LAYERED GABBRO-DIORITE INTRUSIONS OF COASTAL MAINE: BASALTIC INFUSIONS INTO FLOORED SILICIC MAGMA CHAMBERS

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INTRODUCTION

The layered gabbro-diorite intrusions that are the focus of this field trip belong to the Coastal Maine Magmatic Province (CMMP) which consists of more than 100 mafic and felsic plutons emplaced over a time span from the Late Silurian to the Early Carboniferous (Hogan and Sinha, 1989) (Fig. 1). The bimodal character of this province is well established (Chapman, 1962a), and there is widespread evidence for commingling between mafic and felsic magmas (Taylor et al., 1980; Stewart et al, 1988; Chapman and Rhodes, 1992). Chapman (1962a) visualized the mafic plutons as large, sheet-like masses with overlying granite beneath a country rock roof. Gravity studies (Hodge et al., 1982) indicate that many of the granitic plutons are thin with gently-dipping floors, and probably rest on mafic rocks similar to the layered diorite and gabbro that partly surround and dip beneath several of them. The plutons of the CMMP intrude a variety of metasedimentary and metavolcanic rocks in several fault-bounded, northeast-trending terranes featuring different stratigraphies and different structural and metamorphic histories (Williams and Hatcher, 1982). The ages and field relations of these plutons suggest that they postdate the main assembly of these lithotectonic terranes (Ludman, 1986). Hogan and Sinha (1989) suggested that at least some of the magmatism was related to rifting in a region of transtension along a transcurrent fault system.

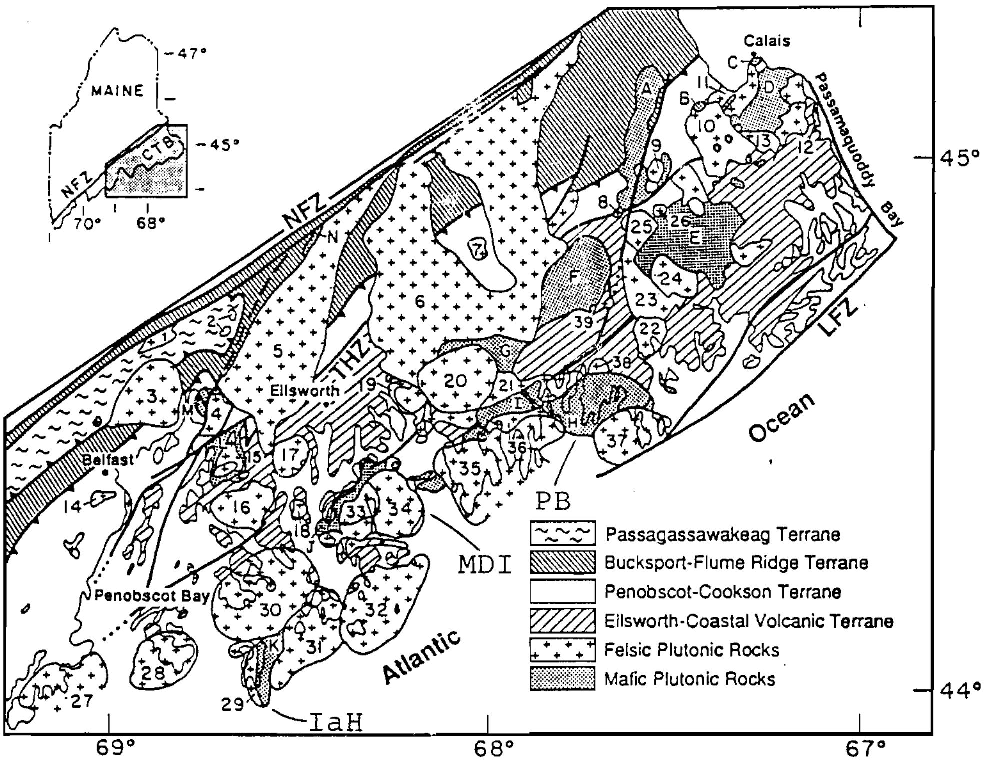


Figure 1. Geologic map of the Coastal Maine Magmatic Province within the lithotectonic terranes of southeastern Maine, taken from Hogan and Sinha (1989). Numbers and letters correspond to their designations for felsic and mafic plutons, respectively. Pleasant Bay Composite Layered Intrusion (PB) (H), Mount Desert Island (MDI) (33, 34, and J), and Isle au Haut (IaH) (29 and K) are described in this field guide.

The three complexes that we will visit (Pleasant Bay, Cadillac Mountain, and Isle au Haut) present superb examples of mafic-silicic layered intrusions (MASLI) which display complex interlayering of gabbroic to granitic rocks (Wiebe, 1993a). MASLI are characterized by gabbroic layers with chilled bases resting on silicic cumulate layers and by the development of silicic pipes and load cast structures along the bases of these gabbroic layers. The basally chilled gabbroic layers record infusions of basaltic magma into shallow-level, pre-existing floored chambers of relatively silicic magma; the pipes and load cast structures record gravitational instabilities caused by the ponding of rapidly cooling basaltic magma on incompletely solidified silicic cumulates. Layers that grade upward from basally-chilled gabbro to highly silicic cumulates provide a cumulate stratigraphic record of the double diffusive interface between stratified basaltic and silicic magmas.

Based on geologic mapping, internal structures, and gravity data these complexes appear to have dimensions, compositions, and a geologic setting that are appropriate for plutonic systems inferred to lie beneath long-lasting silicic volcanic systems in areas of bimodal magmatism - e.g. Yellowstone (Hildreth et al., 1991). Because of their stratigraphic records, and their apparent link to silicic volcanic systems, MASLI have great potential to provide new insights into magma chamber processes and into the connections between the plutonic record and volcanic activity.

THE PLEASANT BAY LAYERED GABBRO-DIORITE INTRUSION

Introduction

The Pleasant Bay layered gabbro-diorite intrusion, located on the coast of Maine between Bar Harbor and Machias, is roughly oval in plan, measuring 12 by 20 km (Fig. 2) (Wiebe, 1993b). It was emplaced into the Ellsworth-Coastal Volcanic Terrane (Hogan and Sinha, 1989). Gravity data (Biggi and Hodge, 1982) suggest that it is basinform in structure with a maximum thickness of about 3 km. The basal contact of the intrusion appears everywhere to dip gently inward, and the disposition of internal layering suggests that the chamber floor consisted of

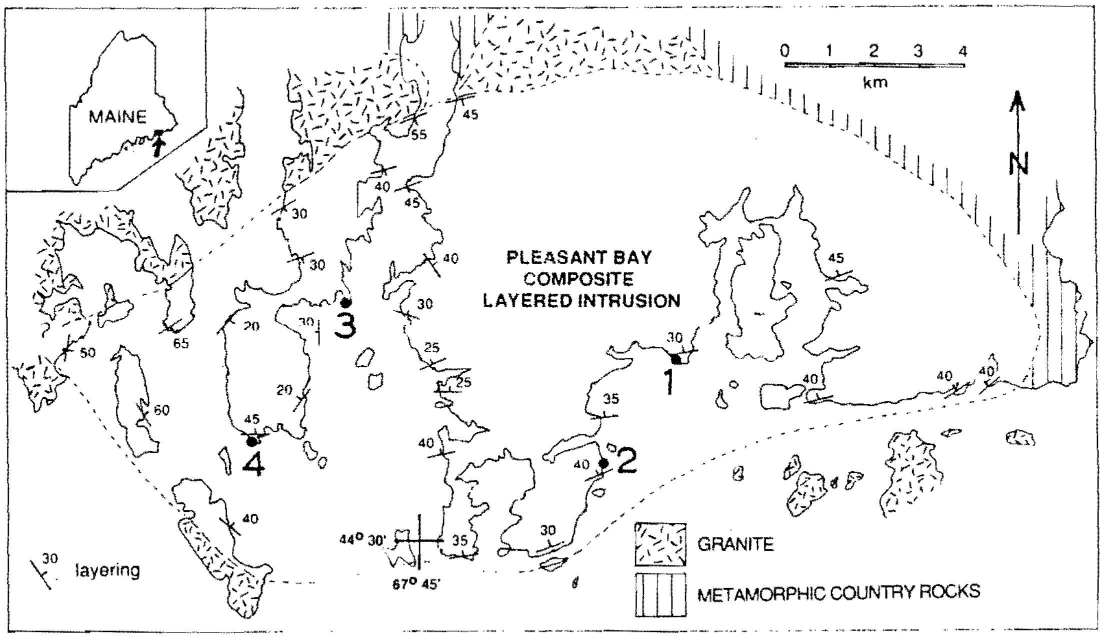


Figure 2. Geologic sketch map of the Pleasant Bay intrusion. The intrusion consists of about 90% medium-grained gabbro and mafic diorite intercalated with (1) subordinate silicic cumulates ranging from leucocratic diorite to granodiorite and (2) strongly chilled gabbroic layers. It has not been subdivided at this scale because of the rapid alternation of these rock types in layers ranging from about 1 to 100 m thick. Bold numbers (1 - 4) refer to field trip stops on Day 1.

two or more irregularly shaped basins (Fig. 2). Where the gabbroic base of the Pleasant Bay intrusion rests on granite, the gabbro is typically chilled against the underlying granite and commonly displays convex-downward lobate forms. At some places, the base of the intrusion consists of pillow-like bodies of chilled gabbro in a hybrid granitic matrix. Basaltic dikes in granite near the Pleasant Bay intrusion commonly trail off into elongate zones of chilled pillows in granite or are strongly re-intruded by the granite. These relations suggest that the granite was incompletely solidified when the gabbro was emplaced. The roof and upper parts of the intrusion have been lost through erosion. Except for minor faulting, it appears to be undeformed. The occurrence of open vugs (up to a few cm across) in some contemporaneous granitic rocks suggests shallow emplacement. Basaltic, granitic, and composite dikes occur widely; they are mutually intrusive and typically have attitudes close to N10°W, vertical.

The intrusion consists of about 90% massive to weakly layered gabbro and mafic diorite, both of which vary widely in grain-size and texture. It also contains medium-grained leucocratic layers and lenses from a few cm to several meters thick that range in composition from diorite to granodiorite and commonly contain chilled gabbroic pillows and partly digested mafic inclusions that resemble mafic enclaves in granitic plutons (Didier and Barbarin, 1991). While these leucocratic layers commonly grade downward to gabbro, overlying gabbroic layers are typically chilled against them.

Field Relations

Layered Units. Two stratigraphic sections in Fig. 3 illustrate sequences of layers and the occurrences of distinctive structures along layer boundaries that are typical of the Pleasant Bay intrusion. These sections have been subdivided into macrorhythmic units with chilled gabbroic bases that grade upward to medium-grained gabbro, diorite or highly evolved silicic cumulates. The top of each unit is truncated by the chilled base of the overlying

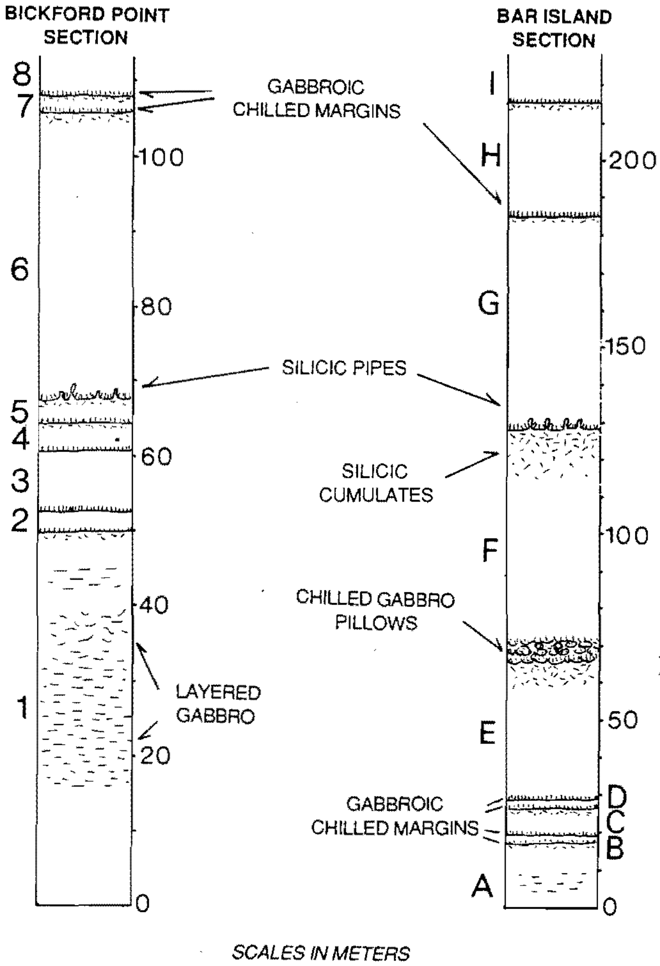


Figure 3. Stratigraphic sections from two locations in the Pleasant Bay intrusion. The Bickford Point section is at Stop #1 in Fig. 2; the Bar Island traverse is at Stop #2. Unpatterned parts of the columns are massive medium-grained gabbro. Individual macrorhythmic units are labelled by letters and numbers alongside the sections. All transitions between different rock types in a macrorhythmic unit are gradational.

unit. Each chilled base records the infusion of basaltic magma into the magma chamber. Cumulates beneath a macrorhythmic unit vary widely in composition, indicating that the composition of resident magma in contact with the chamber floor also varied widely when basalt was injected. The degree of chilling at the base of a unit generally increases as the compositional contrast with the underlying cumulates increases. Although the base of each layer consists of similar chilled gabbroic material with an irregular crenulate, convex-downward boundary, the extent and rate of compositional variation toward the top of each layer is highly variable. Extrapolation from measured sections suggests that the total number of macrorhythmic units in the intrusion probably exceeds several hundred.

