Growth and Impact of a Mafic–Silicic Layered Intrusion in the Vinalhaven Intrusive Complex, Maine

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ABSTRACT

The Silurian Vinalhaven intrusive complex (VIC) is dominated by granite with subordinate gabbrodiorite. It was emplaced at a shallow crustal level (1–2 kbar) into pre-Silurian metamorphic rocks and apparently cogenetic basalts and high-silica rhyolite. The main granite body is about 12 km in diameter and includes a 1 km thick section of inward-dipping, originally subhorizontal, gabbrodiorite sheets that extend more than 10 km along strike, creating a mafic–silicic layered intrusion (MASLI). Fine-grained granite dikes are probably feeders for the silicic magma chamber, and basaltic dikes are probably feeders for the gabbroic sheets. Gabbroic rocks form the bases of macrorhythmic layers from 10 to 150 m thick that grade upward from chilled gabbro through gabbroic cumulates to hybrid rocks and granite; many layers can be traced for several kilometers. Abundant country rock blocks (up to 100 m) occur at many levels within the MASLI. The granite has widespread arcuate schlieren and settled enclaves, which define aggrading magma chamber floors and suggest a depositional origin for most granite below, within and above the MASLI. Mafic magmas are equivalent to low-K tholeiites, and silicic magmas are comparable with high-silica rhyolites (72–78% SiO\textsubscript{2}). Compositional variation in the MASLI reflects both hybridization with granite and crystal accumulation at the base of a compositionally zoned magma chamber. Mafic input heated and enhanced convection in the felsic magma chamber and locally rejuvenated older granite, producing a porphyry that crystallized at higher T and lower H\textsubscript{2}O contents. Thermal arguments suggest that the thickness of the silicic magma chamber was at least hundreds of meters, and perhaps as much as 1 km. Because the extent of the basaltic sheets approached 75 km\textsuperscript{2}, at times the volume of eruptible silicic magma ranged from 10s of km\textsuperscript{3} to 100 km\textsuperscript{3}. The VIC provides a possible smaller-scale template for the magmatic plumbing system beneath large bimodal volcanic systems such as Yellowstone.

Key words: granite; gabbrodiorite; mafic–silicic layered intrusion; magma chamber; fractional crystallization

INTRODUCTION

One goal of igneous petrology is to establish discrete connections between processes in volcanic and plutonic systems (Metcalf, 2004; Bachmann \textit{et al}., 2007). Volcanic studies have long suggested that mafic input into silicic magma chambers is an important process that commonly triggers eruptions (Sparks \& Sigurdsson, 1977; Pallister \textit{et al}., 1992), rejuvenates solidified felsic magma chambers (Molloy \textit{et al}., 2008; Simon \textit{et al}., 2014) and keeps large silicic systems active over millions of years (Hildreth \textit{et al}., 1991). Recent recognition that plutonic bodies have commonly grown by multiple inputs of compositionally varied magmas over an extended time period has brought plutonic processes and time-scales more in line with those of known volcanic systems (e.g. Wiebe, 1974,
Evidence that mafic magma was injected into a more felsic magma chamber as a layer on a chamber floor was first recognized in a small diorite-gabbro intrusion in which layers of marginally chilled gabbro within dioritic cumulates were termed ‘intramagmatic lava flows’ (Wiebe, 1974). Since then, many examples of interlayered mafic and felsic rocks have been recognized (e.g. Chapman & Rhodes, 1992; Harper et al., 2004; Kamiyama et al., 2007; Turnbull et al., 2010) and have been termed mafic–silicic layered intrusions (MASLI) (Wiebe, 1993a). Wiebe & Collins (1998) proposed criteria for recognizing the key process operating in MASLI formed by emplacement of basaltic magma onto a floored silicic magma chamber. These features include a chilled base of a gabbroic layer overlying a less dense, more felsic and more coarse-grained rock. The resulting density inversion causes the mafic layer to tend to sag downward and deform the underlying layer (commonly molding around underlying crystals) and causes upwelling of the underlying less dense material (crystal mush) in the form of flame structures (interstitial liquid from the crystal mush) as well as crystal-rich material in felsic, pipe-like bodies that penetrate the overlying mafic layer before it solidified. These pipes generally record the vertical direction when they formed and are nearly always approximately perpendicular to the mafic layer, indicating that the layer was emplaced subhorizontally.

The Silurian shallow-level, bimodal plutons of the Coastal Maine Magmatic Province and their associated volcanic rocks (mostly high-SiO₂ rhyolite and subordinately basalt) are some of the best-exposed and most accessible systems showing extensive commingling of granite and basalt. These include the Isle au Haut igneous complex (Chapman & Rhodes, 1992; Patwardhan & Marsh, 2011), the Pleasant Bay intrusion (Wiebe, 1993b) and the Cadillac Mountain intrusive complex (Wiebe, 1994). The Vinalhaven intrusive complex (VIC) is a comparable system with some special attributes. Unlike the other bodies, the VIC has excellent coastal outcrops that permitted detailed mapping and sampling of multiple sections through thick and extensive macrocrystalline gabbrodiorite layers. In addition, tilting and erosion of the pluton has exposed the roof of the VIC where granite intrudes its marginally older volcanic carapace. The VIC also preserves many examples of silicic magma rejuvenation owing to basaltic input. Our published work on Vinalhaven has focused on several aspects of the intrusion. Wiebe et al. (2001) studied delta-like accumulations of mafic sheets, tubes and pillows in granite. A study of extensive zones of stoped roof rocks, closely associated with the mafic sheets, suggested that eruptive episodes occurred at the same time as mafic input (Hawkins & Wiebe, 2004). Finally, two publications examined evidence for rejuvenation of the Vinalhaven granite: a detailed study of the largest porphyry body, which was produced by interactions between unconsolidated granite and a large basaltic dike (Wiebe et al., 2004), and a systematic study of CL and Ti zoning in quartz, which demonstrated that quartz in both the coarse-grained granite and the porphyry recorded significant episodes of dissolution and subsequent crystallization at higher temperatures from an H₂O-undersaturated melt (Wiebe et al., 2007b). In this study we focus on the construction of the MASLI within the VIC as well as the impact of basaltic replenishments on the host silicic magma and granite.

GEOLOGICAL SETTING AND PRIOR WORK

Vinalhaven Island (128 km²) is located in southern Penobscot Bay, about 15 km east of Rockland, Maine (Fig. 1). The plutonic rocks on Vinalhaven belong to the Coastal Maine Magmatic Province (Hogan & Sinha, 1989), an association of more than 100 plutons, formerly known as the Bays of Maine Complex (Chapman, 1962). These plutons intruded parallel to NE–SW-trending fault-bounded terranes in the Late Silurian to Early Carboniferous (Hogan & Sinha, 1989). The terranes consist primarily of pre-Devonian meta-volcanic and meta-sedimentary rocks and are thought to be peri-Gondwana continental microplates (Ganderia, Avalon, Meguma) that accreted onto Laurentia during the Acadian Orogeny and closure of the Iapetus and Rheic ocean basins (e.g. Tucker et al., 2001; Murphy et al., 2011).

The tectonic setting of the magmatism that produced these plutons remains elusive. The bimodal nature of the plutons and associated volcanic rocks (Hogan & Sinha, 1989), the geochemical composition of the plutonic and volcanic rocks (e.g. Seaman et al., 1999; Wobus et al., 2006), the regional occurrence of Middle Silurian to Early Devonian strike-slip fault systems, and paleostructural plate reconstructions (e.g. Murphy et al., 2011) suggest a tectonic setting involving a back-arc basin, oblique subduction or oblique extension, and the geochemical contribution to mafic rock compositions of both lithospheric and asthenospheric mantle source components (e.g. Murphy et al., 2011).

The Vinalhaven plutonic rocks are typical of the bimodal complexes in the Coastal Maine Magmatic province, most of which exhibit well-preserved field evidence for mingling of mafic and silicic magmas. Gravity studies suggest that the exposed granitic plutons in the province are only a few kilometers thick, and lie above mafic rocks (Hodge et al., 1982), although it appears likely for several complexes that more granitic rocks occur at depth beneath the mafic rocks. Gravity studies of the Vinalhaven intrusion also suggest that mafic rocks exposed at the surface dip beneath the granite (Riley & Markley, 2007).
Rocks of the Vinalhaven Intrusive Complex (VIC) were first described by Smith et al. (1907), who recognized the close association of mafic and felsic plutonic rocks. More recently, Mitchell & Rhodes (1989) demonstrated that the mafic and felsic rocks were contemporaneous and characterized their geochemistry. Gates (2001) produced a bedrock geological map of North Haven and Vinalhaven Islands, which provided a valuable base for recent detailed petrological studies of the VIC (Wiebe et al., 2001, 2004, 2007a, 2007b; Hawkins & Wiebe, 2004; Beane & Wiebe, 2012).

