

CONSTRUCTION OF THE SUBVOLCANIC VINALHAVEN INTRUSIVE COMPLEX, COASTAL MAINE

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INTRODUCTION

Understanding the mechanisms by which granitic intrusions are emplaced and constructed remains an outstanding problem in petrology and structural geology. For much of the twentieth century, granitic intrusions were thought to form from single, slowly-emplaced diapirs of crystal-rich magmas (e.g., Miller & Paterson, 1999). More recently, however, evidence from field, structural, experimental and theoretical studies suggests granitic plutons grow by the rapid emplacement of crystal-poor magma in dikes (e.g., Petford et al., 2000) that deliver magma to crustal intrusions incrementally over 10^5 - 10^6 years (e.g., Coleman et al., 2004). As such, many granitic intrusions are thought to be constructed from successive, ephemeral magma chambers fed by those dikes, a view that is consistent both with magma chambers interpreted to underlie active silicic volcanic systems, and with the time scales of silicic eruptive centers.

The Silurian granitic intrusions in the Coastal Maine Magmatic Province (Hogan and Sinha, 1989) provide ideal field laboratories for studying incremental pluton growth and, particularly, the relationships between magma chambers, magma chamber processes and plutons (e.g., Wiebe 1993, Wiebe et al., 1997). Within this province the Vinalhaven intrusive complex, which is exposed over 80 km² on and around Vinalhaven Island (Fig. 1), stands out for excellent coastal exposures, superb field

examples of magma mingling and mixing, remarkable preservation of physical features that appear to record the position of silicic magma chambers throughout the growth history of the intrusion, and the potential for recognizing evidence for eruptions in plutonic rocks (Wiebe et al., 2001; 2004; 2007; Hawkins and Wiebe, 2004). Two previous Keck projects on Vinalhaven described the geology of the system (Vinalhaven Keck 1998) and led to a general model for the construction of the intrusion (Vinalhaven Keck 2001). The purpose of this Keck project was to refine the construction history of the intrusion.

GEOLOGY OF THE VINALHAVEN INTRUSION

There are four mappable units in the Vinalhaven intrusion. The dominant intrusive unit is coarse-grained biotite granite that occurs along the exposed margins of the intrusion, where it cross-cuts roughly coeval volcanic rocks and older, deformed Paleozoic rocks (Fig. 1). Granite close to this margin contains tourmaline- and epidote-bearing vugs and cavities, suggesting that this part of the intrusion was close to the roof and crystallized late in the history of intrusion (Hawkins and Wiebe, 2004). The second unit within the intrusion is characterized by gabbroic and dioritic rocks that are interlayered and commingled with coarse-grained granite and hybrid rocks (Fig. 1). Gabbro within this gabbro-diorite unit occurs as bodies ranging in

geometry from extensive sheets, typically meters to tens of meters thick and dipping gently (10-30 degrees) toward the interior of the intrusion (Fig. 1), to irregular masses of pillows set in a matrix of granite or hybridized granite to composite dikes (e.g., Wiebe et al., 2001). Mafic sheets typically preserve a single, lower quenched margin that is deformed into load casts and is perforated by magmatic flame structures and pipes (e.g., Webe and Collins, 1998). Thus, the gabbro-diorite unit represents a layered plutonic stratigraphy replete with paleo-up indicators.

The other mappable units in the Vinalhaven intrusion are small intrusions of fine-grained silicic rocks. The third unit consists of intrusions and dikes of fine-grained, generally aphyric or sparsely porphyritic granite, which we interpret as feeders that fed successive silicic magma chambers throughout the construction history. The fourth unit consists of irregular bodies of fine-grained porphyry, typically containing euhedral phenocrysts, as well as embayed and/or rimmed xenocrysts.