In addition to the macrorhythmic units, some areas of the intrusion have many smaller gabbroic layers and lenses (0.5 to 2 meters thick) that have chilled upper and lower margins against more leucocratic dioritic material. In some areas, parts of layered sequence also contain closely spaced, chilled gabbroic pillows in a dioritic matrix.

Veins, pipes, and diapirs. A variety of veins, diapirs and pipes project from the tops of dioritic layers into overlying basally chilled gabbro. Leucocratic, often pegmatitic granite is commonly concentrated where dioritic material extends between convex-downward lobes of fine-grained gabbro and commonly connects to sharply defined, cross-cutting granitic veins in the overlying gabbro. These structures appear to represent filter-pressing of granitic liquid from the dioritic cumulates. Well-laminated diorite also appears to have moved upward as bulbous diapirs and pipes into chilled gabbro. These structures were apparently caused by the density inversion of light dioritic crystal mush beneath denser, rapidly-cooling, but still mobile gabbroic material. Pipes range in diameter from a few cm to more than 3 m. Their long axes are roughly perpendicular to layering, suggesting that the chamber floor was initially nearly flat and bowed downward during consolidation (Wiebe, 1993b). Gabbro in contact with a pipe is typically chilled near the base of the pipe, and becomes coarser-grained and more contaminated at higher levels. Diorite in the pipes typically has a weak lamination parallel to the pipe margins. Pipe compositions commonly grade upward from diorite at the base to pegmatitic leucogranite and open vugs.

Petrography

Rocks of the Pleasant Bay intrusion can be placed into four broad petrographic groups: (1) fine-grained gabbroic rocks and basaltic dikes, (2) medium-grained gabbroic rocks, (3) leucocratic dioritic layers (diorite to granodiorite), and (4) granitic dikes and veins.

(1) Chilled margins of gabbroic layers and pillows and basaltic dikes have basaltic textures marked by thin, radial clusters of plagioclase laths and strong normal zoning (An_{65-35}). Average grain-sizes typically increase from 0.1 to about 1 mm within several cm of the chilled margins. Euhedral olivine and plagioclase phenocrysts occur sparsely in some rocks. Olivine and augite are the dominant mafic phases; brown hornblende rims are widespread; and many rocks are dominated by brown hornblende. Fe-Ti oxide minerals, biotite, and apatite are ubiquitous accessory minerals. Minor interstitial quartz and alkali-feldspar occur locally. Partly resorbed xenocrysts of quartz and feldspar occur in many chilled rocks. Chilled basaltic pillows (either enclosed by granite in composite dikes or stratabound within silicic cumulates) commonly have margins that are greatly enriched in hornblende and biotite.

(2) Medium-grained gabbroic rocks range from olivine-rich gabbroic cumulates to massive quartz-bearing gabbros to scarce highly evolved Fe-rich cumulates. The most common gabbroic rocks range from hornblende-poor olivine gabbro and gabbronorite to hornblende gabbro that lacks olivine and pyroxene. Orthopyroxene rims on olivine are ubiquitous. Titanomagnetite, ilmenite, biotite and apatite are common accessory minerals; brown hornblende commonly rims the olivine and pyroxene and is particularly abundant near leucocratic dioritic layers. The most primitive gabbros have cumulus olivine and plagioclase $\pm$ augite. Plagioclase typically has strong normal zoning (An_{65-35}) and commonly displays complex oscillatory and patchy zoning. Plagioclase zoning and the abundance of intercumulus material indicates these rocks are orthocumulates. The most evolved rocks contain cumulus oligoclase, fayalite, Fe-Ti oxides and apatite.

(3) Leucocratic dioritic layers include rocks that range in composition from diorite to granodiorite (in the classification scheme of Streckeisen, 1976). Some rocks with higher color index (CI) are commonly dominated by subhedral calcic to intermediate, zoned plagioclase similar to that in the gabbro except that sodic patches and rims are more abundant. Other dioritic rocks contain antiperthitic sodic plagioclase with little zoning (An_{30-20}) or coarsely exsolved ternary feldspar. Perthitic alkali feldspar occurs as separate subhedral grains in some silicic layers. Quartz is generally absent or occurs as a minor interstitial phase. Both the textures and the high total feldspar content of many diorites indicate that they are feldspar cumulates. Brown hornblende is generally more abundant than pyroxene except in some more silicic dioritic rocks where two pyroxenes or fayalite may dominate. Hornblende commonly contains irregular cores of relict augite or cores of fibrous cummingtonite that apparently replaced primary orthopyroxene. Biotite is most abundant in the more mafic diorites. Titanomagnetite, apatite and zircon are common accessory minerals. Petrographic evidence for hybridization is widespread: alkali feldspar occurs as cores in plagioclase; many samples contain both strongly zoned calcic plagioclase laths and larger tabular crystals of weakly zoned antiperthitic oligoclase; the more mafic diorites commonly contain biotite and quartz xenocrysts rimmed by clinopyroxene or hornblende.

(4) The granitic dikes are relatively fine-grained and have roughly equal proportions of plagioclase, perthitic alkali-feldspar, and quartz. CI is typically less than 10, with biotite more abundant than hornblende. Plagioclase crystals show both normal and oscillatory zoning (An_{38-10}). Accessory opaque minerals and apatite are ubiquitous; zircon and allanite are common in many samples.

Geochemistry

Approximately 100 samples from the Pleasant Bay intrusion were analyzed by XRF and ICP for major and trace elements (Wiebe, 1993b). These analyzed rocks fall into four groups: (1) chilled and fine-grained mafic rocks including dikes and layers, (2) fine-grained granitic dikes and veins, (3) medium-grained gabbroic layers, and (4) leucocratic dioritic layers. The first two groups approximate the compositions of basaltic and granitic liquids; the last two have compositions that grade to each other and are strongly affected by crystal accumulation.

Chilled and fine-grained mafic rocks from dikes and layers define smooth curved trendlines on most variation diagrams (Fig. 4). Most of the dike samples plot near the high-MgO end of these trendlines and also plot on the primitive ends of trendlines for incompatible trace elements (Fig. 4). These relations indicate that the dikes are almost certainly feeders for the basally chilled gabbroic layers in the intrusion. The Mg# [= $100Mg/(Mg+Fe_T)$] of chilled margins of layers varies widely, indicating that the mafic magmas underwent variable amounts of fractionation prior to being emplaced in the Pleasant Bay intrusion. In terms of major and trace elements, the least contaminated and most primitive basaltic dikes and chills more closely resemble tholeiites from back-arc basins and ocean islands (cf. Wilson, 1989) rather than basalts related to subduction or continental rifting (Wiebe, 1993b).

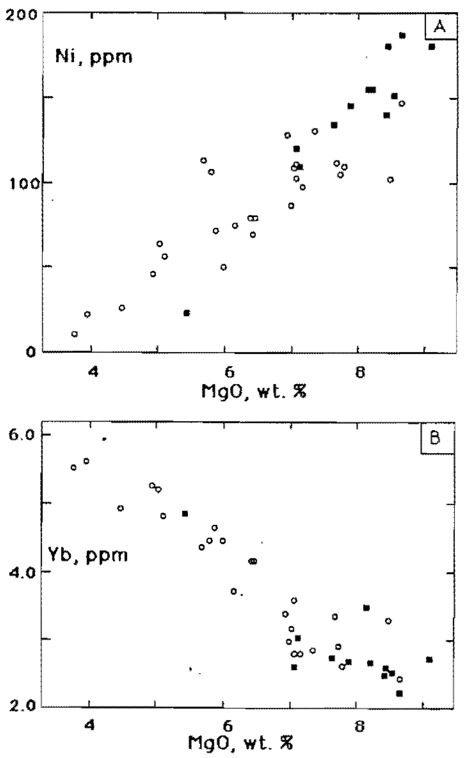


Figure 4. Whole-rock relationships of Ni and Yb to MgO in chilled basaltic material associated with the Pleasant Bay intrusion: chilled gabbroic layers and pillows (open circles) that are intercalated with dioritic layers, and basaltic dikes (solid squares).

Fine-grained granitic dikes and veins typically have 70-75% SiO_2 with a moderate range in K_2O/Na_2O. Compared to dioritic layers in the intrusion, the dikes are higher in normative orthoclase and quartz and lower in anorthite (Wiebe, 1993b). Dike compositions plot in a narrow band along the low-temperature trough in the system quartz-albite-orthoclase (Fig. 5). Their compositions are consistent with crystallization at approximately 1 kb under H_2O-saturated conditions (Tuttle & Bowen, 1958).

Medium-grained gabbroic rocks have major- and trace-element compositions consistent with their being cumulates of plagioclase and olivine (+/- augite and Fe-Ti oxides) from basaltic liquids resembling in composition the basaltic dikes and chilled gabbroic margins (Wiebe, 1993b). Many of the medium-grained gabbroic layers have compositions essentially equivalent to those of the dikes and chilled layers.

Stratabound leucocratic rocks (diorite to granodiorite) have a wide compositional range that does not overlap the granitic dikes and veins (Fig. 5). These rocks are lower in K_2O and SiO_2 and higher in Al_2O_3 and Na_2O (Fig. 6), and their compositions are consistent with the petrographic evidence that they are cumulates dominated by sodic plagioclase.

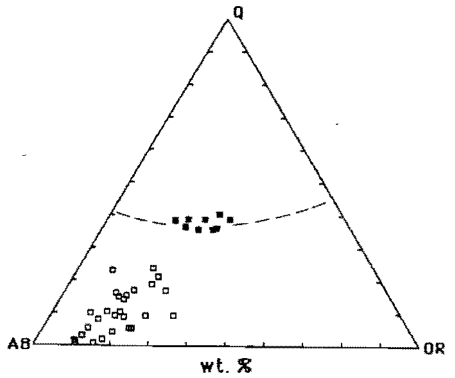


Figure 5. Plot of normative Q-Ab-Or for granitic dikes cutting the Pleasant Bay intrusion (solid squares) and dioritic to granitic layers intercalated with gabbro in the Pleasant Bay intrusion (open squares). The compositions of the granite dikes plot in a tight group near the 1 kbar SiO_2-Ab-Or-H_2O minimum (Tuttle and Bowen, 1958).

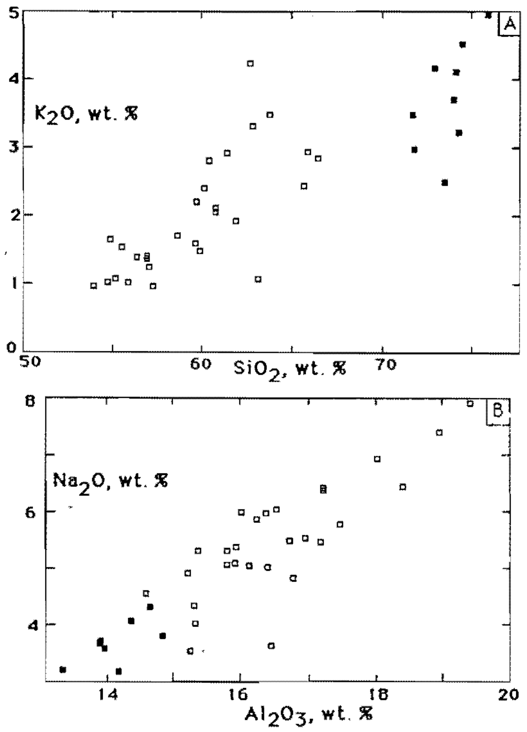


Figure 6. Plots of (A) K_2O vs SiO_2 and (B) Na_2O vs Al_2O_3 comparing dioritic cumulates (open squares) with granitic dikes (solid squares).

Compositional variation in a macrorhythmic unit. In order to characterize the stratigraphic compositional changes in a macrorhythmic unit, six samples from the upper part of macrorhythmic unit F in the Bar Island section (Fig. 3) were analyzed for major and trace elements . Most oxides and trace elements show smooth trends when samples are plotted against their stratigraphic positions (Fig. 7): CaO, MgO, and Sr decrease continuously upward; FeO_T, TiO_2, P_2O_5, and V have maxima, reflecting the incoming of cumulus titanomagnetite, ilmenite, and apatite; and K_2O, Na_2O, Al_2O_3, Zr, and Ba all increase strongly upward. The gabbroic cumulate near the base of the sampled interval has incompatible trace-element abundances that are comparable to those of a chilled gabbroic layer, suggesting (along with textural evidence) that it embodies a large percentage of trapped liquid. The uppermost dioritic cumulate contains cumulus ternary feldspar, Fe-Ti oxides, and pyroxenes, so it presumably crystallized from highly evolved, high-temperature silicic liquid. Its low Rb content suggests that it contains relatively little trapped liquid. Intercumulus liquid in the uppermost dioritic cumulates was probably largely removed by compaction and filter pressing caused by the loading of overlying macrorhythmic units. The expelled liquid probably escaped through silicic pipes that project upward from the top of this unit.

