DIKE SWARMS OF CAPE ANN, MASSACHUSETTS

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INTRODUCTION

Selected dike localities will be visited within the swarms of Siluro-Ordovician through Mesozoic dikes intruding the Cape Ann Granite in Gloucester and Rockport, Massachusetts (Figure 1). The field characteristics of the dikes will be emphasized. This is a repeat of a NEIGC trip led by the author in 2004 plus two additional stops (Stops 2 and 5, Figure 1).

The Silurian (425.97 $\pm$ 0.11 Ma, Thompson and Ramezani, 2008) Cape Ann Granite is the dominant member of the Cape Ann Plutonic Complex which also includes the Beverly Syenite and the Squam Granite (Bell and Dennen, 1972; Dennen, 1981). The complex is intruded by several hundred dolerite, diorite, and felsic dikes. Dolerites are by far the most abundant dike type, accounting for approximately 70%-75% of the dikes (Ross, 2004). Most (75%) of the dikes trend between N45^{o}W and due north with 12% trending N30^{o}E to N60^{o}E (Shaler, 1889). Between 10% and 15% trend within 10^{o} of due east-west.) The dikes range in age from Late Ordovician to at east Late to Middle Triassic (Ross, 1990, 2001). Published dike ages for Cape Ann and eastern Massachusetts are summarized in Ross, 2001 and 2004.

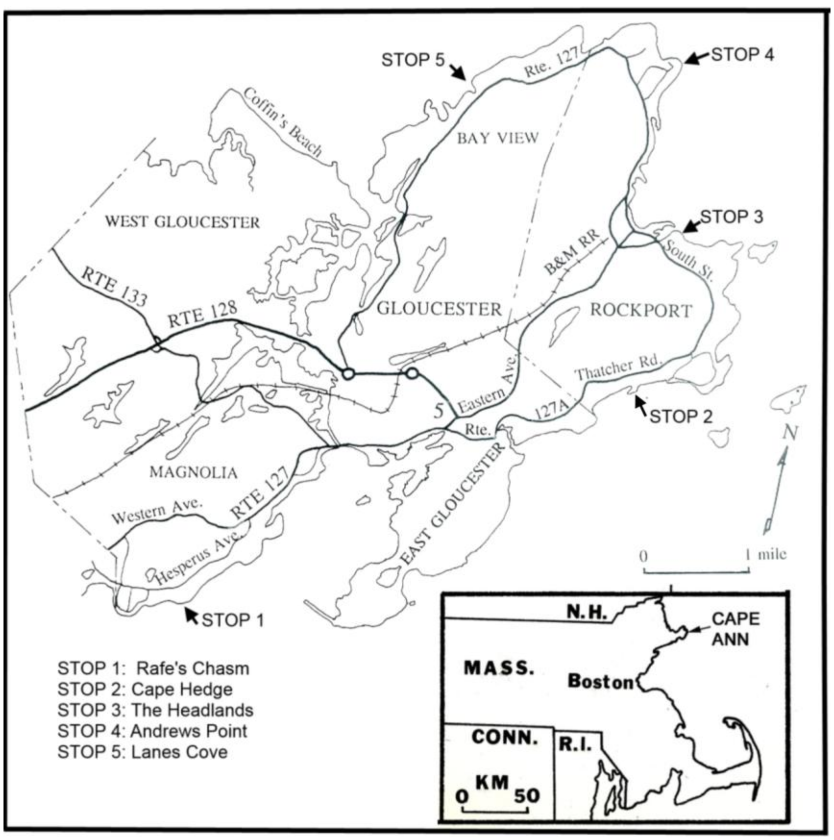

Figure 1. Location map of Cape Ann showing trip stops 1-5.

PALEOZOIC DIKES

Petrography

Dolerites. The Paleozoic dolerite dikes are predominantly fine-grained and aphyric, consisting of calcic plagioclase, augite $\pm$ olivine and rarely biotite. Approximately 25% of the dikes are plagioclase-phyric with phenocrysts generally between 3 mm and 7 mm. One noteworthy set of coarsely plagioclase-phyric, alkaline dolerite dikes with phenocrysts in excess of 3 cm in diameter will be seen on this trip. One possible member of this porphyritic set contains abundant plagioclase megacrysts (xenocrysts ?) approaching 20 cm in diameter will also be seen on this trip. Dominant textures viewed in thin section are subophitic, ophitic, and intergranular. Microporphyritic texture is common near and within chilled dike margins. Most of the dolerites are fresh but altered dolerites present contain saussuritized plagioclase, uralitized pyroxene, and olivine altered to smectite.

Diorites. The diorites are fine-grained and aphyric to plagioclase-phyric with anhedral phenocrysts generally less than 10 mm in diameter and accounting for up to 20% of the mode. Groundmasses consist of abundant, anhedral, brown biotite and green hornblende. Tiny euhedral apatite inclusions in all groundmass phases are common. Euhedral to anhedral magnetite occurs as an accessory mineral.

Trachytes: The trachytes are aphanitic and aphyric to microcline-phyric with phenocrysts generally less than 10 mm in diameter and accounting for up to 15% of the mode. Textures include xenomorphic-granular with microcline phenocrysts which, when present, typically have their euhedrism reduced by resorption at grain margins. At least one dike exhibits pilotaxitic texture. Flow layering is typical with layers consisting of hornblende and biotitite-rich discontinuous layers, streaks, or lenses alternating with feldspar-rich layers. Some also include grain-size layering involving the feldspars ($\pm$ quartz). Besides microcline and sodic plagioclase, hornblende $\pm$ biotite are essential minerals. Quartz is an accessory mineral occuring as anhedral groundmass grains but is absent in at least one dike. Sphene and zircon are present in at least one dike each. Magnetite is present as tiny euhedral groundmass grains in most of the dikes. A pyroxene trachyte at Andrews Point contains abundant green aegerine-augite and arfvedsonite and will be described in more detail in the road log below.

Chemistry

The major element chemistry of the eastern Massachusetts dolerites indicates the presence of tholeiitic, transitional alkalic, and alkaline varieties (Irvine and Baragar, 1971 classification). Transitional compositions are dominant over tholeiites on Cape Ann. The alkaline group can further be subdivided into those with higher total alkalis and SiO_2 than the remainder of the dikes. This group is represented by several coarsely-plagioclase-phyric dikes, two of which will be visited on this trip at Stops 1 and 3.

The tholeiitic E-W-trending dolerites on Cape Ann form a compositional group distinct from the NW-trending alkaline dolerites and altered dolerites analyzed. They are very similar in composition and petrography to E-W-trending dolerites intruding Proterozoic rocks to the south of Cape Ann that also are distinct from NW-trending dikes there. One of these has a K-Ar whole rock age of 254 $\pm$ 8 Ma (Zartman et. al., 1970). It is probable that these and the Cape Ann E-W dolerites are part of the same Late Permian swarm. The NW-trending Cape Ann dolerites are a part of the NW-trending middle-to late Paleozoic dolerite dike swarms intruding Late Proterozoic rocks to the south in the Avalon terrane (Ross, 1990).

The dioritoid dikes form a diverse compositional group ranging from trachybasalt to trachyandesite on the alkali-silica diagram of Le Bas and others (1986). Two dikes at Andrews Point (Stop 4) have higher NB/Y ratios than the other analyzed diorites. The analyzed felsic dikes form a compositionally uniform group plotting in the trachyte field on the alkalis-silica diagram of La Bas (1986).

MESOZOIC DIKES

The Mesozoic dike swarm of eastern Massachusetts, including Cape Ann, has been described elsewhere (Ross, 1992, 1990) and will not be described in detail here. The swarm consists of NE-trending tholeiitic olivine- and quartz-normative dolerites, transitional-alkalic dolerites, alkaline dolerites, and alkaline lamprophyres. Only one Mesozoic date (226 $\pm$ 3 Ma, K-Ar whole rock) has been published for Cape Ann (Weston Geophysical, 1977). This dike is located in West Gloucester just off Route 128 south of Rust Island along Causeway Street. As a group, these rocks are fresh, fine-grained, aphyric dolerites with ophitic textures and mineralogies dominated by labradorite and augite $\pm$ olivine. A few are also plagioclase-phyric. The swarm is part of the Coastal New England igneous province with major and trace element compositions indicating they are related to Atlantic rifting. Their more alkaline affinities compared to Eastern North America and other CNE dikes may be due to the more central location (deeper origin) of the swarm on the horst adjacent to the Connecticut rift basin (Ross, 1992).

