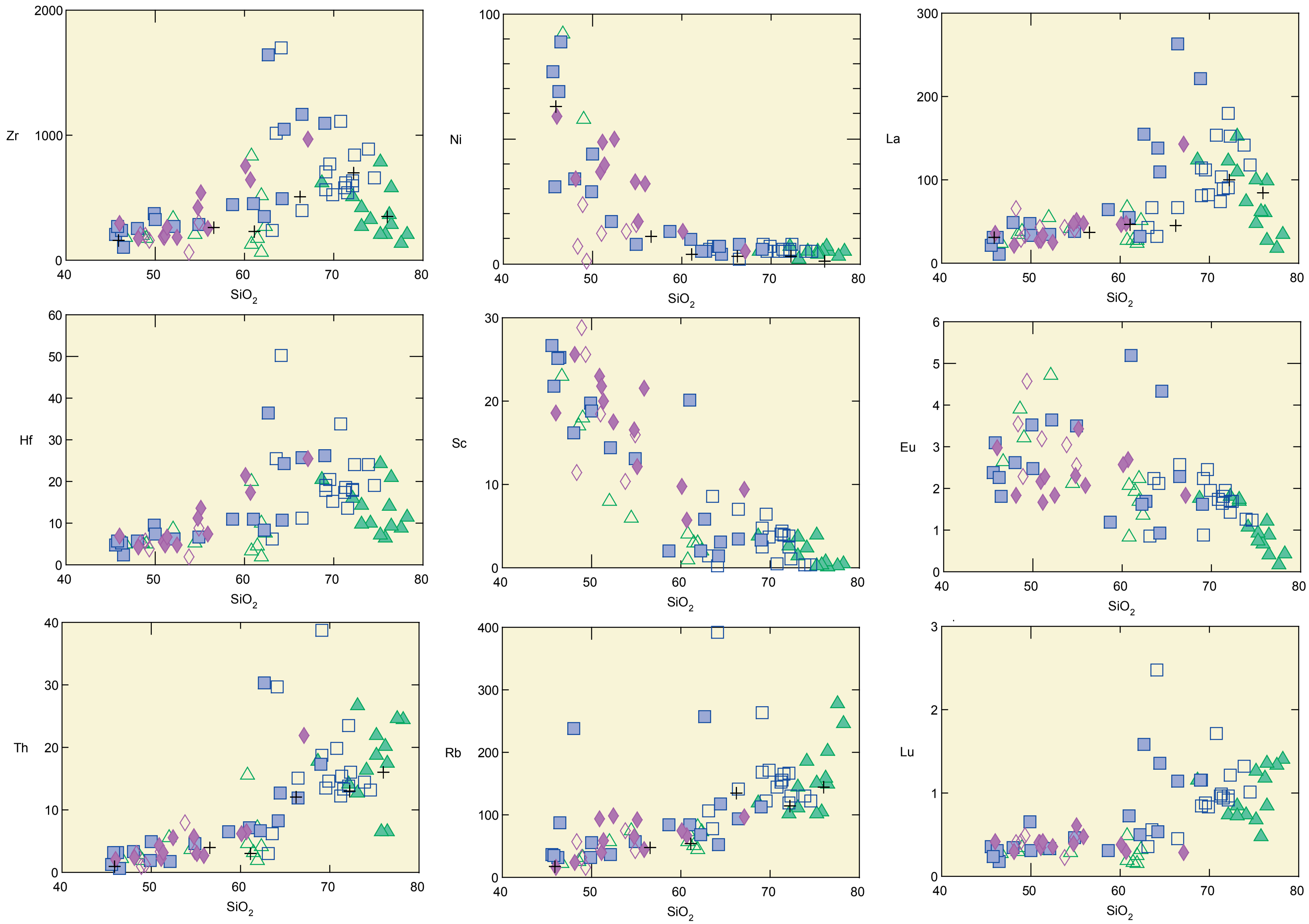

Figure 10. Harker diagrams showing the variation for representative trace elements in ppm with change of weight percent silica. *The Ni diagram is missing three anomalous samples with >150 ppm Ni at Wt.% SiO_2 of 60-65. Data symbols are the same as in Figure 3.