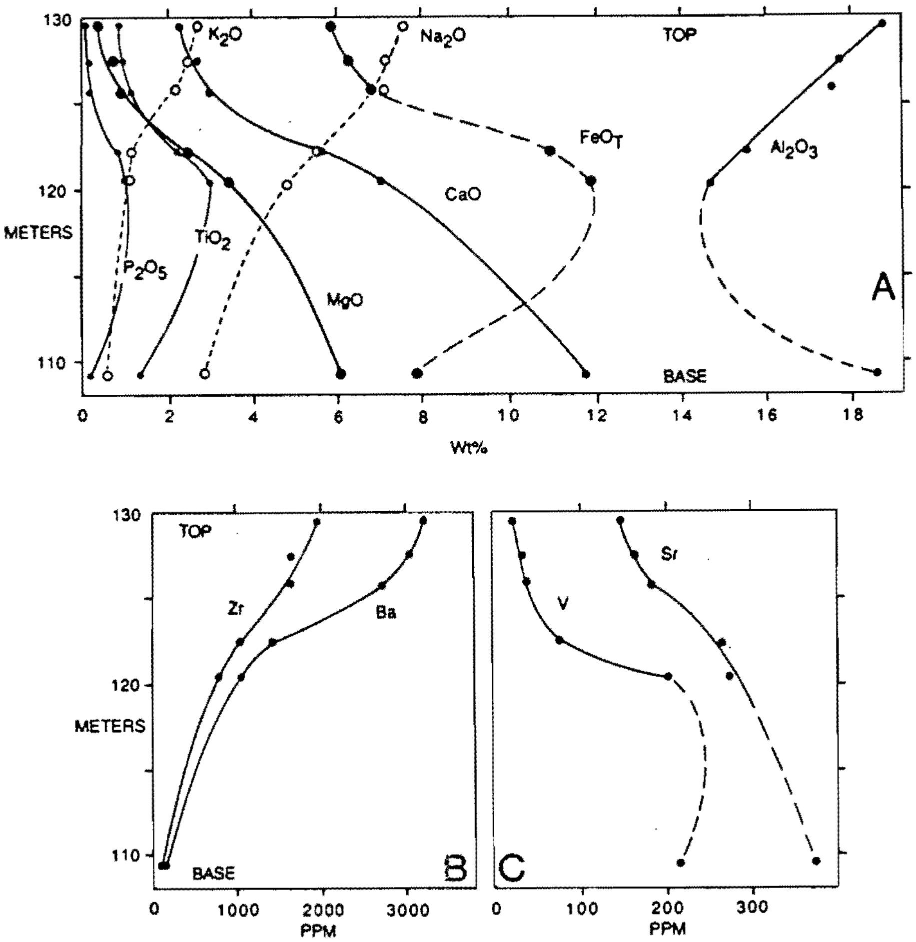


Figure 7. Whole-rock chemical variations in the upper 20 meters of macrorhythmic unit F of the Bar Island section illustrated in Fig. 3. This interval displays a continuous gradation from hornblende-rich gabbro with cumulus plagioclase and augite at the base to leucocratic diorite with cumulus ternary feldspar, two pyroxenes and Fe-Ti oxides at the top. (A) Major elements; (B) Zr and Ba; (C) V and Sr.

Interactions between layered basaltic and silicic magmas

Infusions of basaltic magma apparently occurred at different times when magma at the base of the chamber ranged from relatively primitive basalt to highly silicic magma. The compositions of chilled gabbroic margins suggest that most basaltic infusions were in equilibrium with plagioclase and olivine. The density of this newly resident magma should have increased while plagioclase, olivine and augite crystallized and begun to decrease when Fe-Ti oxides began to crystallize (Sparks and Huppert, 1984). Prior to the incoming of cumulus oxides, new infusions of basaltic magma should have tended to rise into and mix with resident basaltic magma. After resident magmas began to fractionate Fe-Ti oxides or hybridize with overlying silicic magma, basaltic infusions should have ponded on the chamber floor and established the base of a new macrorhythmic unit.

When silicic cumulates were forming on the floor, additions of basaltic magma should have spread across the chamber floor, ponding in the low spots over the silicic cumulates that just formed and displacing upward the silicic magma that had just been on the floor. The stratification of light, relatively cool silicic liquid over hot, dense basaltic liquid would be gravitationally stable, and, if the volume of basalt was sufficiently large, a double diffusive interface would form between the two magmas (Huppert and Sparks, 1984; Clark et al., 1987).

There are several lines of evidence which suggest that upward transitions in macrorhythmic units from gabbro to the most evolved silicic cumulates reflect, at least in part, strong compositional gradients established by mixing between two or more liquids rather than simple fractional crystallization of an originally homogeneous liquid:

(1) The bulk composition of most macrorhythmic units is significantly more silicic than the composition of the basaltic infusion (i.e., the chilled basal gabbro at the base of the unit). Resident silicic magma must contribute to the upper parts of these units.

(2) The lower gabbroic rocks in any macrorhythmic unit have textures and compositions characteristic of extreme orthocumulates, and some even approach liquid compositions. Rocks with such a large proportion of trapped liquid should be very inefficient at promoting fractional crystallization to the highly evolved silicic cumulates.

(3) The very high abundance of Zr and Ba of the highest diorite in Fig. 7 cannot have been produced by fractional crystallization of a basaltic parent liquid, especially considering that the transition occurs within 20 meters of section.

(4) There is abundant petrographic evidence for hybridization between two distinct magmas: alkali-feldspar cores in plagioclase, highly variable development of hornblende and biotite in gabbro, calcic plagioclase xenocrysts in diorite, and highly-digested enclaves of mafic rock in diorite.

(5) The lower gabbroic rocks in a macrorhythmic unit typically are richer in biotite and hornblende than the upper dioritic rocks, and the most evolved silicic cumulates are commonly anhydrous. Fractional crystallization should not produce increasingly dry evolved silicic cumulates.

(6) A study of Sr-isotopes indicates significant and systematic increases in Sr initial ratio across the transition from gabbro to diorite (Wiebe and Sinha, in prep.).

THE CADILLAC MOUNTAIN INTRUSIVE COMPLEX

Introduction

The Cadillac Mountain intrusive complex (CMIC) occurs on Mount Desert Island, Maine, and lies largely within the Acadia National Park (Fig. 8). It is defined here as consisting of three major units: the Cadillac Mountain granite, a hybrid unit of gabbroic to granitic rocks, and the Somesville granite. There are two areas of homogeneous Cadillac Mountain granite (CMG) that are separated by the hybrid unit of complexly interlayered gabbroic, dioritic, and granitic rocks (G-D) (Fig. 8). The Somesville granite (SG) forms a small intrusive body between the layered gabbro-diorites and the larger eastern area of the CMG. The western area of CMG also contains scarce mappable lenses of gabbro-diorite. These units occur in an oval area roughly 14 by 20 km. Gravity data (Hodge et al., 1982) suggest that the gabbro-diorite unit forms a saucer-shaped body, 2 to 3 km thick, (similar to the Pleasant Bay intrusion) beneath a saucer-shaped mass of CMG that is less than 3 km thick at its center. The 3-D shape of the Somesville-granite is not well constrained, but gravity data suggest that it is thin. This intrusive complex appears to have been emplaced very close to an unconformity between the Ellsworth schist and the Bar Harbor Formation. The unconformity also appears to have controlled the emplacement of sill-like masses of homogeneous gabbroic rocks with diabasic textures located to the north and south of the CMIC. Steeply bounded masses of gabbro within the Ellsworth schist appear to have been feeders for the gabbroic rocks. Brief descriptions of the units that make up the country rock are provided in Gilman et al. (1988). Hornblende from the hybrid dioritic unit gives an Ar-Ar age of about 418 +/- 5 Ma (Lux, personal comm., 1993).

Field relations in the CMIC

The larger eastern area of CMG is rimmed everywhere except on its western margin by a basal intrusive breccia (termed a "shatter zone" by Gilman et al., 1988). The western margin of the granite is either in contact with the gabbro-diorite unit or cut by the younger Somesville granite. The intrusive breccia contains blocks of the surrounding country rock (e.g. Ellsworth Schist, Bar Harbor Formation, gabbro); along its southern margin it also contains blocks of the Cranberry Island Series (mainly bimodal volcanics). The breccia appears to truncate the granite of Southwest Harbor. There is little or no evidence in this zone for commingling between mafic and silicic magmas.

Lensoid mafic enclaves occur sparsely in the larger eastern area of the CMG; their attitudes define a basin-form shape that is consistent with the shape indicated by gravity. The granite is cut by at least two arcuate zones of variably porphyritic granophyre that Chapman (1970) originally interpreted as recrystallized zones. The boundaries between granophyre and granite range from sharp to gradational. Near the summit of Cadillac Mountain the CMG contains rounded fine-grained "blobs" of granitic material up to a few meters in diameter. In some areas, the arrangements of these blobs define irregular curvilinear zones, suggesting they formed from the breakdown of silicic dikes passing upward through partially solidified granite. The blobs appear to be randomly distributed in other areas.

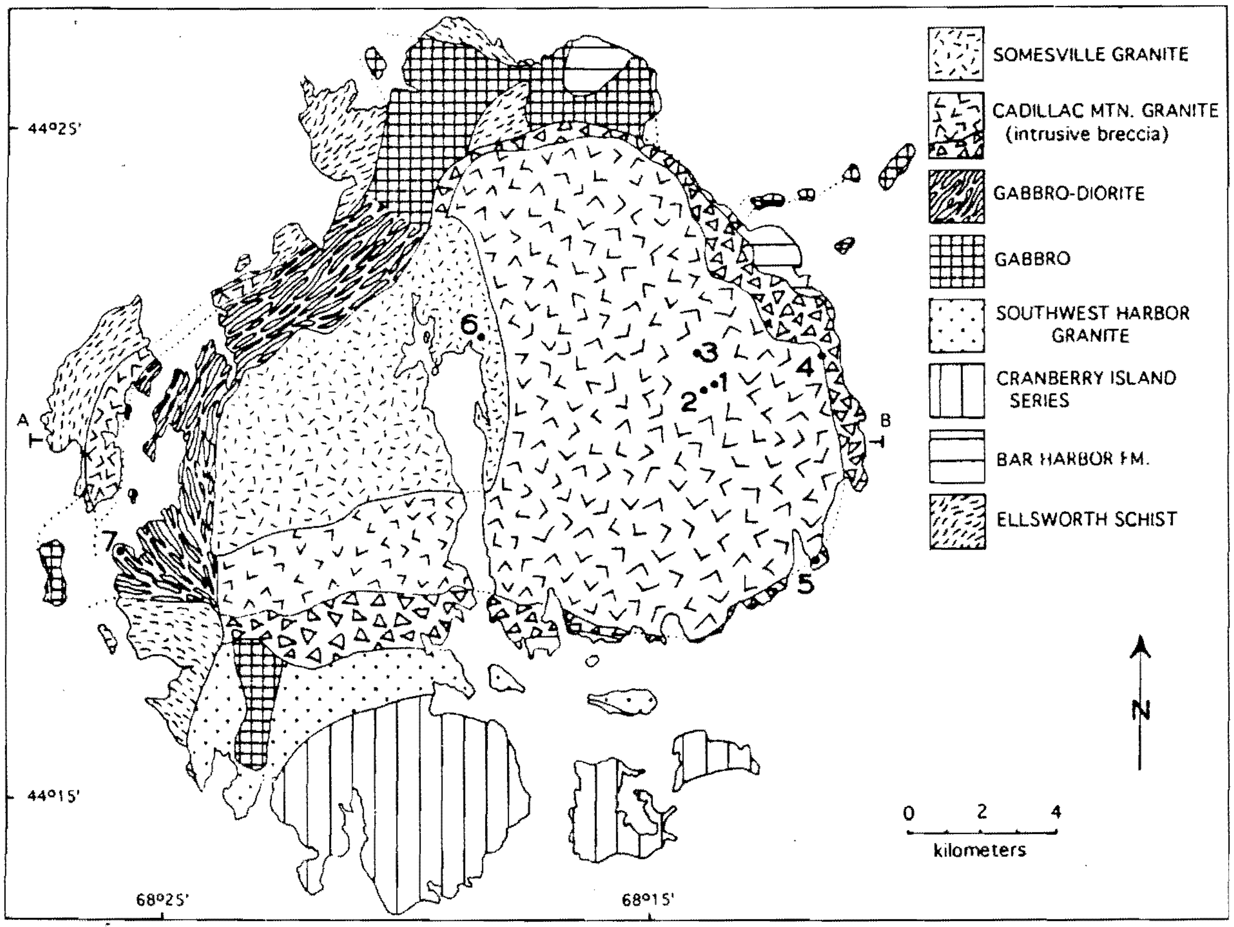


Figure 8. Geologic map of Mount Desert Island modified from maps in Chapman (1970) and Gilman et al. (1988). Numbers refer to field trip stops on day 2.

The CMG is sparsely cut by steep, roughly N-S trending basaltic dikes; rarely some of these dikes trail off into a linear zone of basaltic pillows in contaminated granite.

The smaller western area of the CMG contains several sheet-like masses of variably chilled and pillowed gabbroic material. These layers all appear to dip steeply to the east. Silicic pipes that are approximately perpendicular to one gabbro layer extend upward from the underlying granite through its chilled base. The orientations of the pipes, as in the Pleasant Bay intrusion, indicate that the gabbroic layers were initially deposited roughly horizontally on incompletely solidified granite. Other gabbroic layers clearly grade upward (to the east) to granite through hybrid diorite.

Field relations in the gabbro-diorite unit closely resemble those in the Pleasant Bay intrusion (Fig. 9). Much of this unit can be mapped as macrorhythmic layers that grade upward from basally chilled gabbro to coarser-grained gabbroic, dioritic, or granitic rocks. Compared with the Pleasant Bay intrusion, silicic layers in the G-D unit more commonly approach granitic (instead of dioritic) compositions, and the up-section transitions from gabbro to granite are generally more abrupt. Layering dips moderately (20-50°) to the east in an arcuate pattern roughly conformable with the basinform shape indicated by gravity for both the granite and the gabbro-diorite unit. The orientations of silicic pipes in mafic layers suggest that the layers were originally deposited close to the horizontal and were subsequently bowed downward as the chamber evolved and solidified. The approximate average exposed thickness of the G-D unit is about 1.5 km. This is somewhat less than the thickness of gabbroic rocks inferred from gravity studies to lie beneath the main body of the CMG and suggests that the gabbroic material reaches a maximum thickness near the center of the basin beneath the CMG.

