MICROGRANITOID ENCLAVES IN THE VINALHAVEN INTRUSIVE COMPLEX

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INTRODUCTION

Microgranitoid enclaves are a ubiquitous and widely studied feature of granitoid plutons and associated volcanic rocks in a variety of geologic settings. The Vinalhaven Intrusive Complex in Coastal Maine is a bimodal granite-gabbro intrusion that preserves evidence of magma mingling and mixing (e.g. Hawkins and Wiebe, this volume). Vinalhaven is distinctive because its good outcrop exposure from the floor to the roof of the intrusion makes it possible to study the enclaves in the context of the magma chamber itself, including the magmatic end members that are thought to have mixed to form the enclaves. The Vinalhaven intrusive complex consists of three main units: a coarse-grained granite unit, a fine-grained granite unit, and a gabbro-diorite unit. This study looks broadly at variations in the coarse-grained granite unit throughout the Vinalhaven intrusion, and specifically at spatial, textural, and geochemical variation in enclaves within the coarse-grained granite, in order to reach a better understanding of how the magmatic portions of the system evolved through time.

FIELD RELATIONS & METHODS

The coarse-grained granite unit of the Vinalhaven Intrusion consists mainly of tabular pink perthitic orthoclase, blocky white plagioclase, quartz and biotite + amphibole. Plagioclase may also occur as large poikilitic crystals with inclusions of biotite and amphibole. Textural evidence of magma mixing preserved in the coarse-grained granite includes mafic clots, mafic-rimmed quartz crystals and rapakivi feldspars (orthoclase phenocrysts rimmed by plagioclase). Porphyry bodies also exist within the unit, and contacts between the porphyry and the coarse-grained granite may be sharp or gradational. Aplite dikes are common throughout the coarse-grained granite.

Enclaves within the coarse-grained granite can be divided into several broad categories: porphyritic, equigranular, salt-and-pepper, and aphanitic mafic enclaves (Fig. 1). Salt-and-pepper enclaves are a subset of medium-grained equigranular enclaves that never exceed 1 cm in diameter. Aphanitic mafic enclaves are rare. Enclaves are generally darker in color than the granite in which they occur. They range in size from less than 1 cm to 2.5 m in diameter, though most are less than 20 cm. Porphyritic enclaves are the largest, and salt-and-pepper enclaves are the smallest; there is some overlap in size between porphyritic and equigranular enclaves. Some enclaves are texturally very heterogeneous, and may contain a “double enclave” structure where they partially or fully enclose smaller, finer-grained, more mafic enclaves. Concentrations of coarser-grained minerals adjacent to one side of some enclaves, and thin (up to 2 mm wide) veins of more felsic material tapering toward the center of enclaves, are also possible. Schlieren may be present in association with the enclaves or independently.

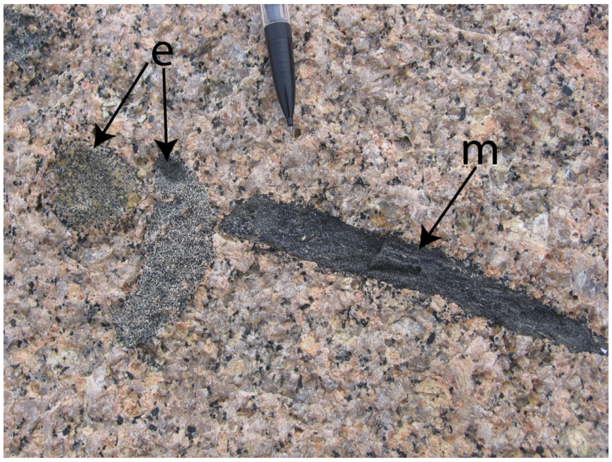

Figure 1. A variety of enclaves in coarse-grained granite at Smith Point, just above the gabbro-diorite unit. Representative equigranular (e) and fine-grained mafic (m) enclaves are labeled. Porphyritic enclaves are also present on this outcrop.