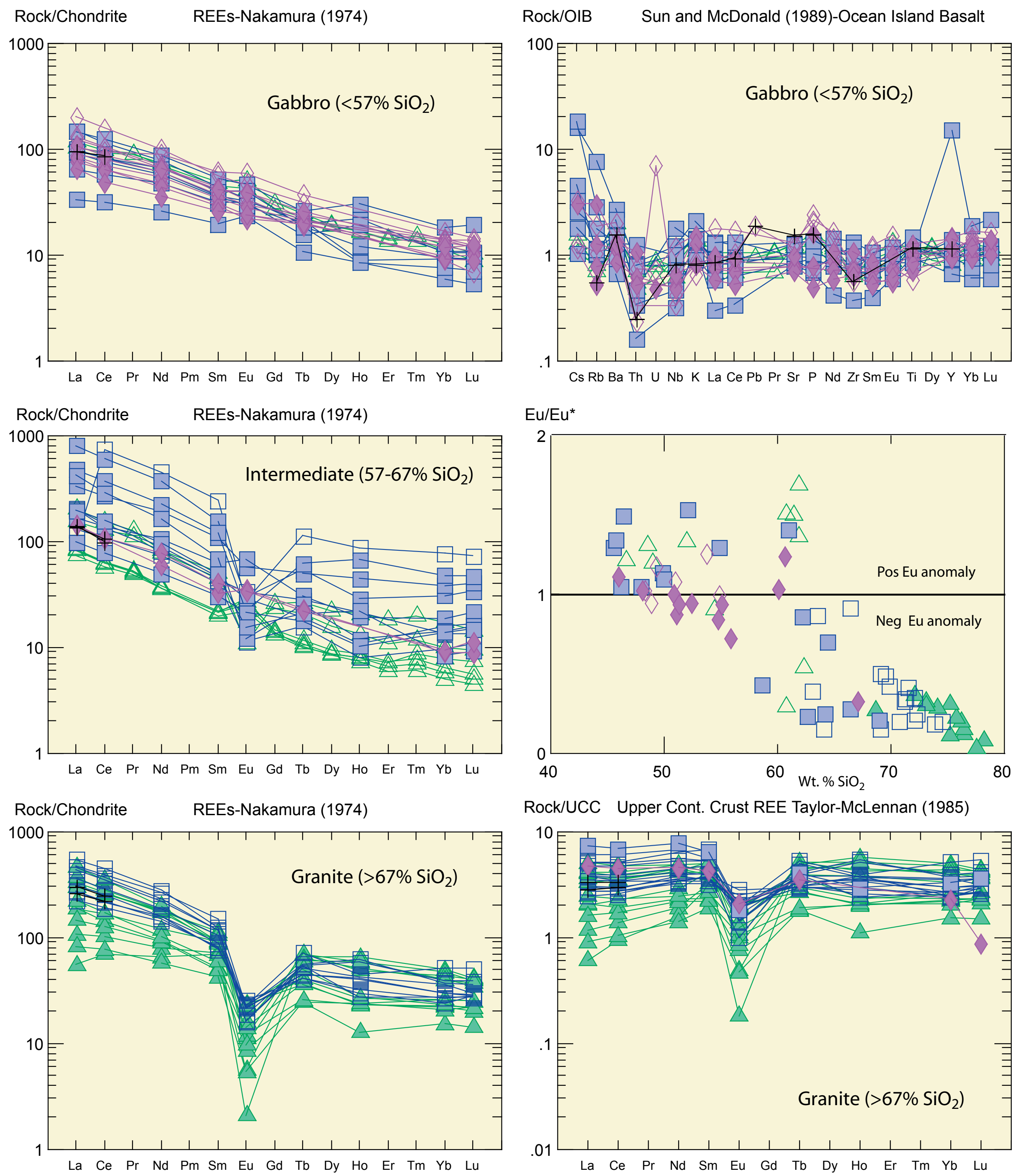

Figure 11. Chondrite-normalized rare earth diagrams on the left and Spider diagrams on the right. Note that the middle diagram on the right is a plot the Eu/Eu* ratio versus silica. Eu* is the predicted Eu content in the absence of feldspar accumulation or depletion and, thus, the ratio is a measure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