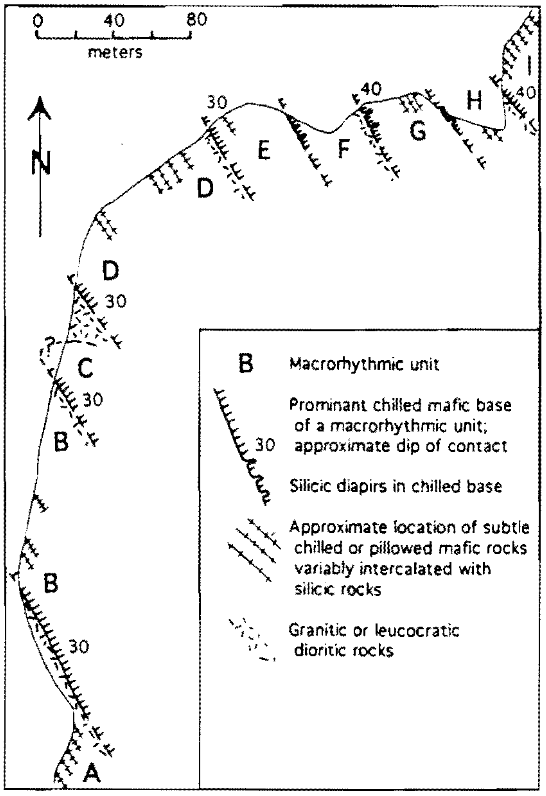


Figure 9. Simplified geologic map of the gabbro-diorite unit on Stewart Head (Stop #7 in Figure 8). Unpatterned areas along the coast are gabbro to mafic diorite.

Petrography

Cadillac Mountain granite. The Cadillac Mountain granite is a relatively homogneous, massive, medium- to coarse-grained, hypersolvus granite with CI less than 10. Both quartz and perthitic alkali-feldspar are equant and range in diameter from 2 to 7 mm. At lower elevations in the intrusion sodic plagioclase cores are common in alkali-feldspar, and many crystals show delicate oscillations of the two feldspars in the transition between core and rim. Hornblende is the dominant mafic mineral, minor biotite is common. Both minerals are typically interstitial. Opaque minerals, zircon and apatite are ubiquitous accessory phases; allanite, titanite, and fluorite occur sparsely. Some rocks near the eastern base of the intrusion close to the "shatter zone" are distinct from typical CMG in containing variable amounts of sodic plagioclase (An_{20}), subhedral clinopyroxene and, rarely, fayalite.

Mafic clots (enclaves) commonly less than 1 cm in diameter are widespread throughout much of this granite (Seaman and Ramsey, 1992). They are dominated by small subhedral plagioclase and hornblende with subordinate opaque minerals and apatite. Their texture resembles some of the finer-grained mafic rocks in the gabbro-diorite unit. Disaggregation of these clots appears to explain scarce occurrences of small plagioclase and concentrations of hornblende crystals in the granite.

Somesville granite. The Somesville granite is a medium- to coarse-grained two-feldspar granite with a CI less than 10. It is dominated by large (up to 10 mm) equant alkali-feldspar with smaller (1-4 mm) equant quartz and subordinate, small (typically 0.3 to 1 mm), complexly-zoned plagioclase (An_{30-15}). Biotite is the dominant mafic mineral; hornblende is scarce and commonly absent. Accessory phases include opaque minerals, apatite, titanite, zircon, and allanite. Fluorite is scarce. This granite also contains a variety of mafic enclaves (Seaman and Ramsey, 1992).

Several textural features suggest that this granite has been affected by hybridization with mafic material. Partly disaggregated mafic clots rich in hornblende and plagioclase occur sparsely, and hornblende commonly appears to be more abundant where small plagioclase is also more abundant. In many rocks, some plagioclase crystals have rounded, more sodic cores inside more calcic zones; rarely, plagioclase rims occur on irregular, cores of alkali-feldspar. Both types of zoning appear to record a corrosional event related to magma mixing.

Granitic dikes that sharply cut the gabbro-diorite unit have minerals and textures that closely resemble the Somesville granite.

Gabbro-diorite unit. Because of the the wide compositional range of rocks in this unit, petrographic description is broken down into three broad groups: gabbroic, dioritic, and granitic. All of these rocks are found interlayered and all are interpreted as having formed by sequential deposition on the floor of a magma chamber - in a manner comparable to the layered rocks in the Pleasant Bay intrusion. The gabbroic rocks range from chilled margins that texturally resemble basaltic dikes to medium-grained mafic cumulates. The dioritic rocks show the greatest petrographic evidence for hybridization.

Chilled margins of gabbroic layers typically have basaltic textures with radiating thin lathes of plagioclase comparable to the basaltic dikes that cut all units. Plagioclase is strongly zoned (An_{70-30}). The mafic minerals in chilled margins of gabbroic layers are dominated by hornblende with subordinate augite, orthopyroxene, and opaque minerals - in contrast to the basaltic dikes which are generally dominated by augite with subordinate olivine. Biotite is scarce in the dikes and more common in the chilled layers. Xenocrysts of alkali-feldspar, sodic plagioclase, and quartz occur sparsely in dikes and chilled layers and are commonly rimmed by augite or hornblende.

Coarser-grained gabbroic layers are typically massive with randomly arranged plagioclase. Some have subhedral olivine; augite and/or hornblende are typically ophitic to subophitic. Plagioclase commonly shows strong normal zoning (e.g. An_{70-30}); in many rocks it is complexly zoned with sodic patches, oscillations and strong reversals. Accessory opaque minerals and apatite are ubiquitous. Many of the gabbroic rocks can be described as extreme orthocumulates with cumulus plagioclase, olivine +/- augite and opaque minerals.

Gabbroic rocks commonly grade upward to intermediate dioritic rocks that display abundant petrographic evidence for hybridization between mafic and silicic magmas. Although most diorites are dominated by plagioclase and hornblende, many contain equant alkali-feldspar crystals or cores of alkali-feldspar in some plagioclase crystals. Crystals of intermediate plagioclase (An_{50-40}) commonly contain rounded cores of more sodic plagioclase. Augite is common and typically has thick rims of hornblende. Blocky subhedral biotite crystals occur in some diorites and are commonly included by hornblende. Some rocks can be characterized as orthocumulates with subhedral cumulus plagioclase and hornblende. Accessory opaque minerals and apatite are ubiquitous; zircon, titanite and allanite are commonly present.

The most silicic layers in the G-D unit closely resemble the Cadillac Mountain granite.

Geochemistry

Introduction. Approximately 120 rocks from the CMIC have been analyzed by XRF and ICP for major and trace elements. Representative compositions of the main units are given in Table 1.

Cadillac Mountain Granite. Except for very minor cumulates of sodic plagioclase +/- clinopyroxene near the eastern base, medium-grained rocks from the CMG range between about 72 to 75% SiO_2. All rocks are low in CaO and have very low Mg#[=100Mg/(Mg+Fe)]. They show little compositional variation in major elements, but a relatively wide range in many trace elements (e.g., Rb, Ba) (Fig. 10). This compositional range and the petrographic

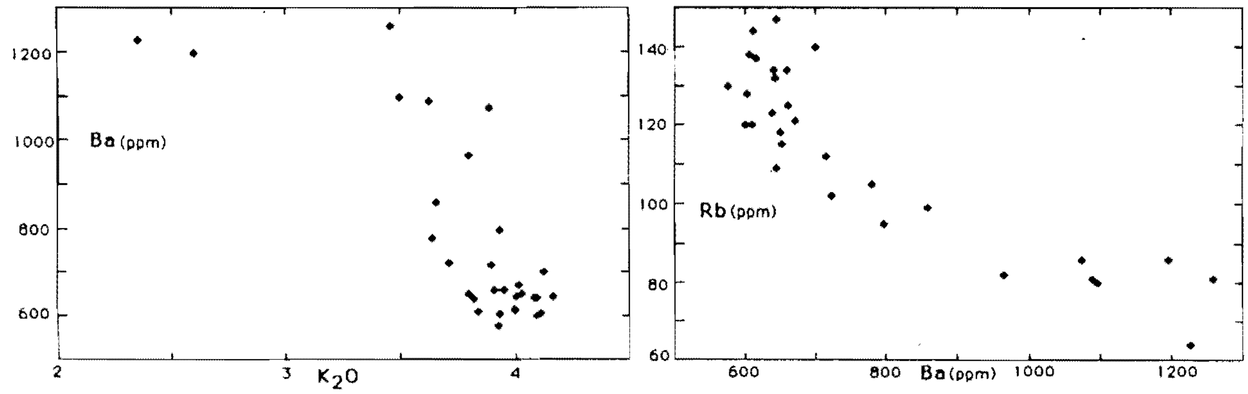


Figure 10. Plots of K_2O vs Ba and Ba vs Rb for the Cadillac Mountain granite.

characteristics of the CMG are typical of many A-type granites. Samples taken along a traverse from the eastern margin of the body to the summit of Cadillac Mountain (approximately between field-trip stops 4 and 1 in Fig. 8) appear to indicate a significant compositional variation with elevation: granitic rocks near the eastern base are relatively enriched in Ba and Zr and depleted in some incompatible elements (e.g., Rb, Be) (Fig. 11). These relations suggest that the compositions of the lower granites have been affected by accumulation of feldspar and zircon.

Table 1. Representative chemical analyses of rocks from the Cadillac Mountain intrusive complex.

	Basaltic dike	Chilled gabbro	Gabbro-diorite unit (mafic to silicic cumulates)					Cadillac Mountain granite		Somesville granite	
	32C	6A	67Y	101A	126B	117C	112B	81	93	151	150
SiO_2	48.85	46.63	46.31	50.58	56.83	66.40	70.30	72.94	74.43	76.56	74.04
TiO_2	1.35	1.12	1.27	1.00	1.75	0.92	0.74	0.30	0.32	0.17	0.26
Al_2O_3	16.41	17.80	13.78	19.15	15.58	13.36	13.39	12.79	12.28	12.83	13.40
Fe_2O_3	1.99	1.33	2.05	1.75	3.57	2.46	1.59	1.96	1.47	0.40	0.51
FeO	6.98	8.50	9.70	7.65	6.15	3.57	2.43	1.62	1.54	0.81	1.00
MnO	0.18	0.15	0.19	0.16	0.16	0.09	0.07	0.12	0.09	0.03	0.04
MgO	8.35	8.47	12.89	3.52	2.54	1.45	1.26	0.15	0.23	0.14	0.33
CaO	10.57	9.44	8.72	10.15	5.96	3.30	2.03	0.80	0.84	0.93	1.35
Na_2O	2.38	2.91	2.56	3.03	4.07	4.20	3.45	4.61	3.94	3.38	3.45
K_2O	0.66	0.59	0.37	0.50	1.05	2.37	4.04	3.76	4.06	4.63	4.24
P_2O_5	0.13	0.13	0.17	0.09	0.54	0.22	0.14	0.03	0.05	0.00	0.03
LOI	2.25	3.80	1.24	1.47	2.06	1.00	1.35	0.67	0.70	0.37	0.53
TOTAL	100.10	100.87	99.25	99.05	100.26	99.34	100.79	99.75	99.95	100.25	99.18
Rb	28	23	6	10	26	54	130	82	120	198	177
Sr	219	200	207	441	349	172	143	48	53	29	69
Ba	85	91	97	142	219	511	572	964	601	324	444
Y	28	27	27	17	55	69	48	41	93	54	41
Zr	134	101	111	158	430	662	249	651	574	159	212
V	212	198	195	241	154	73	68	4	6	9	15
Ni	102	145	325	19	11	14	14	4	4	3	2
Cr	246	250	911	10	7	12	19	0	0	4	9
Be	1.2	1.7	0.9	1.4	1.2	2.3	2.3	1.8	3.3	2.9	2.9
Co	43	44	49	33	0	17	18	0	0	1	1
Sc	36	33	32	30	20	14	10	7	5	4	5
Ce	23	22	27	20	77	95	77	123	147	66	83
Yb	3.2	2.7	2.3	ND	5.2	6.9	4.7	5.0	9.2	6.5	4.7

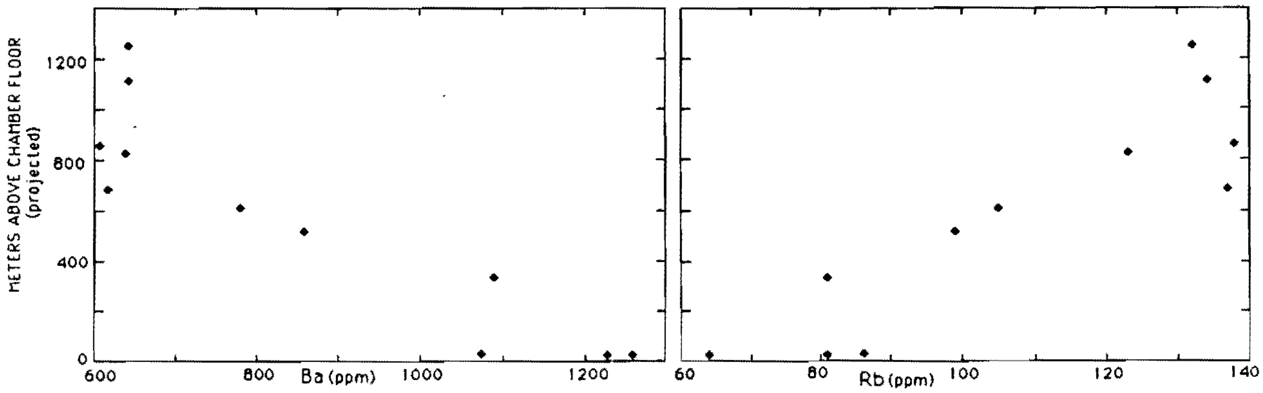


Figure 11. Plots of Rb and Ba against elevation above the floor of the eastern side of the Cadillac Mountain granite. The line of section is approximately from stops 4 to 1 (see Figure 8). The floor of the granite was projected along a dip of 30° to the west.

