# Origin of Enclaves in the Vinalhaven Granite-Gabbro Complex, Coastal Maine

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## INTRODUCTION

The Vinalhaven Granite-Gabbro complex consists of three main units: medium-grained granite, fine-grained granite and gabbro-diorite. The medium-grained granite is the largest unit on Vinalhaven and partially encompasses a fine grained granite, the last unit to crystallize in the center of complex. The south and east coasts of the island are composed of a layered sequence of gabbro, diorite and hybrid rocks which form a curved sheet-like mass that dips to the northwest under the two granites. The presence of many depositional features such as granitic pipes and load casts suggest that the layered gabbro was formed by a series of mafic injections which ponded at the base of a granitic magma chamber. Granite and quartz diorite occur on several islands to the south and east of the mafic unit and appear to underlie the gabbro-diorite. Injections of mafic material into the chamber allowed for variable amounts of mixing and mingling to occur along the contact between the medium-grained granite and gabbro.

## FIELD RELATIONS

Enclaves occur sparsely in both the fine- and medium-grained granite. Enclaves are poorly sorted in size and have different characteristics in the two granites. Felsic and mafic enclaves in the medium-grained granite were collected in two locations: 1) in the middle of the granite complex (the 1950 Quarry) and, 2) near the contact with the layered gabbro (Old Harbor). Enclaves collected in Old Harbor tend to be globular (up to 80cm) and have diffuse boundaries with the host. Rare mafic enclaves (up to 10cm) have sharp margins with the host, tend to be elongate and much smaller than felsic enclaves. The fine-grained granite commonly contains felsic and composite enclaves. Felsic enclaves have sharp to moderately diffuse boundaries with the host. Composite enclaves (up to 10cm) are common in the Booth Pond Quarry and consist of a rounded mafic core with crenulate margins enclosed by a host enclave of intermediate composition (Fig. 1).

## PETROGRAPHY

**Medium-grained Granite and Enclaves:** The medium-grained granite contains equal amounts of plagioclase, microcline and quartz, less than 10% biotite and is equigranular. Plagioclase crystals (1- 2mm) have normal and oscillatory zoning (An12-An22). Microcline crystals tend to be equant (1- 8mm), have cross-hatch twinning and a perthitic texture. Equant quartz crystals are up to 4mm. Mafic minerals include biotite and trace amounts of hornblende. Accessory minerals include apatite, titanite, zircon, allanite and opaques.

Enclaves found in the 1950 Quarry exhibit wide compositional ranges. Felsic enclaves contain equant plagioclase (up to 2mm) with normal and oscillatory zoning (An42-12). Plagioclase (up to 4mm, An33-16) megacrysts are comparable in size and shape to crystals within the host granite, but are rounded with corrosional zones. The megacrysts contain normal zoning with reversals and zone truncations (Fig. 2). Rounded microcline megacrysts (1-4mm) have a perthitic texture and cross-hatch twinning and are commonly surrounded by a plagioclase (An12) rim; this type of texture is called rapikivi. Rapikivi occurs in variable stages of development. Quartz megacrysts (2mm in diameter) are rounded and in some cases are surrounded by a mafic rim of biotite and hornblende (Fig. 3). Mafic minerals (0.1mm average grain size) include biotite, found in association with oxides, and hornblende, which is more common in the enclaves than in the granite. Rounded, mafic patches (up to 7mm in diameter) occur within the enclaves. The patches consist of equant plagioclase crystals with a rim of calcic material, hornblende with relic pyroxene cores, equant biotite and apatite.

Felsic enclaves in Old Harbor contain plagioclase megacrysts (2- 5mm), along with variable development of rapikivi. These enclaves can be distinguished from the felsic enclaves in the 1950 Quarry, because they exhibit a preferred flow orientation and flattened quartz crystals (1mm- 4mm). Scarce mafic enclaves consist of fine-grained biotite with interstitial plagioclase, microcline and quartz.