ROAD LOG

The assembly point is on Route 128 in Beverly, MA just beyond the Brimbal Avenue overpass at Exit 19 (do not take Exit 19). Exit into "service area" (Sunoco Station, Burger King, Dunkin Donuts) and park along outer edge of lot near its north exit.

Mileage	
0	Exit parking lot of "service area" and proceed north on Route 128. Note NE-trending dolerite dike exposed in roadcut near north end of entrance ramp onto Route 128. This dike is tholeiitic and exhibits fairly well-developed columnar jointing visible here in three dimensions.
4.8	Take exit 16 (Pine Street) and go right onto Pine Street toward Manchester-By-The-Sea.
6.3	Left onto Route 127 (Bridge Street). Proceed through Manchester on Route 127 to junction with Raymond Street.
9.3	Right onto Raymond Street.
9.8	Continue on Norman Avenue (see Figure 2).
10.2	Continue on Hesperus Avenue one-quarter mile and park in small lot on right at Rafe's Chasm Park. Follow the trail about a quarter of a mile through the woods to the shore.

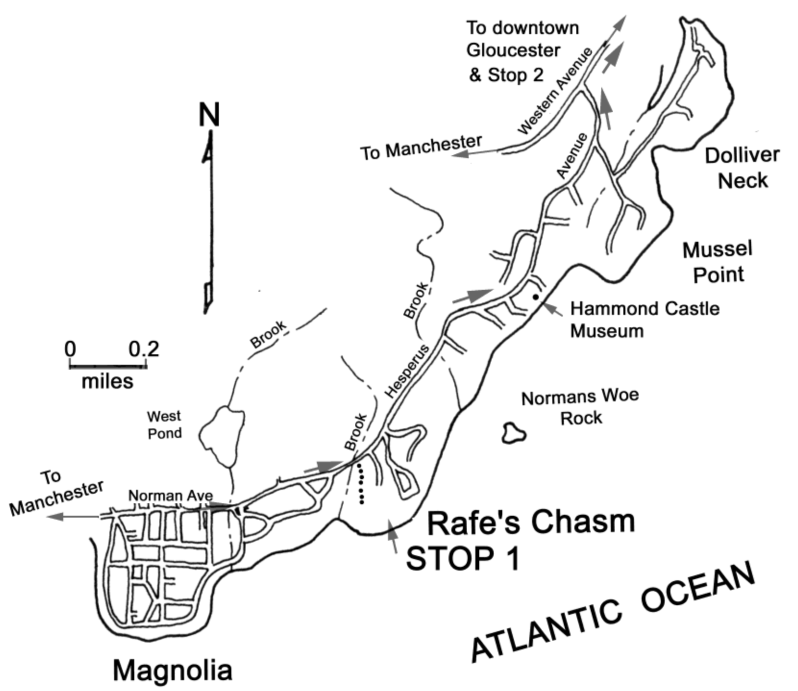

Figure 2. Location mapor Stop 1, Rafe's Chasm.

STOP 1. DIKES AT RAFE'S CHASM PARK, GLOUCESTER. UTM 19T 360388 E, 471558 N. (1 hour). See Figure 3 for dike locations A-E referred to below. The two north-trending dikes (A and B, Figure 3) are exposed just to west (left) below the end of the trail (Figure 4).

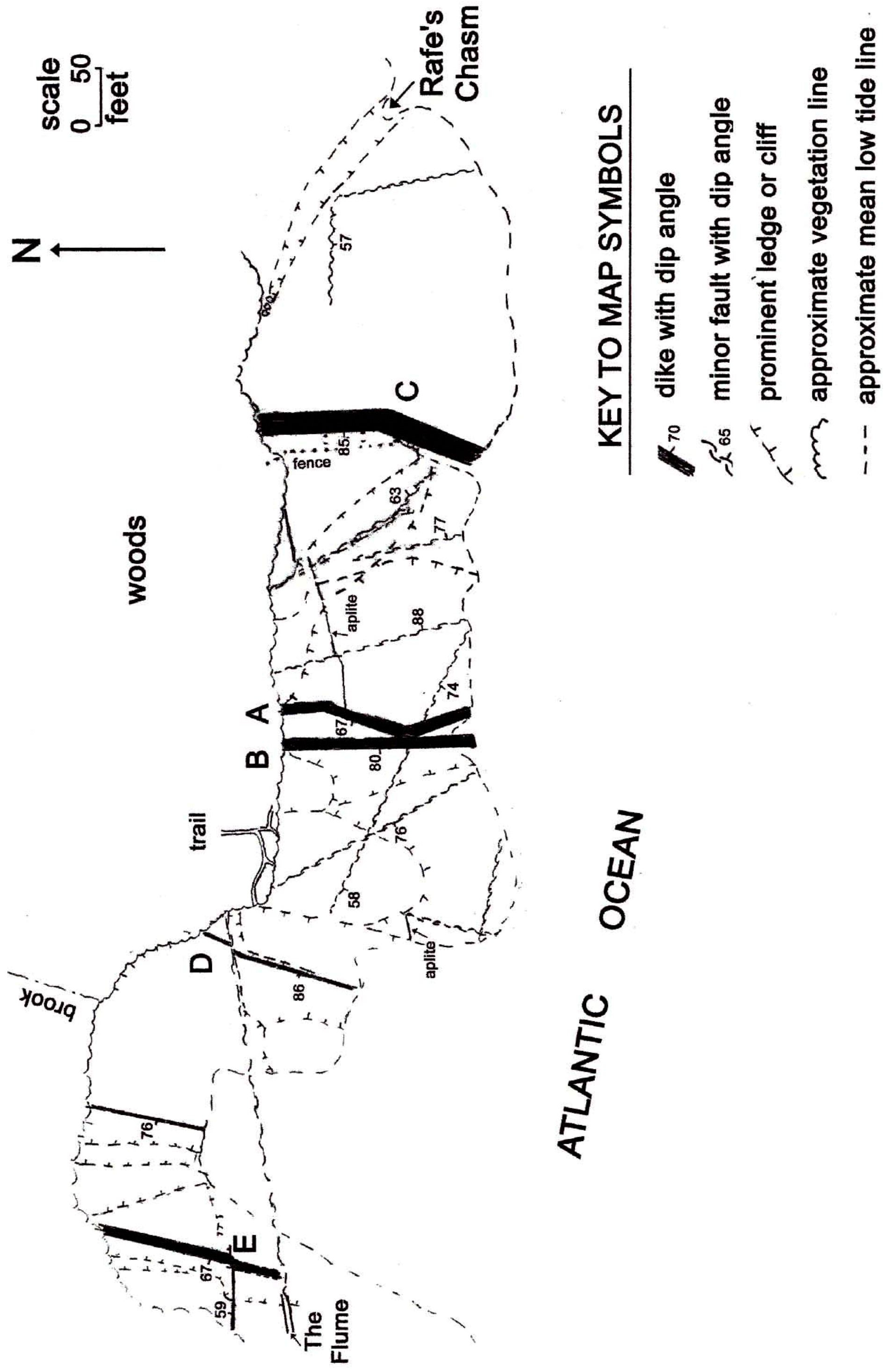

Figure 3. Geologic map of Rafe's Chasm park

Megacryst-rich dolerite (dike A, Figure 6)

Dike A is 4.5 m thick, dips 70^{o}W to vertical and bends sharply twice along its nearly N-S strike (Figure 3). At one point dike B cuts into the chilled west margin of Dike A and is chilled against it, indicating Dike B post-dates dike A. Dike A contains abundant plagioclase megacrysts (xenocrysts ?) approaching 20 cm in diameter. The megacrysts occur as discrete crystals, synneutic grains, and large clusters of crystals forming bodies up to at least 170 x 73cm (this largest one exposed only at low tide). These clusters are essentially anorthosite xenoliths and may represent cumulates within a layered gabbroic body beneath the Cape Ann Granite. The host dike may have intruded the gabbro pluton, incorporating xenoliths from anorthositic layers or the dike may have emanated from the gabbro magma after plagioclase cumulates had formed, and carried some up as discrete megacrysts and megacryst clusters. The host dike is plagioclase-phyric with sericitized phenocrysts up to at least 3 cm in diameter. The groundmass plagioclase is relatively fresh but the clinopyroxene is thoroughly uralitzed. Apatite and anhedral biotite are present in the groundmass along with magnetite and ilmenite. Megacrysts, megacryst clusters, and phenocrysts are concentrated within the interior of the dike (> 50%) due to flow differentiation.

