Interactions between Mafic and Silicic Magmas in the Vinalhaven Pluton, Vinalhaven, Maine

Holli Frey
Department of Geosciences, Franklin and Marshall College, Lancaster, PA 17604-3220
Faculty sponsor: Robert A. Wiebe, Franklin and Marshall College

INTRODUCTION

Along the south and east coast of Vinalhaven Island, an interlayered gabbro-diorite unit forms a sheet-like body, 100s of meters thick that dips to the northwest beneath the granite and rests on older plutonic rocks that are exposed on islands to the southeast. Widespread load-cast and pipe structures indicate that the gabbro-diorite unit represents a sequence of basaltic injections that ponded on crystal mush at the base of a magma chamber and variably interacted with overlying granitic magma. The purpose of this study is to characterize the different types of interactions between mafic and silicic magmas: zones of basaltic pillow accumulations (pillow mounds) and a layered section with basaltic replenishments.

FIELD RELATIONS

The field area for this study consists of coastal exposures located on southern Vinalhaven Island, namely Clayter's Beach (pillow mound), Lane Island (pillow mounds), and Hocus Point (stratigraphic section).

Pillow mounds. In the gabbro-diorite unit, there are several mounds, up to more than 100 meters in diameter, that consist of tightly-packed meter scale, chilled basaltic pillows, lenses, and sheets. The matrix between individual chilled bodies ranges in composition from hybrid dioritic rocks to granite and in thickness from about 0 to 10 cm. The arrangements of flattened chilled bodies define structures which variably resemble domal, deltaic, or trough accumulations of pillows. Some of these mounds occur in a graben that cuts previously solidified portions of the layered gabbro-diorite unit. The mounds appear to represent the flow fronts of basaltic injections that moved onto and spread across the chamber floor.

One pillow mound (west Lane Island mound) is a bold coastal outcrop roughly 15 by 15 meters with about 7 meters of relief. Flattened pillows define a trough which is exposed on vertical faces both normal and parallel to the trough axis. The base of the trough rests on a thin, 7 cm thick, sub-horizontal seam of coarse-grained granite which is continuous with the granitic matrix between the pillows. In the section normal to the trough axis, the pillows are more flattened and tightly packed at the central base of the trough and become larger and more nearly equant towards the trough margins. Parallel to the trough axis, the well defined pillows grade in one direction to tubular bodies and then to massive gabbro.

Stratigraphic Section. The section exposed on Hocus Point is approximately 1 km thick and grades from massive gabbro to coarse-grained granite, interrupted by several episodes of meter-scale basaltic replenishments. The base of the section is marked by chilled basaltic material resting on coarse-grained granite. This mafic material coarsens upward and becomes more leucocratic up-section. The replenishments are characterized by chilled bases, load-casts, subtle pillow shapes, and gradational tops. The chilled base of the gabbro coarsens upward to massive coarse grained gabbroic material within a few meters. The replenishments do not appear to affect significantly the overall compositional trends of the section. About 600 m from the base of the section, the mineralogy has changed significantly so that the rocks are biotite-hornblende rich granites. Because of their relatively high color index (CI=25), these rocks will be referred to as intermediate felsic rocks. These intermediate rocks grade to a more typical coarse-grained granite (CI=6) at the top of the section.

PETROGRAPHY

Forty-three samples were studied to determine mineralogical and textural trends within the pillow mounds and the stratigraphic section. The samples can be grouped into four categories: 1) quenched gabbros (basaltic pillows and replenishments); 2) massive cumulate gabbros; 3) intermediate felsic rocks; 4) coarse grained granites (some matrix to pillows and the top of the stratigraphic section).

1) The quenched gabbros are comprised primarily of thin, normally zoned (An 75-20), euhedral plagioclase lathes (1 mm x .1 mm), equant olivine crystals and anhedral clinopyroxene. Plagioclase lathes commonly occur in radiating clusters. Minor interstitial orthopyroxene, biotite and/or hornblende are also present.

2) The cumulate gabbros are similar to the quenched gabbros, mineralogically and texturally, but are coarser grained. Euhedral plagioclase lathes (up to 7 mm x 3 mm) have sodic patches in calcic cores, but retain

strong normal zoning. Corroded clinopyroxene cores are commonly surrounded by brown hornblende rims. Oxides, most likely ilmenite, are rimmed by biotite.