**Fine-Grained Granite and Enclaves:** The fine-grained granite contains equal amounts of plagioclase (An15-22), microcline and quartz and less than 5% biotite. Microcline crystals (up to 2mm) have cross-hatch twinning and a perthitic texture. Blocky biotite crystals are found in association with opaque minerals. Accessory minerals include apatite, titanite, zircon, allanite and opaques.

Felsic enclaves contain plagioclase megacrysts and quartz with mafic rims. Microcline megacrysts occur sparsely. Composite enclaves are common in the fine-grained granite and consist of a mafic core enclave encompassed by an enclave of intermediate composition. The core enclave consists of fine-grained hornblende and biotite along with interstitial, radiating laths plagioclase and quartz. Intermediate enclaves are composed of plagioclase (0.5mm), rounded quartz and quartz with a mafic rim of equant biotite. Rounded, mafic patches occur in the intermediate enclaves with a similar composition to the core enclave. Accessory minerals in the enclaves are the same as in the granite. In both the granite and enclaves biotite is associated with oxides.

## GEOCHEMISTRY

Major and some trace elements of 23 rocks were analyzed using the XRF at Franklin and Marshall College. These samples are plotted (Fig. 3-5) along with the compositions of representative chilled mafic pillows associated with the gabbro diorite unit near the base of the Vinalhaven granite. In addition, REEs were determined for 13 rocks by INAA at the University of Oregon.

The medium- and fine- grained granites (73%) have similar compositions and are slightly peraluminous. The granites have low concentrations of CaO, MgO and $Fe_2O_3$ and high concentrations of $K_2O$ and $SiO_2$ (Fig. 3-5). The fine-grained granite has a lower concentration of Ba than the medium-grained granite (Fig. 5).

Most of the enclaves in the medium-grained granite range from 68 to 74% $SiO_2$ and have compositions comparable to the host granite. These enclaves generally have high concentrations of $K_2O$ and low concentrations of CaO and MgO. They can be separated into two groups based on Ba concentrations at comparable $SiO_2$ concentrations. One group has Ba concentrations between 46-125 ppm and the other group has Ba concentrations of 170-218ppm. The single analyzed mafic enclave (55% $SiO_2$) has very high K and Rb for such a mafic rock.

Felsic and intermediate enclaves in the fine-grained granite range from 67-71% $SiO_2$ and are comparable to felsic enclaves in the medium-grained granite. The cores of composite enclaves range from 50-52% $SiO_2$ and closely approach the composition of chilled basaltic pillows (Fig 5). Compared to the chilled mafic rocks, core enclaves have lower CaO, MgO and $Fe_2O_3$ concentrations and higher $K_2O$ concentrations.

Chilled basaltic pillows (48% $SiO_2$) were plotted to compare the enclaves with a known mafic liquid composition contemporaneous with the formation of the enclaves. The chilled pillows are tholeiitic, have the greatest concentrations of $Fe_2O_3$ and are low in incompatible elements (Fig. 4). Enclaves in the fine-grained granite lie approximately on linear trends between chilled pillows and granite but show a gap between 52 and 66% $SiO_2$.

## DISCUSSION

Field relations indicate that basaltic liquid ponded at the base of the granite and commingled with it. In addition, cumulate deposits on the floor of the chamber grade upward from gabbro through hybrid rocks to granite. These relations indicate that magma mixing was an important process near the base of the chamber. Both petrographic relations and geochemical variation of the enclaves strongly support an origin by magma mixing.

Plagioclase crystals of similar size and shape in both the granite and enclaves show zoning truncations which probably result from compositional changes due to magma mixing (Wiebe, 1968). Resorption and reversals in zoning are consistent with injections of mafic magma. Microcline crystals in the enclaves are similar in size and shape to the crystals found in the host granites. These large crystals have similar zoning and perthitic texture. The composition of the enclave would not promote the growth of such large microcline crystals which therefore must have formed in a cooler, felsic environment (Vernon, 1991). Rapikivi textures form when microcline crystals from the felsic liquid, mix into mafic liquid and become unstable. The edges of the microcline crystal go into solution and plagioclase forms along the corroded edges (Hibbard, 1981).