The silicic "blobs" that occur near the summit of the Cadillac Mountain and the transgressive granophyre zones have compositions that generally define smooth trends on plots of major and trace elements against SiO_2. They range in composition from about 70 to 78% SiO_2. Between 72 and 75% SiO_2 their compositions are nearly identical to the CMG; at high SiO_2 they trend to high values in K_2O and Rb and very low values in MgO, CaO, FeO, TiO_2 and Sr (Fig. 12). These most evolved silicic blobs have compositions that closely resemble high-SiO_2 rhyolites associated with ash-flow tuffs.

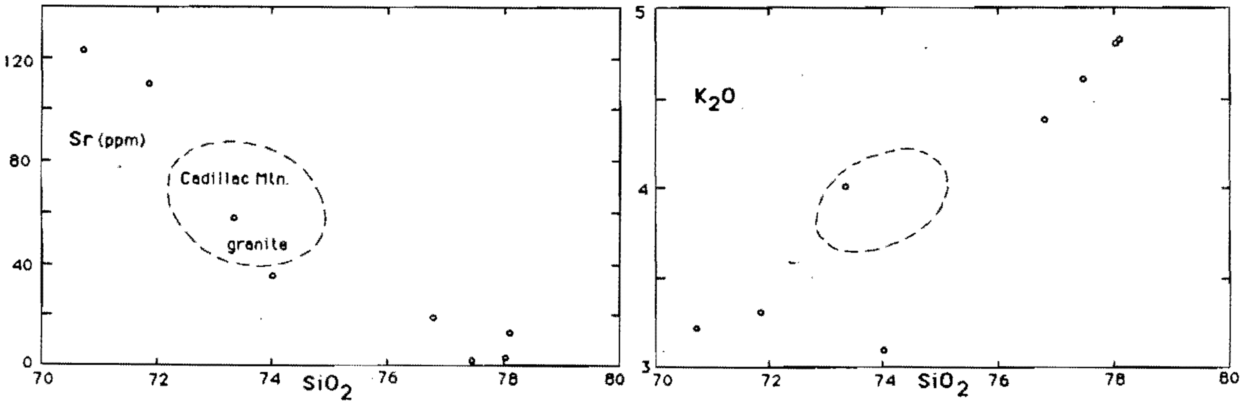


Figure 12. Plots of Sr and K_2O against SiO_2 for chilled silicic "blobs" (stops 1 and 2 in Figure 8) and transgressive bodies of granophyre in the Cadillac Mountain granite. Dashed areas enclose compositional ranges of typical CMG.

Somesville and other granitic rocks. Relative to the CMG, the Somesville granite is characterized by higher SiO_2, K_2O and Rb, and lower Ba, Zr, and Ce (Table 1). On plots of major and trace elements against SiO_2 the Somesville granite is distinct from the CMG and, instead, appears to fall close to or within the compositional trends defined by smaller granitic plutons and dikes that cut the gabbro-diorite unit (Fig. 13). The most silicic samples of the Somesville granite appear to approach closely the compositions of the most silicic blobs within the CMG.

Gabbro-diorite unit. The chilled pillows and margins of mafic layers that occur as part of this layered sequence of rocks have compositions that appear to approximate mafic liquids and that are very similar to the N-S trending basaltic dikes (Table 1). Both suites show a similar range in MgO and comparable trends for both major and trace elements plotted against MgO (Fig. 14). These relations strongly suggest that the basaltic dikes represent feeders to the gabbroic component of the G-D unit. The wide compositional range and trends of the chilled liquids are consistent with variable fractional crystallization of plagioclase, olivine and augite at depth, prior to the emplacement of the basaltic magmas into the CMIC.

The compositions of medium-grained rocks from layers in the G-D unit range from about 45 to 75% SiO_2 with a scarcity of samples between 50 and 55% SiO_2 and between 7 and 4% MgO (Fig. 15). This compositional gap coincides with a gap in CIPW normative anorthite (between An_{55} and An_{40}). The rocks with lowest SiO_2 have compositions that are consistent with their being cumulates from the mafic chilled liquids and dikes. The rocks with highest SiO_2 closely approximate the average compositions of the CMG. The compositions of rocks with intermediate SiO_2 cannot be solely explained by bulk mixing between basaltic and granitic compositions. Instead, their compositions appear to reflect (as do their textures) some hybridization between mafic and silicic magmas, along with the accumulation of plagioclase feldspar and variable amounts of other phases, including pyroxene, hornblende, Fe-Ti oxides, and apatite.

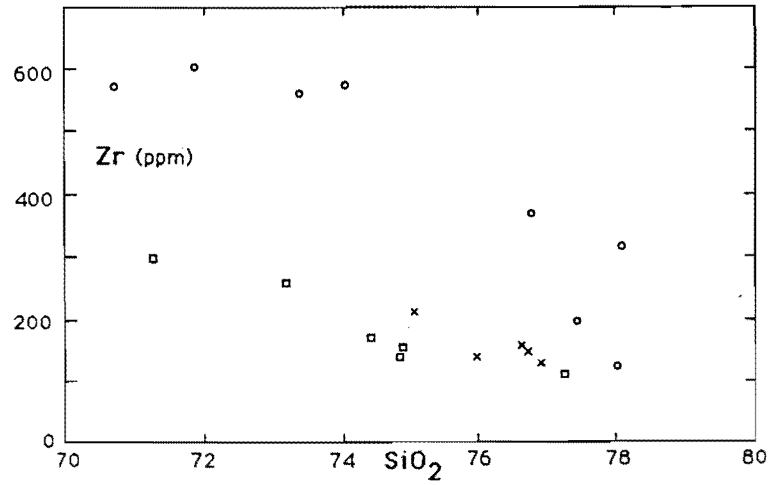


Figure 13. Plot of Zr against SiO_2 for silicic blobs in CMG (open circles), the Somesville granite (x's), and granitic dikes that cut the gabbro-diorite unit (open squares).

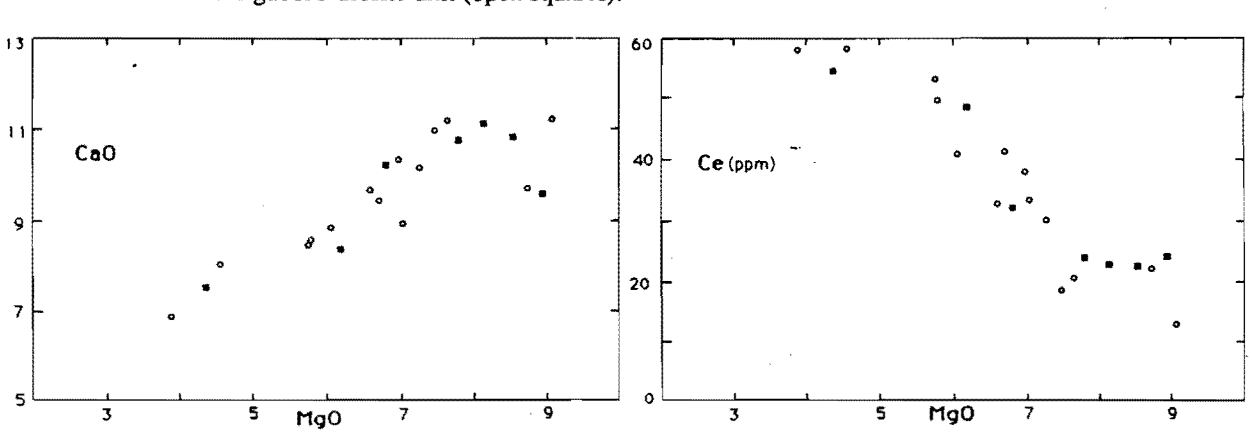


Figure 14. Plots of CaO and Ce against MgO for basaltic dikes (solid squares) and chilled gabbroic layers within the gabbro-diorite unit (open circles).

Evolution of the CMIC

A tentative model for the evolution of the Cadillac Mountain intrusive complex can be discussed with the aid of a schematic cross-section which is reasonably well constrained by field relations and gravity studies (Fig. 16). The CMIC appears to have been initiated by injections of silicic magma that established a sub-horizontal, lensoid chamber at the unconformity between the Ellsworth schist and the Bar Harbor Fm. It is possible that injections of mafic magma had already occurred at the same level, establishing some of the mafic sills north, east, and south of the CMIC. Once established, the chamber of the CMG acted as a trap for later basaltic injections which ponded on its floor, leading at many times to strong compositional gradients in liquids near the base of the chamber. The solidification of these multiple injections of mafic magma ultimately produced the complexly layered gabbro-diorite unit. Episodic turbulent events at the boundary between the liquids probably led to local mechanical mixing between rapidly solidifying mafic magma and silicic magma. The small mafic enclaves in the CMG probably originated during these events. Their distribution at all elevations in the CMG strongly suggests that silicic magma in the chamber underwent thorough convection.

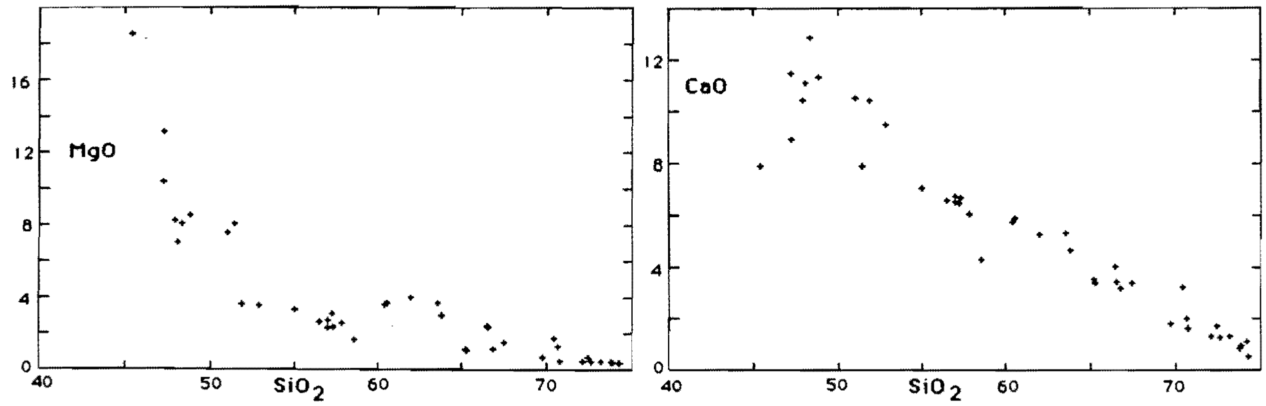


Figure 15. Plots of MgO and CaO against SiO_2 for medium-grained layers (gabbroic to granitic) in the gabbro-diorite unit.

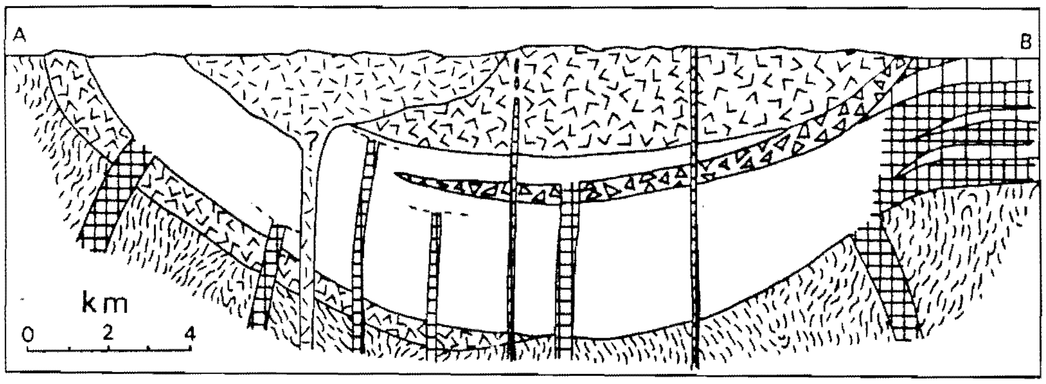


Figure 16. Schematic east-west section through Mount Desert Island drawn along a section line between A and B in Figure 8. No vertical exaggeration. Patterns as in Figure 8 except that here the hybrid gabbro-diorite unit is unpatterned.

The extensive intrusive breccia that forms the northern, eastern, and southern boundaries of the CMG may represent a single large event that resulted in eastward expansion of the silicic magma chamber. It is likely that some basaltic magma continued to enter the chamber after this event because basaltic dikes of comparable composition continued to be emplaced even after the upper portions of the CMG were solidified.