Fig. 1. Geological map of Vinalhaven Island. Pre-Silurian rocks exposed along the NE margin of the VIC are strongly foliated metamorphic rocks of the Calderwood Formation. Silurian, mostly unfoliated, rocks exposed along the coast include siliciclastic rocks of the Seal Cove Formation and volcanic and volcanioclastic rocks of the Vinalhaven rhyolite. Locations mentioned in the text: AN, Arey Neck; B, The Basin; BW, Big White Island; Cl, Carvers Island; CN, Coombs Neck; CP, Calderwood Point; DP, Dog Point; DY, Dyer Island; Gl, Greens Island; IR, Indian River; Li, Lanes Island; NI, Narrows Island; OH, Old Harbor; PI, Penobscot Island; RH, Roberts Harbor; SI, Sheep Island; VC, Vinal Cove. Modified after Gates (2001).

The VIC was emplaced into early Paleozoic deformed, low-grade schists of the Calderwood Formation and, along its northwestern margin, into essentially undeformed Silurian sedimentary and volcanic rocks, which appear to contain eruptive products cogenetic with the intrusion (Fig. 1). Contact metamorphism is well developed in the country rocks along the northern and northwestern sides of the intrusion, and post-magmatic hydrothermal assemblages occur throughout the intrusion as discrete veins and on some joint surfaces. Although the rocks form a gently
dipping structural basin, there is little evidence for regional deformation or metamorphism subsequent to cooling of the intrusion. Primary igneous field relationships, textures and mineral compositions are remarkably well preserved (e.g. Wiebe et al., 2007a).

The VIC consists of three main map units (Fig. 1). The most extensive unit is coarse-grained granite that forms the core of the island and is in contact along its northern (upper) margin with country rocks. At several locations, small bodies of porphyry occur within this granite and have contacts that range from sharp to gradational over several meters. One body of porphyry is associated with and locally commingled with a large basaltic dike (Wiebe et al., 2004). The second largest unit is gabbrodiorite, which consists of interlayered mafic, hybrid, and granitic rocks (MASLI) (Fig. 1). It forms a curved, sheet-like body, hundreds of meters to more than 1 km thick, which dips 10–30° to the north and west beneath coarse-grained granite. The gabbrodiorite unit also rests on granitic rocks that are more than 1 km thick, which dips 10–30° to the country rock in the northern part of the island, occur in association with the gabbrodiorite unit (Hawkins & Wiebe, 2004). These xenoliths contain pelitic metamorphic mineral assemblages (including andalusite + spinel) consistent with pressures between 1 and 2 kbar (Porter et al., 1999). The third unit of the VIC is an equant body of fine-grained granite that forms a small inner core to the complex. This body cuts the gabbrodiorite unit and coarse-grained granitic rocks sharply along most of its periphery; only along the northern boundary of the fine-grained granite does the contact with coarse-grained granite appear to be gradational, exhibiting mingling and exchange of crystals.

The VIC intrudes bimodal volcanic rocks along its NW margin (Fig. 1). The volcanic section consists of early basaltic flows and sills (the Vinalhaven diabase) and later ash-flow tuffs and flow-banded rhyolite flows or domes with associated air-fall and block-and-ash-flow tuffs (Wobus et al., 2006). High-precision U–Pb zircon ages of the VIC and associated volcanic rocks indicate that the exposed portions of the pluton were emplaced over c. 0.7 Myr at about 419 Ma, whereas the exposed volcanic section erupted over at least 0.5 Myr at 421 Ma (Hawkins et al., 2009). Hawkins et al. (2009) used geological, petrological, geochemical and geochronological evidence to suggest that the gap in age between the intrusion and the volcanic section reflected incomplete preservation of the volcanic section and incomplete exposure of the intrusion, rather than a lack of consanguinity, and that the intrusion was constructed over about 2.0 Myr between 421 and 419 Ma.

FIELD RELATIONS

Coarse-grained granite

Coarse-grained granite dominates the northwestern half of the VIC, appears to occur along the margin of the entire VIC, and is interlayered with mafic and intermediate rocks of the gabbrodiorite unit. In various areas it both locally grades into and is cut sharply by porphyry and fine-grained granite. Although the coarse-grained granite is largely homogeneous and lacks strong planar or linear fabrics, it has irregularly distributed enclaves, schlieren and texturally heterogeneous areas, and is cut by contemporaneous silicic dikes (Fig. 2). These features are well exposed in the northern third of Greens Island (Fig. 1) where the granitic rocks are texturally heterogeneous on the scale of meters to tens of meters with highly irregular intermingling of coarse-grained granite and porphyries with varying percentages of phenocrysts.

Enclaves

Mafic, intermediate and felsic enclaves of various sizes occur in much of the coarse-grained granite. The most common and widely distributed are fine-grained mafic enclaves, 2–10 mm in diameter. These enclaves vary in abundance from a trace amount up to 1%; areas of granite with the higher abundances occur both near and far from the gabbrodiorite unit. Larger mafic enclaves, up to 20 cm in diameter, typically with chilled margins, occur only within tens of meters above the top of the gabbrodiorite unit (Wiebe et al., 2008). Felsic enclaves occur widely but sparsely in coarse-grained granite. They are comparable in composition and texture with the mapped bodies of porphyry and range in size from about 20 cm to 1 m. Inclusions of leucogranite comparable in texture and composition with the host granite range in size from ~1 m to more than 4 m. Many felsic enclaves and granite inclusions are associated with steep arcuate to cylindrical schlieren (Wiebe et al., 2007a).

Planar to arcuate schlieren

Gently dipping groups of planar to arcuate schlieren occur widely but sparsely in the granite. The schlieren are thin (typically less than 1 cm thick) uniform, graded or cross-bedded layers enriched in ferromagnesian minerals relative to the surrounding coarse-grained granite (Wiebe et al., 2007a). They closely resemble similar features widely reported in other granites (e.g. Gilbert, 1906; Emelens, 1963; McCarthy & Groves, 1979; Wahrhaftig, 1979). These distinctive schlieren layers are particularly well developed within 100 m of the southwestern margin of the granite, where they typically dip inward at ~30°.

Porphyry

Porphyry occurs as discrete mappable bodies as well a component of restricted areas of texturally heterogeneous granite (Fig. 2). The largest mapped body of porphyry, associated with a 60 m thick basaltic dike, has been described in detail (Wiebe et al., 2004). Contacts between all porphyry bodies and the enclosing coarse-grained granite are typically gradational over a few
centimeters and commonly highly irregular with mutually intrusive relations. Single mapped bodies of porphyry north of Greens Island (Fig. 1) have contacts with coarse-grained granite that are gradational toward the interior of the intrusion and sharply cross-cutting where the porphyry extends towards the western contact, suggesting that the coarse-grained granite was more completely crystallized toward the western margin of the intrusion when the porphyry was emplaced. All the mappable bodies of porphyry (Fig. 1) occur in coarse-grained granite above the gabbronorite unit.

Fine-grained granite

Fine-grained granite occurs as a single, mappable body (Fig. 1) that sharply cuts coarse-grained granite and the gabbrodiorite unit. Most exposures of this granite (mainly in quarries) are homogeneous and massive and free of inclusions; some coastal exposures show commingling between somewhat coarser and finer granites. Fine-grained granite dikes up to several meters in width cut coarse-grained granite near the western boundary of the fine-grained granite body. Many dikes, up to 20 m thick, sharply cut coarse-grained granite and the gabbrodiorite unit in exposures along the coast, most abundantly from Lanes Island to Narrows Island (Fig. 1). One dike of fine-grained granite cuts sharply through coarse-grained granite and is deformed and truncated by schlieren inward toward the pluton interior.

Gabbrodiorite unit

The gabbrodiorite unit occurs as an arcuate body that extends about 12 km along strike from the southern to the eastern coastline of Vinalhaven Island (Fig. 1). Most of the gabbrodiorite unit can be subdivided into macrorhythmic layers, each of which has a strongly chilled gabbroic base against the underlying rock; many grade upward to more evolved rocks ranging from diorite to granite. These macrorhythmic layers appear to form a stratigraphic sequence that is cut, at a number of locations, by mafic, silicic, and composite dikes (chilled basaltic pillows in fine-grained granite).

Macrorhythmic layers

A typical macrorhythmic layer is thicker than a few tens of meters and generally grades upward at some level to dioritic rocks (containing abundant felsic xenocrysts and other evidence for incomplete mixing between mafic and felsic magmas) and coarse-grained granite. Some of the thickest layers can be traced laterally for...
more than 3 km. The top of each layer is marked by the chilled gabbroic base of the overlying layer. The lithology at the top of a layer may vary from evolved gabbro to granite. The thickness of measured macrorhythmic layers ranges from about 5 to 150 m and averages about 60 m. The upward transition from chilled basaltic base to overlying coarse-grained granite may be gradational over tens of meters or relatively abrupt. Locally, the top of the gabbrodiorite map unit, beneath overlying coarse-grained granite, is marked by strongly chilled sheets, tubes and pillows of basalt in granite.