A Lamprophyre (dike B, Figure 3)

On the basis of its mineralogy, texture, and alkaline chemistry, Dike B is classified as a camptonite. Dike B is augite-phyric with phenocrysts up to 2 mm in diameter in thin section and accounting for less than 5% of the rock. Many of the subhedral to euhedral, squarish to elongate, small augite phenocrysts, when viewed in thin section, are seen to have cores replaced by tiny opaque oxides, and kaersutite microlites. These cores are often surrounded by a thin rim of fresh, optically continuous augite. Fresh olivine microphenocrysts are also present with only minor alteration to smectite and carbonate along fractures. Subhedral kaersutite grains are abundant to scarce (vary with location in dike) as small prismatic microlites in the groundmass and also forms scattered phenocrysts (up to 2 cm in diameter visible in outcrop). Biotite, apatite, and opaque oxides are minor groundmass accessory minerals and, within the core of the dike especially, subhedral to euhedral quartz occurs in scattered amygdales with carbonate. Rare pink microcline xenocrysts up to 2.8 cm are also present. One thin section contains one, subhedral, 8 mm diameter, synneutic xenocryst of oligoclase with partially resorbed cores and rounded margins.

Dike B is 2.9 meters thick and dips 75^{o}-83^{o} west. The marginal zones of the dike contain vesicular layers parallel to the contacts and extending inward 12 cm to form sharp contacts with a second vesicular zone extending inward another 40 cm. Vesicles nearer the dike margin are elongate giving a sheeted appearance to the rock. Farther inward in the marginal zones the vesicles are filled with calcite and quartz to form amygdales.

Compared to Dike A, dike B has fairly-well developed columnar jointing across its width. Mesozoic dikes on Cape Ann and elsewhere in eastern Massachusetts typically have far better developed columnar jointing than older dikes, regardless of thickness. This is due to the shallower depth of intrusion exposed for the Mesozoic dikes than the older dikes at any given locality (Ross, 1990). Columnar jointing is favored by relatively rapid rates of post-solidification cooling and lower confining pressures (Ross, 1990), conditions that are favored by shallower crustal depths (or on the surface in the case of lavas). Two dikes at the same locality but of vastly different ages generally will represent different crustal depths (younger = shallower) if significant uplift and erosion has occurred between their intrusion. This suggests that Dike B is, if not Mesozoic, at least significantly younger than dike A.

Plagioclase-phyric dolerite (dike C, Figure 3)

Dike C to the east has been extensively eroded to form a broad chasm (Figure 6). It is 15 meters thick and strikes N23^{o}E near the water, bending to N3^{o}W inland a few meters and dips 85^{o}W. It contains a few plagioclase phenocrysts up to 10 mm in diameter in a groundmass of plagioclase and augite.

Rafe's Chasm

Rafe's Chasm lies about 75 meters farther east beyond dike C (Figure 3). The chasm is on private property which may prohibit our visiting it on this trip (Figure 7).

Figure 5. Closeup of plagioclase feldspar phenocrysts and a xenocryst in Dike A. Largest one is a cluster of three megacrysts that appear to be the result of synneusis.

Altered dolerite (dike D, Figure 3)

To reach dike D, retrace your steps back west to and beyond dikes A and B (Figure 5). Dike D is cut by an ENE-WSW trending fault which can be projected eastward across an embayment to a very pronounced, narrow, and deep chasm called "The Flume" (Figure 3). A thin, sheared, and badly altered dolerite dike is present adjacent and nearly parallel to the fault near Dike D. Dike D is microporphyritic (plagioclase and augite), intergranular and contains xenoliths up to 5 mm in diameter that consist of abundant kaersutite, plagioclase, magnetite, apatite $\pm$ calcite and chlorite in their cores.

Continue westward about 75 meters to dike E (Figure 3). Along the way you will cross a 60 cm thick aphyric, dolerite dike trending N12^{o}E and tippling 70^o-80^o W (Figure 3).

Composite dike with magma mingling (dike E, Figure 3)

Dike E is a composite dike in which a felsic magma intruded up the core of a partially crystallized dolerite dike thus providing an unusual example of magma mingling within a dike. The dike strikes N14^{o}E and dips 67^{o}W with a total thickness of 2.5 meters. Its outer 40-56 cm margins are aphyric and fine-grained with sharp interior contacts with the felsic-mafic mixed core of the dike. The dolerite margins are not chilled against the felsic dike core. The marginal dolerite has subophitic texture and consists of sericitized plagioclase and fresh, equant augite plus abundant blades and acicular grains of ilmenite and equant plates of what is probably ilmeno-magnetite. Apatite forms as acicular needles on plagioclase and augite. Secondary chlorite occurs in scattered small vesicles and interstitially altering augite. Thin, faint, discontinuous vesicular zones are aligned parallel to the contact locally.

The 1.5-1.6 meter thick felsic core of the dike consists of a microcline- and quartz-phyric granite with rounded and embayed phenocrysts up to at least 6 mm in diameter accounting for approximately 15% of the rock and set in an aphanitic to fine-grained groundmass of microcline and quartz. Accessory minerals include allanite, sphene, and zircon. Secondary minerals include pennine chlorite, epidote, quartz, and calcite in interstices and scattered vesicles.

Approximately 30% of the core consists of altered dolerite forming irregular to ovoid bodies and wavy, elongate strings in which most of the intergranular augite is completely altered to smectite. Plagioclase occurs as relatively fresh microphenocrysts, scattered small (2-3 mm) phenocrysts and groundmass microlites. Needles, blades, and skeletal grains of ilmenite are abundant. Rounded, fractured microcline xenocrysts up to at least 3 mm in diameter are fairly common and are identical to those in the felsic host. Biotite forms thin rims on some grains and along interior, open fractures in xenocrysts that appear to have undergone decompression fracturing and separation during ascent. Other than being more altered, these dolerite bodies are the same as that in the dike's margins.

The form of these dolerite bodies indicates they were pliable, if not partially molten at the time the felsic liquid was injected up the core of the dolerite dike. This clearly demonstrates the coexistence of mafic and felsic magmas at the time of intrusion of this dike. Evidence of commingling of felsic and mafic will also be seen at Stop 4.

Figure 6. Dike C in chasm eroded by waves along dike's south margin at stop 1.

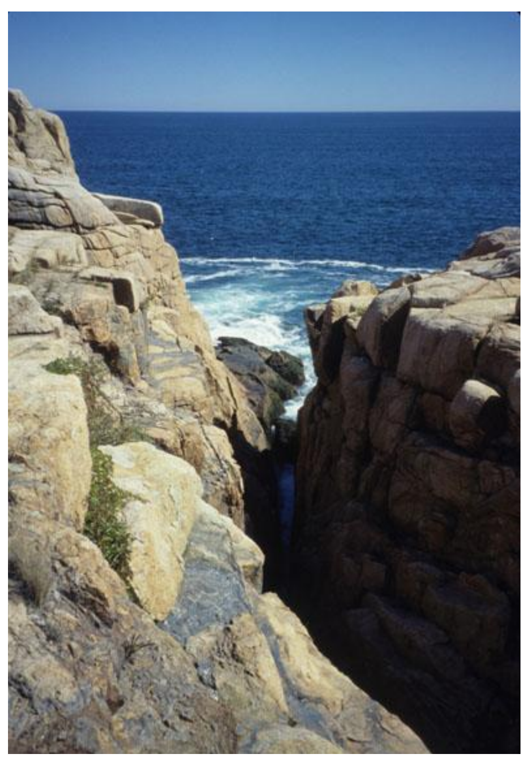

Figure 7. Rafe's Chasm eroded along joints in Cape Ann Granite at Stop1. The chasm is about 12-15 meters deep and about 8 meters across at its widest point. There are no remnants of the chilled margins along the chasm walls, unlike most chasms with dikes in them, and there is no dike exposed inland at and beyond the tip of the chasm. The bend in the chasm parallels two joint sets visible adjacent it and I suspect they controlled its orientation. Shaler (1889) and Dennen (1992) also show no dike in Rafe's Chasm on their maps.

Figure 8. Composite dike at locality E (Figure 3).

Figure 9. Closeup of core of composite dike (dike E) showing irregular to ovoid mafic bodies enclosed in a granitic matrix at Stop 1.