The strong compositional gradients in the lower elevations (in Rb, Ba, Be, Zr, etc.) suggest that, early on, while convection was still active, there was some tendency to accumulate early-formed crystals (e.g. alkali-feldspar, zircon) on the chamber floor and to concentrate residual liquid upward. The apparent lack of compositional gradients at higher elevations may indicate gradual stagnation of the chamber as infusions of basaltic magma waned.

The silicic blobs near the summit of Cadillac Mountain and the arcuate zones of intrusive granophyre appear to represent rapidly quenched samples of evolved silicic magma that was erupting out of the chamber after its roof was largely solidified. Field relations suggest that all of this granophyric material could have been approximately contemporaneous because the granitic mush, through which the evolved silicic melt rose, was relatively brittle (cooler and more crystallized) toward the margins of the CMG and relatively plastic (hotter and less crystallized) in the interior.

The Somesville granite may represent a late stage liquid related to the CMG. The chemical compositions of the most silicic Someville granites closely resemble the most silicic chilled granophyric liquids within the CMG, and field relations suggest that the Somesville granite and the CMG granophyres could have been contemporaneous. Much of the geochemical and petrographic character of the less silicic Somesville granites can be explained by contamination with partly crystallized mafic magma. This interpretation is consistent with the fact that the SG is restricted to an area immediately above the gabbro-diorite unit. Also, outcrops along the contact of these units indicate that mafic magma was available when the Somesville granite was emplaced.

THE ISLE AU HAUT IGNEOUS COMPLEX

Introduction

The Granite-Gabbro-Diorite rocks of the Isle au Haut Igneous Complex (as named by Hogan and Sinha, 1989) are situated at the southernmost exposed sequence of the Coastal Maine Magmatic Province, on the island of Isle au Haut. The island is located about 8 km south of Stonington, on Deer Isle, Maine. The complex is composed mainly of a heterogeneous 390 Ma granite (28 km^2) (Pb/U ages by R. W. Luce, personal comm., 1987) which intrudes older silicic volcanics to the west. The eastern third of the island consists of a layered 413 Ma gabbro-diorite-quartz monzodiorite complex (51 km^2) (Fig. 17). Most of the mafic units on the island proper are diorites; however, a coarse-grained layered gabbro forms most of the small islands and ledges to the east. A homogeneous granite intrusion crops out on small islands to the east of the mafic complex and field evidence indicates that it has probably been emplaced contemporaneously with the layered gabbros of the mafic complex. We have found no direct field evidence for comagmatic interaction of the western Isle au Haut granite with the mafic rocks, and suspect that it may have a younger intrusive relationship given the preliminary ages mentioned earlier. However, because of the large uncertainty in ages (± 17 Ma) it is not inconceivable that this granite could also be contemporaneous with the mafic rocks; possibly down-faulted to its present position. Most of the mafic rocks exposed on Eastern Head peninsula (the southern end of the island) are gabbro, locally interlayered with diorite and quartz monzodiorite (Fig. 18). Regional structural events have tilted these layers to a post magmatic attitude of N 10° E; 35° W which has exposed an almost complete and continuous cross-section of ten layers within the mafic complex (Fig. 19).

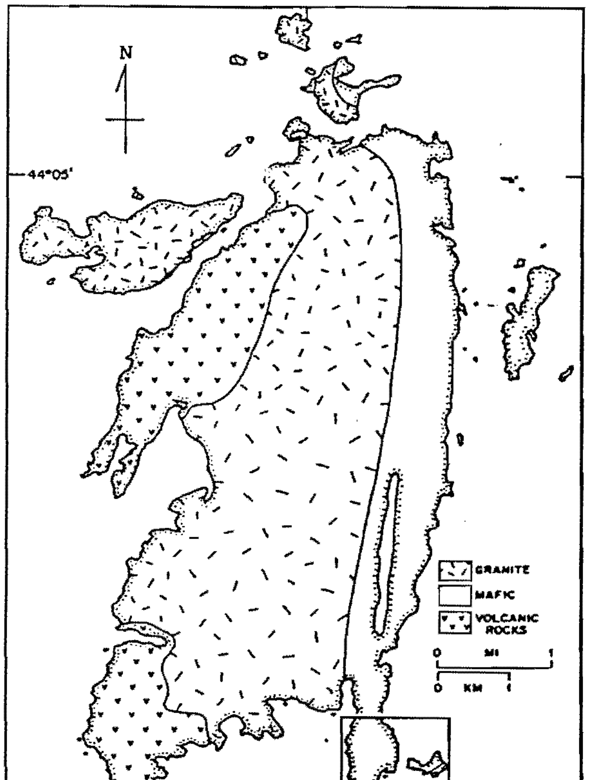


Figure 17. Generalized geologic map of the lithologic units which comprise the Isle au Haut Igneous Complex, taken from Smith et al.(1907) and Luce (1962). Box shows area of our concentrated research.

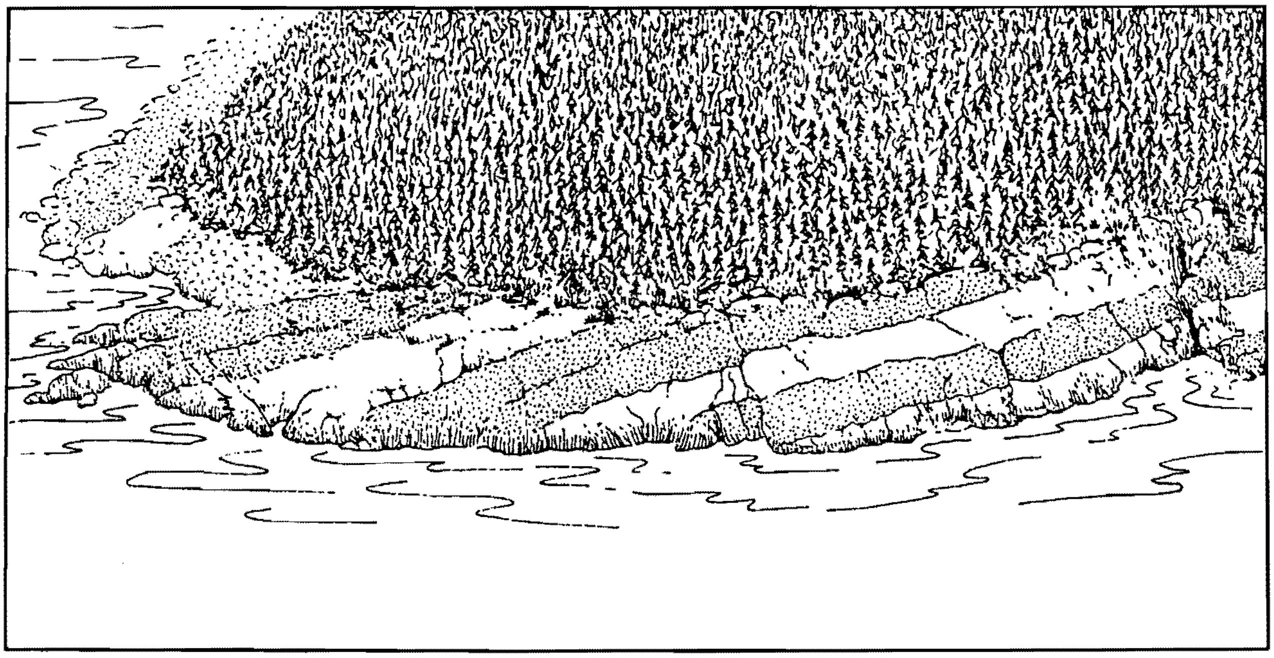


Figure 18. Sketch of aerial photograph shows alternating sequence of layers exposed along the southern shoreline of Eastern Head.

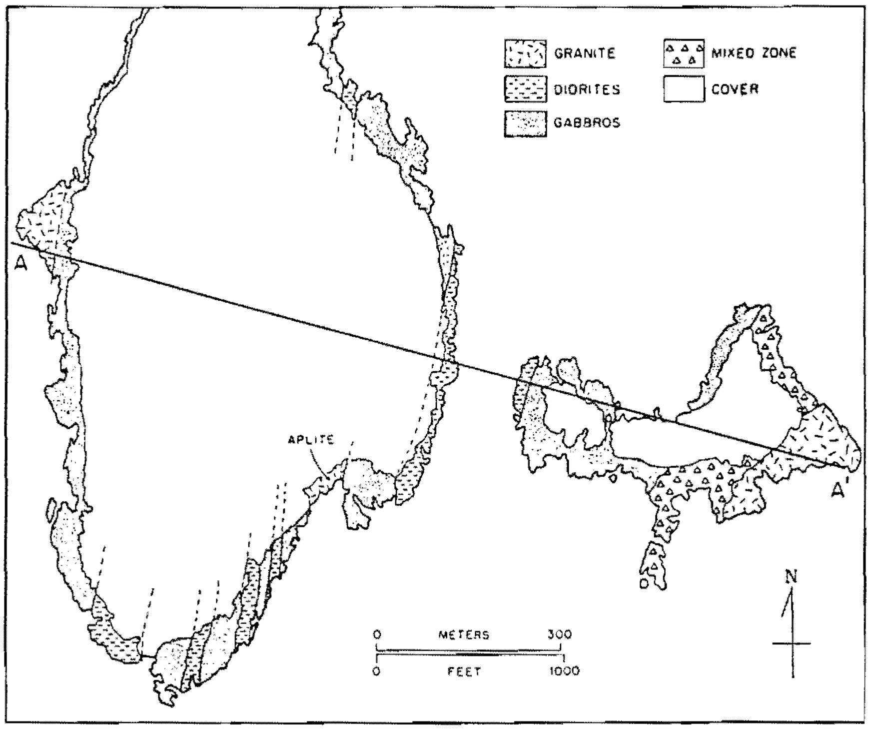
Field Relations

The southernmost exposures on Isle au Haut reveal an alternating layered sequence of five diorites sensu lato and five gabbros (units AA - I) dipping to the west (Fig. 20). The gabbroic units are biotite hornblende gabbros and range in thickness from 7 to 106 m. At their bases, they have very fine-grained contacts, approximately 4-5 cm thick, which appear to have chilled against the underlying dioritic units. Immediately above this chilled rind, the grain-size progressively coarsens over 5 meters to a coarse gabbro with 6 mm plagioclase laths and large 11 mm equant hornblende crystals. Local wisps of coarse plagioclase-rich pegmatitic crystals occur randomly throughout the units.

At the chilled interface of the gabbro and the underlying diorite units are lobate, cuspate structures (Fig. 21) which can best be described as "load cast structures" (Pettijohn et al., p. 124, 1972; Reineck and Singh, p. 84, 1980). Others have found it necessary to adopt this sedimentological term for similar igneous structures (Wiebe, 1974, 1993a,b; Thy and Wilson, 1980; Parsons and Becker, 1986). Within the dioritic units, immediately below the chilled contacts, are randomly spaced, globular, mafic "pillow-like" structures ranging in size from a few centimeters up to a meter in diameter. Similar features have been described as "load ball structures" (Parsons and Becker, 1986); however, due to their chilled texture, we prefer to use "pillow" to convey both a structural and petrogenetic connotation. Although commonly found less than one half meter from the contact, some "pillows" are completely detached from the gabbro. They are very fine-grained, with chilled margins, and are texturally and chemically identical to the fine-grained margins of the gabbro from which they were detached. Both the "load cast structure" of the chilled gabbroic contact and the chemistry and texture of these "pillows" with their adjacent contacts provide strong evidence for the gabbro chilling against the dioritic units, and for the sinking of largely molten "pillows" into the underlying unconsolidated diorite.

At the same interfaces, fingers or pipes of a part of the dioritic unit penetrate upwards into the gabbro unit for several meters (Fig. 21). These fingers and pipes plunge 53°; E 9° S, a direction which coincides with the poles to the planes of the layered units, confirming that the magma layers were originally horizontal when emplaced.

The pipes are cylindrical in form and tend to be spaced about 1 - 1.5 meters apart. The gabbro is chilled against the pipes for tens of centimeters above the diorite-gabbro contact. The pipe diameter tends to increase from about 8 cm. to as much as 50 cm with increasing height in the gabbro (15 meters). Local large conduits over 1.6 meters in diameter have also been found. With increasing height in the gabbro unit, the frequency of the pipes decreases and the contact of the dioritic pipes with the gabbro becomes more diffuse. At higher levels, xenoliths of the gabbro occur within the dioritic pipes. These xenoliths include hybrid compositions as well as gabbros. The ultimate fate, and relationship of these dioritic pipes to the uppermost part of the thicker gabbro layers, is not fully understood.



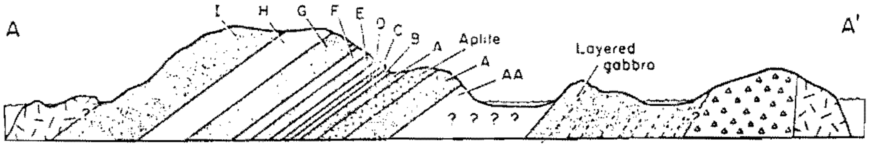


Figure 19. Geologic map and cross-section (vertical exaggeration 4x) of the composite layering of Gabbro-Diorite units and granites exposed on Eastern Head peninsula and Eastern Ear island.

With thinner gabbro layers (e.g. layers C and E), the pipes can be traced almost entirely to the overlying dioritic layer without any indication of tapering or mixing in the gabbro. We cannot tell from field relationships whether they amalgamate to form the overlying dioritic layer, breach the top of the gabbro magma to become resorbed into an overlying liquid, or eventually diffuse and mix with the gabbro.