3) The intermediate felsic rocks contain about 20% quartz, 25% plagioclase, 30% alkali feldspar, 20% mafic minerals and minor apatite. The plagioclase (An30) lathes (10 mm x 5 mm) commonly include quartz and clinopyroxene droplets. The alkali feldspar displays extensive perthitic exsolution. Hornblende is the dominant mafic mineral and is commonly poikilitic, with abundant inclusions of plagioclase and alkali feldspar.

4) The coarse-grained granitic rocks contain about 25% quartz, 20% plagioclase, 50% alkali feldspar, and 5% mafic material with accessory biotite, apatite, and zircon. The plagioclase lathes display weak normal zoning (An 24-18) are commonly resorbed and corroded. The alkali feldspar crystals are perthitic and commonly rimmed by plagioclase, giving the rock a rapakivi texture. A fine-grained matrix of a micro-granophyric texture is commonly present.

The modal abundances of the mafic minerals and quartz in the samples from the stratigraphic section on Hocus Point, as well as the stratigraphic elevation of the basaltic replenishments, are shown in **Fig. 1**. The mafic and quartz contents vary inversely as the gabbro grades to granite. The gabbroic samples at the base of the section are dominated by clinopyroxene with subordinate orthopyroxene, hornblende, and biotite. The amount of biotite is anomalously high for gabbroic rocks and it occurs both as large equant crystals and interstitially. The percent of biotite varies only slightly in the section, ranging from 5-10%. The percent of hornblende increases from 3% at the base of the section to 15% in the intermediate rocks, before disappearing altogether in the granite. The modal percent quartz increases up-section.

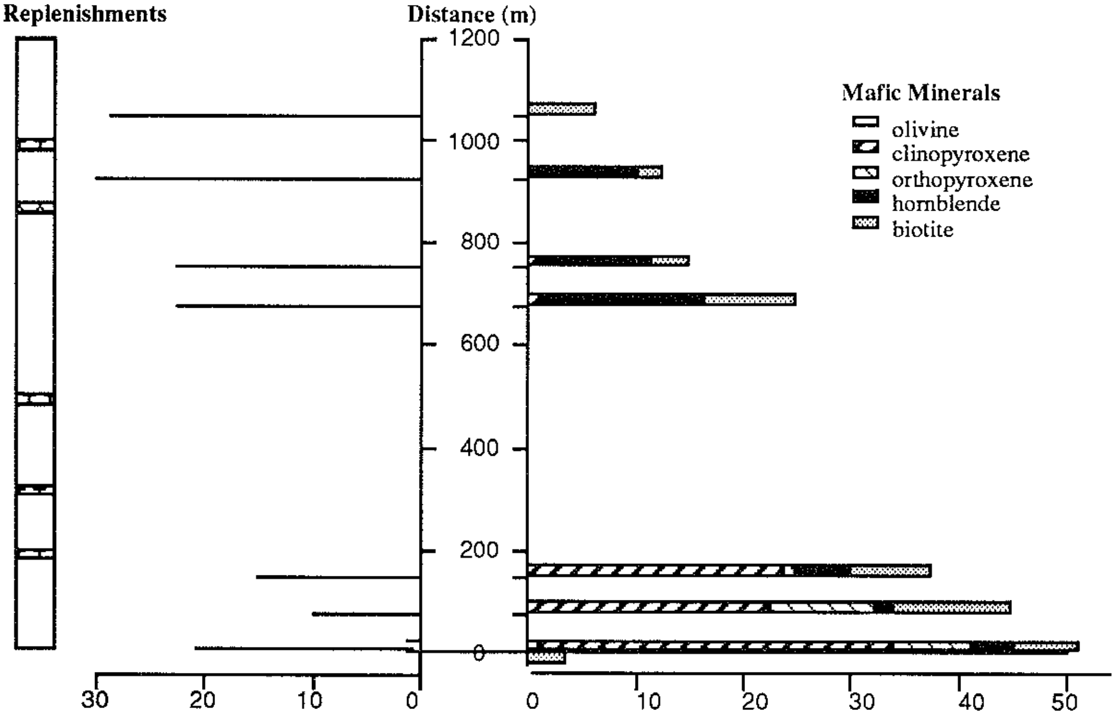

Figure 1. Modal distribution of quartz and mafic minerals in stratigraphic section