11.8	Return to cars and continue north 1. 6 miles on Hesperus Avenue to its junction with Route 127 (Western Avenue) and turn right onto Western Avenue (Figure 5).
13.7	Continue 1.9 miles north on Western Avenue to Rogers Street and turn right at Tally's service station onto Rogers Street which quickly makes a sharp left.

14.4 Go 0.7 miles on Rodgers Street to Main street and continue on Main Street to Bass Avenue. Proceed on Bass Avenue to junction with Route 127A (Thatcher Road).
Turn left onto Thatcher Road (127A). Continue on Thatcher Road 2.1 miles to Seaview Street (this is a small on street on right and hard to see). Drive to the large gravel parking lot at the end of Seaview Street and park at the far (southern) end. Walk south to a low outcrop just short of the footbridge at Cape Hedge (Stop 2).

STOP 2: DIKES AT CAPE HEDGE, ROCKPORT. UTM 19T 367730 E, 472180 N.

On the northwest side of the cape near Saratoga Creek (Figure 11) a coarsely, porphyritic dolerite dike with abundant large plagioclase phenocrysts up to at least 30 mm in length is partially exposed in a small, low outcrop. It is at least 3 feet thick, strikes az. 44^{o} and dips approximately 59^{o}-69^{o}SE. It resembles the "Headlands" dike at Stop 3 which projects south along its strike very close to the Cape Hedge outcrop, suggesting they are the same dike.

An interesting felsic dike occurs on the SE side of Cape Hedge, the rocky promontory that separates Long Beach from Cape Hedge Beach (Figure 9). Along the ocean side of the promontory a thin, wavy, dark, plagioclase-phyric dike rich in biotite and magnetite is cut by a nine foot thick, lighter-colored rhyolite aplite dike containing phenocrysts of quartz and perthite (Figure 10). The darker, wavy dike is discontinuous and lies along the north contact of the lighter colored, rhyolite dike that was intruded along it. The dikes dip 60 to 62 degrees northwest, thin to the southwest and pinch out where they are cut by a second north-trending, dark, felsite dike with scattered 6-8 mm plagioclase phencocrysts and dipping 30^{o} west (Figure 11). Chunks of the darker dike along the margin of the aplite dike were removed by the aplite magma and incorporated as numerous small xenoliths (Figures 12 and 13).

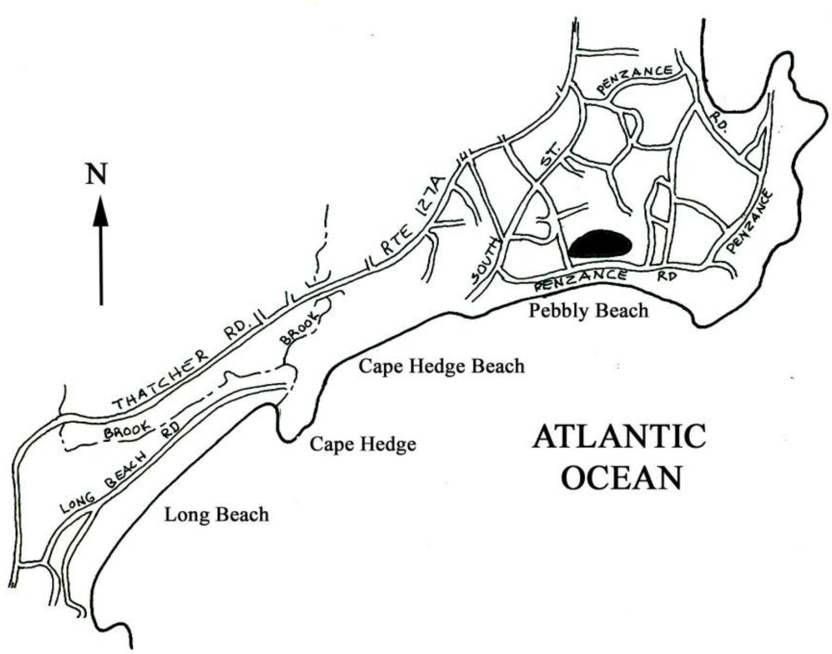

Figure 9. Location map for Stop 2, Cape Hedge

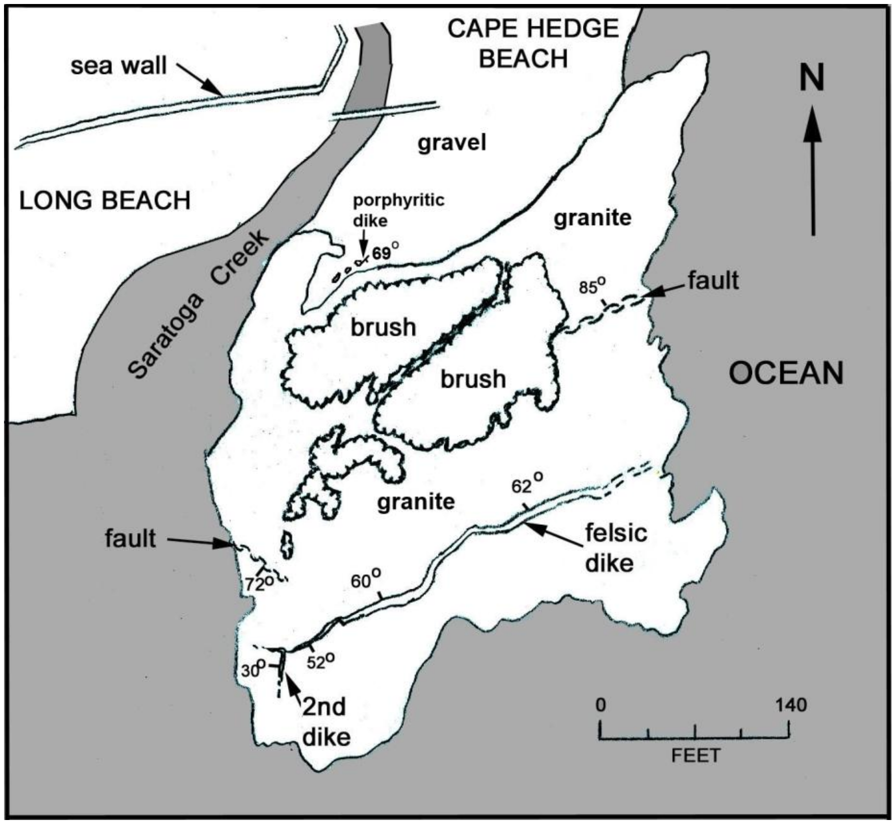

Figure 10. Geologic map of Stop 2 at Cape Hedge, Rockport. The coarsely plagioclase-phyric dike is similar in appearance to the Headlands dike at Stop 3.

Figure 11. Felsic dike (arrow) cutting Cape Ann Granite at Cape Hedge.

Figure 12. Upper contact of the rhyolite dike (lower half of photo) with the Cape Ann Granite. Note the abundant xenoliths of a porphyritic dark felsic dike within the rhyolite.

Figure 13. Xenolith of a dark porphyritic felsic dike within the rhyolite dike. The phenocrysts in the xenoliths are plagioclase oxidized to a dark reddish-brown in a groundmass rich in magnetite and plagioclase or locally, biotite and plagioclase.

Return to cars and drive back to Route 127A and turn right onto 127A (Thatcher Road).

16.7	Turn right onto Norwood Avenue
16.9	Turn left on Atlantic Avenue
17.0	Park in rocky "lot" on right side of street next to brushy area. The asphalt trail to The Headlands Park (STOP 3) is at the bottom of the hill where Atlantic Avenue takes a sharp left.

STOP 3: A PLAGIOCLASE-PHYRIC DIKE AT THE HEADLANDS. UTM 19T 367711 E, 4724712 N. (40 minutes). See Figure 15 for locations referred to below.