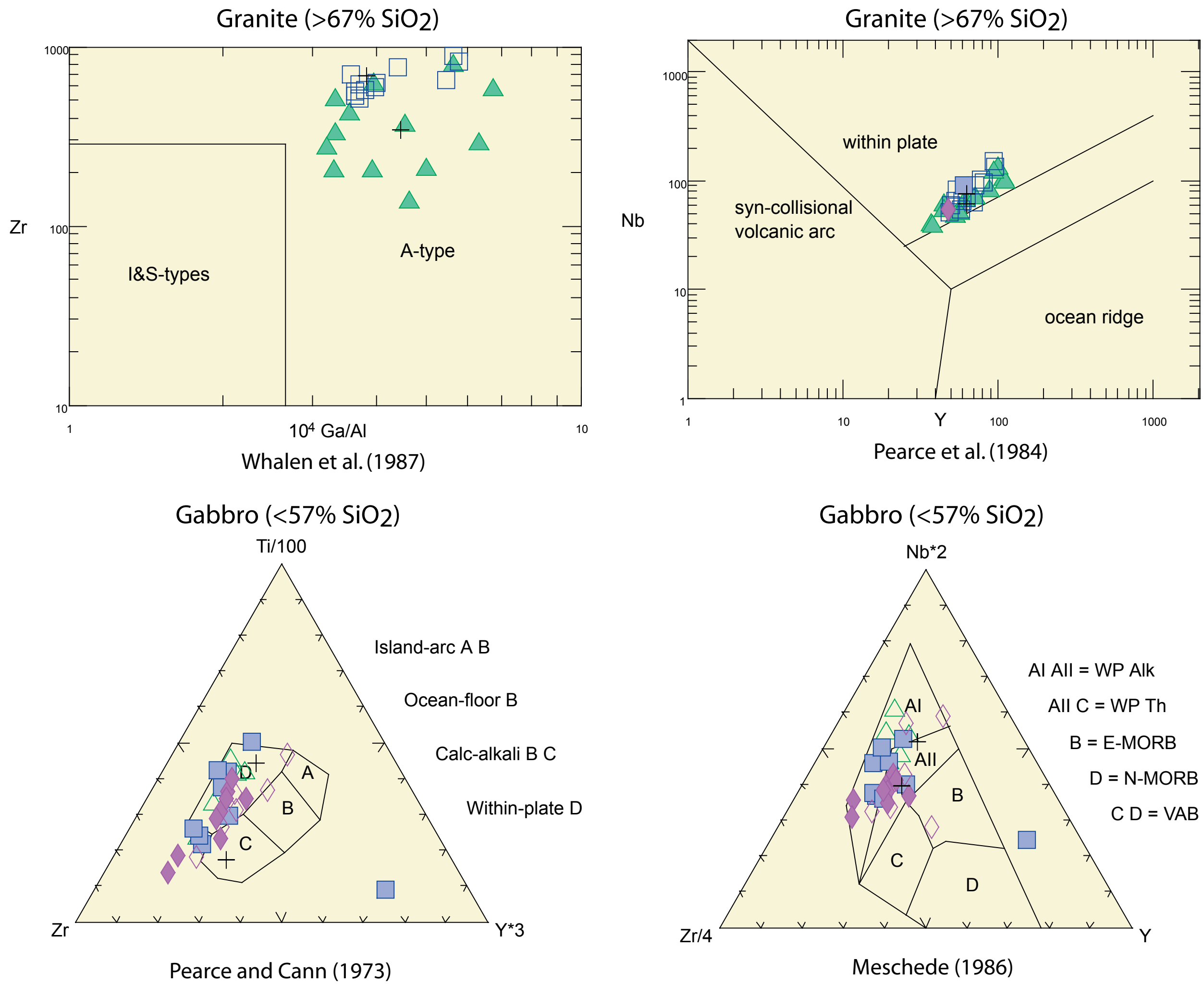

Figure 12. Discrimination diagrams commonly used to characterize the tectonic setting of igneous rocks. The gabbros have been plotted on diagrams typically used to classify basalts. WP alk = within plate alkaline. WP Th is within plate tholeiitic. VAB is volcanic arc basalt. Data symbols are the same 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. Begin your trip at the junction of Routes 1A and 114 at the north end of Salem State College in Salem, MA. From the intersection, head north on Route 114, following it to Route 128 (about 3 miles). Follow Route 128 north to Grant Circle, the western junction of Route 127 with Route 128, just east of the high bridge over the Annisquam River (about 16 miles). From Grant Circle, drive northwest on Route 127 (Washington St.) toward Annisquam and Pigeon Cove (about 6 miles). Turn left onto Gott Avenue at the Halibut Point State Park sign. Park in the visitors' lot on the right (see Figure 13). A $2 parking fee is charged from mid-May to mid-October.

STOP 1. 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 will see at Andrews Point (Stop 2).

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?

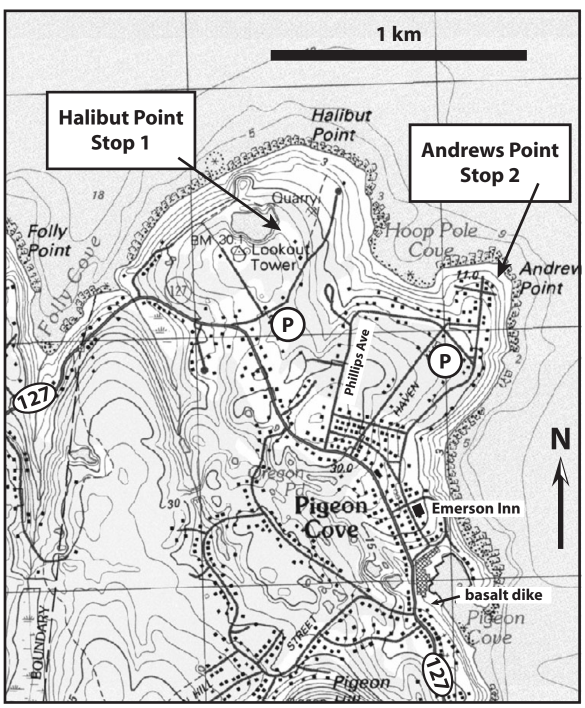

Figure 13. Location map for Stops 1 and 2 based on the Rockport 7.5 minute quadrangle. The "P" indicates where to park.

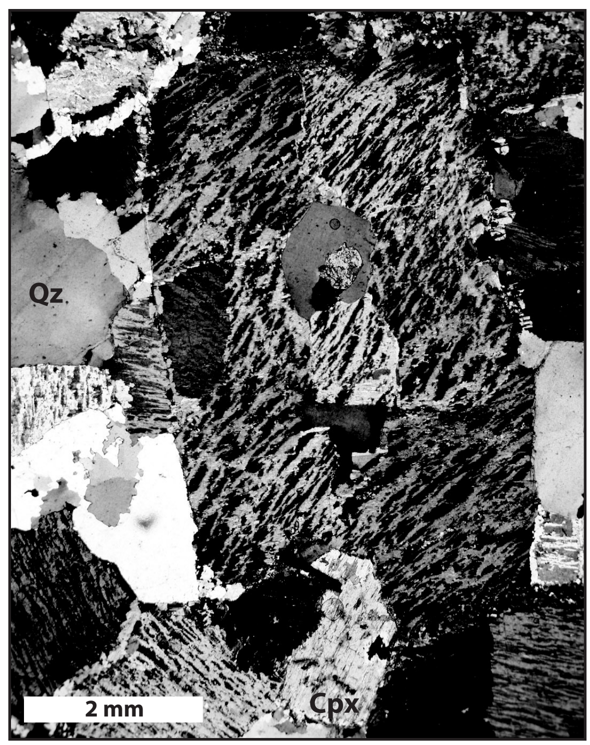

Figure 14. A photomicrograph of the Cape Ann granite in crossed-polarized light showing the microperthite texture. Quartz (Qz) and aegirine-augite (Cpx) are also visible.

Discussion questions:

(1) This granite has a high modal proportion of alkali felspar (microperthite - see Figure 14) and most 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 The road log begins at the exit from Halibut Point State Park. Turn left onto Route 127.