The granite was studied at a variety of stratigraphic levels within the pluton, ranging from just above mafic injections to the top of the intrusion. At each field site, the granite was characterized by documenting variations in the texture or fabric, presence of rapakivi feldspars and mafic-rimmed quartz crystals, and the orientation and size of any schlieren or aplite dikes. The enclaves were then described in terms of size, texture, and color, and quantified. Enclaves larger than 1 cm in diameter were counted by two or more people within grids marked on the outcrops. If their counts differed by greater than 20 percent, they were repeated. The grids ranged in size from 8 ft^2 to 650 ft^2, and multiple adjacent grids were made where possible to maximize the counted area at a given field site. At least 70 ft^2, and often greater than 300 ft^2, were counted at each field site. Salt-and-pepper enclaves were counted separately because it was necessary to look at them much more closely to distinguish them from lichens or poikilitic plagioclase crystals. These smaller enclaves were counted within two 3 ft by 3 ft squares on each outcrop. If the two small counts differed by greater than 20 percent, a third count was performed to ensure that the small counts were representative of the larger outcrop.

RESULTS
ENCLAVE COUNTS

Enclave counts indicate that the enclaves are heterogeneously distributed through the coarse-grained granite unit. Small enclave counts ranged from 0 to 30 enclaves per m^2, and large enclave counts ranged from 0 to 15 enclaves per m2. The concentration of enclaves may vary widely over several meters, especially near contacts with the layered gabbro-diorite unit. Higher in the chamber, enclaves appear to be sparser and more evenly distributed. Enclaves of a variety of textures and compositions occur on outcrops at all levels of the coarse-grained granite; they are not sorted by stratigraphic height. There is no strong correlation between size and location in the chamber, although enclaves larger than 1000 cm^2 were found only in close proximity to mafic sheets and porphyry bodies (Fig. 2).

PETROGRAPHY

Although the coarse-grained granite is generally uniform texturally and compositionally throughout the magma chamber, there is a great deal of variability in enclave microstructure and mineralogy.

Salt-and-pepper enclaves consist mainly of subhedral amphibole and plagioclase, with minor biotite. Mafic minerals account for roughly half of the groundmass. Larger equigranular enclaves are generally finer-grained than the salt-and-pepper enclaves. They have fairly high color indices (35-60), with the main minerals being plagioclase and amphibole. The amphibole and plagioclase may occur as elongate lathes, or as more equant intergrowths. Quartz occurs only interstitially, and may poikilitically enclose euhedral biotite and feldspar. Equigranular enclaves may be slightly coarser-grained toward the center, rimmed by very thin (up to 1 mm) chill zones. They are commonly texturally heterogeneous over a scale of several mm. Contacts between equigranular enclaves and the coarse-grained granite are more gradational than those of any of the other types of enclaves.