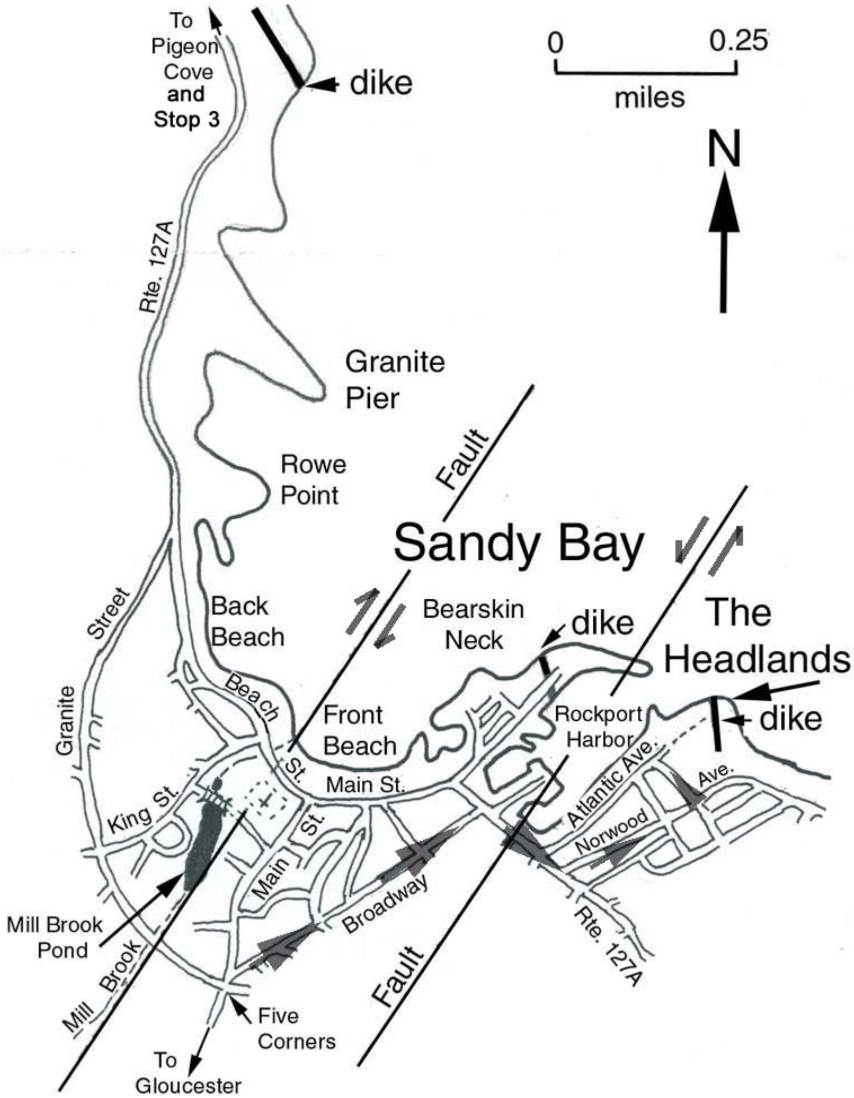

Figure 14. Location map for Stop 3, "The Headlands"

A thin Mesozoic (?) dolerite dike (dike B, Figure 15)

Dike B is exposed as erosional remnants on a relatively smooth, gently westward-sloping granite surface (locality A, Figure 15) formed by the preferential erosion of dike B which is visible at the base of a ledge rising at the back of this surface (Figure 16). The dike is 6.3 cm thick here, strikes $N10^{o}$ E and has an unusually low dip of 22^{o} E. It is plagioclase-phyric with 2-3 mm phenocrysts making up13% of the mode. Augite forms scattered microphenocrysts and tiny intergranular microlites in the groundmass along with magnetite. This dike is a tholeiite. A short distance to the east the dike cuts Dike C (intersection visible at low tide). Its NE trend, relative freshness, and its cutting of Dike C suggest that dike B is Mesozoic. Several thin dikes (D, E, F, G, H, Figure 15) with identical petrographies are exposed farther east beyond dike C.

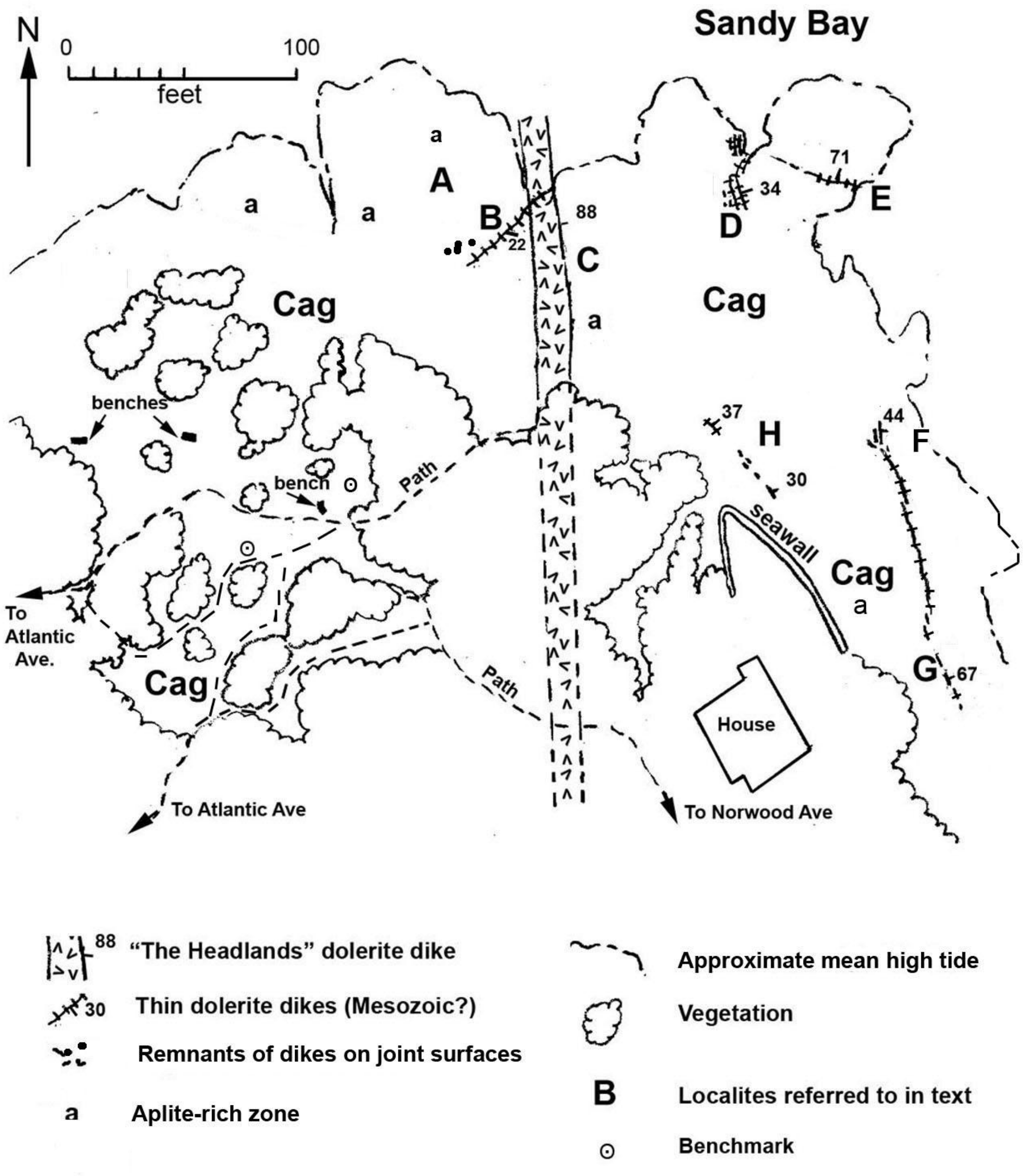

Figure 15. Geologic map of The Headlands, Rockport.

A coarsely plagioclase-phyric dolerite dike (dike C, Figure 15)

Dike C is a 5.7 meter thick, coarsely plagioclase-phyric, alkaline altered dolerite dike trending N 14^{o}W to N7^{o}W and dipping 88^{o}E. A deep is chasm eroded into its west margin (Figure 17). The dike consists of plagioclase (An30-67), augite, biotite, magnetite, ilmenite, apatite, quartz, baddeleyite, and rare zircon. It has a U-Pb age (baddeleyite) of 400 $\pm$ 5 Ma (Ross, 2001) compared to an earlier K-Ar whole rock age of 351 $\pm$ 13 (Weston Geopysical,1977). A detailed study of the effects of flow differentiation on the distribution and alignment of the

Figure 16. Thin dike at base of ledge at Locality B. Note the well-developed columnar jointing.

plagioclase megacrysts, as well as chemical variations across the dike was completed by the author (Ross, 1986). The results of that study will only briefly be summarized here.

