The petrology and evolution of basaltic magma upon entering a granitic magma chamber: Vinalhaven, Maine

Megan Mandernach
Department of Geology, The College of Wooster, Wooster, OH, 44691
Faculty Sponsor: Lori Bettison-Varga, The College of Wooster

INTRODUCTION

Large silicic magma chambers often form at convergent plate margins as heat rising from the mantle melts the overlying continental crust. If mafic magma from below later penetrates a silicic magma chamber, the resulting igneous body will be strongly bimodal. Successive injections of basaltic magma into a silicic magma chamber are recorded by repeated cycles of gabbro and diorite at the base of the magma chamber.

It is important to determine how the mafic and silicic magmas interacted at the base of the Vinalhaven pluton in order to constrain the physical conditions in the magma chamber at the time of the basaltic injection. Theoretically, it would be difficult for these magmas to homogenize because their viscosities, densities, and temperatures are so different (Campbell and Turner, 1986); however, the presence of significant volumes of diorite at the base of the Vinalhaven pluton indicates that magma mixing must have occurred on some appreciable scale. The evidence for this mixing process can be gained from the petrographic and geochemical characteristics of the dioritic hybrid rocks, and it may give insight to the formation of intermediate magmas. The presence of erupted andesites indicates that the volume of intermediate magma in the magma chamber was significant.

The purpose of this study is to describe the relationship between the gabbroic and dioritic rocks at the base of the Vinalhaven pluton, to provide an explanation for the formation of intermediate rocks, and to correlate successive influxes of basalt into the magma chamber.

FIELD RELATIONS

The field areas for this study are along the eastern coast of Vinalhaven Island (Figure 1). The southwestern field area, Arey Neck, is separated from the northeastern field area, Calderwood Point, by a metamorphic block approximately 1.25 km wide. Each field area is an internally continuous series of commingled granite and gabbro complexes. It is assumed that these rocks crystallized from the base up and that later injections of basaltic magma solidified on top of previous injections. Field relations do not suggest a sill-like emplacement of the gabbros.

Proceeding upsection from east to west, the rocks cycle through repeated pseudostratigraphic units. Fine-grained (quenched) gabbros grade to coarse-grained gabbros which grade to dioritic hybrids. A later injection of quenched gabbro truncates the diorite to start a new pseudostratigraphic unit. The thickness of the pseudostratigraphic units increases upsection. There is extreme lateral and vertical variation in rock type and mingling features, making correlation, even across narrow peninsulas, highly infeasible. Pipes of dioritic material rising through gabbro and gabbroic pillows resting in a dioritic matrix are very common throughout the field areas.

PETROGRAPHY

Three distinct types of rocks are found at the base of the Vinalhaven pluton.

1. The fine-grained (quenched) gabbros are comprised of plagioclase (~1 mm x 0.1 mm), small (~0.5 mm) equant olivine crystals, anhedral clinopyroxene (~0.5 mm), minor intercumulate orthopyroxene (~0.4 mm), and minor biotite. Quench textures observed include radiating lathes of plagioclase and clinopyroxene included in plagioclase.
2. In the coarse-grained (cumulate) gabbros, plagioclase grains are large (up to 5 mm x 2 mm), tabular, and strongly zoned. Oxides are often rimmed by biotite. Clinopyroxene grains are large (2 mm x 2 mm), intercumulate, and sometimes partly altered to amphibole. Anhedral olivine grains are sometimes rimmed by amphibole.
3. The primary minerals in the diorites are plagioclase, alkali feldspar, quartz, amphibole, and biotite, and most grains are very large (2-10 mm). There are minor amounts of oxides, relic clinopyroxene, zircon, and acicular apatite. Most clinopyroxene has altered to actinolite.

The dioritic hybrids show many textures compatible with hybridization between mafic and felsic magmas. Major reaction textures include clinopyroxene grains only found with thick amphibole rings around them, rapakivi textures, the intergrowth of biotite and amphibole, fine-grained mafic enclaves within hybrids, and amphibole-mantled quartz. Minor textures include acicular apatite, boxy cellular plagioclase, and the general disequilibrium of all large phenocrysts.