Generally, the diorites form homogeneous units with little variation in texture or structure. Stratigraphically lower units are a biotite-hornblende quartz diorite changing upwards through the section to hornblende quartz monzodiorites. These range in thickness from 7 m to 24 m. At contacts where dioritic units overlie the gabbros, several types of relationships occur. At stratigraphically higher levels, the contacts are somewhat diffuse and wispy over a restricted area. As opposed to gabbro overlying diorites, no penetration of one unit into the other is found and the gabbros and quartz monzodiorites do not appear to interact away from the contact. With lower units, however, the contacts can be obscured by physical mixing and hybridization. In the case of the dioritic unit D and the underlying gabbro C, the contact between the units is an approximation and some samples assigned to unit D show more mafic and hybrid compositional characteristics. Figure 22 presents an idealized summary of the different relationships observed at the outcrop.

The conclusions to be drawn from these field and textural relationships are inescapable. The gabbros and underlying diorites represent coexisting, compositionally distinct, layered magmas. The fingers or pipes provide compelling evidence that the diorite, or some component of the diorite, was liquid and intruded into molten gabbros. The chilled margins of the gabbros reinforce this conclusion and indicate that the temperature contrast between the magmas effected the crystallization of the gabbro against the diorite. It is also evident that the magmas were gravitationally unstable and were attempting to overturn. Moreover, during crystallization of the gabbro, a downward necking of gabbroic fingers or lobes into the underlying diorite eventually detached as sinking pillows. Owing to the more viscous nature of the diorite, the pillows were unable to descend farther than half a meter or so.

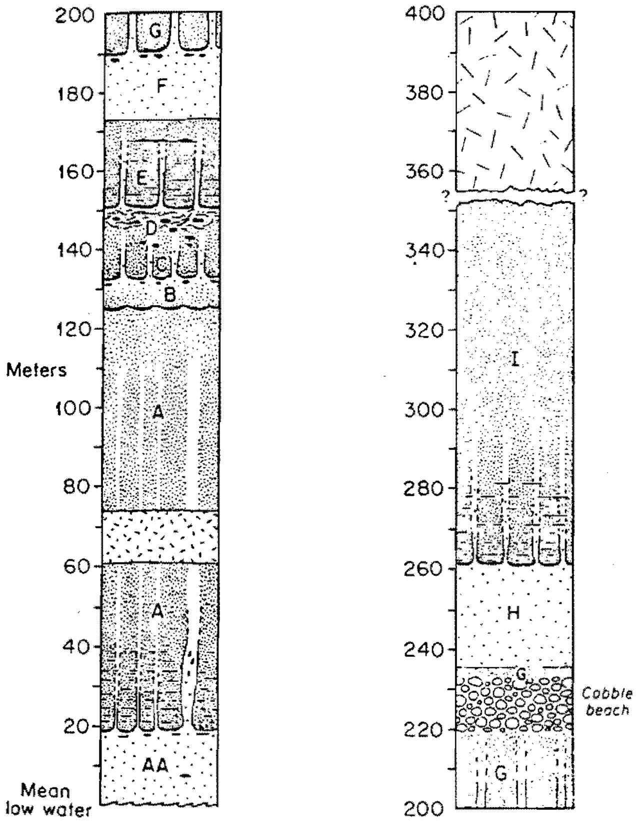


Figure 20. Schematic stratigraphic column across the southern coast of Eastern Head showing the exposed relationships of gabbroic (dark stipples) and dioritic (light stipples) layers and their thicknesses. An aplite sill at 60 m and the Isle au Haut Granite at 358 m are shown by fine and coarse hash marks respectively. All contacts are clearly exposed except where indicated.

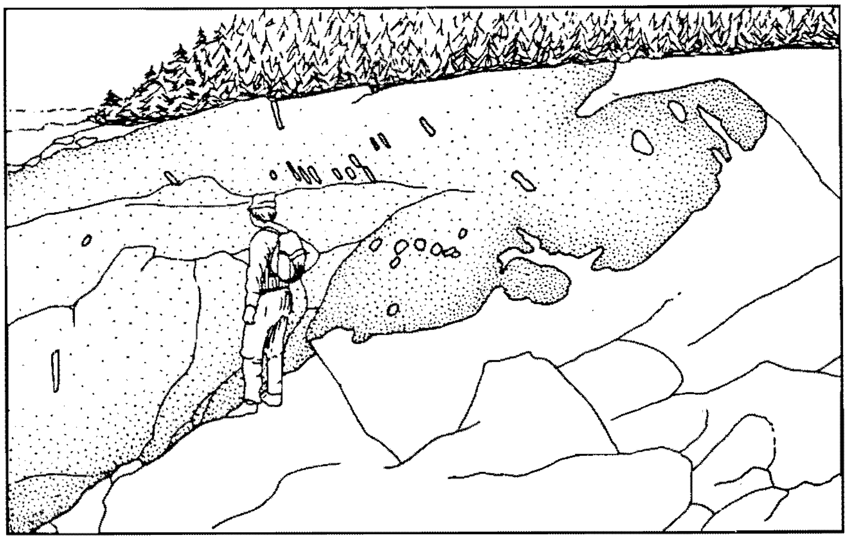


Figure 21. Sketch from a photograph of the contact between gabbro I overlying quartz monzodiorite H. Contact shows cuspate "load cast" structures and pipes intruding into the gabbro.

Petrography

Gabbros. Rocks from the gabbroic units show little modal variation throughout the stratigraphic succession. All five layers are hornblende gabbros from the lowest layer through the uppermost layer (Fig. 23). They contain between 40 and 50 modal plagioclase which is compositionally zoned from An_{62} cores to An_{35} rims. Plagioclase crystals near diorite contacts are clear laths from core to rim. Away from these contacts the crystals tend to be lightly to moderately corroded, or contain resorbed cores. The nature of these crystals, obviously in disequilibrium with their surroundings, may reflect exchange of volatiles or other components of the dioritic units with the gabbros. The rims are almost everywhere clear. Except for one sample from the lowest unit (A), none of the gabbroic units contains alkali feldspar or quartz.

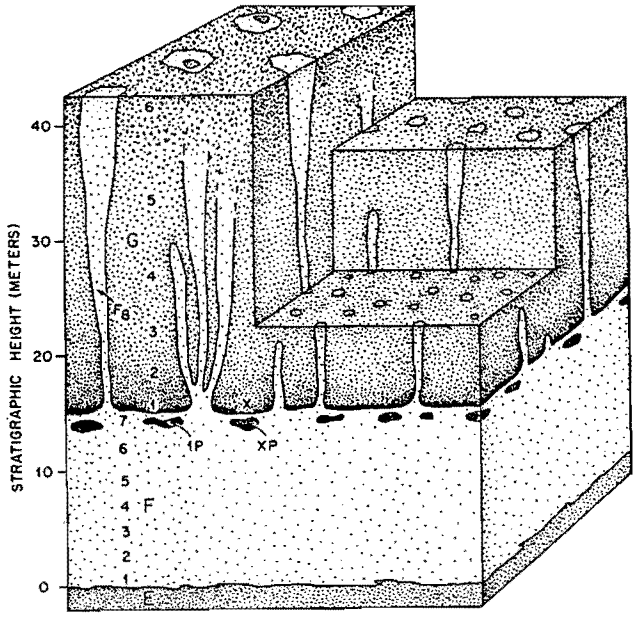


Figure 22. Block diagram showing schematic contact relationships between gabbros E and G and quartz monzodiorite F. This relationship is consistent for all contacts with the exceptions of diorite B overlying gabbro A and diorite D over gabbro C (which shows complex mixing and intermingling, as shown in Fig. 3). Sample location indicated by numbering.

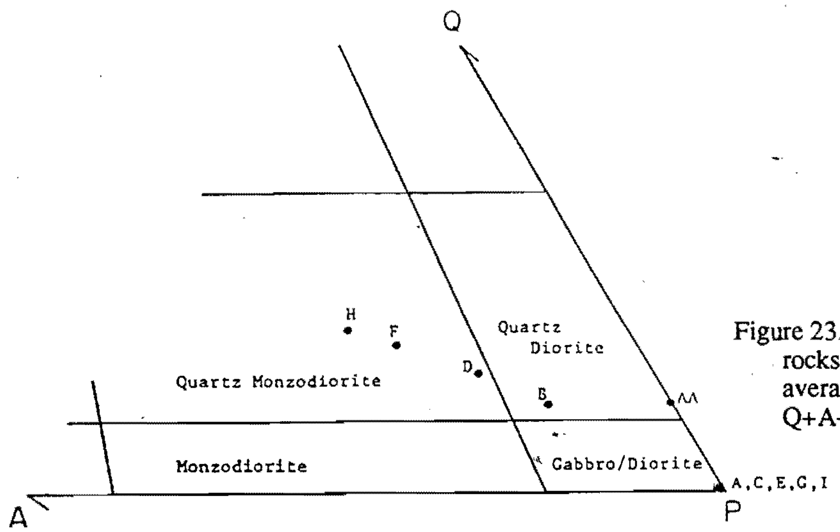


Figure 23. IUGS classification of igneous rocks (after Streckeisen, 1976) and the average modal analysis for each layer. Q+A+P = 100.

The predominant mafic mineral is a subhedral to anhedral pargasitic hornblende (nomenclature according to Leake, 1978), poikilitic with plagioclase, which ranges from 17 to 54 modal percent. The cores of many of the hornblendes are strongly altered and may indicate relict clinopyroxene. Biotite and titanomagnetite commonly rim the hornblende and occasionally are intergrown with it. Accessory minerals consist almost exclusively of apatite, but zircon and sphene are present, albeit infrequently, as very late-stage phases. Epidote and chlorite (which may be quite abundant) are sporadically present as alteration products.

At the lowermost contacts, the gabbros are fine-grained and have intergranular to intersertal textures. Away from the contacts, the texture changes from subophitic to ophitic and can best be described as coarse cumulate. A few of the units show fine rhythmic layering and one layer (A) shows a local collapse of obvious layering.

Compositionally, the gabbroic units are tholeiitic, subalkalic with little chemical variation. They resemble within-plate tholeiites using the classifications of Pearce and Cann (1973) and Meschede (1986) and are restricted to the calc-alkaline series of Peccerillo and Taylor (1976) as shown in Figure 24. Plotted on an AFM diagram (Fig. 25), the gabbros are largely uniform in composition. Departures from the group can be ascribed to very local physical mixing and hybridization with the diorites. This appears to have been restricted to a thin region between gabbro I and quartz monzodiorite H and within the mixed zone comprising quartz diorite D. The gabbros are relatively uniform in composition for both compatible and incompatible elements within each unit and throughout the stratigraphic succession (Fig. 26).

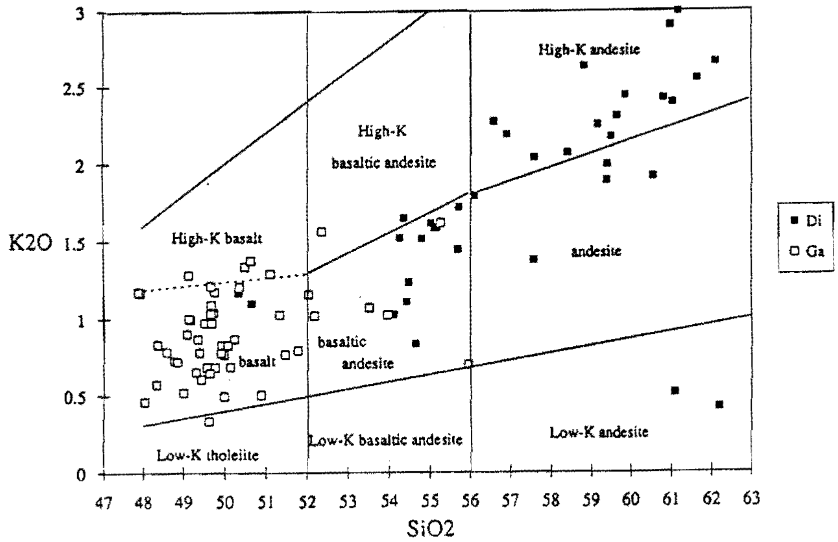


Figure 24. Composition of the gabbros and dioritic units on the K_2O and SiO_2 diagram; boundaries of arc tholeiite, calc-alkaline, and high-K calc-alkaline series of Peccerillo and Taylor (1976).

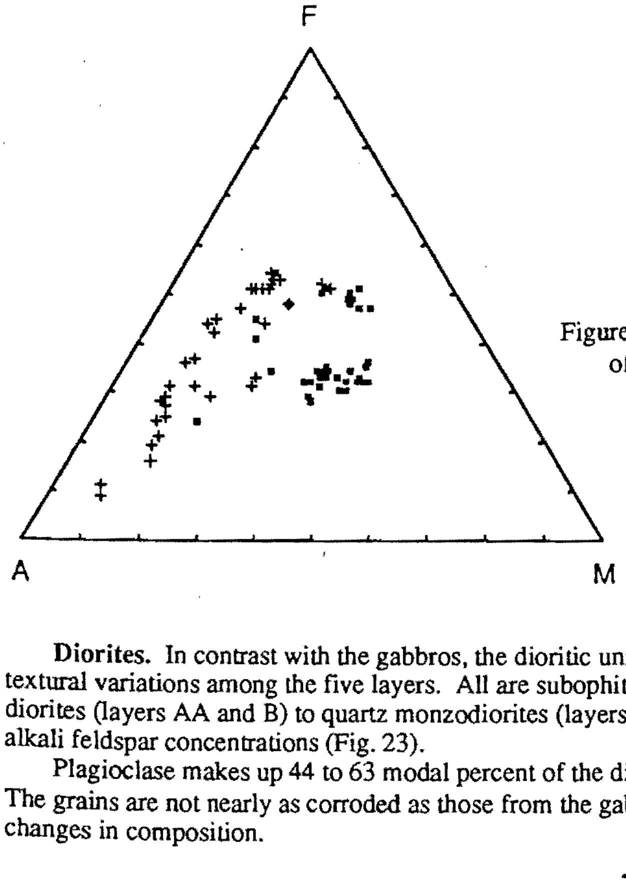


Figure 25. AMF diagram ($Na_2O + K_2O$ - FeO^* - MgO) of the gabbros (solid squares) and diorites (crosses).