The largest plagioclase phenocryst measured here is 12.0 cm long. Phenocryst abundance increases inward from the aphyric chilled margins to a maximum concentration of over 50% and near its center. The average sizes of the phenocrysts also increase inward. There are several subtle grain-size reversals near the east margin suggesting magma pulses occurred. The degree of phenocryst alignment parallel to the dike contacts is weak but measurable and more pronounced nearer the chilled margins than in the center of the dike. This alignment is due to magma flow and is more pronounced near the chilled margins where shear rates are higher in the zone bounded by flowing magma on one side and the solidified chilled margin on the other. This shear is responsible for rotating phenocrysts into parallel or subparallel alignment with flow. Also shearing could more readily rotate the smaller phenocrysts located there compared to the much larger grains in the dike interior (Ross, 1986).

The dike is also exposed at Bearskin Neck to the north across Rockport Harbor where it is offset to the west from its locality at the Headlands. Farther north across Sandy Bay, the dike re-emerges from the sea where it is exposed along the shore of Pigeon Cove (visible from here). This segment is offset back eastward from the one on Bearskin Neck but is still offset west of its exposure at the Headlands. Two northeast-trending faults, one up Rockport Harbor, and one up Sandy Bay (Dennen, 1992), have apparently offset the Headlands dike in a left-lateral and right lateral fashion respectively (Figure 14).

A petrographically and chemically similar dike is exposed along Route 128 in West Gloucester and a third similar dike is exposed at Briar Neck (Stop 2). An identical dike is located 56 km southwest in Weymouth, Massachusetts in a roadcut on Route 3 (Ross, 1990). Other than its slightly lower Nb content, the Weymouth dike is chemically very similar to the Headlands dike. It is not inconceivable that the dikes at Weymouth and Cape Ann, if not the same dike, then are members of a distinct set possibly derived from the same magma.

Other thin dolerite dikes (D through H, Figure 15)

Segments of several additional dolerite dikes identical to Dike B are exposed as discontinuous segments east of dike C (Figure 15). The most noteworthy features visible in the field is the exposure of well-developed columnar

Figure 17. The coarsely porphyritic dolerite dike at The Headlands, Rockport. The chasm is along the west (left) margin of the dike and the shrub is at the east (right) margin of the dike. Andrews Point (Stop 4) is visible on the horizon.

Figure 18. Plagioclase phenocrysts in center of Headlands dike. Note faint flow alignment parallel to the knife.

jointing at localities D and G as well as a pronounced horn extending into the granite at E (Figure 20). An interior chilled margin occurs near the western contact of the dike at locality G.

Figure 19. Smaller plagioclase phenocrysts near east margin of Headlands dike.

Figure 20. Dike at locality E with a thin "horn" branching off from it. Columnar jointing is relatively well developed in the dike and horn and the polygonal shapes of individual columns can be observed in cross section on the broad vertical face eroded into the margin of the dike.

17.9	Return to cars and continue down Atlantic Avenue and turn right onto Mt. Pleasant Street (Route 127A, see Figure 14).
18.0	Continue to Dock Square and onto Main Street.

18.2	Bear right onto Beach Street and continue past Front Beach and Back Beach.
18.6	Bear right onto Granite Street (Route 127; see Figure 14).
19.9	Turn right on Phillips Avenue (see Figure 21).
20.3	Continue on Point Dechene Avenue.
20.5	Turn Right on Longbranch Avenue and park along left side and at end of street.

STOP 4. DIKES AND MAGMA "PILLOWS" AT ANDREWS POINT. UTM 19T 367635 E, 4727231 N.

The area to be visited at Andrews Point is a large xenolith at least 80 meters in length and consisting of syenite and granite aplite cut by diorite dikes, a dolerite dike, a pyroxene trachyte dike, a granite aplite dike, pegmatite dikes, and a dike of Cape Ann Granite (Figure 22).

Pyroxene trachyte dike (dike A, Figure 22)

Dike A is a pyroxene trachyte (sÖlvsbergite of Wones and Goldsmith, 1991) consisting of scattered microcline phenocrysts to 2 mm in diameter in an aphanitic, xenomorphic-granular groundmass of microcline, plagioclase, aegerine-augite, arfvedsonite (Na-amphibole with blue pleochroism), and magnetite. The flow banding consists of streaks of aligned aegerine-augite and arvedsonite grains and slight grain size variations of the feldspars. The dike contains granite xenoliths (a meter-long one is present at Locality A) and veins and streaks of granite are present near contacts. The dike also outcrops in the northwest corner of the map area (Figure 22).

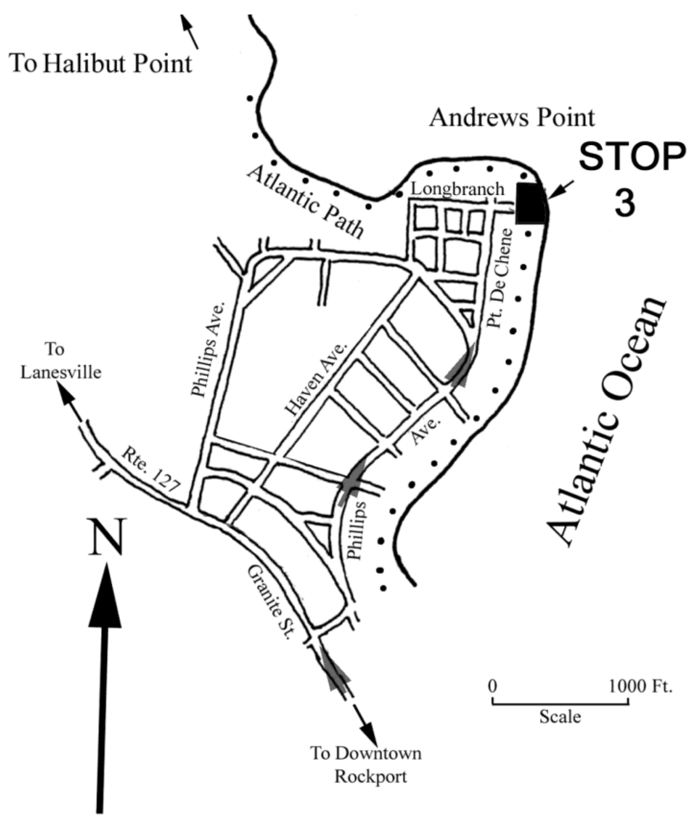

Figure 21. Location map of Andrews Point, Rockport (Stop 4).

Near where the dike enters the ocean to the south, it is cut at a low angle by a fault with an apparent 2.4 meter left-lateral offset (Locality D, Figure 22). However, since the dike dips 88°NE, a normal offset of 9 meters with subsequent erosion of the footwall (east of fault) would result in a 2.4 meter northward erosional shift of the dike to produce the apparent strike-slip offset. The right-lateral offsets of the contacts between the Cape Ann Granite, the syenite, and the aplite were all produced in the same manner. Note their offsets are opposite that of the trachyte dike due to their southerly dips, further indicating strike-slip motion did not occur on this fault. A thin, sheared, altered dolerite dike is exposed within the eroded fault where it cuts the aplite (Figure 22).

The pyroxene-trachyte has not been analyzed but two dikes approximately 450 meters south of the area shown in Figure 22 have been analyzed and plot in the trachyte field on the alkali-silica diagram of LeBas et. al. (1986; Figure 3). These dikes do not contain arfvedsonite or aegerine-augite, however.

Figure 23. Pyroxene trachyte dike cutting Cape Ann Granite in extreme NW corner of Figure 22. This is the same dike as at locality B to the south (Figure 22).

Two windows have been eroded through the Cape Ann Granite on the footwall side of the fault to expose the underlying aplite sheet (Localities C and D, Figure 22). The upper contact of the aplite with the granite can be seen in the west-facing cliff along the fault southeast of locality B and along the margins of windows C and D (Fig. 22).

Aplite sheet

At Locality E (Figure 22) the south-dipping (25°) upper contact of the aplite sheet with the Cape Ann granite is exposed and can be traced across the outcrop. The aplite does not appear to be chilled against the granite and tongues of the granite extend several centimeters down into the aplite indicating the granite intruded the aplite. The attitude of the upper contact with the granite is highly variable (Figures 22 and 26) and does not indicate the folding of the aplite sheet as shown by Wones and Goldsmith (1991).