The chilled bases of macrorhythmic layers vary from nearly planar to highly convolute. They are typically nearly planar where the top of the underlying layer is mafic to intermediate in composition and highly convolute where the chilled base rests on a thick (1 to >100 m) section of coarse-grained granite (Fig. 3a and b). Granite beneath the bases of macrorhythmic layers was commonly remobilized and intruded the bases of layers as diapiric pipes and sheets ranging in width from a few centimeters to several meters (Fig. 3). Country rock blocks occur widely within the gabbrodiorite unit (Fig. 1). They typically range in size from several tens of meters to a few centimeters, although some are at least 200 m in length. Blocks are most abundant within the upper granitic portions of the layers, although chilled mafic layers commonly occur on top of country rock blocks (Hawkins & Wiebe, 2004).

Extensive accumulations of pillows, tubes and thin (<50 cm) sheets occur widely in the gabbrodiorite unit (Wiebe et al., 2001), especially at the base of some macrorhythmic layers and laterally where layers thin at their outer margins; for example, the thick macrorhythmic layer 2 near the bases of sections A–D (Figs 4 and 5). The pillow mounds are characteristically built initially of subhorizontal sheets and tubes; sheets and tubes that accumulate above the base steepen, commonly abruptly, to dips approaching 70° and may build outward at that attitude for more than 10 m, producing cross-bedded, deltaic accumulation of pillows [see fig. 3b of Wiebe et al. (2001)].

Mafic layers dip gently (5–30°) inward beneath coarse-grained granite. Commonly, thin vertical sheets of granite or linear rows of steep granitic pipes trend in the dip direction, separating the trough-like chilled gabbroic bases of the layers. In 2D sections perpendicular to the dip, the basal contact of chilled basalt on granite resembles multiple sedimentary load cast structures; where 3D exposures permit, it is possible to see that

Fig. 3. Field photographs of granitic diapiric bodies cutting the bases of macrorhythmic layers. (a) Distant view of base of gabbroic layer resting on coarse-grained granite. (b) Close-up view of the same contact, showing diapiric upwellings of granite extending more than 10 m upward into the gabbroic layer. (c) Thin felsic pipes connected to felsic top of underlying macrorhythmic layer. (d) Three-dimensional exposures of a cluster of coarse-grained granitic pipes in gabbro on Greens Island.
they are actually sections through basal fingers, tubes or lenses. These linear zones probably record the direction of flow (Snyder & Tait, 1995). Overall, the attitudes of the macrorhythmic layers define an inward-dipping basinal structure. Granitic pipes are approximately perpendicular to the layers.

**Stratigraphy of the gabbrodiorite unit**

The internal structure and lithological variation of the gabbrodiorite unit provide a stratigraphic framework for understanding its growth and development. The most probable correlation between measured sections occurs from section A to D (Figs 4 and 5). Here the base of layer 2 rests on granite that contains abundant country rock blocks. This correlation is further supported by the presence of an ~20 m thick feeder dike (see below) very close to section B, where the layer is thickest (Fig. 5). In these sections blocks of country rock are absent in the overlying macrorhythmic layers except at the granitic top of a macrorhythmic layer in section D (Fig. 5). The uppermost layers in sections B–D are truncated by the younger fine-grained granite body.

West of section A the gabbrodiorite unit terminates in two thick, gently dipping lenses separated by coarse-grained granite (Fig. 4). The southern lens on Greens Island rests on coarse-grained granite with large (tens of meters in diameter) country rock blocks and appears to be a single layer that correlates with the gabbro on Lanes Island and the lowest layer in sections A–D. The upper boundary of this layer dips gently NW (5–10°) beneath coarse-grained granite. Two isolated areas of gabbroic rocks occur to the north at a higher level in granite along the NE coast of Greens Island. The smaller area has a strongly chilled, arcuate base against the underlying granite that plunges northward; the larger area lacks a chilled margin. Both of these may be fragments of mafic rocks that foundered into the granite from the overlying northern lens. Outcrops of the more northerly (upper) lens on Vinalhaven Island are much more extensive and indicate that it also rests on coarse-grained granite, which lacks country rock blocks and dips NE at 20–30°. This lens consists of many smaller macrorhythmic layers and contains extensive areas dominated by tightly packed basaltic sheets, tubes and pillows, typically less than 1 m thick (Fig. 6). The upper boundary of this package of layers dips gently NW to NE beneath coarse-grained granite; it may correlate with the transition from gabbrodiorite to granite at the top of section A.

Nearly all of the small islands and ledges within 500 m SE of the bases of sections A–D consist of metamorphic country rocks (Fig. 4). Large country rock blocks (up to 80 m) also occur for about 500 m along the Vinalhaven coast just east of section D, and limited inland exposures suggest that they continue inland.

![Detailed geological map of the gabbrodiorite unit. The location of measured stratigraphic sections (A–F) shown in Figs 5, 8 and 11 should be noted.](https://academic.oup.com/petrology/article-abstract/56/2/273/2380135)
and to the north. These occurrences suggest that a band of country rock blocks of the order of 500 m wide separates an upper series of layers (section D to Greens Island) from a lower sequence of layers (sections E and F). Two large islands further offshore from sections A–D (Sheep and Carvers islands; Fig. 1) lack country rock blocks and are dominated by macrorhythmic layers of gabbroic and dioritic rocks cut by diapiric bodies (tens of meters wide) of coarse-grained granite, which indicate that a thick layer of coarse-grained
granitic crystal mush occurred beneath the mafic layers when they were emplaced.

Sections E and F consist of a few thick macrorhythmic units dominated by gabbro and intermediate rocks that appear to underlie the country rock blocks at the base of sections A–D. The base of these sections rests on coarse-grained granite containing numerous country rock blocks ranging in size from a few centimeters to 30 m. The islands east of sections E and F appear to expose underlying macrorhythmic layers composed of gabbro, intermediate rocks and granite. Country rock blocks as large as several tens of meters are common, indicating that these blocks occur at several discrete stratigraphic intervals in the gabbrodiorite unit. Macrorhythmic layers on these islands dip westward, consistent with those on the main island. North of section F, layers thin toward the northern termination of the gabbrodiorite, where they are truncated by diapiric bodies of coarse-grained granite.

The broad inland area of gabbrodiorite west of sections E and F to the area north of the fine-grained granite body is poorly exposed. Scarce outcrops of mafic rocks are fine- to medium-grained gabbro and appear to lack compositionally graded layers. Nearly vertical granitic pipes (10–12 cm in diameter) occur in one outcrop of gabbro and indicate nearly horizontal layering and the presence of granite beneath gabbroic rocks. North of the fine-grained granite body, some strongly chilled gabbroic layers rest on coarse-grained granite and grade upward to dioritic and granitic rocks typical of macrorhythmic layers exposed along the southern coast. These layers clearly interfinger with coarse-grained granite and terminate to the west. Exposures of country rock in the broad area mapped as gabbrodiorite are common in an ~500 m wide band that extends from the coast (Fig. 4, between the base of section D and the top of section E), but still only as scattered outcrops, typically at higher elevations. Attitudes of layering in the country rock blocks appear to be random, so it is unlikely that the area is a 100% country rock [as mapped by Gates (2001)]. It seems most likely that the country rock occurs as large blocks comparable with those exposed along the coast (up to ~80 m) within mafic rocks of the gabbrodiorite unit.

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The highest macrorhythmic layers, exposed on two small islands south of Penobscot Island (Fig. 1), dip gently to the north and define an ~90° arc of about 1 km radius (see also Fig. 4). Immediately above the gabbrodiorite unit, coarse-grained granite is locally heterogeneous and contains lensoid, meter-long enclaves of felsic to intermediate porphyry with gradational contacts with the granite host. Country rock blocks (up to 15 m) occur locally along the upper contact of the gabbrodiorite unit.

