Field Relations, Petrology, and Geochemistry of Layered Gabbro-Diorite Units on the West Coast of Mount Desert Island, Maine

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Introduction

A repeating sequence of layered mafic to intermediate plutonic rocks makes up the western edge of the Silurian Cadillac Mountain Intrusive Complex that dominates Mount Desert Island, Maine. In an attempt to understand the petrogenesis of these rocks, a detailed study was taken of three distinct macorhythmic units, as defined by Wiebe (1992), along the coast at Stewart Head. Each sequence was presumable derived from an injection of basaltic magma into a convecting felsic magma chamber, producing layered rocks that grade upwards from gabbro to diorite. By examining the record of these injections it is possible to analyze how the different magmas interacted before and during crystallization.

Field Description

Each sequence of layers in the gabbro-diorite constitutes a macrorhythmic unit with a chilled gabbroic base that grades upward into more felsic compositions and ends with the chilled base of another unit. This study covers 130 meters of wavy coastline. Strike measurements and an average dip of 30 degrees for the entire section give an actual thickness of 48.7 meters. Unit 1 is at the bottom of these section and is 12 meters thick; unit 2 is 9.9 meters thick; unit 3 is 9 meters thick. Between each layer are mini-units or eroded areas.

Each chilled zone records the influx of basaltic magma into the cooler evolving felsic magma chamber. Each preserves irregular layers with some lobate sections falling several inches into the underlying cumulates. Often, thin fine-grained mafic laminae are found rimming these chilled 'pillows'. The five chilled bases examined in this study vary significantly in thickness (1.5cm - 6cm) and degree of chilling

Moving upsection from a chilled zone, over similar lengths of stratigraphic thickness, different layers achieve dramatically different degrees of compositional evolution. Two units grade to more intermediate compositions but one appears not to have evolved at all. The rocks are predominantly medium-grained, after the chilled zone, and massive. In one unit, however, there is some accumulation of sodic-plagioclase in distinct layers 2-5cm thick.

In each unit, dioritic material from underlying layers extends upwards through the chilled zone and emerges as pipes and diapers in the overlying unit. The source of this material can be seen where the dioritic cumulates warp and line the irregular lobate forms of the overlying chilled gabbro. The cumulates appear to be filter-pressed and forced upward by the weight of the descending chilled material. They are warped and sometimes show lamination parallel to the edge of the gabbro. This deformation indicates that the cumulate material was not completely crystallized in each unit when a replenishment of basalt was injected to begin the next. Also, these pipes show variable behavior in the overlying gabbros. Some pipes pass through the overlying layers unaffected, some are blocked by chilled zones, and others disperse in the layer immediately above.

Petrography

Petrographic analysis of 27 thin sections characterizes the evolving mineralogy of the three units. The samples can be divided into three sections: chilled zones, heterogeneous layers, and pipes.

1. The **chilled zones** include fine grained tabular plagioclase which invades and encloses medium grained amphibole and pyroxene (semi-ophitic). These fine grained chilled zones grade quickly (1mm) into medium grained basalt (defined by chemistry) with olivine, OPX, CPX, hornblende, equant plagioclase (An_{65-42}) , and biotite. Apatite and magnetite are found in trace amounts. OPX alters to cummingtonite, chlorite, and talc, and plagioclase alters to sericite. The relative amounts of each mineral vary significantly.

2. The **heterogeneous layers** which make up each section vary significantly in mineral composition. Plagioclase compositions range from An_{45-28}, sometimes with calcic cores surrounded by more sodic rims. Plagioclase displays variable alteration and patchy zoning. These rocks contain variable abundances of hornblende and biotite. Relict CPX, olivine, and biotite are often found surrounded by late hornblende. Sodic alkali feldspar, apatite, zircon, magnetite, and chlorite are found in trace amounts. The variable abundances of these minerals do not display definite trends upsection. Pyroxenes become generally less abundant and more altered upsection while primary hornblende and biotite become generally more abundant. The one constant is that quartz only appears in the uppermost layers of the more evolved units, units 1 and 3.

3. Most **pipes** show enrichment in plagioclase (An_{28-25}), quartz, biotite, and hornblende. Crystals vary both in grain size (medium to coarse) and shape (euhedral to subhedral). Some samples contain sodic plagioclase while others have significant concentrations of CPX. One sample defies these characteristics as it has no quartz, only trace amounts of biotite, and abundant OPX and CPX. The pipes show variable amounts of alteration.