Rounded quartz crystals form in response to the instability produced when a crystal from a low temperature melt is introduced into a mafic magma. A solution forms along the edges of the crystal and reduces the latent heat of crystallization from the surrounding melt and in turn increases the amount of undercooling and nucleation rate (Vernon, 1991). Therefore the addition of fine grained minerals formed in the mafic melt are likely to aggregate around the crystal edge (Vernon, 1991).

In combination with petrographic observations, geochemical variation supports an origin by mixing. Figure 3 shows a linear linear trend between mafic and granite end members.

Enclaves were probably mixed into the granite by convective stirring. Heating of the felsic liquid would promote convection and transport small pieces of chilled material upward to the center of the chamber, while large felsic globules would settle to the bottom of the chamber. There is a kind of sorting when one considers both size and density. Those enclaves with similar compositions to the granite have globular, diffuse boundaries, whereas, mafic enclaves have moderately diffuse to sharp boundaries and are much smaller.

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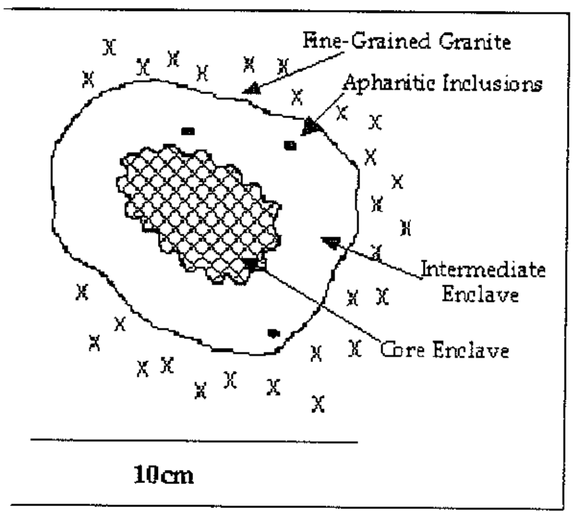


Figure 1: Composite enclave in the fine-grained granite.

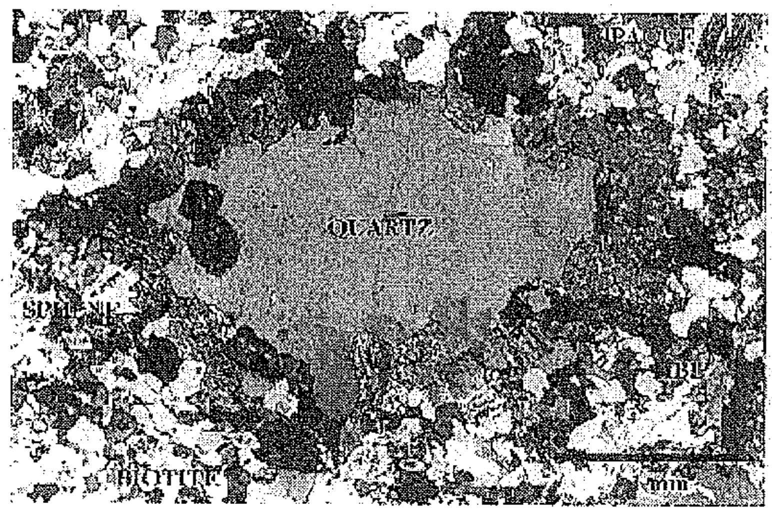


Figure 2: Quartz with mafic rim.