**Dikes that cut the gabbrodiorite unit**

Dikes of fine-grained granite, basalt and composite dikes of chilled basalt in fine-grained granite cut the gabbrodiorite widely; no dikes with intermediate
compositions were observed. A number of basaltic dikes (typically 1–3 m thick) cut the gabbrudiorite unit; they rarely occur outside that unit in granite. One large gabbrudoric dike cuts steeply through and remobilizes commingled granitic, hybrid and mafic rocks beneath layer 2 of section B (Fig. 5). It is exposed along the shore for about 50 m and has a width of about 20 m. These lengths represent the minimum dimensions as the dike extends offshore beyond low tide. The dike is curved: over much of its length, it trends roughly east–west and dips about $60^\circ$ S, but at the western end of the exposure it trends N40E and dips more steeply to the SE. Thin, straight, granitic pipes, about 2–3 cm in diameter, penetrate this curved boundary with a consistent southward plunge of about $80^\circ$ (Fig. 7). The orientation of the pipes indicates a post-emplacement rotation of about $10^\circ$ to the north, which is consistent with the gentle northward dips of the macrorhythmic layers. Because these pipes approximate vertical at the time of emplacement, this dike was also approximately vertical.

Composite dikes consisting of chilled basaltic pillows in fine-grained granite cut the gabbrudiorite unit at several locations within the lowest macrorhythmic layer of sections A–D (Fig. 5). The two largest bodies extend more than 100 m along the shore and have minimum thicknesses of about 10 m. Their compositions closely match those of homogeneous granitic and basaltic dikes (see below). Granite consistently occupies the margins of the dikes, indicating that emplacement of granitic magma initiated the dike. Basaltic pillows are typically molded against each other and separated by thin (<1 cm) seams of granite and typically form up to 80–90% of the dike volume, as commonly observed in other composite dikes (e.g. Snyder et al., 1997).

PETROGRAPHY

Felsic rocks
The felsic rocks were the focus of detailed earlier studies (Wiebe et al., 2004, 2007a, 2007b; Beane & Wiebe, 2012). Thorough descriptions of coarse-grained granite, fine-grained granite and porphyry have been given by Wiebe et al. (2007b), who also provided a detailed study of cathodoluminescence (CL) and Ti zoning in quartz. All three rock types have the composition of granite—slightly dominated by alkali-feldspar and quartz with subordinate plagioclase and a color index (CI) generally <5, including biotite and accessory Fe–Ti oxides, allanite, apatite, titanite and zircon. Porphyry typically has partly resorbed phenocrysts with sizes and compositions comparable with those of crystals in coarse-grained granite and a very fine-grained matrix. CL and Ti zoning in quartz (Wiebe et al., 2007b) indicate complex oscillatory zoning with resorption episodes in both coarse-grained granite and porphyry, in contrast to simple normal zoning of quartz in fine-grained granite. CL zoning in rounded quartz in porphyry typically has bright narrow rims (high Ti) that truncate internal zoning.

Gabbrudiorite unit

Gabbroic rocks
Gabbroic rocks have massive textures and range from very fine- to medium-grained with tabular, normally zoned plagioclase (An$_{10-35}$), augite, olivine and Fe–Ti oxides. Chilled rocks are characterized by basaltic textures with radiating sprays of plagioclase of high aspect ratio. Some chilled rocks have spherulitic intergrowths of plagioclase and olivine. Although hornblende and biotite are minor phases in most gabbroic rocks, they are locally the dominant mafic phases where gabbro is in contact with granitic rocks. In the coarser-grained interior of gabbroic dikes, plagioclase up to 2 mm in length occurs with smaller equant olivine and poikilitic augite up to 4 mm in diameter. Some strongly chilled basal margins of macrorhythmic layers contain xenocrysts of sieve-textured sodic plagioclase with small augite blebs and equant quartz with augite or hornblende rims. Transitions upward from chilled basal margin to cumulate gabbro are commonly heterogeneous texturally, with irregularly distributed coarser- and finer-grained areas.

Pillow margins are sharply chilled and commonly have crenulate, convex-outward projections against the matrix. In thin-section, their textures are
characterized by skeletal and radiating clusters of plagioclase with variable proportions of hornblende and augite. Towards the center of most pillows, grain size and the amount of pyroxene increases, and the amount of hornblende decreases. Fine-grained gabbroic rocks of pillow interiors contain much less hornblende and consist primarily of thin laths of normally zoned (An75–20) euhedral plagioclase, equant olivine crystals and anhedral augite. Plagioclase laths commonly occur in radiating clusters with augite, exhibiting a subophitic texture. Minor interstitial orthopyroxene, biotite and/or hornblende, and opaque minerals are also present. Subsolidus alteration products (e.g. chlorite, epidote) are scarce to absent in most gabbroic rocks.

Intermediate rocks

Intermediate rocks with CI between 15 and 30 typically have fine-grained, granular textures dominated by plagioclase (An90–20) and hornblende with varying amounts of biotite and Fe-Ti oxides, and contain some finer-grained mafic clots. Xenocrysts of equant quartz occur commonly, typically with rims of hornblende, and sodic plagioclase (An25–20) and alkali feldspar, typically highly corroded, occur both as isolated crystals and as cores to intermediate plagioclase. Granitic patches up to 1 cm in diameter are heterogeneously distributed in some layers, making up 5–15 modal % of the rock. Textures of the intermediate rocks may vary widely in a single thin-section—from more fine-grained mafic areas with granitic xenocrysts to more coarser-grained, more felsic areas. Some samples have highly variable plagioclase compositions and zonal patterns. For example, larger, weakly zoned, sodic plagioclase grains with or without a more calcic rim occur in the same thin-section as smaller, and more tabular calcic plagioclase with strong normal zoning. Larger alkali-feldspar crystals occur sparsely in some hybrid rocks. These intermediate rocks grade upward over distances of several meters to typical coarse-grained granite at the tops of many macrorhythmic layers.

Mineral and modal variations in macrorhythmic layers

Modal analyses of samples from five of the measured stratigraphic sections demonstrate the extreme variation in mineralogy of the macrorhythmic layers (Fig. 8 and Supplementary Data Electronic Appendix 1; supplementary data are available for downloading at http://www.petrology.oxfordjournals.org). Gabbroic rocks dominate the sections, and some layers lack an upper intermediate or granitic component. In general, augite and olivine are the dominant mafic minerals in the lower gabbroic parts of the layers, where color index is about 40 and ranges between 30 and 70. Typically, the modal per cent of olivine increases upward above the chilled base from about 10% to as much as 30% and then olivine disappears upward. Orthopyroxene in most sections is only a minor phase, but is more abundant in the lowest layer in section A and throughout section F. The chilled bases of some layers are enriched in biotite relative to the overlying coarser-grained gabbroic rocks, and some chilled bases contain corroded equant quartz rimmed by hornblende. Upward in sections where color index declines to <25, hornblende and biotite are the dominant ferromagnesian minerals. These intermediate rocks have plagioclase of intermediate composition, but also commonly contain larger, corroded crystals of sodic plagioclase, apparently xenocrysts derived from granite. Alkali feldspar (not shown in Fig. 8) and quartz occur in the upper parts of most layers, and the transition from olivine- to quartz-bearing rocks is relatively abrupt, commonly <5 m.

WHOLE-ROCK GEOCHEMISTRY

Analytical methods

Whole-rock samples were analyzed for major and some trace elements by X-ray fluorescence (XRF) at Franklin and Marshall College using a Philips 2404 XRF vacuum spectrometer equipped with a 4 kW Rh X-ray tube. For major element analysis nine parts Li2B4O7 were mixed with one part rock powder and fused into a homogeneous glass disc. Working curves were determined by analyzing 51 geochemical rock standards, data for each having been compiled by Govindaraju (1984). Analytical errors associated with measuring major element concentrations range from <1% for Si and Al to ~3% for Na. Trace element briquettes were prepared by mixing 7000 g of whole-rock powder with 14000 g of pure microcrystalline cellulose. Analytical errors for the trace elements range from 1–2% for Rb, Sr, Y, Zr, etc., to 5–6% for Ba. All XRF data are listed in Supplementary Data Electronic Appendix 2. Most rare earth elements (REE) and several other trace elements were analyzed by laser ablation inductively coupled plasma mass spectrometry in glass discs of whole-rock samples at Michigan State University (Supplementary Data Electronic Appendix 3). Some samples were analyzed by instrumental neutron activation analysis at Oregon State University in 1998 (Supplementary Data Electronic Appendix 4).

Mafic, felsic and composite dike

Dikes that fed the plutonic system are either mafic, having less than 50% SiO2, or silicic, having more than 74% SiO2 (Fig. 9). Fine-grained, aphyric mafic dikes form a tight cluster on plots of major element oxides with 7–9% MgO and 47–50% SiO2 (Fig. 9), as well as for Al2O3, Fe2O3(t), CaO, Na2O and K2O. Major element compositions are similar to those of low-K tholeiites. Basaltic dikes are characterized by REE patterns (Fig. 10a) that are flat to weakly light REE (LREE) enriched [(Ce/Yb)n = 1–3 and (Ce/Y)h = 0.4–2.2] and that lack Eu anomalies. La concentrations range from 15 to 85 times chondrite, and Yb from 15 to 30 times chondrite.
Fine-grained, aphyric felsic dikes are comparable in composition with high-silica rhyolites with 74–78% SiO$_2$, 4–6% K$_2$O, and 2–3% Na$_2$O (Fig. 9). These biotite-bearing rocks are chemically metaluminous to mildly peraluminous. The silicic dikes exhibit REE patterns characterized by flat heavy REE (HREE), prominent negative Eu anomalies, and moderately enriched LREE (Fig. 10). Lanthanum values range from 60 to 150 times chondrite and Yb from 19 to 27 times chondrite. Granitic host and chilled mafic pillows in composite dikes have the same restricted compositions as homogeneous granitic and basaltic dikes, except where the granitic matrix is contaminated by fragments of brecciated pillow margins.