The basal contact of the aplite with the underlying syenite dips 20°S and is visible below Locality F in the north-facing cliff which parallels the contact (Figures 22 and 25). Before climbing down to examine it, look northward

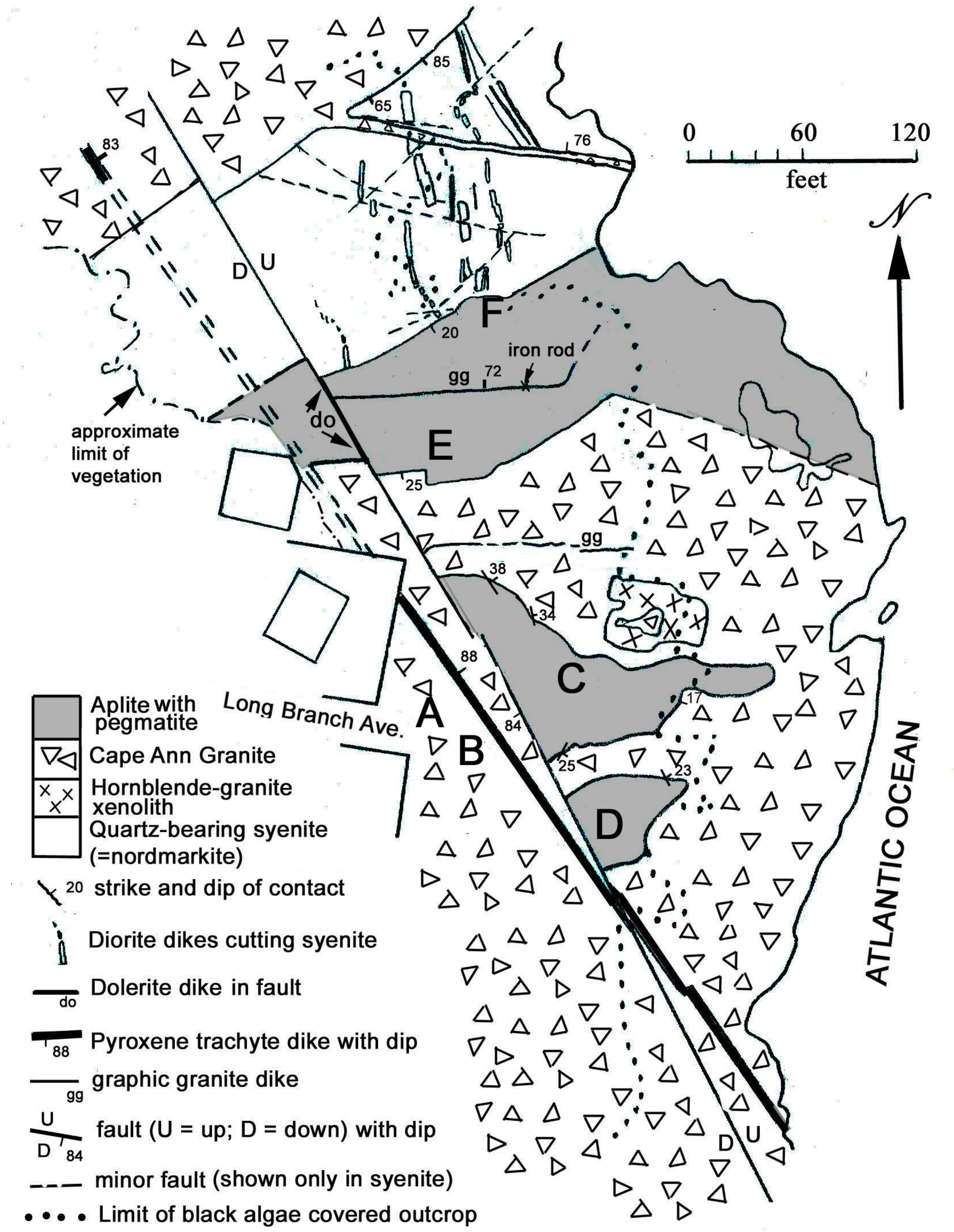

Figure 22. Geologic Map of Andrews Point, Rockport (modified from Ross, 2004 and 1990).

from the high point at locality F across the lower outcrops (Figure 24). A series of north-trending dark dike segments are visible within the syenite. These are diorites, some of which form agma pillows within the syenite.

Scattered patches of pegmatite occur near the center of the aplite (between localities E and F and at C and D, Figure 22). The dark micaceous mineral in the pegmatite is annite, the iron-rich end member of the biotite series. This is the type locality for annite (no hammers).

Diorite dikes and magma pillows

A series of diorite dikes are present within the syenite and are truncated in the south by the aplite sheet and in the north by the Cape Ann Granite (Figure 25). The thickest of these extends north from locality F as a series of *en echelon* segments cut by several minor strike-slip faults (dike 2, Figure 25). These dike segments are also underlain by the syenite, thus forming elongate pods rather than a continuous sheet (Figures 25 and 26). The thicker dike is veined by the syenite which has also in-filled between dike segments. It is clear that the diorite intruded into a still mobile syenite magma and separated into aligned segments along strike and vertically to form magma pillows. Two thinner diorite dikes to the west (dikes 5 and 6, Figure 25) also form magma pillows and the ends of the longer segments are distinctly rounded. Dikes 8, 9, and 10 to the east (Figure 25) are very thin and more intact, indicating they intruded the syenite somewhat later than the pillowed dikes. Except for dikes 9 and 10, the diorites are plagioclase-phyric with phenocrysts up to 6 mm long accounting for 1-5% of the rock. In addition to plagioclase, the groundmass consists of green hornblende, brown biotite, with accessories including magnetite, quartz, and apatite. The major and trace element compositions of the only two Andrews Point diorites (dikes 2 and 5, Figure 25) that have been analyzed have essentially the same compositions (Ross, 1990).

Figure 24. Viewing north from locality F (Figures 22 and 25). Segment of dike 2 (Figure 25) lies to the right of person and a second segment lies beyond that and offset (left-lateral en echelon).

The possible genetic relationship of the syenite, aplite, and Cape Ann Granite is unclear. The syenite and the aplite sheet cutting it comprise a large xenolith within the Cape Ann granite, a dike of which cuts the syenite and the diorite dikes (Figure 25). Wones and Goldsmith (1991) considered only the syenite to be a "foundered block"

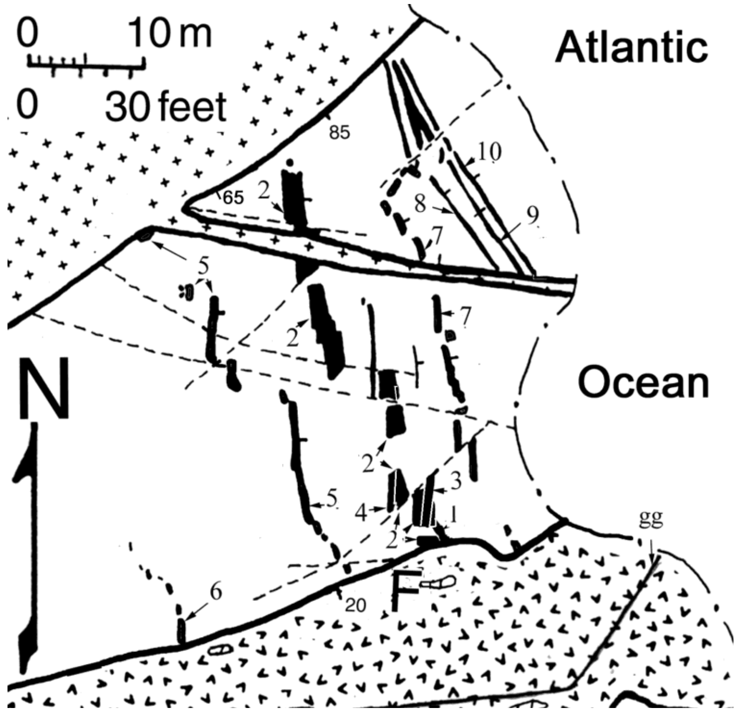

Figure 25. Geologic map of the northern portion of the Andrews Point area, Rockport (Stop3). Modified from Ross (1990).