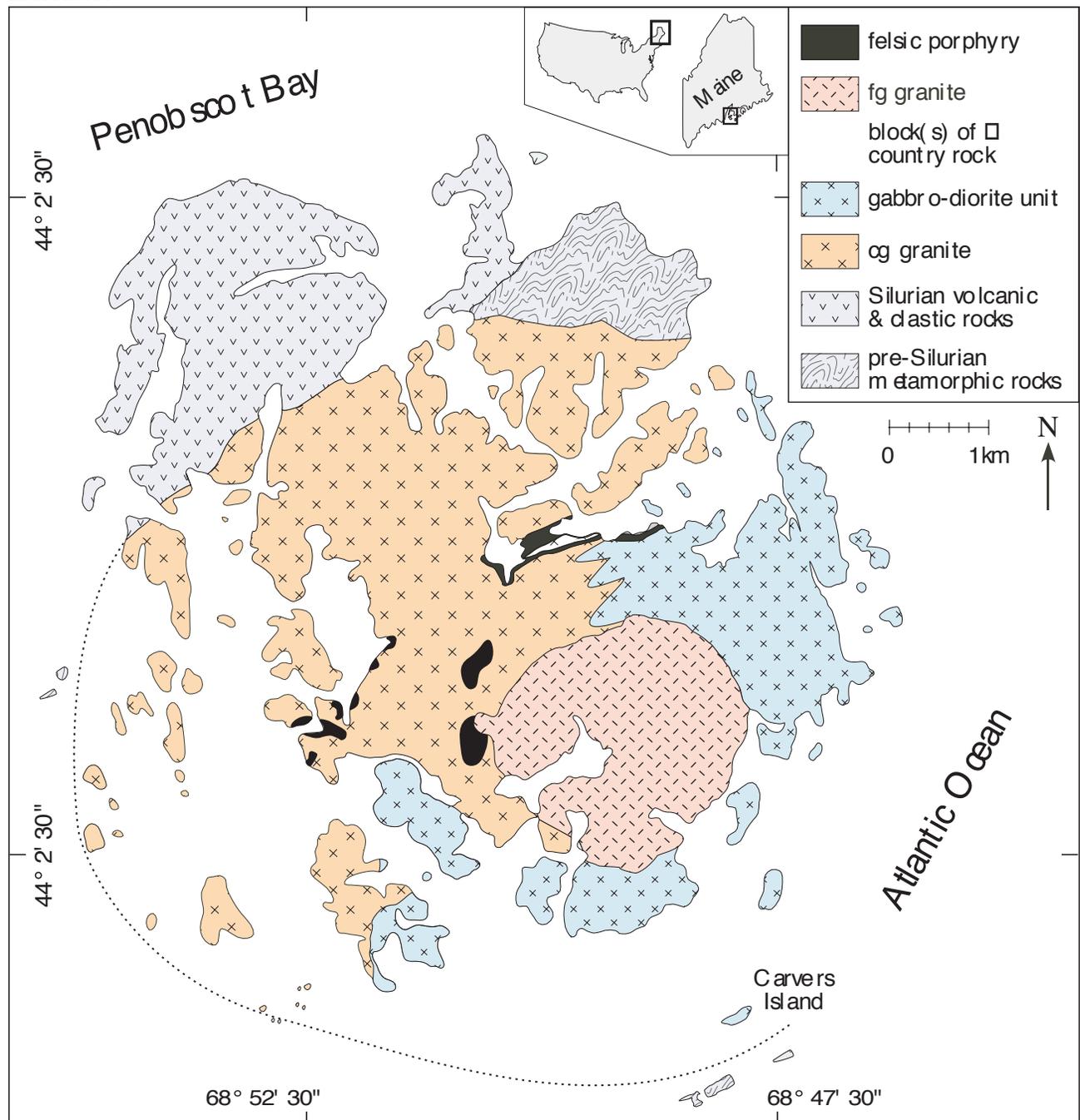


Figure 1: Simplified geologic map of the Vinalhaven complex showing the country rocks, the four main intrusive units, and the location of country rock xenoliths.

These porphyry bodies display sharp to gradational contacts with coarse-grained granite, and are examples of rejuvenated (remelted) and remobilized crystal mush (Wiebe et al., 2004). Some of these porphyry bodies preserve groundmass textures indicative of rapid crystal growth, and perhaps devitrification, possibly reflecting pressure quenching during an eruption from a Vinalhaven magma chamber (Wiebe et al., 2004).

INCREMENTAL CONSTRUCTION OF THE INTRUSION

Field evidence indicates that the Vinalhaven intrusion was constructed incrementally from successive feeder dikes. Fine-grained granite dikes and intrusions, as well as some porphyry intrusions, represent silicic feeders, whereas mafic dikes and plugs that cut mafic sheets represent mafic feeders. The system began as a granitic intrusion, but shortly after the initial magma body was established in the crust, both mafic and felsic magma replenished the system. Felsic magma intruded the system to replenish the existing chamber(s). Mafic magma rose to the rheologic boundary at the floor of the extant magma chamber and then spread out to form a mafic sheet. Interaction of the mafic sheet with granitic mush below and crystal poor granitic melt above resulted in the hybridization of the upper parts of mafic sheets to form hybridized diorite. Successive mafic sheets define the aggradation of magma chamber floors, resulting in a stratigraphic sequence that preserves the growth history of the intrusion over the time interval when mafic magma intruded the system. In the coarse-grained granite, a variety of subtle schlieren, discontinuous trough layering, and schlieren associated with large enclaves, extends this 'stratigraphic record' of magma chambers throughout the intrusion (e.g., Wiebe et al., 2007). This body of field evidence for incremental growth is supported by detailed U-Pb dating of zircons from granite samples

at various stratigraphic positions in the intrusion. The U-Pb ages are consistent with relative stratigraphic ages and indicate that the intrusion was constructed over 0.5 to 1.0 million years (Hawkins and Wiebe, in preparation).