GEOCHEMISTRY

Four samples were analyzed by ion neutron activation analysis at Oregon State University, and twenty-four samples were analyzed by X-ray fluorescence analysis at Franklin and Marshall College. Most samples can be divided into two distinct groups by their silica contents. The quenched and cumulate gabbros contain 46.69-51.74% SiO_2, and the dioritic hybrids contain 62.52-66.96% SiO_2. The silica variation diagrams show strongly linear trends for Fe_2O_3, MnO, CaO and K_2O and a slightly curvilinear trend for MgO (not shown). Other silica variation diagrams for major elements are somewhat scattered, and silica variation diagrams for trace elements show great compositional variability. The gabbros are enriched in Cr and Ni and are depleted in Ba, Rb, Y, and Zr relative to the diorites. There are no major or trace element differences between the cumulate gabbros and the quenched gabbros.

Spider plots of the REE data show parallel flat trends for the quenched gabbros (Figure 2). The trend for the cumulate gabbro is nearly parallel to those of the quenched gabbros although it is slightly depleted in LREE and slightly enriched in HREE relative to the quenched gabbros. The trend for the diorite is very similar to the granite trend. The LREE are much more enriched (~90 times) than the HREE (~25 times) compared to chondrite compositions. Both the diorite and the granite trends show strong negative Eu anomalies.

DISCUSSION

Since dioritic magma is not the direct product of melting intermediate rock, there are two conventional processes which explain the formation of intermediate magma. Dioritic magma can either be produced by crystal fractionation of a mafic melt or by mixing a mafic melt with a silicic melt. Crystal fractionation will occur with or without a nearby silicic magma, but magma mixing is dependent on the liquid coexistence of end-member magmas. Geochemical evidence is very useful in determining the effect of fractional crystallization on the cooling history of a rock since petrographic evidence for fractional crystallization is much more cryptic. Both magma mixing and fractional crystallization can produce straight trends on major element diagrams, but trace element diagrams can help discriminate between these processes.

Evidence for Fractional Crystallization. The curved trend seen in Figure 3a cannot be explained by end-member magma mixing because the Ni concentrations in the intermediate rocks are much lower than would be expected by pure mixing. Since Ni is highly compatible with olivine, the curvature of the graph can be explained by fractional crystallization of olivine from the mafic melt (Bloomfield and Arculus, 1989). Also, the Sr concentration in the mafic rocks is highly variable although the concentration of Sr in the hybrid rocks is intermediate between the mafic and silicic rocks (Figure 3b). Sr is compatible with plagioclase so the range in Sr concentrations in the mafic rocks is likely due to variations in the proportions of plagioclase and pyroxene being crystallized (Chappell et al., 1987).

Evidence for Magma Mixing. Silicic magma chambers act as traps for rising basaltic magma as it ponds at the base of the chamber and interacts with the surrounding granitic magma (Wiebe, 1994). Following thermal equilibration, magma mixing can occur by mechanical stirring and by chemical diffusion. The degree of mechanical stirring depends on the initial disturbance caused by the injection of basalt into the chamber, and the degree of chemical and isotopic diffusion depends on the difference in temperature, density, and viscosity between the magmas.

Petrographic evidence for rapid thermal equilibration between the basaltic influx and the resident magma is given by the crystal growth patterns in the quenched gabbros. The quenched samples were fine-grained and the plagioclase grains tended to grow in radiating lathes. If a high-temperature basaltic magma is in contact with a low-temperature silicic magma, the nucleation rates in the basaltic magma are high. As a result, plagioclase grains will be small and thin to increase the surface area available for crystallization. Since it is difficult for plagioclase to nucleate, grains will radiate out from a common center of nucleation to accommodate the rapid crystallization.

Mechanical mixing of magmas involves the physical transfer of crystals from one magma to another. If a basaltic magma is injected into a magma chamber with enough turbulence to cause mechanical stirring, hybridization will occur rapidly because stirring increases the surface area between the magmas and speeds equilibration (Metcalf et al., 1995). Field observations confirm that the diorites have highly heterogeneous compositions, and petrographic evidence for mechanical stirring is abundant. The metamorphic xenoliths found in the diorites indicate the environment was highly turbulent. The diorites contain many pockets of fine-grained material rich in biotite and amphibole which suggests that a rapidly crystallized mafic melt had later been physically stirred into a more felsic melt. In several samples, quartz grains are rimmed by amphibole and biotite, suggesting that they had been transported to an environment in which quartz crystals were not stable. The presence of acicular apatite crystals and intergrown hornblende and biotite also supports the magma mixing hypothesis. Because mixing features like these are abundant, temperature and viscosity conditions at the base of the Vinalhaven pluton must have allowed for significant physical interaction between the mafic and felsic magmas.