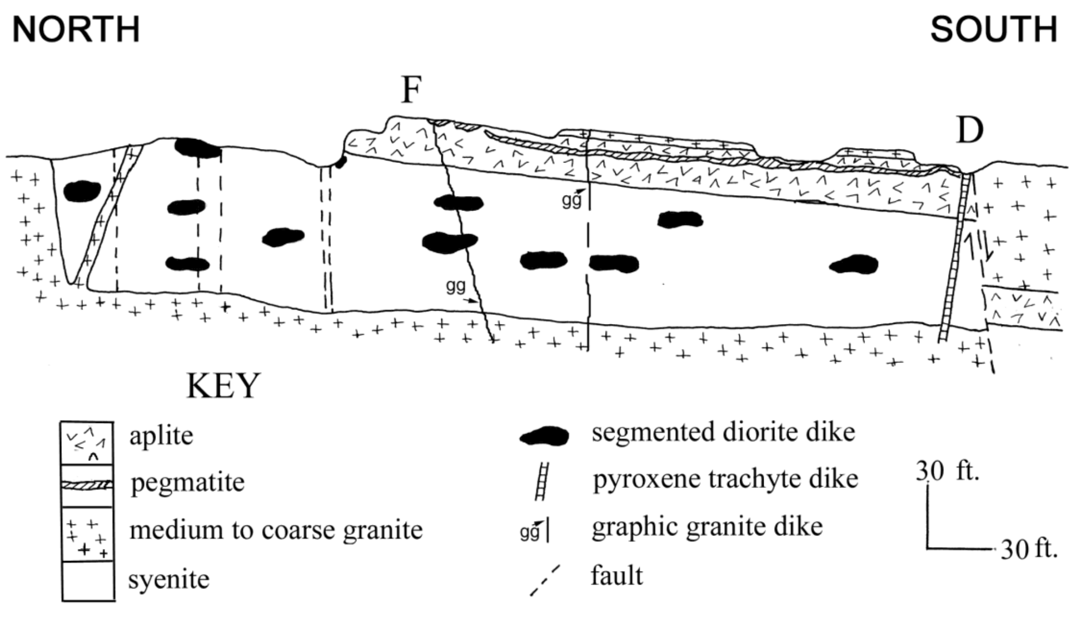

Figure 26. North-South geologic cross section of the Andrews Point area, Rockport (Stop 4).

that was later intruded by the aplite and the Cape Ann Granite. As mentioned above, the contact of the aplite and granite is locally very irregular with tongues of granite extended several centimeters down into the aplite indicating the granite intruded the aplite. It is not clear if the xenolith is a cognate xenolith torn from the solidified chilled margins of the Cape Ann Granite or if it represents a block removed from the country rock. If it is a cognate xenolith, then the diorite magma pillows indicate the coexistence of mafic magma(s) and the Cape Ann Granite magma. As seen earlier at Rafe's Chasm (Stop 1, dike E), it is clear that felsic and mafic magmas did coexist. Elsewhere on Cape Ann there is evidence of magma pillows within the Cape Ann Granite (Toulmin, 1964; Dennen, 1981; Ross, 1985, 1990, 2004; Hon et. al., 1993). These diorites may represent the results of mixing of the Cape Ann Granite with a gabbroic magma intruded at greater depths and which provided the heat for crustal melting to produce the Cape Ann granite magma.

21.1 Retrace the route back to Route 127 (Granite Street) turn right and continue 2.1 on Route 127 to Andrews Street in Lanesville.
23.2 Right onto Andrews Street and proceed less than 0.1 miles to parking lot behind breakwater (Figure 27).

STOP 5. DIKES AT LANES COVE, LANESVILLE. UTM 19T 35340 E, 4726385 N.

A 22 foot thick dolerite dike is exposed in the outcrop at the northern end of the breakwater on the north side of the cove (Figure 27). A second dolerite dike occurs about 50 feet farther north (Figure 27). A prominent cliff has been eroded along the north face of this 5.7 foot thick dike which also exhibits faint columnar jointing across its width. Curved, lens-shaped dike-like segments containing granite xenoliths and a few, small purplish plagioclase phenocrysts are present north and south of these two dikes and are cut by them.

Walk to the south side of Lanes Cove via Andrews Street, Lanes Cove Road, and Duley Street (Figure 27). About 150 feet beyond the south end of the southern breakwater (Figures 27 and 28), and near the vegetation line, a large (36 X 18 feet) dike-like segment is exposed that contains very large purple plagioclase crystals as isolated xenocrysts or in clusters within oval-shaped xenoliths (Figure 29). Purple, aphanitic xenoliths are also present. It appears that this body intruded as a dike into a still mobile, perhaps partially crystallized (but much cooler) granite magma. The dike separated into segments, two more of which occur a short distance south of the segment presently being observed.

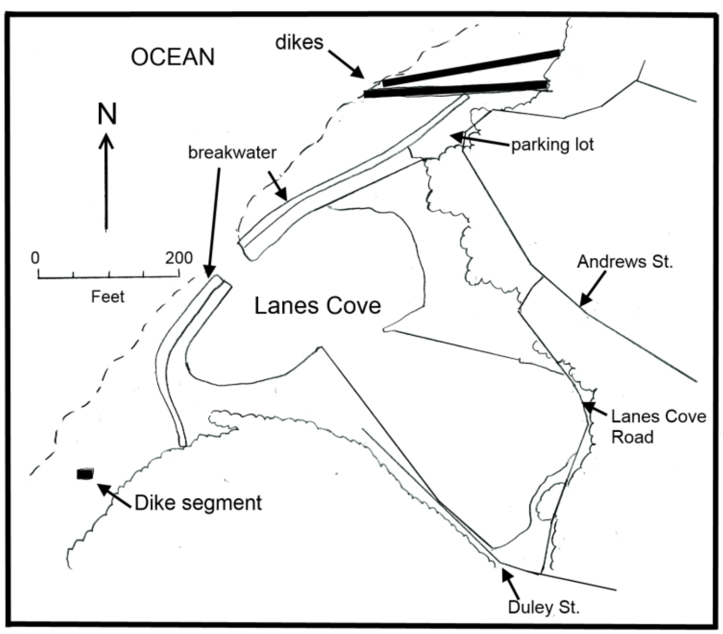

Figure 27. Location map for Lanes Cove, Lanesville section of Gloucester.

Figure 28. Dike segment exposed on ocean front about 150 feet south of the south end of the breakwater south of the entrance to Lanes Cove. Contact with the lighter colored Cape Ann Granite forms the sharp line running up from the lower left-hand corner of the photo.

Figure 29. Close-up of rounded xenolith containing large purple plagioclase phenocrysts.

segment as well as a 24 cm thick, fine-grained granite dike. Note that these do not continue out of the dike into the granite. This indicates the granite veins were injected into the dike segment before it reached its present position and so were torn away from their extensions in the granite.

The margins of the body are aphanitic due to chilling of the dike magma against the cooler granite magma. The dike magma did not disintegrate into small bodies such as those elsewhere on Cape Ann (end of Route

128 for example) because it was more effectively chilled and the granite magma here may have been more thoroughly crystallized and thus more resistant to the breakup of the dike magma. The granite magma probably was still mobile, however as evidenced by the fact that the three dike segments were moved apart either by the momentum of their intrusion or subsequent flow of the granite magma. There are several granite pegmatite veins cutting the dike

An alternative hypothesis is that these three large dike segments are merely xenoliths torn from an older, solidified gabbro country rock by the granite magma as it forced its way through. However, it seems unlikely that only the dike would be removed from the gabbro country rock by the granite magma. At least some of the gabbro forming the original country rock for the dikes would likely have been carried away as well, some still attached to the margins of the dike segments and some occurring as discrete xenoliths. Also, the dolerite dike was hybridized by contamination with the granite, which could only have occurred if the dolerite were liquid when it encountered the granite.

Just north of this segment small ovoid dark blebs up to 2 inches in diameter are scattered in the granite. These may be droplets “thrown” from the mafic dike magma as it intruded into the granite magma. Mafic "droplets" also occur near the next dike segment to the south.

These dike segments and their included xenoliths and xenocrysts suggest that a gabbroic body is present at depth beneath the Cape Ann Granite. Judging from evidence here and at other localities such as Andrews Point and the end of Route 128, the gabbro and Cape Ann granite magmas were coeval and probably cogenic. The chemistry and petrography of the Cape Ann Plutonic Complex is compatible with it having been derived by dry partial melting in the lower crust due to heat transferred from a mafic magma below (Hon et al.,2008). Subsequent magma mixing and fractionation occurred in the shallow crust to produce the CAPC (Hon et al. 2008).

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