**Felsic rock units**

Rocks from the fine-grained granite map unit are geochemically similar to the felsic feeder dikes with several minor differences: slightly lower SiO$_2$ (72–74%) and K$_2$O, and slightly higher TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$(t), MgO and CaO than the granite dikes. The fine-grained granite unit is also characterized by higher Sr, Zr and Hf.

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**Fig. 8.** Plots of modal analyses of five sections through macrorhythmic layers in the gabbrodiorite unit. Locations of the measured sections are shown in Fig. 4.
Fig. 9. Compositional variation of selected major and trace elements for feeder dikes and silicic rocks. (a–c) Harker diagrams for mafic and silicic feeder dikes. (d) SiO$_2$ vs TiO$_2$ for silicic rock units. It should be noted that silicic feeder dikes have higher SiO$_2$ contents than other silicic rock units. (e) Trace element patterns for average silicic rock unit compositions normalized to the average of silicic feeder dikes. It should be noted that coarse-grained granites exhibit a positive Eu-anomaly and elevated HREE, Y, Zr, and Hf.
concentrations, as well as more enriched REE patterns, particularly the LREE, than the granite dikes and coarse-grained granite (Figs 9e and 10e).

Coarse-grained granitic rocks overlap in major element composition with felsic dikes and the fine-grained granite map unit, with SiO2 varying from 73 to 77% (Fig. 9d). The coarse-grained granite is generally enriched in TiO2, P2O5 and Zr relative to the fine-grained granitic rocks. Like the other felsic rocks, coarse-grained granite exhibits REE patterns (Fig. 10e) characterized by flat HREE, prominent negative Eu anomalies, and moderately enriched LREE. Relative to granite dikes, the coarse-grained granite is slightly enriched in HREE, Zr and Hf and exhibits a positive Eu anomaly (Fig. 9e).

Porphyry has compositions identical to the coarse-grained granite, reflecting its origin by rejuvenation of coarse-grained granite (Wiebe et al., 2004). Because the geochemistry of the porphyry has been thoroughly documented in our earlier paper, we omit descriptions of the porphyry here.

Gabbrodiorite unit
To characterize the gabbrodiorite unit we analyzed the whole-rock composition of 247 rock samples (Supplementary Data Electronic Appendix 2), 130 of which were collected from the six measured sections shown in Figs 4 and 5. Samples from the measured sections exhibit systematic compositional variation within macrorhythmic layers (Fig. 11) that is consistent with the stratigraphic variations in modal mineralogy (Fig. 8). The sections are dominated by rocks with <52% SiO2 and 6–10% MgO. It should be noted that the composition of fine-grained gabbro at the base of macrorhythmic layers varies vertically within a given measured section and from section to section (Fig. 11). Within a given macrorhythmic layer, the upward transition from a typical mafic rock (48–50% SiO2 and 7–9% MgO) at the base to diorite or granite at the top is abrupt where we have the tightest stratigraphic control (Figs 8 and 11). For example, in section C (Narrows Island), layer C5 varies in composition from 48% SiO2 at the base to 74% SiO2 at the top over 84 m of stratigraphic thickness. However, most of that compositional variation occurs in two narrow stratigraphic intervals: from 53% SiO2 to 66% SiO2 over 4 m of section, and from 68% SiO2 to 74% SiO2 over 5 m of section. Likewise, in layer F2 of section F (Coombs Neck) almost all of the compositional variation within this 44 m thick layer occurs over a 2 m interval near the top of the layer.

Most fine-grained gabbro samples from throughout the gabbrodiorite unit closely match the composition of mafic dikes in terms of major elements (Fig. 12) and REE patterns (Fig. 10a–d). However, chilled samples from the base of some macrorhythmic layers and mafic pillows have >52% SiO2 and <6% MgO, partially bridging the compositional gap between felsic and mafic dikes (Fig. 12).

The compositional gap is filled when all of the rocks from the gabbrodiorite are plotted against MgO (Fig. 13). The data span the compositional gap along broad curving arrays with a negative slope (e.g. SiO2, Na2O, K2O, Ba, Rb) or broad curving arrays with a positive slope (e.g. Al2O3, CaO, Ni) that verge with triangular arrays (e.g. TiO2, Fe2O3t, MnO, P2O5, Zr, Sc, Y, Nb, V, Zn, Ga). In general, the mafic and felsic dike plots at opposite ends of these arrays and trends (Fig. 13) and intermediate compositions (3–7% MgO) display the greatest compositional variation. For example, in Fig. 13b rocks with 5% MgO have from 0.6 to 3.8% TiO2. REE patterns for the gabbrodiorite unit are similar to those for mafic dikes. Coarse-grained granite within...
the gabbrodiorite unit is enriched in HREE, Y, Zr and Hf and exhibits a more prominent positive Eu anomaly than the coarse-grained granite unit (Fig. 9e).

MELTS MODELING OF MAFIC MAGMA

Because the VIC exhibits field and geobarometric evidence consistent with shallow crustal emplacement depths (1–2 kbar), we employed the MELTS model (Ghiorso & Sack, 1995; Asimow & Ghiorso, 1998) to constrain the depth at which the mafic magma equilibrated prior to emplacement into the VIC. Two groups of rocks offer the closest approximation to mafic liquid compositions in the VIC: fine-grained gabbros from dikes and fine-grained gabbros from the gabbrodiorite unit that overlap in composition with the mafic dikes (Fig. 12). To explore the viability of using the plutonic rocks as liquid compositions, we selected 31 samples of fine-grained gabro that preserve basaltic textures and primary mineralogy, and are characterized by >7 wt % MgO and <0.7 wt % K2O.

Application of the MELTS model to whole-rock compositions required assumptions regarding the volatile content of the melt, the oxygen fugacity of the starting liquids, and the phases in equilibrium with the liquid. To constrain the volatile concentration we modeled fractionation of several of the most primitive whole-rock compositions normalized to initial H2O concentrations ranging from 0 to 1 wt %. These model fractionation trends were then compared with the observed VIC compositions for aphyric rock samples. Model liquids containing 0.2 wt % H2O produced the best fit to the rocks. Our second assumption involved normalizing starting model liquids to FeO/Fe2O3 ratios consistent with the fayalite–magnetite–quartz (FMQ) buffer at the pressure of interest. To model the pressure of equilibrium we used MELTS to locate the pressure at which a given sample composition yielded ≥95 wt % liquid in equilibrium with olivine + feldspar + pyroxene.
Given these assumptions, the relative model pressures are probably more significant than the absolute values. Despite these assumptions and the age of the plutonic rocks, the 31 whole-rock compositions yield realistic liquid and mineral compositions at reasonable crustal conditions (Fig. 14). Moreover, samples from the mafic dikes yielded similar temperatures and pressures to samples from the gabbrodiorite unit. Mafic dikes yield liquid compositions in equilibrium with olivine (Fo$_{70-86}$) + feldspar (An$_{60-80}$) + pyroxene at model pressures of 2–4.4 kbar and model temperatures of 1190–1240°C. Fine-grained gabbros from the gabbrodiorite unit yield liquid compositions in equilibrium with olivine (Fo$_{70-86}$) + feldspar (An$_{60-80}$) + pyroxene at model pressures of 2.5–4.4 kbar and model temperatures of 1185–1240°C.

**DISCUSSION**

**Significance of feeder dikes**

The fine-grained, aphyric dikes of both felsic and mafic composition, the abundance of composite dikes with strongly chilled mafic pillows, and the apparent absence of fine-grained, aphyric dikes of intermediate composition provide strong evidence that the VIC is a bimodal magmatic system. All three types of dikes cut the intrusion at different levels within the gabbrodiorite unit and intruded resident material that exhibited a range of rheologies, from solid rock to crystal mush, suggesting that feeder dikes supplied silicic and mafic magma to the system over much of the VIC’s magmatic history. The large contrast in composition (and physical properties) between these magmas promoted magma mingling rather than magma mixing (e.g. Sparks & Marshall, 1986) within the VIC. However, the apparent absence of feeder dikes with intermediate composition suggests that if magma mixing occurred in the crust beneath the VIC, the resulting magmas were not emplaced at the exposed level of the VIC.