STUDENT PROJECTS

The first few days on Vinalhaven were spent introducing students to the geology of the intrusion and explaining the work completed in previous studies. During this time, the students also learned about the variety of problems that were available and to learn first-hand how those problems related to the many goals of our ongoing research on the intrusion. The resulting student projects addressed the following four goals:

- 1) to further refine the stratigraphy of the layered unit along segments of coastlines;
- 2) to characterize the distribution of enclaves, schlieren, trough layering, and xenocrysts and xenoliths in the coarse-grained granite unit;
- 3) to explore the utility of zoning in zircon crystals to reveal evidence for magma chamber processes; and
- 4) to examine the microstructure of fabrics and deformed rocks that occur locally in the intrusion.

The projects chosen by the students not only complemented previous work on the intrusion, but also provide a firm basis for our future NSF-funded research on both the intrusive and volcanic components of the system. Each student's project is described below.

Stratigraphy of the Gabbro-Diorite Unit

Daniel Hawkins & Nick Cuba chose to study

complex interactions between resident granitic magma and episodic replenishments of basaltic magma in an area of the layered gabbro-diorite unit. Their goal was to clarify the stratigraphy and petrochemistry of a particularly complex sequence of mafic sheets in a several-hundred-meter-thick package that includes one of the thickest mafic sheets in the intrusion, as well as a significant mafic feeder. Daniel's and Nick's detailed field observations, stratigraphic sections, careful petrography, and both whole rock and mineral chemistry will provide a firm basis for correlating mafic sheets across much of the southern coast. As such, their projects will integrate nicely with four comparable studies done in the 1998, two studies completed in 2001 and one project completed by a non-Keck student in 2002.

Distribution of Enclaves in the Coarse-Grained Granite

Alice Colman and Willy Guenther chose to make very detailed observations on the distribution of structures, particularly magmatic enclaves, in the coarse-grained granite unit. At the beginning of their projects, they worked together to develop a consistent procedure for counting and characterizing enclaves, schlieren, xenocrysts and xenoliths per unit area of exposed coarse-grained granite. Then Alice and Willy applied their counting procedure to well-exposed outcrops of granite at different localities, thereby providing detailed observations of granite structures at all stratigraphic levels in the intrusion. This research provides new data that will help us recognize the fossilized remains of silicic magma chambers in the coarse-grained granite and provide an important constraint on the processes that operated in those chambers.

Stratigraphy of Zoned Zircon Crystals

Matthew Hoffman completed a detailed study of the intragrain stratigraphy preserved in zoned zircon crystals from coarse-grained granite col-

lected at three stratigraphic levels in the intrusion: within the gabbro-diorite unit; at the top of the gabbro-diorite unit; and stratigraphically far above the gabbro-diorite unit. He developed a protocol for characterizing the growth history of individual crystals using fundamental stratigraphic principles and applied that protocol to about 40 zircon grains per sample. Matt's results show that obvious (xenocrystic?) cores occur at all stratigraphic levels and that unconformities in the magmatic growth domains, representing time periods of zircon dissolution, are most abundant in granite from the gabbro-diorite. Matt's approach can be utilized to inform future analyses of trace element mineral chemistry for Ti geothermometry, Hf isotope composition, and U-Pb geochronology of the cores.

Intrusive History of a Dike Swarm

Owen McKenna chose to study microstructures in two field localities in the gabbro-diorite unit: a swarm of fine-grained granite dikes that cross-cut coarse-grained granite; and a deformed composite dike in the gabbro-diorite unit. Owen produced detailed outcrop maps of his two field sites, measured fabrics and structures, and collected a suite of oriented samples for both detailed petrography and microstructural analysis. Owen's preliminary results from both localities indicate that deformation probably spanned the rheological transition from crystal mush to solid rock, but a significant component of the deformation occurred in the solid state. Owen's work provides insight into localized structural adjustments during latest stages of the magmatic history and the subsolidus history of the pluton.

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