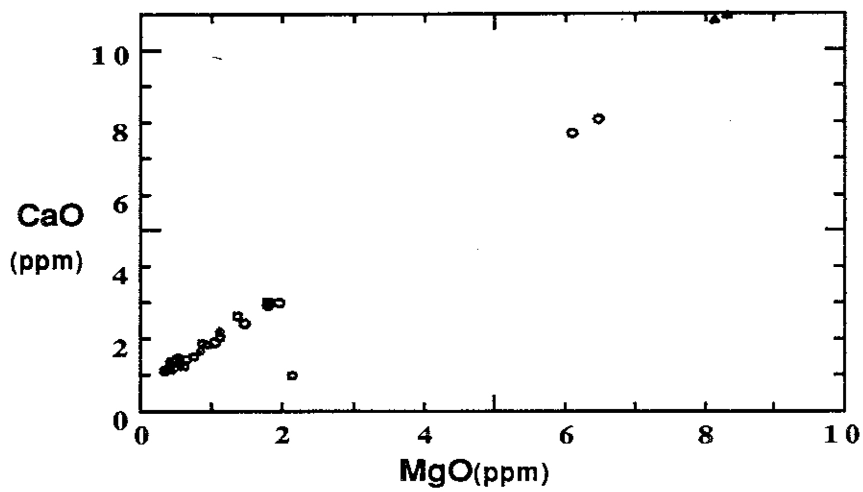


Figure 5: CaO vs MgO variation diagram.

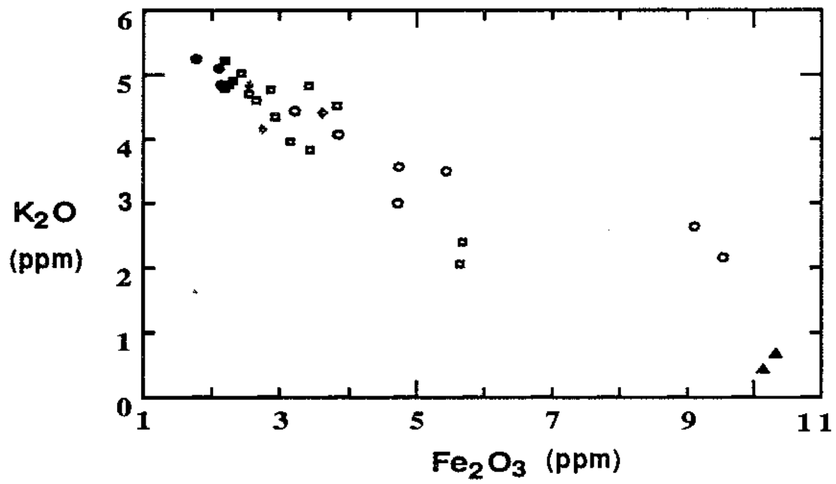


Figure 4: $K_2O$ vs $Fe_2O_3$ variation diagram.

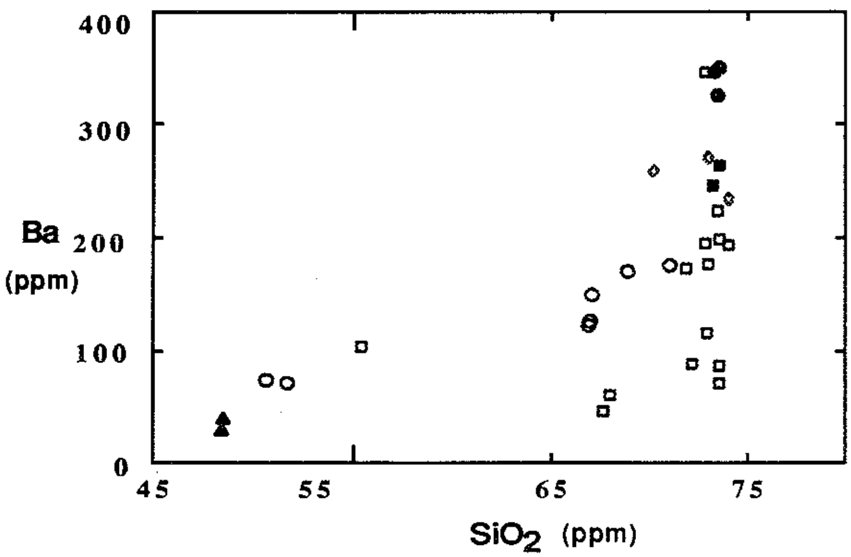


Figure 5: Ba vs $SiO_2$ variation diagram.