Diorites. In contrast with the gabbros, the dioritic units are texturally homogeneous and show no structural and textural variations among the five layers. All are subophitic. Modally, the layers change upwards from quartz diorites (layers AA and B) to quartz monzodiorites (layers D, F and H) which increase towards higher quartz and alkali feldspar concentrations (Fig. 23).

Plagioclase makes up 44 to 63 modal percent of the dioritic units and shows normal zoning from An_{30} to An_6. The grains are not nearly as corroded as those from the gabbros, nor do core to rim variations appear as abrupt changes in composition.

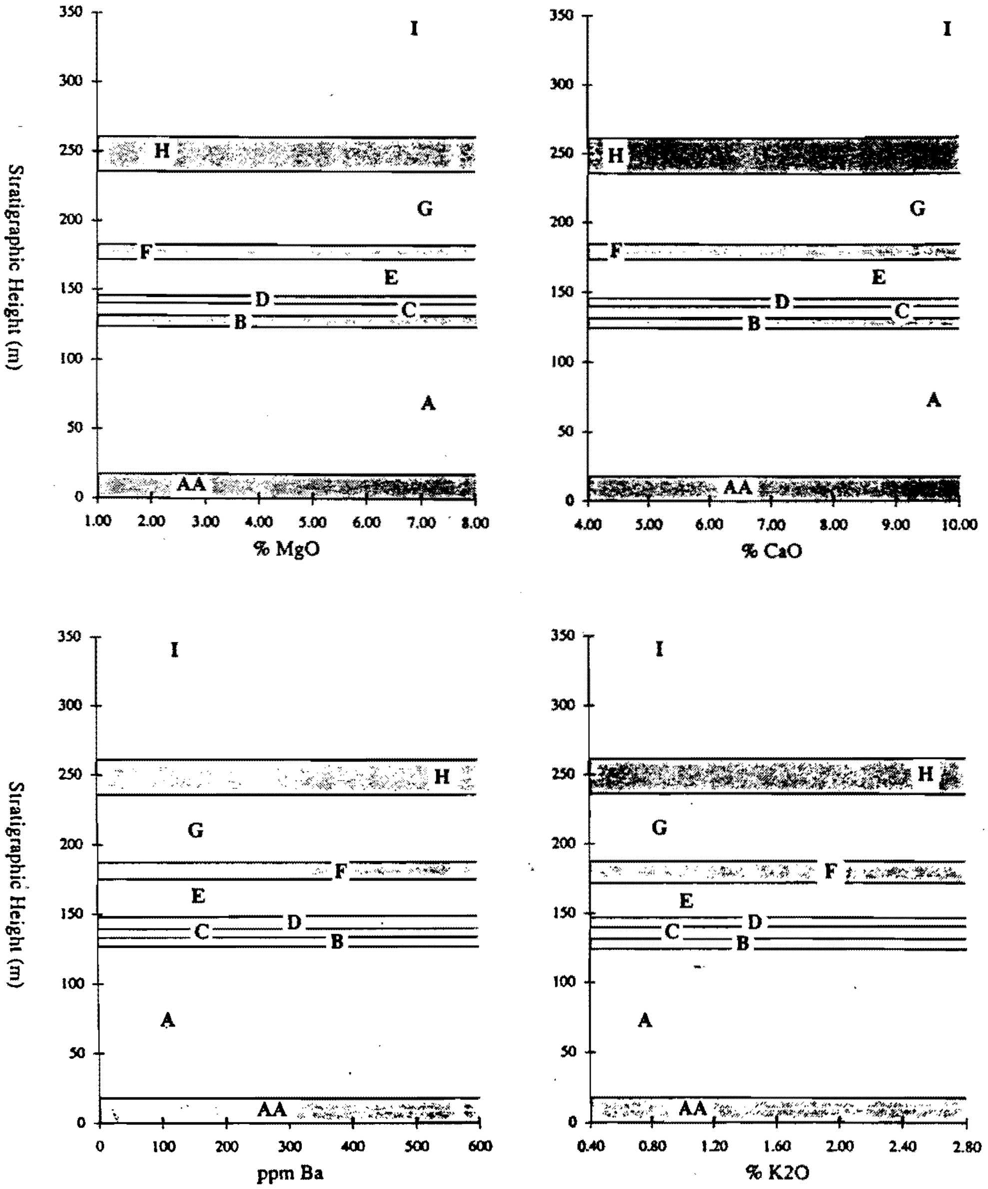


Figure 26. Average incompatible and compatible element compositions (wt. %) versus stratigraphic height for samples in the alternating layered series. Average composition ignore obvious effects of hybridization at some boundaries. Gabbros are layers A, C, E, G, and I; dioritic layers are AA, B, D, F, and H. Boundary between layers shown as solid horizontal line.

Alkali feldspar is interstitial and also present as a very late stage rim to plagioclase, but only in layers B and above. With increasing stratigraphic height, alkali feldspar becomes more abundant and appears to become a possible cumulus phase. Late-stage, interstitial, anhedral quartz increases in amount with stratigraphic height, though not as dramatically as alkali feldspar.

The dominant mafic phase is again hornblende, but it is edenitic in composition. Biotite is commonly intergrown with (or replaces) the hornblende, rims it, and also forms an interstitial member. Titanomagnetite rims both these mafic phases. There is also actinolite which may be the alteration product of pyroxene.

Accessory minerals include late-stage sphene, zircon, rutile, and substantial apatite in some samples. Epidote and iron oxide staining are present as secondary minerals.

At Eastern Head, the dioritic units show no obvious foliation, but are generally massive. This massive texture is in stark contrast to the diorite which makes up the northern two-thirds of the island and has a strong plagioclase foliation. Finally, xenoliths are rare; however, two dioritic units (AA and F) have one isolated and heavily resorbed xenolith apiece.

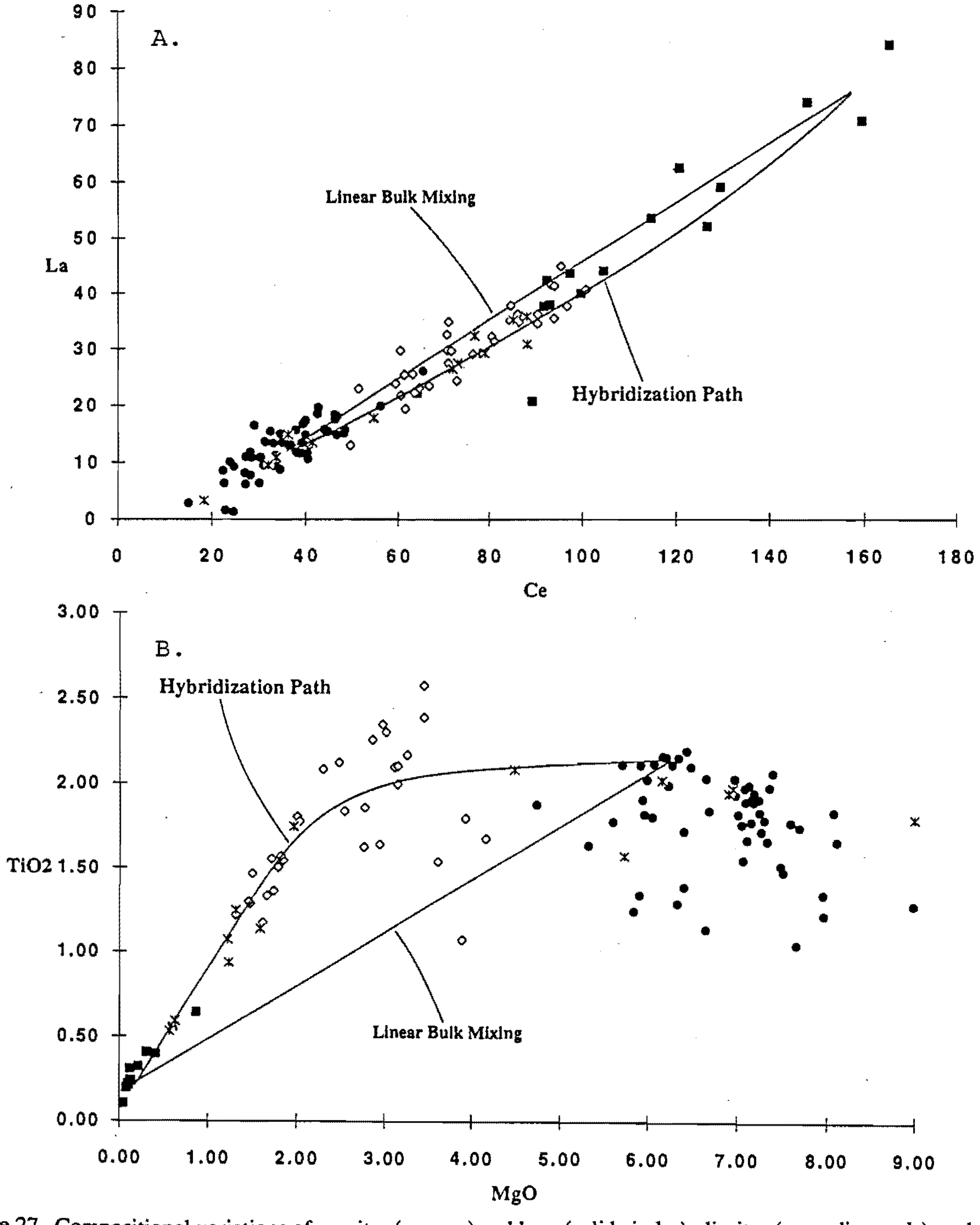


Figure 27. Compositional variations of granites (squares), gabbros (solid circles), diorites (open diamonds), and hybrids (crosses) with respect to: (A) La and Ce, showing similar diffusivities, and (B) MgO and TiO_2, showing different diffusivities. Linear mixing trend is calculated from average granite to chilled gabbro compositions. Hybridization path is drawn to fit hybrid compositions.

Chemically, the dioritic layers are andesitic with an evolving calc-alkaline trend (Fig. 24). Incompatible elements increase in abundance, whereas compatible elements decrease, with stratigraphic height, in accordance with the change from quartz diorite proper to quartz monzodiorite (Fig. 26). There are also strong variations within each unit which are sympathetic to the overall stratigraphic trend. The pipes differ from their associated diorites in composition. They are strongly depleted in many elements that are abundant in the diorites (e.g. K_2O, Zr), and they have syenitic affinities. Occasional pipes terminate a short distance into the overlying gabbros. These concentrate actinolite and epidote at their terminus.

On the Origin of the Diorites

Four possible models may be entertained for the origin of the dioritic units: (1) cumulates from the overlying Isle au Haut granite; (2) fractionation products of the underlying gabbros, with an assimilated granite component (AFC); (3) cumulates from a dioritic magma, with no genetic connection with either the gabbros or granites; or, (4) the product of mixing between the granite and gabbro. The geochemical and mineralogical data do not support the first two models. Using appropriate distribution coefficients for the phases which make up the diorites, neither fractionation of the gabbro, nor cumulate trends from the granite, produce the compositions of the dioritic units. The third model is plausible, but less satisfying. This leaves the possibility that the diorites are the products of a mixing event between the granite and gabbro in a stratified silicic magma reservoir as the most plausible solution.

Mixing has often been proposed to explain the interactions of bimodal magmas. In the plutonic environment, where commingling is common, linear arrays of major elements have been used to support mixing models between two endmembers. Typically, the major elements used to constrain the data are the network forming members (e.g., SiO_2, MgO, Fe_2O_3, CaO, etc.). Trace element data, however, are frequently scattered and non-linear. Recently, Lesher (1990) explored the possibility that mixing may not produce linear trends. Instead, due to differing diffusivities among the elements, non-linear hybridization trends tend to be favored over a linear bulk mixing trend. The dioritic units on Eastern Head are consistent with this interpretation.

In order to test this hypothesis, we have collected and analyzed hybrid samples from intimately mixed granite and layered gabbro to the east of the island. From elements with similar diffusivities (e.g., La and Ce), the hybridization trend closely matches a linear bulk mixing line (Fig. 27A). On the other hand, elements whose diffusivities are very dissimilar (e.g., TiO_2 and MgO) show a marked bowing in the hybridization path away from a linear bulk mixing trend (Fig. 27B). Data from the dioritic units conform more closely with these curved hybridization paths, and not with a linear bulk mixing line. Therefore, we propose that the diorites are the cumulate product of a hybrid magma which formed from a mixing event between the granite and the gabbro.

CONCLUSIONS

We believe that mafic-silicic layered intrusions (MASLI) like those visited on this field trip are extremely common and occur in a wide range of tectonic settings (Wiebe, 1993a, b). They represent the plutonic record of complex magma chambers comparable to those inferred to exist beneath many long lasting silicic volcanic systems. They provide compelling evidence for (1) multiple infusions of mafic magma into floored chambers of relatively silicic magma and (2) the existence of compositionally stratified magma chambers. Some MASLI provide a stratigraphic record of interactions between mafic and silicic magmas along double-diffusive boundaries. MASLI have great potential to provide new insights into magma chamber processes and into connections between the plutonic record and volcanic activity.

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