0.5 Turn left onto Phillips Avenue.

0.9 Bear right 90° with Phillips Avenue (see Figure 13).

1.0 Park along the right side of Phillips Avenue where it is bordered by a wooded area. Parking is forbidden or restricted to residents with parking stickers along portions of these roads. Check the signs. Walk along the road east to a T-intersection, then walk north along the road to a public path to the shore. The pegmatite outcrops are about 60 m to the southeast along the outcrops that ramp to the water (see Figure 16). Expect the wind to be strong and cold.

STOP 2. 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 1, small pegmatites can be found here containing blue quartz and other interesting minerals (see Figure 15). 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

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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?

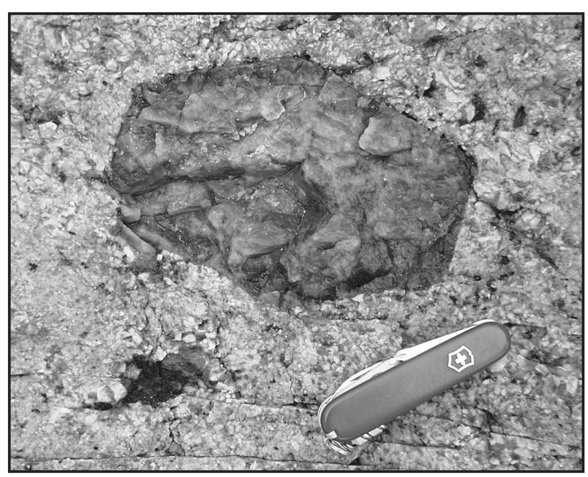


Figure 15. Photographs of pegmatites on Andrews Point. On the left are very large, darker (blue) quartz crystals in a lighter feldspar matrix. The whole pegmatite is surrounded by aplite. On the right is a closeup view of a euhedral quartz crystal with a 9-cm-long pocket knife for scale.

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 1). How can fayalite occur with quartz here whereas forsterite and most other olivines never occur with quartz?

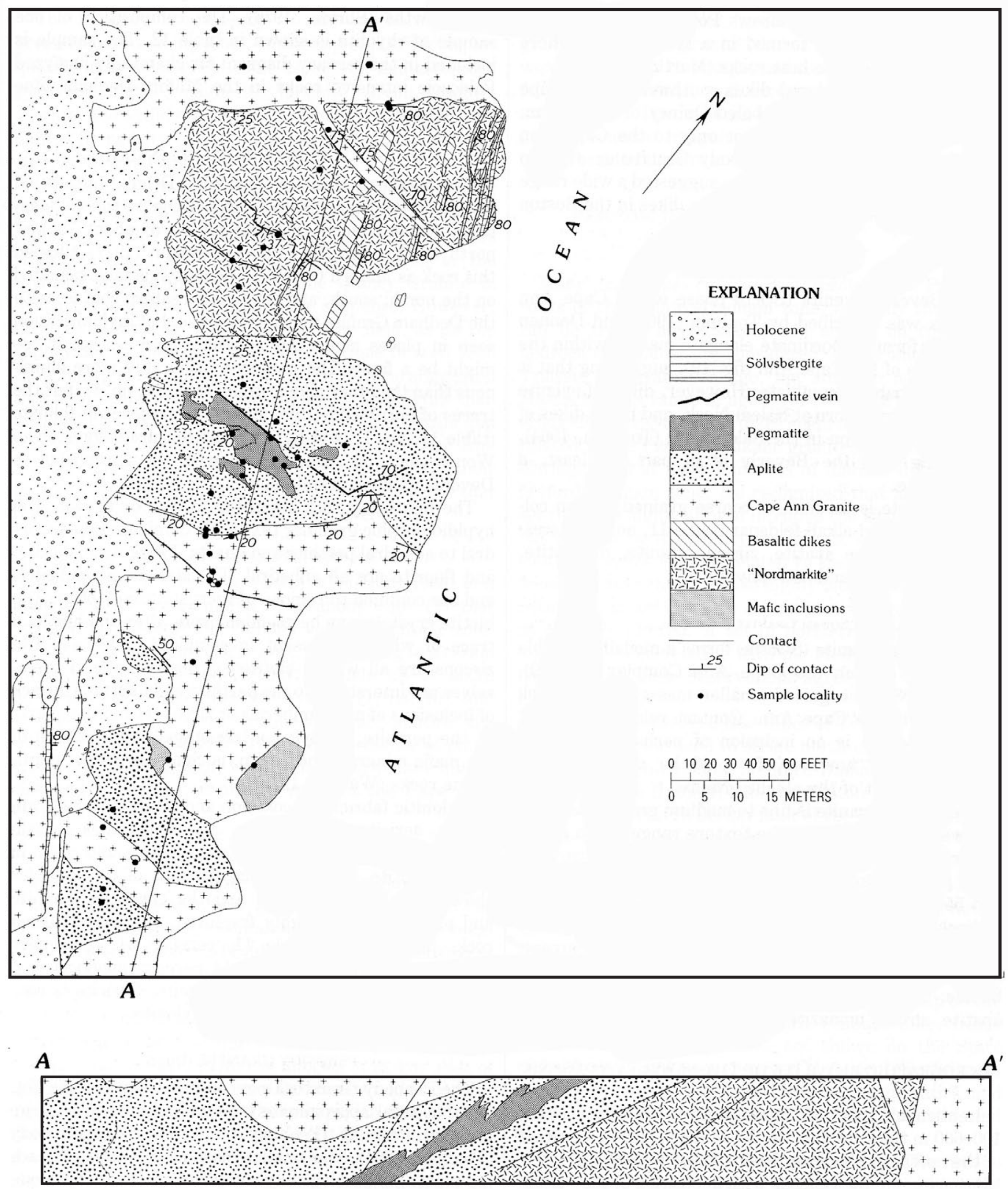
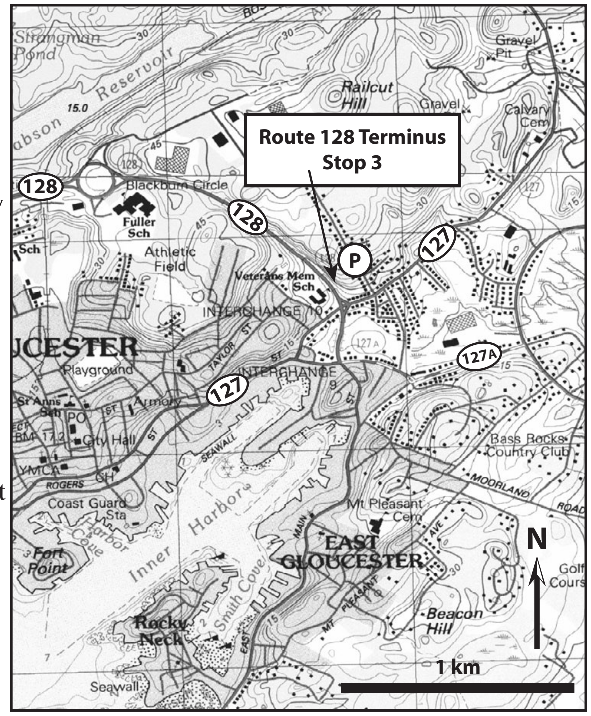