Geochemistry

Twenty-two samples were analyzed at Franklin and Marshall College in Lancaster, Pennsylvania. X-ray fluorescence (XRF) analysis provided major element data while trace and rare earth element data were found with Inductively Coupled

Plasma (ICP) analysis. Ten samples were also analyzed using INAA, performed at XRAL Activation Services in Ann Arbor, Michigan. These ten samples were chosen so as to characterize Unit 1 and to compare all the chilled samples.

In units 1 and 3, several definite trends exist. CaO and MgO decrease continuously and alkalies become considerably enriched upsection. The only exception to this is in unit 3 where a mini-replenishment creates opposite trends. Unit 1 records maxima in TiO_2, P_2O_5, FeO_t, and V whereas unit 3 does not record these maxima. Unit 2 records none of the aforementioned trends. It becomes enriched in mafic minerals and depleted in alkalies for seven meters of actual thickness and then records fractional crystallization above that.

A total alkalies vs. silica diagram shows the wide range of compositions in these layered rocks, with SiO_2 values from 46.5 to 61.5 percent, representing rock types from gabbro to diorite. The samples most enriched in silica represent diapiric material and the samples depleted in SiO_2 record the chilled bases and unit 2. **SEE FIGURE1 BELOW:**

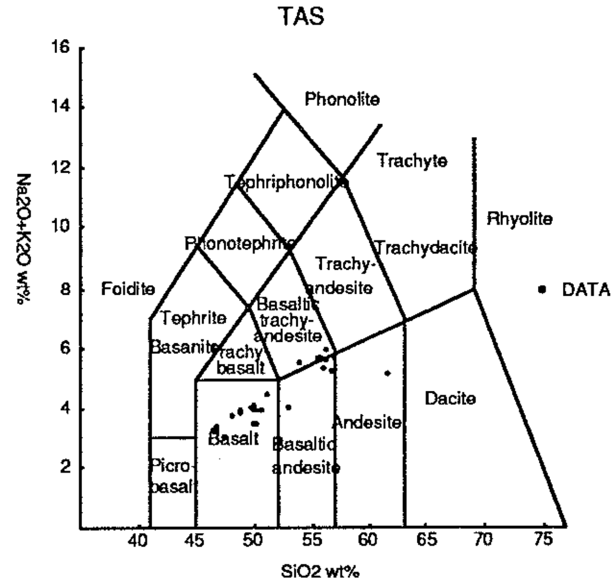


Figure 1. Samples plotted on a Total Alkali vs. Silica diagram (after LeBas, et al. 1986)

Plotting MgO' (defined as MgO/MgO+FeO) is useful because MgO' is highly sensitive to fractional crystallization, particularly to settling of olivine (**figure 2**). Both units 1 and 3 show significant drops in MgO' which may correlate with the fractionation of olivine or other Mg-bearing minerals (OPX) (Wilson, 1989). The peak of MgO' in unit 3 records a mini-replenishment of basalt. Again, unit 2 does not follow the trends defined by the other two units.

By normalizing all units to mid-ocean ridge basalts (**figure 3**), it is clear that all the rocks are highly evolved and display significant evidence of crustal contamination. Even the chilled samples (2,10,17,21.5) show significant enrichments in LILs which indicates they are not good indicators of the original mantle-derived magma composition. Unit 2, however, shows less deviation from the normalized MORB, indicating that it is the least evolved unit.

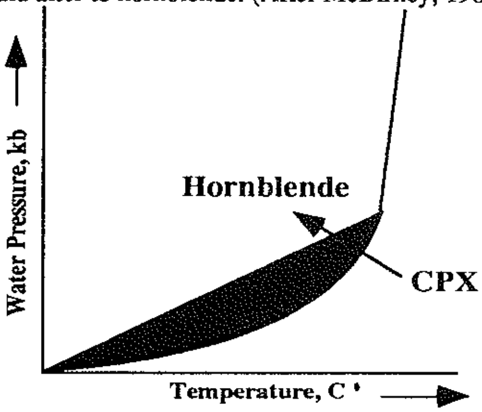
As suggested in the MORB diagrams, units 1 and 3 show significant depletions of Cr upsection that unit 2 does not exhibit (**figure 4**). Cr enrichment appears to be very much related to the influx of basaltic magma. Cr then follows a general depletion trend until it reaches trace amounts. This depletion is likely a function of the olivine and clinopyroxene fractionation indicated in thin-section. Cr may also be related to the fractionation of magnetite. These links to fractionating minerals are supported by the remarkable resemblance of Cr depletion to the trends in MgO' displayed in figure 1. Also, as with the mafic minerals, unit two displays trends opposite to the other two units, as it becomes enriched in MgO' and Cr before becoming depleted near the top.