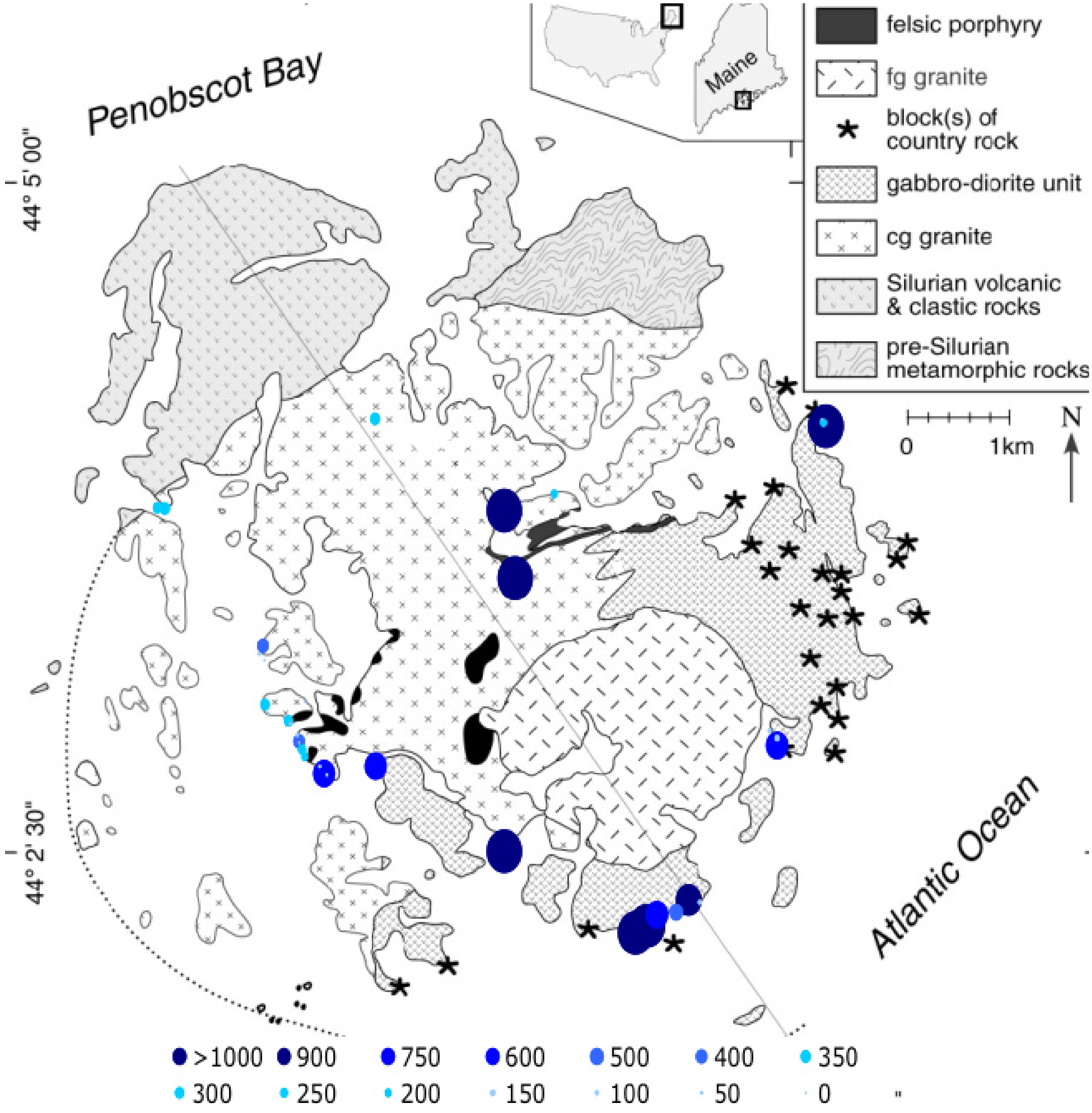

Figure 2. Distribution of large enclaves within the coarse-grained granite. The size of the largest enclave on each outcrop (cm2) is represented by a dot, with larger, darker blue dots corresponding to larger enclaves. Enclaves > 1000 cm2 only occur in close proximity to mafic sheets and/ or porphyry bodies.

The main groundmass crystals for the equant porphyritic enclaves are quartz, plagioclase, and Porphyritic enclaves have a fine-grained groundmass and phenocrysts of perthitic orthoclase, plagioclase, and quartz up to 1 cm long. Porphyritic enclaves can be divided into two categories based on whether the groundmass crystals are equant or elongate. orthoclase. They are the most felsic group of enclaves (color index 2-16). The equant-grained porphyritic enclaves are the only ones that contain rapakivi feldspars (Fig. 3). Enclaves with a higher mafic content would have been more strongly chilled, which would have caused the high aspect ratios in the groundmass crystals (up to 20:1, as opposed to the equant crystals typical of slower cooling in the more felsic porphyritic enclaves). Elongate lathes of plagioclase and amphibole in these enclaves may be arranged in radiating clusters or more randomly (Fig. 4). Mafic rims on quartz phenocrysts (up to 0.3 mm thick) are common, though they vary in thickness and are not present on every quartz phenocryst, even within a single sample.