Two lines of evidence, however, suggest that magma mixing may not have operated in the crust beneath the VIC. First, felsic dikes intruded throughout much of the history of the intrusion (perhaps as long as 2 Myr) and yet exhibit restricted compositional variation for most elements at 74–78% SiO$_2$. In addition, the fine-grained granite map unit, which intruded late in the magmatic history and has 72–74% SiO$_2$, is mildly enriched in incompatible trace elements relative to the dikes (Fig. 9). Together with the absence of intermediate dikes, these observations suggest that the silicic magmas were probably not derived by fractionation of basalt at depth. Second, most of the fine-grained gabbros from dikes and from the gabbrodiorite unit appear to have equilibrated at MELTS model pressures equivalent to the emplacement depth of the VIC (Fig. 14). The few dikes that yielded significantly higher MELTS model pressures, 2.8–4.4 kbar, show no petrographic or geochemical evidence for magma mixing at depth. Rocks of intermediate composition occur almost exclusively in the gabbrodiorite unit within macrorhythmic layers (MASLI).

**Emplacement and growth of the MASLI**

We estimate conservatively that the mafic rocks have a total thickness of about 1 km and an along-strike length of about 12 km. Gravity data suggest that the mafic rocks extend northward beneath coarse-grained granite by 6 km or more. The total volume of mafic input to the exposed (known) portions of the VIC is, therefore, of the order of about 75 km$^3$. Precise U–Pb ages of zircon rims from samples collected below, within and above the mafic rocks suggest that all of this basalt was probably emplaced over 0.2–0.9 Myr (Hawkins et al., 2009). In this section we examine evidence for mafic input and sequential emplacement of the macrorhythmic layers.

**Basaltic dikes**

Basaltic dikes identical in composition to the chilled bases of the macrorhythmic layers cut the gabbrodiorite unit. Their compositions strongly suggest that comparable dikes fed the basaltic components of the macrorhythmic layers. Field relations and the close match of major and
trace element compositions of the largest exposed dike beneath the base of section B (described above) and basal chill of layer 2 of that section strongly suggest that it is the feeder for macrorhythmic layer 2, which can be traced from Lanes Island to section D (Fig. 4). This dike cuts and remobilizes granitic and hybrid rocks beneath the base of the layer. Immediately above the dike, the layer is >100 m thick, whereas the correlative layer thins substantially in measured sections to the west and east (Figs 4 and 5). In the more distant sections, the layers have thinner basal sections of gabbroic rocks that grade upward more rapidly to more evolved (lower MgO and higher SiO₂), intermediate rocks than in section B (Figs 5, 8 and 11). The bases of the furthest sections are also marked by thick accumulations of chilled sheets, tubes, and pillows, which we believe are due to reduced and episodic flow at the marginal extensions of the macrorhythmic layer. Because the dominant direction of flow was down-dip toward the interior of the pluton (see above), outward thinning of this layer strongly suggests that the basalt spread laterally away from the dike.

**Emplacement of the macrorhythmic layers**

Experimental studies indicate that the emplacement of basaltic dikes into a floored silicic chamber should
produce mafic sheets that spread onto a thin layer of melt-rich felsic magma and develop fingers in the direction of flow owing to flow-front instability as they spread out within the more viscous silicic magma (Snyder & Tait, 1995; Jellinek & Kerr, 1999). Crystal mush beneath the basaltic sheets must have initially had sufficient yield strength to support the mafic sheets (probably >50% crystals), and felsic magma above the mafic sheet should have been weak, probably with <50% crystals. Heat from the cooling basaltic layer would have further reduced crystallinity in the overlying felsic magma.

Most mafic layers probably initiated as thin (<1 m) flows that chilled along their base against the underlying felsic crystal mush and along their top beneath the overlying magma. Layers like this are common in other MASLI along the Maine coast (e.g. the Pleasant Bay and Cadillac Mountain intrusive complexes; Wiebe, 1993b, 1994); in cross-section these layers resemble thin pahoehoe sheets. They occur only locally in the VIC; instead, here it appears that the rate of influx relative to the rate of cooling allowed the initial thin sheets to inflate to thicknesses as great as 100 m. Self et al. (1998) suggested that <1 m thick pahoehoe flows can inflate by many meters over a period of several weeks, so it is possible that some of the thickest basaltic portions of macrorhythmic layers could have been emplaced within less than a few months. In generating layers tens of meters thick, the continued influx would have been emplaced above the chilled base of the initial layer (within mafic magma) and either beneath the initial upper chilled boundary or, if that boundary layer was disrupted, beneath overlying felsic to intermediate magma. Initial crystallization temperature near the base of the layer was probably above 1150°C, and the upper intermediate to granitic portions of the layers ultimately crystallized at decreasing temperatures as low as 750°C. Based on the analysis of Snyder (2000), a 50 m thick basalt layer emplaced beneath a thick silicic chamber (>100 × basalt thickness) could cool by 200°C in ~5 years, or longer if the silicic chamber were smaller.

The distribution of deltaic accumulations of pillows and tubes at the bases and thinning margins of macrorhythmic layers (e.g. layer 2 of sections A–D in Fig. 5) suggests that they formed at the lateral margins of a basaltic flow during its inflation. The lensoid form of this large macrorhythmic layer suggests that it could be viewed as a thick pahoehoe lava flow that flowed gently down-dip toward the interior of the chamber. Comparable pillow mounds occur abundantly near the western terminus of the gabbrodiorite unit against coarse-grained granite and at the top of the gabbrodiorite unit beneath coarse-grained granite (Fig. 6). The lateral terminations of macrorhythmic layers as accumulations of tubes and sheets in both of these settings suggest that these margins had a reduced rate of flow with fingers freezing in direct contact with granitic magma.

### Origin of compositional variation in the MASLI

Macrorhythmic layers in the gabbrodiorite unit provide the physical setting in which to evaluate fractionation and hybridization processes that operated during and following emplacement of mafic magma, as mafic sheets, into the VIC. During emplacement of basaltic magma at the base of a silicic magma chamber, large contrasts and rapid changes in viscosity and convective velocity along the boundary between basalt and overlying silicic magma probably caused turbulence and mutual entrainment of crystals and melt (Huppert & Sparks, 1984). The hybrid intermediate rocks between gabbro and granite in the macrorhythmic layers are consistent with this process. Initially, the temperature at this boundary would have been intermediate between that of felsic magma (~750°C) and basaltic magma (~1150°C), at about 950°C. A downward crystallization front would have been established at the top of the gabbroic layer and diffusional exchange of alkalis and H₂O should have been effective, as observed elsewhere along contacts between hot dry basaltic magma and cooler, more hydrous felsic magma (Wiebe, 1993b). Hence, both biotite and hornblende would crystallize in the mafic magma, locking up those chemical components in crystals and maintaining strong compositional gradients in adjacent mafic and felsic melts. Because basaltic layers more than a few meters thick do not preserve an upper chilled margin, and instead grade upward to hybrid and felsic rocks, the chilled margins formed at the top of mafic sheets during emplacement must have been destroyed where mafic input exceeded that thickness. Most of the chilled margins were probably transported downward by convection and underwent partial melting and recrystallization, generating the commonly observed textural heterogeneity in the transition from chilled base to
cumulate gabbro. However, some disrupted pieces of the boundary layer were probably transported upward into the felsic magma and are now represented by the small (<2 cm) fine-grained mafic enclaves disseminated throughout the granite.

An upward gradation from basalt to hybrid and granitic rocks at the top of a macrorhythmic layer indicates that any initial upper chilled margin was removed, permitting exchange of melt and crystals between mafic input and more evolved, cooler and less dense resident magma. The resulting gradation in a macrorhythmic layer provides a record of crystal accumulation from a compositionally stratified magma chamber with hotter basaltic magma beneath cooler hybrid and granitic magmas. As the lower gabbroic rocks accumulated and crystallized, the overlying intermediate and felsic magmas would initially have risen in temperature with suspended crystals undergoing partial dissolution. Crystallization of these stratified magma chambers proceeded from base to top, resulting in the vertical gradation from basal gabbro to hybridized diorite to granite. The lithological, petrographic and geochemical characteristics in vertical sections through the macrorhythmic layers provide insights into the timing and nature of fractionation and hybridization.