Figure 16. An outcrop map and cross section of Andrews Point modified from Wones (1983) and Pelke (1972). The public path to the shore is just off the top of the map.

1.0 Continue east on Phillips Avenue to a T-intersection.
1.1 Turn right at the T with Phillips Avenue and follow it as it bears left to Emerson Inn (see Figure 13).
1.5 Turn right with Phillips Avenue.
1.6 Turn left onto Route 127.
1.8 Parking lot for the former Cape Ann Tool Company. On the south edge of this parking lot, a basalt porphyry dike occurs with large plagioclase phenocrysts. This rock was sold by Wards and can be found in the teaching collections of many colleges. Access to the site has been closed in recent years following the closing of the forge. However, if the site is opened again in the future, this is a good teaching stop.
2.5 Bear right with Route 127. (127A goes straight.)
5.4 Turn right onto Harrison Avenue (a small side street) and park on the right. This is the last street on the right before the eastern junction of Route 127 with Route 128, at a traffic light. Walk back to Route 127 and follow it to Route 128. Continue around the corner to the north along Route 128 to the large outcrops on the right. Be very cautious and watch for traffic! The sidewalk ends at the corner and turning vehicles will not be watching for pedestrians here. Keep off the road and behind the guardrail for safety.



STOP 3. ROUTE 128 TERMINUS, GLOUCESTER. GRANITE WITH MAFIC PILLOWS(?) (40 MINUTES) This stop was described by Dennen (1976, Stop 11) and Hon et al. (1993, Stop 1-10). Contrasting mafic and felsic rocks in the roadcut here present striking textures that are visible from a passing car. Dennen (1976) sees "Inclusions of gabbro-porphyry (laboradorite phenocrysts) in quartz-poor Cape Ann Granite facies." Hon et al. (1993) see "Granitic host and laboradorite phenocrystic basaltic magmatic pillows…." Rounded contacts and fine-grained margins on the mafic "blobs" are consistent with chilling of a basaltic liquid in a grantitic liquid. Pinkish plagioclase crystals up to 5 centimeters across are visible in the mafic porphyry or as xenocrysts in the felsic host. The outcrop provides plenty of features to stimulate discussion for petrologists in training (see Figure 17).

Observations to make:
(1) What are the two rock types here?
(2) Describe the texture of the mafic rocks here.
(3) What are the pinkish minerals? Where do they occur?

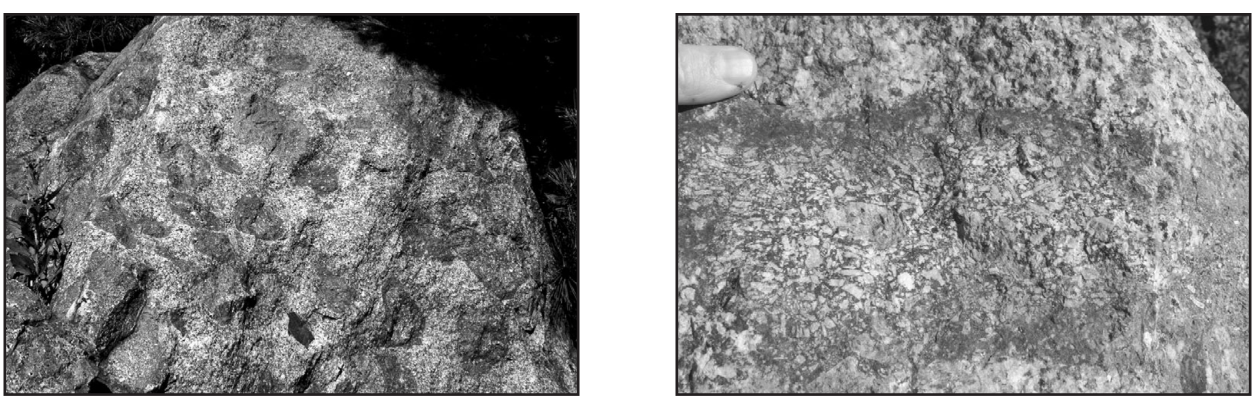
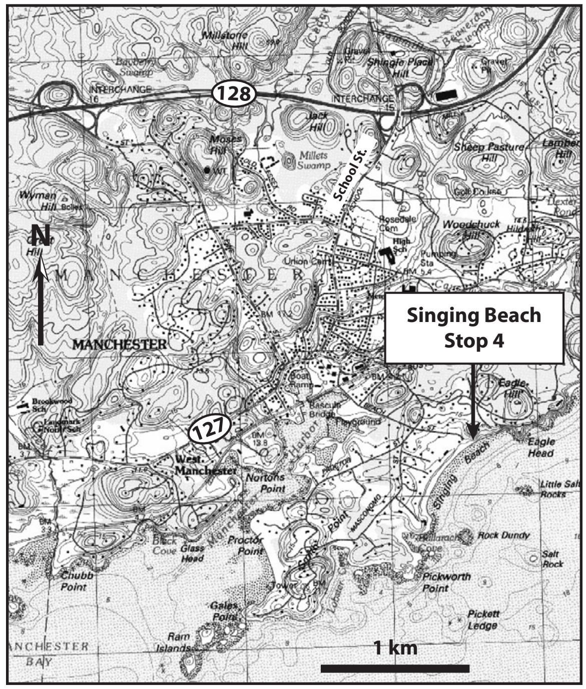