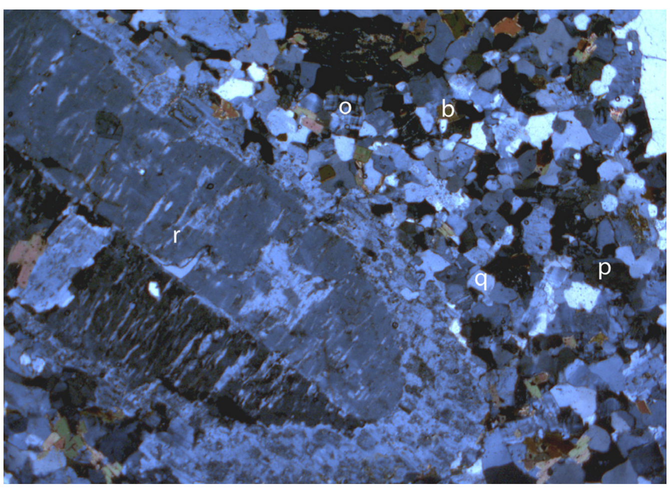

Figure 3. Porphyritic enclave with equant groundmass of quartz (q), plagioclase (p), orthoclase (o), and biotite (b). Note rapakivi feldspar phenocryst (r). Field of view is 5 mm. XPL. Figure 3. Porphyritic enclave with equant groundmass of quartz (q), plagioclase (p), orthoclase (o), and biotite (b). Note rapakivi feldspar phenocryst (r). Field of view is 5 mm. XPL.

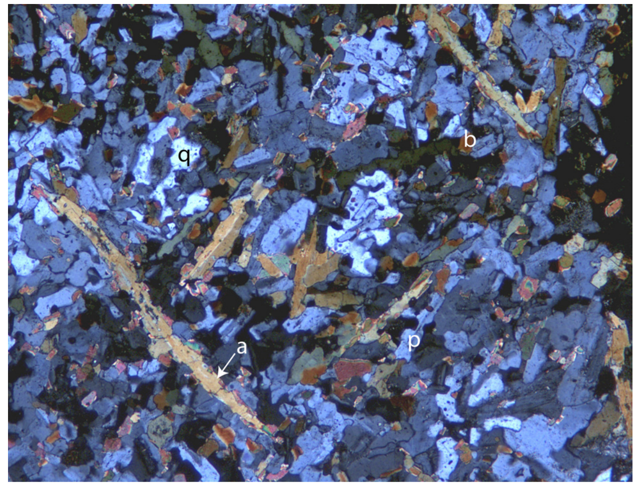

Figure 4. Porphyritic enclave with elongate groundmass of amphibole (a), plagioclase (p), anhedral quartz (q) and equant euhedral biotite (b). Field of view is 5 mm. XPL.

GEOCHEMISTRY

Major and trace element concentrations of enclaves, coarse-grained granites, porphyries, and aplite dikes were analyzed using X-Ray Fluorescence at Franklin and Marshall College. Samples from this study were compared to a database of XRF analyses of hybrid and gabbroic rocks from the Vinalhaven Pluton, also analyzed at Franklin and Marshall College. The coarse-grained granite itself is uniform compositionally throughout the pluton, and samples plot in a tight cluster for most elements (Fig. 5). Coarse-grained granites have 73.8 to 75.4 weight % SiO_2 and 0.2 to 0.4 weight % MgO. Enclaves have 60.0 to 73.0 weight % SiO_2, and 0.5 to 2.5 weight % MgO. The most felsic enclaves (equant-grained porphyritic enclaves) approach granitic compositions, and overlap with the porphyries. They are from some of the highest locations in the chamber (although these locations also contain more mafic enclaves). There is a great deal of chemical variation among the more mafic enclaves (equigranular and elongate-grained porphyritic enclaves), and two enclaves from the same location may differ in, for example, SiO_2, by 5-10 weight %. Enclaves fall broadly along a mixing line between Vinalhaven's granites and gabbros, generally within the geochemical range of hybrid samples. There are several notable exceptions, however, where the more mafic enclaves depart from these trends. They are depleted in K_2O, and enriched in Na_2O.

the mafic sheets; differences in these properties could have caused the geochemical and textural variation exhibited by the enclaves (Wiebe and Collins, 1998). The influx of heat from the mafic injections would have initiated convective currents in the overlying granite; instabilities at