All of the units display a remarkable relationship of Ba and Zr. The two elements parallel each other perfectly (**figure 5**). They both are depleted in the chilled zones of units 1 and 3 and become progressively enriched upsection. Unit 2 differs from these units as it never becomes very highly evolved.

Discussion

A variety of processes have combined to form the diverse rocks in the layered gabbro-diorites. Field relations indicate the presence of two distinct types of magma, one much hotter and denser than the other. This is shown by the chilled basaltic margins. Chilled pillows falling down into underlying more silicic material, the presence of diapiric material, and other remnants of re-intrusion by granite shows that granite was incompletely solidified during each basaltic influx. Also, there is considerable chemical and petrographic evidence for fractionation in units 1 and 3. Fractional crystallization, however, could not have been the only factor. Late hornblende signifies the migration of volatiles from the cooler, more hydrous resident magma to the hot, relatively drier basalt. Hornblende surrounding biotite cannot be easily explained with fractional crystallization. Also, there is considerable evidence that crystals were reacting with the melt. There are abundant instances of partly assimilated calcic plagioclase cores surrounded by more sodic plagioclase and of CPX rimmed by hornblende. This could be brought on by some combination of influx of water and cooling temperatures **(figure 6 below)**:

Figure 6. Figure illustrates how, with increasing water pressure and decreasing temperature, CPX could alter to hornblende. (After McBirney, 1984. p.128)



The sporadic occurrence of secondary hornblende indicates that the amount of H_2O and other volatiles varied in units and migrated within them. Lastly, unit 2 differs from the other two units in its enrichment in compatible elements upsection. This may be the result of an extended influx of basaltic material or of cumulate processes which concentrated those heavy mafic minerals. For cumulate processes to explain these concentrations, the question remains concerning how this could work gravitationally. Research this semester will address this question by looking at models of convecting magma chambers. Other questions will be addressed this semester, such as: why do pipes form in some layers and not in others?; what accounts for the parallel relationship of Ba and Zr; and, most generally, how do the observed trends relate to the variable sizes of replenishments and the nature of the basaltic magmas interaction with the resident magma?

Figure 4. Chromium Depletion Trends
This plot shows how Cr concentrations fluctuate across the three units. Chills are represented by the larger marker point◆

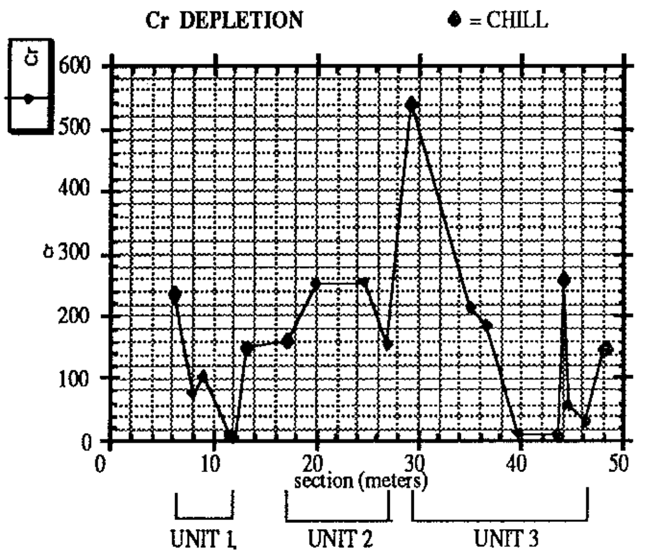


Figure 5. Ba & Zr Trends
This plot shows Barium and Zirconium's parallel behavior through the three units. The samples which record chills are labeled by the arrows at the bottom of the plot.