Figure 17. Photographs of the mafic pillows(?) at Stop 3. On the left is an outcrop photo showing the shapes and close proximity of the pillows, which are 10-20 cm across. On the right is a closeup view of one of the pillows showing abundant plagioclase phenocrysts and a possible chilled margin.

Discussion questions:

(1) Explain how the two rock types can occur together at this location.

(2) How do these textures constrain the geologic history of Cape Ann?



5.4 Turn around and return on Harrison Avenue to Route 127. Turn right onto Route 127 west.
5.5 Turn right (north) onto Route 128 towards Boston.
6.3 Blackburn Circle. Continue around rotary with Route 128 toward Boston.
7.0 Grant Circle. Continue around rotary with Route 128 toward Boston.
12.4 Take Exit 15 for Essex/Manchester.
12.7 Turn left on School Street towards Manchester.
13.9 T-intersection. Turn left on Union Street.
14.0 Turn right on Beach Street (with Route 127).
14.1 Continue straight on Beach St. (Route 127 turns left.)
14.5 Continue straight on Beach Street at stop sign.
14.7 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, and 2004 Trip C1). 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 of very dry climates. Singing beaches produce higher frequency (500-2500 Hz) sounds than booming sands (50-80 Hz).

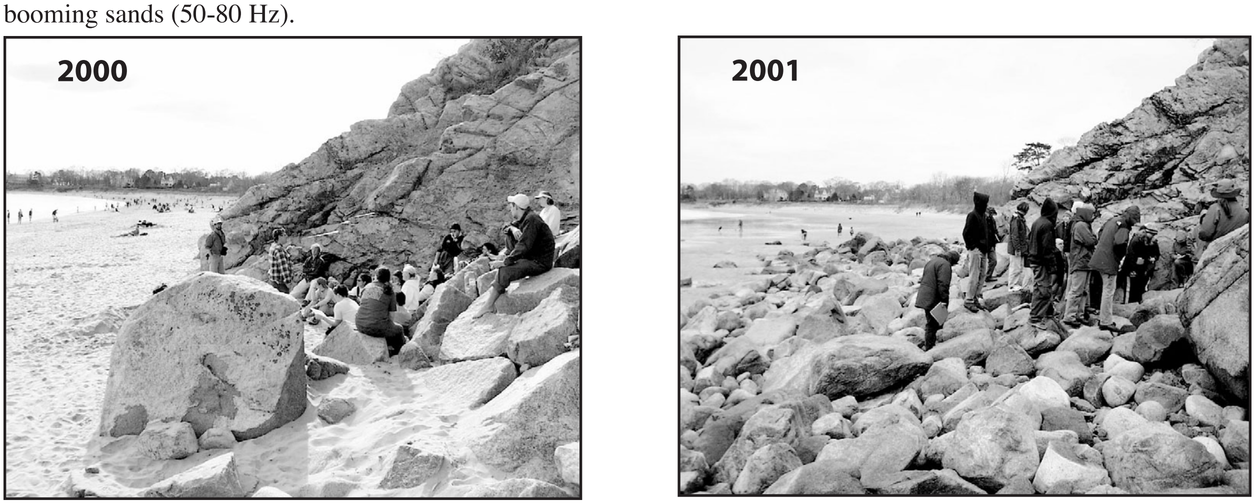


Figure 18. Another interesting feature of Singing Beach sand is its annual winnowing and deposition to create pronounced "winter "and "summer" beaches. Shown below are photos of Singing Beach on 26 March 2000 and on 1 April 2001. The level of the sand is at least one meter lower in 2001 than in 2000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

Observations to make:

(1) Is this the same rock that occurs at Halibut Point? 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?

14.7 Exit the parking lot and drive west on Beach St.
15.3 Continue straight as Route 127 joins Beach Street from the right.
15.4 Turn left with Route 127 and follow Route 127 for several miles to its end in Beverly.
16.7 Cross the Beverly/Manchester town line.
18.0 Turn left with Route 127 onto Hale Street.
20.9 Woobury Street. If you would like to see the Beverly Syenite in Beverly, turn left here to visit Lynch Park on Woodbury Point (in 0.2 miles turn left on Ober Street). These rocks were described by Toulmin (1964a, Stop 5) and by Dennen (1976, Stop 1) and should be visited at low tide. We will see similar rocks at the next two stops.
21.3 Turn left onto Lathrop Street with Route 127.
22.0 Turn right onto Stone Street with Route 127.
22.3 Turn left onto Cabot Street, which is Route 22.
22.4 Join Route 1A to cross a high bridge over the Danvers River. Route 22 ends.
23.4 Turn left onto Webb Street.
23.7 Bear left onto Fort Avenue.
24.4 Pass the entrance to the Northeastern Massachusetts Aquiculture Center (NEMAC) at Cat Cove, Stop 6.
24.7 Salem Willows Park. Park where you can and walk to the beach at the northeast end of the amusement area (see Figure 19).