Source. The ratio of a given pair of incompatible elements will be constant for any uncontaminated magma. Therefore rocks which have the same ratio of these incompatible elements are likely to be genetically linked to the same parent magma. Figure 4 shows that the quenched and cumulate gabbros have the same Zr/Nb and Rb/Ba ratios, but the diorite ratios are intermediate between the gabbro ratio and the granite ratio. This indicates that the gabbros were derived from the same parent magma, but the diorites were produced by magma mixing between mafic and felsic magmas.

CONCLUSIONS

The events recorded at the base of the Vinalhaven pluton are consistent with other plutons in the Coastal Maine Magmatic Province. At least five injections of basaltic magma into the magma chamber are recorded in the Arey Neck and Calderwood Point field areas. The chilled margins at the base of each unit are chemically consistent, suggesting that the injections are derived from the same parental magma. Geochemical data does not indicate any significant change in basaltic magma composition over time.

Although fractional crystallization occurred on small scales within large influxes of basaltic magma, it did not produce the wide variation of rock types observed at the base of the Vinalhaven pluton. As influxes of basaltic magma penetrated the floor of the silicic magma chamber, the magmas coexisted as liquids before the gabbro crystallized. During this time, chemical diffusion as well as mechanical mixing severely affected the composition of the basaltic magma, producing repeated gabbro-diorite units on the floor of the magma chamber. These units are characterized by chilled gabbroic bases which grade to coarse-grained cumulate gabbros which grade to heterogeneous dioritic hybrids. Crystallization of the mafic magma was complete long before mechanical mixing and chemical diffusion homogenized the magmas.

REFERENCES CITED

Bloomfield, A. L., and Arculus, R. J., 1989, Magma mixing in the San Francisco Volcanic Field, AZ, Contributions to Mineralogy and Petrology, v. 102, p. 429-453.

Campbell, I. H., and Turner, J. S., 1986, The influence of viscosity on fountains in magma chambers, Journal of Petrology, v. 27, p. 1-30.

Chappell, B.W., White, A. J. R., and Wyborn, D., 1987, The importance of residual source material (restite) in granite petrogenesis, Journal of Petrology, v. 28, p. 1111-1138.

Metcalf, R. V., Smith, E. I., Walker, J. D., Reed, R. C., and Gonzales, D. A., 1995, Isotopic disequilibrium among commingled hybrid magmas: evidence for a two-stage magma mixing-commingling process in the Mt. Perkins Pluton, Arizona: The Journal of Geology, v. 103, p. 509-527.

Mitchell, C. B. and Rhodes, J. M., 1989, Geochemistry of the granite-gabbro complex on Vinalhaven Island, Maine, *in* Tucker, R.D. and Marvinney, R.G., eds., Igneous and metamorphic geology (Studies in Maine geology): Augusta, Maine, Maine Geological Survey, p. 45-57.

Wiebe, R. A., 1994, Silicic magma chambers as traps for basaltic magmas--the Cadillac Mountain intrusive complex, Mount Desert Island, Maine: Journal of Geology, v. 102, p. 423-437.

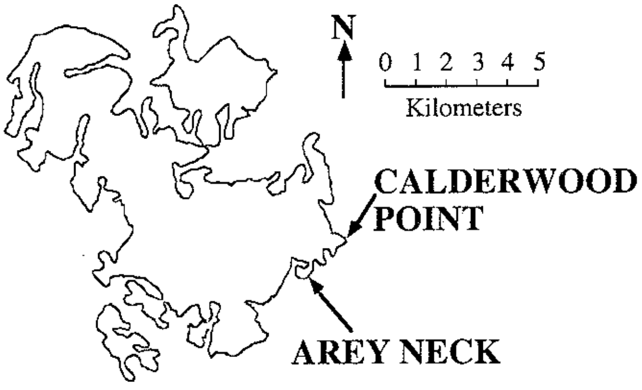

Figure 1. Map of Vinalhaven Island showing the relevant field areas for this study.