Most chilled mafic bases of macrorhythmic layers with >8 wt % MgO appear to preserve the compositions of the mafic magmas that replenished the VIC over time. Some chilled bases, however, preserve xenocrysts of quartz rimmed by hornblende, contain higher concentrations of elements greatly enriched in the underlying granite (e.g. K2O and Rb, residing in increased abundance of biotite), and have compositions that approach linear mixes of granite and fine-grained gabbro (three chilled margins with ~4% MgO, Fig. 12). Excess silica from this mixing may be the reason for the absence of olivine and prominence of orthopyroxene in layer 2 of Section A (Fig. 8), which lies above a thick zone of chilled basaltic pillows in coarse-grained granite. These fine-grained gabbros indicate that hybridization occurred locally during (and immediately following) emplacement of flowing basaltic sheets (e.g. Bain et al., 2013). The development of fingers along the flow front provided ample opportunity for upward transport of interstitial melt and crystals from the underlying layer of felsic crystal mush into the gabbro sheet (Snyder & Tait, 1995, 1998). The resulting compaction of the granitic crystal mush accounts for the geochemical differences between coarse-grained granite, fine-grained granite and felsic dikes (Fig. 9d and e).

In most macrorhythmic layers these basal chills are immediately overlain by medium- to coarse-grained gabbros that exhibit cumulate textures, and are enriched to strongly enriched in compatible elements (MgO, Ni, Cr, etc.). Thus, once the sheets came to rest, fractional crystallization of mafic magma was an important process during consolidation. The mafic cumulates must have defined a rheological boundary with overlying crystal-poor mafic to intermediate liquid because when, at this stage, crystallization was interrupted by the new mafic input, the mafic flow was emplaced on, and variably quenched against, the mafic cumulates (e.g. layers 2 and 3 in section A). As the mafic cumulate layer increased in thickness, the modal mineralogy systematically changed to reflect the evolution of the overlying liquid.

Cumulate gabbros typically grade upward to intermediate hybrid rocks that contain xenocrysts of quartz and feldspar, indicating that the physical conditions in the consolidating mafic sheet and the physical characteristics of evolving melt were appropriate for magma mixing. Samples with these characteristics typically have 58–68% SiO2 and 2–5% MgO. The appearance of quartz and feldspar xenocrysts is gradual in some layers and abrupt in others, suggesting that the processes operating at this stage varied from layer to layer (Figs 8 and 11). Abrupt changes in the cumulates suggest that the mixed melt in the magma bodies above some MASL was compositionally stratified, perhaps reflecting double diffusive convection.

In summary, the compositional variation of the gabbrodiorite unit, which spans the compositional gap defined by the bimodal feeder dikes, reflects mainly processes that operated in magma bodies within the VIC. Fractionation of mafic magma and hybridization involving fractionated mafic magma and resident silicic magma—both the underlying crystal-rich silicic magma and the overlying crystal-poor silicic magma—accounts for the compositional variation observed in the gabbrodiorite unit.

**Thermal impact of mafic input on silicic magma chambers and granite**

*Convection in silicic magma chambers overlying mafic sheets*

Because of their textures and compositions, mafic enclaves within the Vinalhaven granite were almost certainly derived from the tops of basaltic sheets. Their sizes and distribution have the potential to provide insights into convection within the granitic magma above the mafic sheets. Based on work by Snyder (2000), convection in silicic magma overlying recently emplaced thick (>10 m) mafic sheets would have reached a velocity of 0.5–2 m day−1 within a few weeks. The thermal gradient established within the silicic magma would take years to tens of years to decay per kilometer of thickness, and as it decayed the convective velocity would decrease.

Granite within tens of meters above mafic sheets contains mafic enclaves as large as 20 cm in diameter. Using Stokes’ Law, \( v_t = 2 g D \alpha \rho_f^2 / 9 \eta \), and assuming that shear viscosity, \( \eta \), of granitic magma = 10⁴ Pa s and
$\Delta \rho = 500 \text{ kg m}^{-3}$, a mafic inclusion of that size should sink at a velocity of about 1 m day$^{-1}$, a rate that falls within the range of expected convective velocities ($0.5$–$2.0$ m day$^{-1}$) that develop shortly after emplacement of a mafic sheet. This suggests that crystallization of tens of meters of granitic crystal mush accumulated as convective velocity decayed, so that all the larger mafic enclaves settled to the chamber floor. Much smaller mafic enclaves (up to 2 cm in diameter) are widely dispersed throughout the Vinalhaven granite far above any known mafic sheet. Assuming the same parameters, a mafic enclave with a radius of 1 cm would have settled downward at a rate of about 0.1 m day$^{-1}$. Initially, these enclaves would have stayed in suspension within the magma because of their very slow settling rate; they apparently remained dispersed in the granitic magma as increased cooling and increased viscosity precluded their settling further.

**Rejuvenation of coarse-grained granite**

The dominant effects of dry mafic input on the resident granitic magma would be to reduce crystallinity, raise the temperature, and reduce the activity of $\text{H}_2\text{O}$, partly because of dissolution of anhydrous crystals and partly because of selective diffusion of $\text{H}_2\text{O}$ into the crystallizing mafic magma, causing abundant crystallization of hornblende and lesser biotite there. A thick sheet (>10 m) of basaltic magma at the base of a silicic magma chamber should establish a double diffusive boundary between the lower, hotter basaltic magma and the upper, cooler silicic magma (Huppert & Sparks, 1984; Clark et al., 1987). This would result in rapid transport of heat upward from the basalt into the overlying silicic magma and induce convection in both magmas. This heat will tend to reduce the crystallinity of the silicic magma, raise its temperature, and probably enlarge the chamber by ‘defrosting’ crystallization fronts on the roof and margins of the chamber. Quartz crystals in the overlying coarse-grained granite provide clear evidence of episodes of remelting and crystallization at increased temperatures of up to 100°C or more (Wiebe et al., 2007b).

Field relations indicate that the gabbroic layer at the south end of Greens Island dips gently northward beneath granite at least as far as The Basin where many porphyry bodies intrude granite (Fig. 1). Gravity data suggest that the gabbroic layer occurs at increasingly deeper levels to the north. On Greens Island, its base is highly disrupted by diapiric bodies (irregular linear as well as more equant diapirs) of remobilized granite from below (see Fig. 3b)—up to 1–3 m in width or diameter. Other areas of isolated diapiric bodies of granite perforate (and apparently pass through) the expanse of mafic rocks to the north.

To the NW immediately above the gabbroic layer, granite is texturally homogeneous and contains enclaves of porphyry (up to 1 m in size). These enclaves are connected to steep cylindrical schlieren that rise up to a few meters above the enclaves and disappear. Their margins are rounded, and because no crystals are cut, the enclaves probably contained interstitial melt when they settled downward in the silicic crystal mush. They appear to represent higher temperature and drier packets of rejuvenated granite, probably bodies that were generated by remelting below the mafic sheets and then buoyantly transferred upward into the growing chamber of silicic magma. There, rapid quenching increased their density, allowing them to settle downwards in the crystal mush. In the same areas, moderately dipping, tractional schlieren occur in the granite, indicating flow and deposition from currents of crystal-laden magma. These relations indicate that a silicic magma chamber existed above the mafic sheets and that deposition of crystals led to aggradation of the chamber floor.

In the northern third of Greens Island where the gabbroic layer is at a deeper level, the granitic rocks are texturally heterogeneous on the scale of meters to tens of meters with highly irregular intermingling of coarse-grained granite and porphyries with varying percentages of phenocrysts. Contacts between different textural varieties of granite are gradational over distances of centimeters to meters. We believe that these heterogeneous felsic rocks record interactions at the top of the silicic magma chamber situated above the gabbroic layer—involving both rejuvenated silicic magmas within a growing magma chamber as well as diapirc upwellings of rejuvenated silicic magma from below the mafic layers.

Further north (Dog Point, Dyer Island, The Basin; Fig. 1), discrete areas of porphyry break through coarse-grained granite. Most porphyry bodies have contacts with coarse-grained granite that are gradational over several centimeters. The body on Dog Point cuts coarse-grained granite sharply (cutting across crystals) at its SW end, but is gradational to the NE, suggesting that the granite was more completely solid toward the intrusion’s western margin than in the interior. The discrete character of the porphyry bodies suggests that these rejuvenated felsic magmas were injected farther upward into a stronger solidification front at the top.

The older granite that formed the roof of the silicic magma chamber established above the mafic sheet at the south end of Greens Island exhibits features that suggest that it had initially formed by crystal accumulation within an earlier magma chamber. Moderately dipping tractional schlieren have orientations that suggest flow and deposition of crystal mush largely towards the north and west (Fig. 2). Several rounded blocks of leucogranite, up to at least 6 m in length, are well exposed along the eastern shore of The Basin (Fig. 2). These larger blocks are associated with steep, thick schlieren, indicating that the blocks sank from their source (the roof of an earlier chamber) into a crystal mush at the base of an earlier magma chamber. Other comparable steep schlieren not visibly associated with granitic blocks occur along this coast: these schlieren...
almost certainly also record the downward passing of stopped granitic blocks. These relations indicate that this older granite formed by crystal accumulation within an earlier silicic magma chamber; the occurrence of granitic blocks within the granite suggests that the granitic roof of this chamber was also affected by stoping.