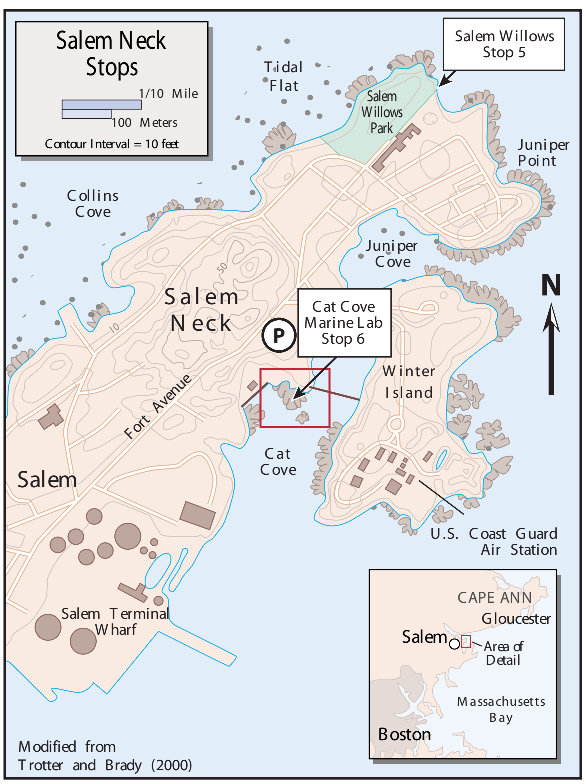


Figure 19. On the left is a location map for the Salem Neck stops. On the right is a photomicrograph of the trachytic syenite from Salem Willows viewed in cross-polarized light.

STOP 5. SALEM WILLOWS. BEVERLY SYENITE. (40 MINUTES) The rocks between the beach and the pier to the north are Beverly Syenite with a trachytic texture (see Figure 19). 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?

Observations to make:

(1) Describe the texture of this rock.
(2) How much quartz is in the felsic rock here?

Discussion questions:

(1) What igneous processes lead to syenites?
(2) 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?

24.7 Leave Salem Willows Park heading southwest along Fort Avenue.
25.0 Turn left into the parking area for Northeastern Massachusetts Aquiculture Center (NEMAC) of Salem State College. Walk past the buildings and south to outcrops on the shore.

STOP 6. CAT COVE MARINE LAB (NEMAC). SALEM GABBRO-DIORITE, BEVERLY SYENIITE, AND RELATED ROCKS (40 MINUTES) Permission to access this site should be obtained in advance from the director of the Northeastern Massachusetts Aquiculture Center (NEMAC). This stop 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 8). 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…." Some very coarse (pegmatitic) varieties of syenite occur in a large outcrop 15 meters offshore to the south, but easily accessible at mid- to low tide. To the west near the masonry wall are outcrops of Salem Gabbro Diorite. This 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, this rock shows peritectic textures of amphibole growing around pyroxene (see Figure 20).

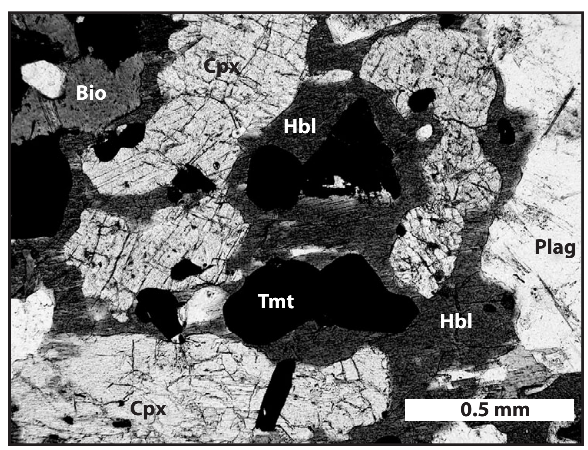


Figure 20. Photographs of Cat Cove rocks. On the left is an outcrop showing basalt pillows(?) in a syenite matrix. These features are crosscut by a basalt dike with chilled margins. A penny is shown for scale. On the right is a photomicrograph of a coarse-grained mafic rock (essexite) showing peritectic growth of amphibole (Hbl) around both clinopyroxene (Cpx) and titanomagnetite (Tmt).

Observations to make:

(1) 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.

Discussion questions:

(1) Are the ellipsoidal mafic rock masses 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) Show and discuss the geochemical data for these rocks.

25.0 Turn left from the parking area for NEMAC onto Fort Avenue heading southwest.
25.4 Bear right onto Webb Street.
25.5 Turn left onto Essex Street.
25.9 Turn left at the light onto Washington Square West, which is Route 1A.
26.1 Turn right onto Derby Street with Route 1A.
26.2 Take the first left, turning onto Lafayette Street heading south with Route 1A.
26.4 Route 114 joins Route 1A from the right. You will follow Route 114 to its end.
27.2 Traffic light at Salem State College. Bear left with Route 114 away from Route 1A, which bears right.
28.3 Bear left with Route 114 at light onto Lafayette Street.
28.9 Turn left at light with Route 114.
29.2 End of Route 114. Turn right at light onto Ocean Avenue.
29.8 Causeway to Marblehead Neck (see Figure 21).
30.2 Bear right with Ocean Avenue.
31.5 Park on right at the entrance to Castle Rock. Walk southeast to the shore on the public path.