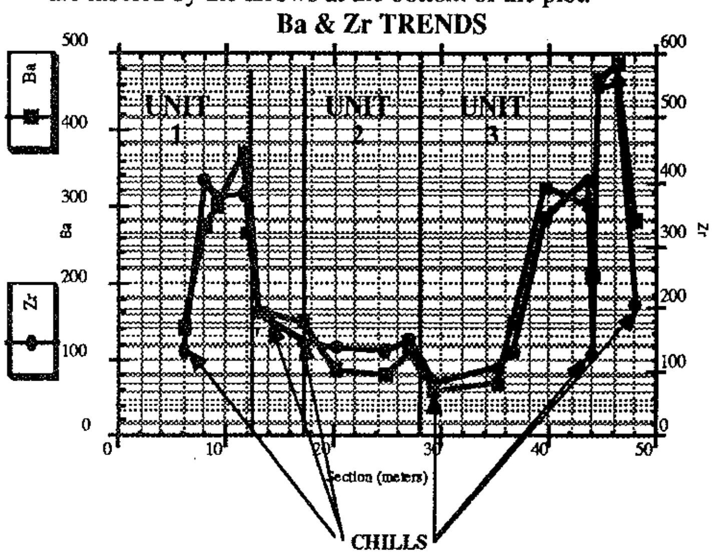


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Figure 2. MgO'
Plotting MgO' (defined as MgO/(MgO+FeO) is useful because MgO' is highly sensitive to fractionation. Unit 2 does not follow the general trends defined by the other two units.

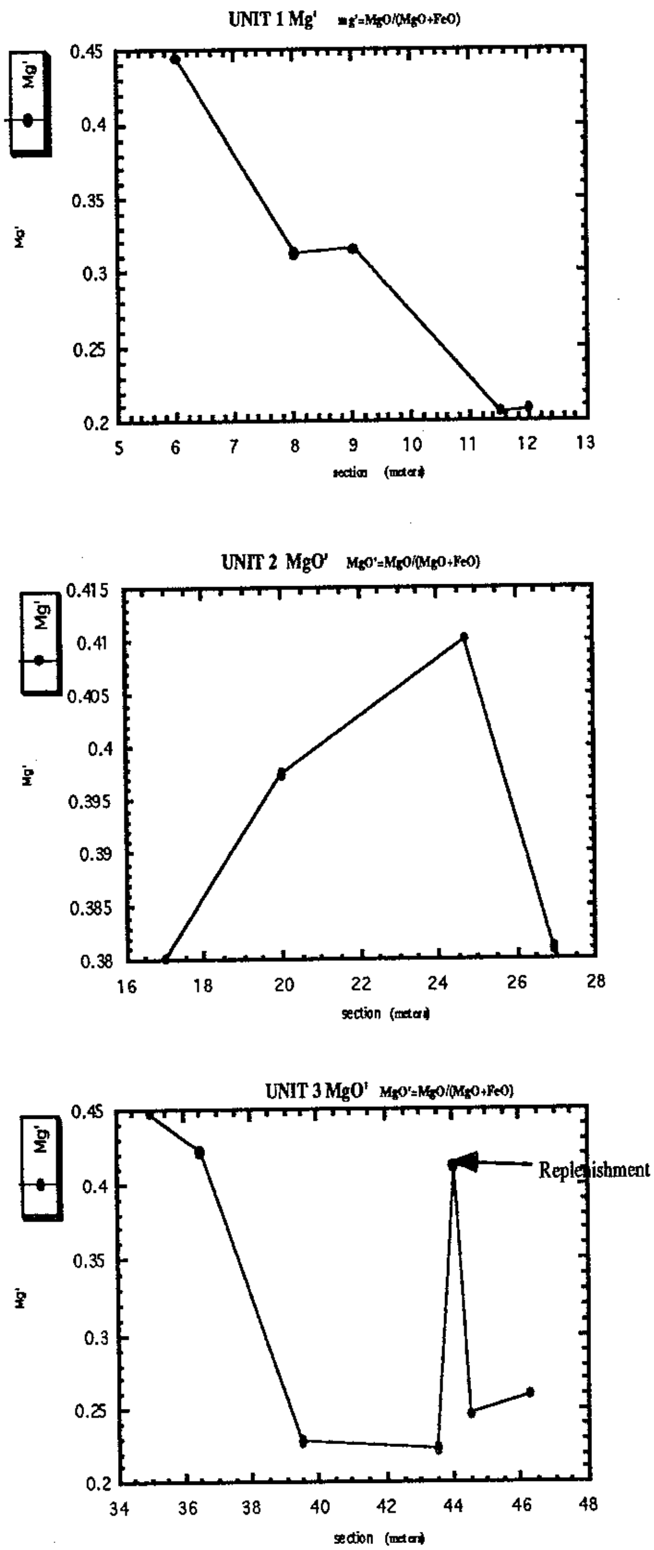

Figure 3. Units normalized to MORB composition
Each layer is shown as a single line. Unit 2 does not show the same variations as units 1 & 3. (After Pearce, 1983)