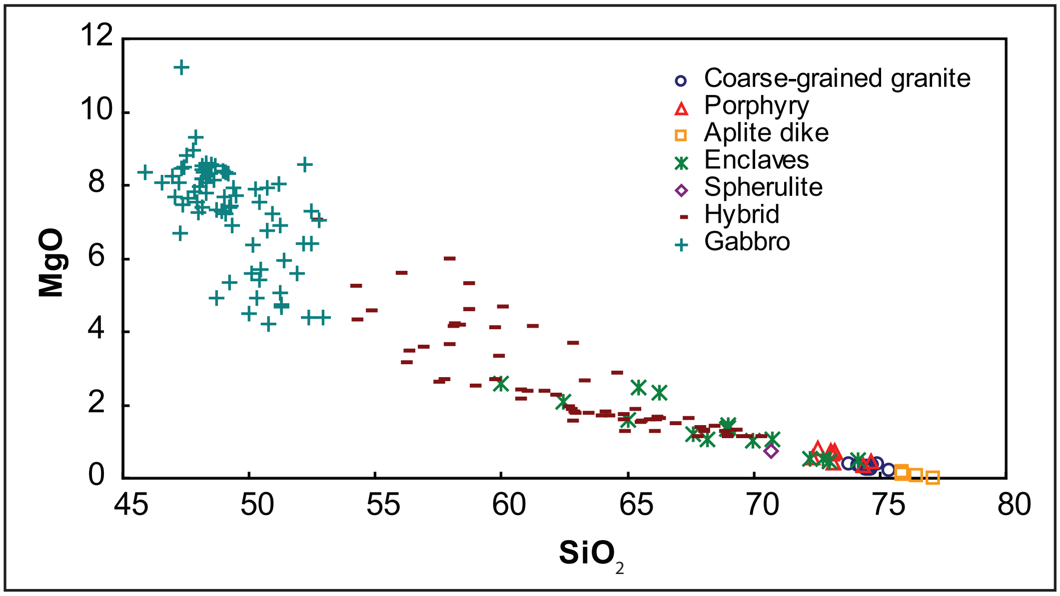

Figure 5. Harker plot for CaO vs. SiO2 (weight percent). Enclaves plot within the mixing trend defined by the progression from gabbros to hybrids, porphyries, granites, and aplite dikes.

DISCUSSION

Field evidence of injections of mafic magma into the Vinalhaven intrusive complex has been documented in previous studies (e.g. Wiebe et al., 2001). When large volumes of mafic magma were injected into the magma chamber, they would have heated the overlying granitic mush enough to allow chemical exchange across the contact between the two layers, resulting in the hybridization of the mafic layer (Wiebe and Collins, 1998). None of the analyzed enclaves were in the compositional range of the gabbros; rather, all but the three most felsic enclaves were in the range of the hybrids (Fig. 5). The initial temperature, composition, and volume of the magma emplaced by each injection would have affected the degree of hybridization of the interface between the two layers could have caused blobs of hybrid magma to be entrained into the granitic unit and transported elsewhere (Wiebe and Collins, 1998).

The close textural and compositional similarities between the equant-grained porphyritic enclaves and larger porphyry bodies suggest a genetic link between the two (Wiebe et al., 2007). Where injections of mafic magma rejuvenated crystal-rich portions of the magmatic system, similar instabilities at the interface between the porphyry and the granite could have caused blobs of porphyry to be entrained into the coarse-grained granite unit (Wiebe et al., 2007). Late in the magmatic system's history, mafic input occurred only on the east side of the intrusion (Hawkins and Wiebe, 2004). Despite this fact, equigranular enclaves and both types of porphyritic enclaves are found at all levels of the intrusion, including far above the last mafic sheet that was emplaced (Fig. 2). Other features that are indicative of magma mixing such as mafic clots, mafic-rimmed quartz crystals, and rapakivi feldspars are also found throughout the coarse-grained granite (Hibbard, 1991). This suggests that large-scale convection occurred throughout the magma chamber(s), even late in their consolidation history. The lack of large porphyritic enclaves far above mafic sheets and porphyry bodies (Fig. 2) suggests that either the convective currents were not strong enough to transport these bodies far from their sources, or that the granite in which they were emplaced was not rheologically strong enough to support them (Wiebe et al., 2007).

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