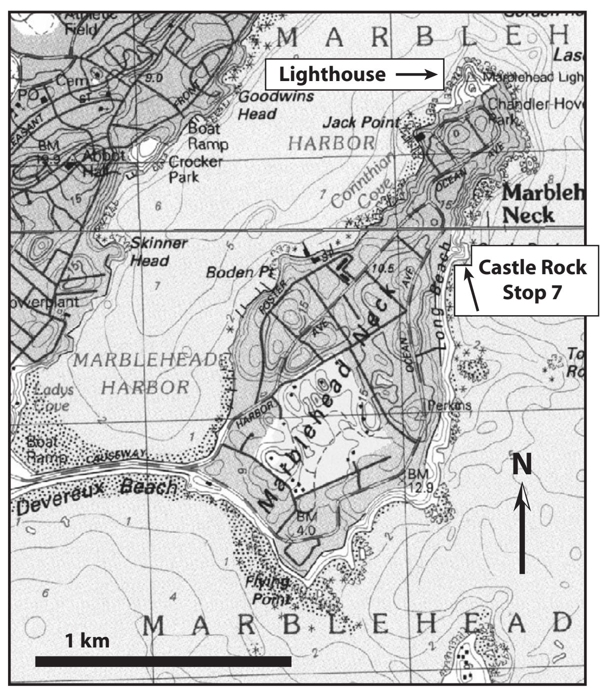


Figure 21. On the left is an outcrop photograph of dark, plagioclase-phyric vitrophyre and light agglomerate (with dark vitrophyre clasts) at Castle Rock. A penny is visible for scale. On the right is a location map for Marblehead Neck from the Marblehead North and Marblehead South 7.5-minute quadrangles.

STOP 7. 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. 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 by Dunning (Hepburn et al., 1993) and others (Meg Thompson, personal communication) 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.

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?

31.5 If you would like to see more felsic volcanic rocks, continue northeast on Ocean Avenue, bearing right at all intersections.

31.9 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 22). 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. Turn right from the lighthouse parking area continuing around Marblehead Neck to the causeway. Follow Ocean Avenue back to a T- intersection with Route 114. Turn left (at the light) onto Route 114 and follow it back to Salem State College.

Figure 22. Photograph of dark, banded, and flow-folded vitrophyre near the flagpole adjacent to the Marblehead Neck lighthouse. A penny is included for scale.

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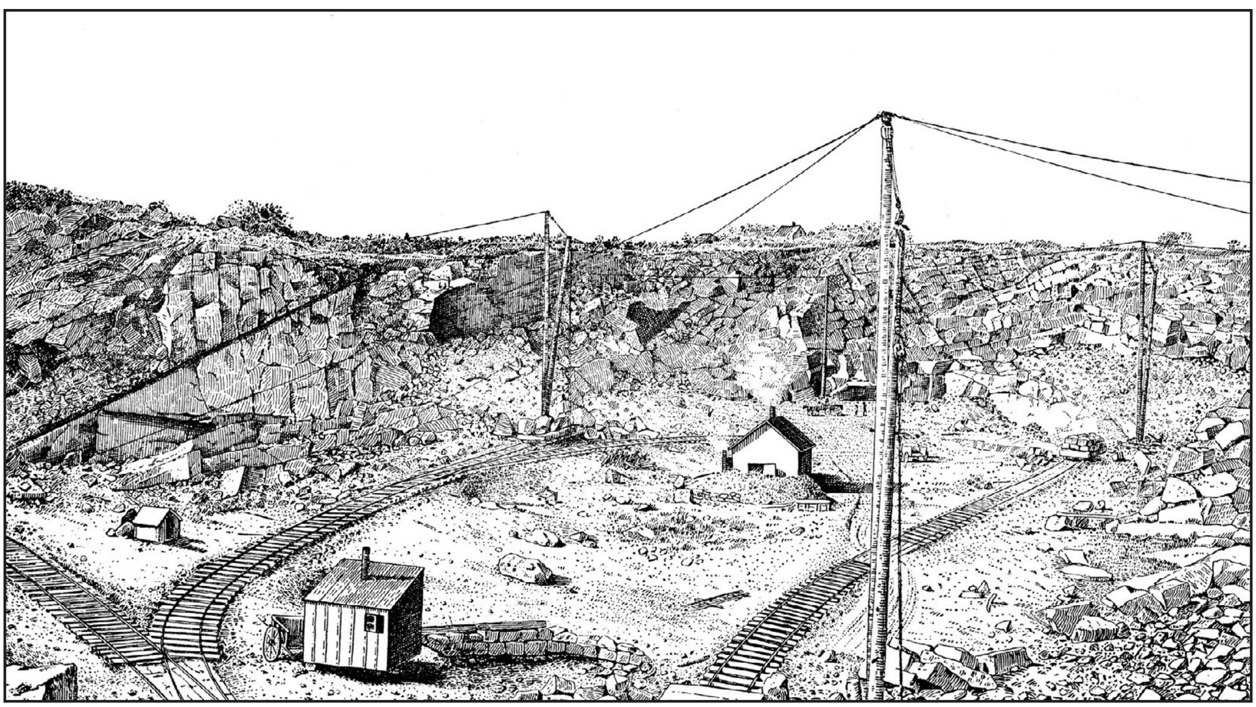

Rockport Granite Company's quarry at Halibut Point, looking west. Modified from Plate LXV of Shaler (1889).