GEOCHEMISTRY

Thirty-seven samples were analyzed by X-ray fluorescence analysis at Franklin & Marshall College. The samples can be divided into three groups based on their silica contents (**Fig 2**). The gabbroic rocks contain 46-56% SiO2, the felsic intermediate rocks contain 63-67% SiO2 and the coarse-grained granites contain 68-74% SiO2. Plots of stratigraphic height in the chamber versus most major and trace elements show linear trends and rocks of intermediate composition. In **Fig. 3a**, %MgO decreases linearly with stratigraphic height after the influx of mafic material at 0 meters. The %MgO in the granitic rocks at the base and top of the section are virtually indistinguishable. **Fig. 3b** shows a similar trend, but the amount of K2O increases up-section.

ORIGIN OF COMPOSITIONAL VARIATION IN STRATIGRAPHIC SECTION

Based on petrographic and geochemical analyses, magma mixing appears to be the dominant process, with fractional crystallization playing a minor role. In several of the coarse-grained granitic samples, there are patches of fine grained mafic material, consisting of hornblende, biotite, and altered clinopyroxene. These types of mineral assemblages are unlikely to crystallize from a granitic melt and are so different texturally, that there is little doubt of mechanical mixing of two distinct magmas. The gabbroic rocks also provide evidence for magma mixing. The presence of quartz crystals, completely surrounded by rims of hornblende, biotite, and clinopyroxene, suggest that the quartz was unstable in the mafic melt and likely transported from another environment. Some of the coarse gabbro samples have a very heterogeneous texture, with patches of fine grained quenched gabbros adjacent to coarse gabbro. This may be the result of quenched material being partially incorporated into the mafic melt. The presence of these types of features in both the granitic and gabbroic samples suggests that despite temperature and viscosity differences between mafic and felsic magmas, magma mixing did occur.

Considering the thermal contrast between mafic and felsic melts, it is not likely to produce 1000 m of intermediate rock/magma by interaction along a double diffusive convection boundary (Huppert and Sparks, 1984). In order for magma mixing to occur on this scale, the volume of mafic melt must be much greater than the volume of felsic melt (Frost and Mahood, 1987). Field relations indicate that basalt was injected into a silicic magma chamber and flowed across the crystalline mush floor in tubular flow units. As the basalt flows into the chamber, it should override a layer of granitic liquid (Snyder and Tait, 1998). Small amounts of granitic material can then percolate upwards in veins or pipes through the ponded mafic layer because of the density inversion. Because the granite becomes superheated, it is able to mix with and become incorporated into the mafic melt. This type of process would help explain the presence of early crystallizing biotite in the gabbros, as a consequence of mixing. Because the granitic samples at the base and top of the section are so similar, it stands to reason that a large volume of basaltic material disrupted the chamber and initiated magma mixing. The meter-scale basaltic replenishments probably quenched too rapidly to permit magma mixing.

EMPLACEMENT OF PILLOW MOUNDS

The excellent 3D coastal exposures of pillow mounds on Vinalhaven Island make it possible to constrain mechanisms of formation. Based on field relationships, it is clear that massive gabbro grades into tubular flow units, which then break into discrete pillows. The west Lane Island mound is ideal for studying this transition, as two perpendicular faces are exposed. **Fig 4** is a schematic representation of a vertical face, normal to the trough axis and presumed direction of flow. **Fig 5** is a schematic representation of the vertical face parallel to the trough axis. In **Fig 5**, flow lobes are numbered to indicate the sequence of deposition and emplacement of lobes. As lobe 1 flowed over previously emplaced pillows, the front of the lobe grew cooler and unable to flow. However, magma was still flowing in the tubular flow unit. Because this magma could not continue flowing through lobe 1, it broke out of its flow unit and formed a new lobe (2) which flowed over lobe 1. As lobe 2 solidified, lobe 3 formed and flowed into the posterior of lobe 2. Lobes 4 and 5 were likely created in a similar manner, although it is not apparent in **Fig 5**.

The emplacement mechanism for these plutonic pillow mounds is not unlike that of submarine pillow basalts and pahoehoe flows. Using underwater photography, Moore (1975) showed that as magma comes into contact with water, the outer skin of the pillows quenches immediately, while lava continues to flow into the pillow. Because the pillow has chilled or even solidified, the flowing magma is forced to break out and create another flow tube. Schematic representations of this process (Walker, 1992) are strikingly similar to representations of plutonic pillow mounds. A similar process of flow fronts solidifying and lava overriding these flow fronts has been documented in pahoehoe flows at Kilauea (Walker, 1991).