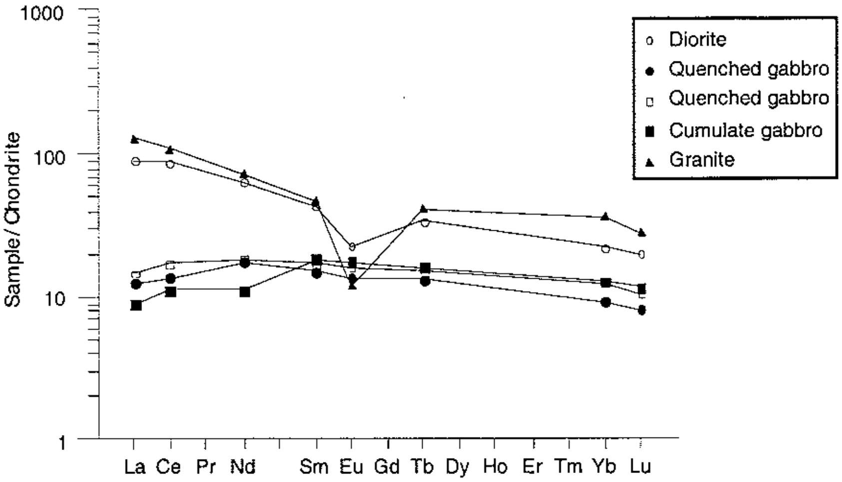

Figure 2. Chondrite-normalized REE plot for typical gabbro, diorite, and granite samples. Granite data is approximated from Mitchell and Rhodes (1989).

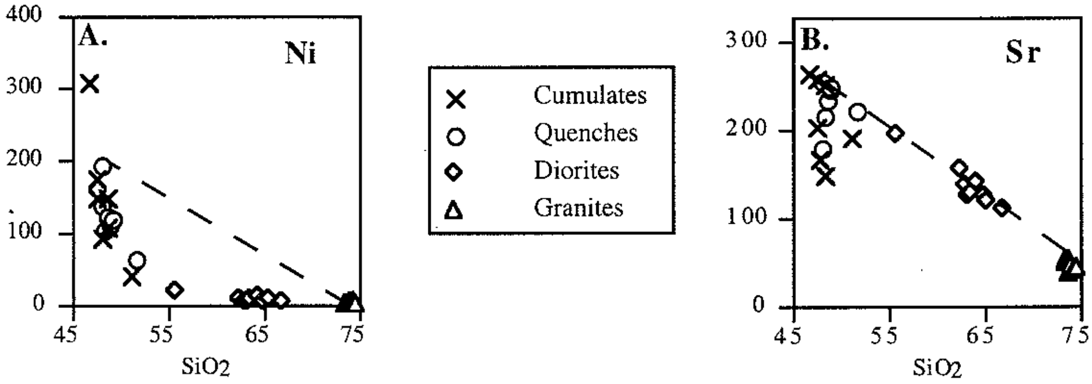

Figure 3. Silica variation diagrams for selected trace elements showing trends probably caused by fractional crystallization. Some trace element concentrations exhibit a strongly curved trend between gabbro and granite end-members (A). Mafic scatter also indicate fractional crystallization (B). The broken line represents the trend expected by pure magma mixing. Silica concentrations are in weight percent and trace element concentrations are in parts per million. Granite data is from Mitchell and Rhodes (1989).

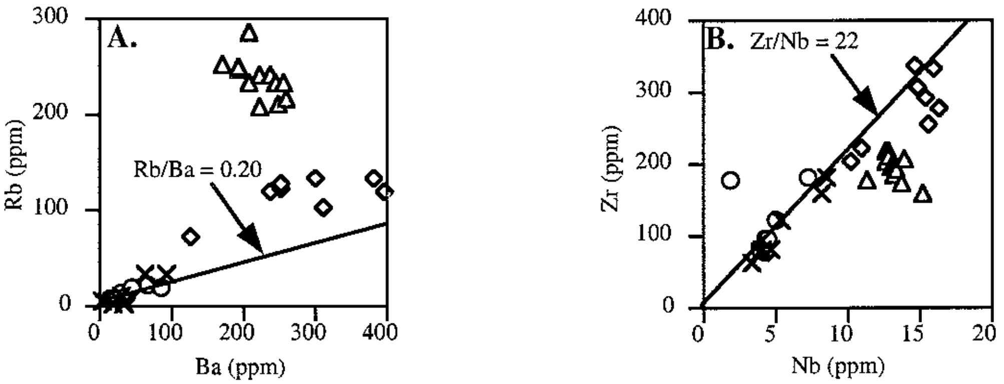

Figure 4. Incompatible element plots for Vinalhaven gabbros, diorites, and granites. Both graphs indicate that the diorite composition has been affected by granitic magma. The incompatible element ratios in the quenched gabbros are shown by the given line. Plot symbols are the same as in Figure 3, and granite data is from Mitchell and Rhodes (1989).