Experimental studies further support the ideas behind the pillow emplacement model. Snyder and Tait (1995) have shown that when a liquid with viscosity similar to basalt is injected into a substance equating a granitic crystalline mush, the basalt forms "fingers" or flow tubes, not unlike those seen in outcrop.

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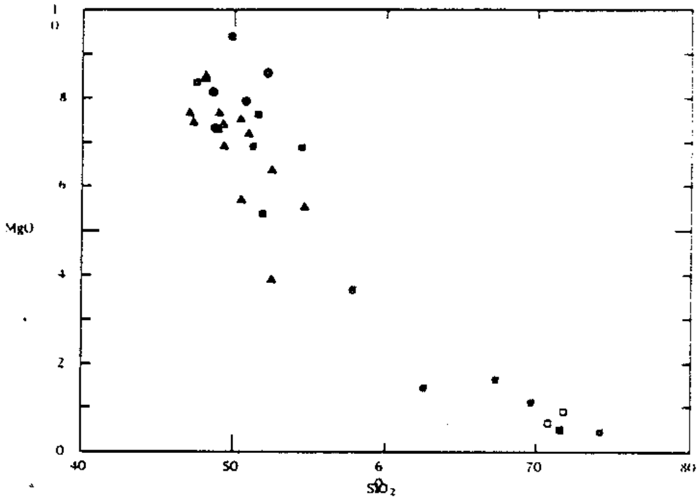

Figure 2. Harker diagram illustrating compositional range of samples. Stars-stratigraphic section; closed squares-coarse gabbro; closed circles-replenishments; closed triangles-pillows; open squares-granite

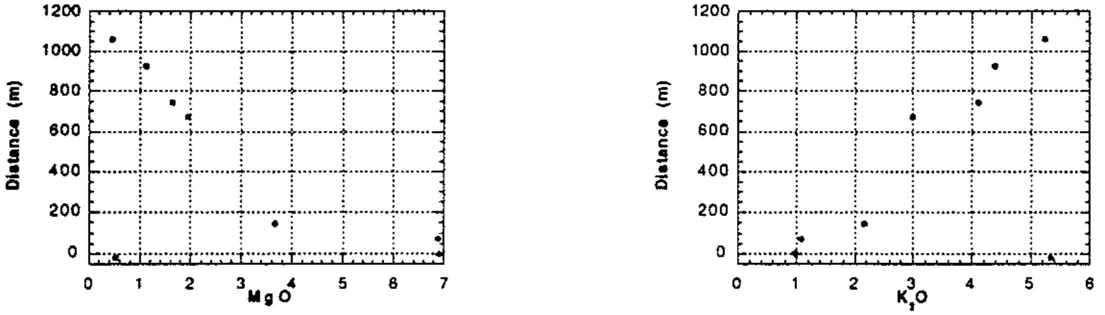

Figure 3. %MgO and %K_2O vary as a function of stratigraphic height

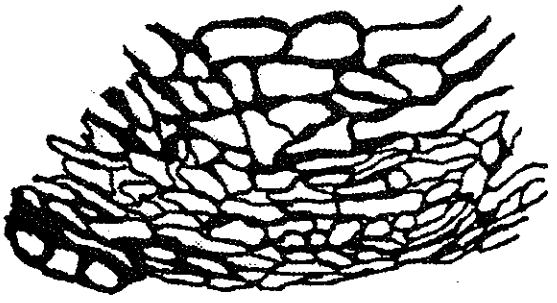

Figure 4. Face perpendicular to flow direction - west Lane Island mound

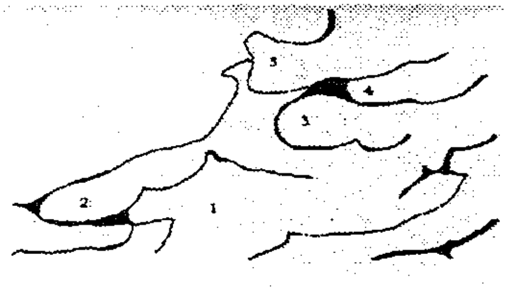

Figure 5. Face parallel to flow direction shows sequence of emplacement-west Lane Island mound