Two larger porphyry bodies occur to the east. They are sharply cut by the fine-grained granite body and related dikes (see Fig. 1), indicating that they were solid prior to the emplacement of the fine-grained granite. The upper lens of gabbroic rocks at the western end of the gabbrodiorite unit appears to dip 20–30° NE beneath coarse-grained granite. These porphyry bodies may have risen from rejuvenated granite above that gabbroic sheet. Alternatively, they may represent rejuvenated granite produced by heat from macro rhythmic layers now removed by the fine-grained granite. The largest and youngest porphyry body occurs to the north at Vinal Cove (Fig. 1). Its generation was directly related to emplacement of a 60 m thick basalt dike. Because it was the focus of an earlier detailed study (Wiebe et al., 2004), it is not discussed further here.

In summary, these field relations demonstrate that episodic emplacement of basaltic magmas led to episodic rejuvenation of coarse-grained granite and the growth of new silicic magma chambers. Outcrop-scale features preserved in granite affected by rejuvenation indicate that these rocks formed earlier as cumulates in previous magma chambers. Recycling of crystals was therefore a significant process in the growth and solidification of the Vinalhaven granite. Complex zoning of quartz crystals in coarse-grained granite and porphyry corroborate the recycling concept (Wiebe et al., 2007b).

The link between mafic input and roof collapse of the silicic chamber

Nearly all country rock blocks in the VIC are closely associated with the gabbrodiorite unit. The restricted stratigraphic distribution of the blocks indicates that country rock blocks were stoped during short-lived roof collapse events rather than continuously over the lifetime of the chamber (Hawkins & Wiebe, 2004). We suggest that these strata-bound roof blocks record collapse of the roof during eruptions from contemporaneous magma chambers in the VIC, probably triggered by the influx of basaltic magma (Hawkins & Wiebe, 2004): (1) country rock blocks on small islands east of (and beneath) measured sections E and F appear to represent the earliest exposed episode of roof collapse; (2) the very extensive blocks beneath the lowest macro rhythmic layer of sections A–D and west to Greens Island and eastward above measured sections E and F (a distance of more than 10 km) may represent one large, possibly caldera-forming eruption; (3) the more restricted blocks at higher stratigraphic levels to the east may represent the last series of smaller eruptions from a greatly restricted chamber.

Estimating the volume of silicic magma during mafic input

The gabbrodiorite unit contains macro rhythmic layers dominated by gabbroic sections (SiO₂ < 60 wt %) that range from about 10 to 100 m in thickness. The heat from these injections went dominantly upward, via convection into an overlying silicic magma. The nature of preservation does not reveal the thickness of this silicic magma at the time of mafic injection, but, assuming that the areal extents of mafic and silicic magmas are comparable, a rough, order-of-magnitude estimate of thickness can be made via thermal arguments. We relate the heat content of characteristic mafic replenishments to the maximum temperature increase in the silicic magma as given by the observed reverse zoning in Ti (and CL) of the quartz crystals (Wiebe et al., 2007b). Most quartz crystals record a single major event of corrosion with a mantle of high-Ti quartz suggesting a temperature increase of from 30 to 80°C. All of the measured sections of the gabbrodiorite unit have at least one macro rhythmic unit in which the gabbroic portion (SiO₂ < 60 wt %) is 60–100 m thick (Fig. 5). The mass of felsic magma can be calculated by

$$m_{\text{felsic}} = \frac{m_{\text{mafic}}(C_{p,\text{mafic}}(\Delta T_{\text{mafic}}) + L_{\text{mafic}})}{(C_{p,\text{felsic}}(\Delta T_{\text{felsic}}) + xL_{\text{felsic}})}$$

where $C_p$ is heat capacity, $L$ is latent heat, $\Delta T$ is cooling of basalt and heating of rhyolite (in °C), $m$ is mass of magma, and $x$ is weight fraction of dissolved crystals in granite during heating. In a $T$–H₂O plot of the phase relations for the granite minimum composition at 1 kbar, the slope of the reaction $L + Cr$ (crystals) indicates that ~0.5 wt % of crystals will melt for a $T$ increase of 1°C ( Holtz & Johannes, 1994). Hence, the fraction of crystals melted in felsic magma is ~0.005$\Delta T_{\text{felsic}}$. Mass can be correlated with thickness ($D$) by adjusting for density differences between the mafic and felsic magmas, hence

$$D_{\text{felsic}} = \frac{1.18D_{\text{mafic}}(C_{p,\text{mafic}}(\Delta T_{\text{mafic}}) + L_{\text{mafic}})}{(C_{p,\text{felsic}}(\Delta T_{\text{felsic}}) + 0.005 \cdot L_{\text{felsic}})}$$

where $D_{\text{mafic}} = 20–100$ m, $\Delta T_{\text{mafic}} = 350$°C (1150–800°C), $\Delta T_{\text{felsic}} = 20–100$°C (based on Ti zoning in quartz), $C_{p,\text{mafic}} = 1484$ J kg⁻¹°C⁻¹, $C_{p,\text{felsic}} = 1604$ J kg⁻¹°C⁻¹, $L_{\text{mafic}} = 3.96 \times 10^5$ J kg⁻¹, and $L_{\text{felsic}} = 2.5 \times 10^5$ J kg⁻¹. Values are from Spera (2000) for dry gabbro with a liquidus $T$ of 1200°C and granite with 2% H₂O and a liquidus $T$ of 900°C.

The temperatures from quartz zoning place an approximate upper bound on the temperature increase in the silicic magma, and place a lower bound on the thickness of silicic magma needed to absorb the heat provided by the mafic injections (Fig. 15). Given the thickness of the mafic magma and the thermodynamic properties of the two magmas, the lower bound on thickness of the silicic magma is at least hundreds of meters, and perhaps as much as 1 km. If it were
thinner, it would have responded with a greater temperature increase.

Growth of the Vinalhaven Intrusive Complex

Detailed mapping has established a sequence of events during growth of the exposed parts of the VIC. Geological, petrological, and geochemical evidence along with high-precision U–Pb zircon geochronological data for both the VIC and the associated effusive rhyolite suggest that the intrusion was constructed incrementally over about 2 Myr between 421 and 419 Ma (Hawkins et al., 2009). High-precision U–Pb zircon ages indicate that the exposed portions of the pluton were emplaced over about 0.7 Myr at about 419 Ma (Hawkins et al., 2009). We use a schematic oblique section of the exposed portions of the VIC (Fig. 16) to illustrate the history of the growth of the complex (see Fig. 1 for the geographical locations of episodes described).

The oldest granite is exposed along the western and southern margins of the VIC (Figs. 16a)—on Big White and Sheep islands respectively (Fig. 1). Younger granitic magmas provided the cumulate crystal mush on which all exposed mafic rocks were emplaced. This oldest exposed granite contains small mafic inclusions that must have been derived from earlier injections of basaltic magma, so a complex history of the VIC must be preserved in unexposed plutonic rocks at depth.

After the exposed granitic base of the VIC grew by crystal accumulation, episodic basaltic input by dikes fed isolated mafic sheets at different levels in the eastern half of the VIC (exposed on Sheep and Carvers islands) (Figs 1 and 16a). More extensive mafic sheets associated with large blocks of roof country rock occur along the eastern part of the VIC between Calderwood Point and Coombs Neck (Fig. 1). At higher stratigraphic levels (see Fig. 5), thick mafic sheets rest on coarse-grained granite associated with country rock blocks along the SE to south coast of Vinalhaven Island and extend from section D westward to section A (Fig. 5) and on to Greens Island (Figs 1 and 16a). The lateral extent of these mafic sheets (~10 km) probably matches the extent of a contemporaneous silicic magma chamber.

The westernmost part of the gabbrodiorite unit is well exposed and preserves a complex magmatic history (Fig. 16b). A lower thick mafic sheet, exposed on Greens Island (Figs 1 and 4), overlies coarse-grained granite that hosts several large country rock blocks. The quenched base of this mafic sheet is pierced by well-developed clusters of magmatic pipes of coarse-grained granite (Fig. 3d). At its western termination, this mafic sheet is penetrated by larger diapirs of mobile granite crystal mush trapped beneath the layer (Fig. 3a and b).

The granite above this stratigraphically lower mafic sheet preserves abundant evidence for a period of substantial accumulation of coarse-grained granite, including tractional schlieren as well as cylindrical schlieren associated with both porphyry enclaves and angular blocks of granite that sank in a crystal mush with downward increasing strength (Wiebe et al., 2007a). The occurrence of granite blocks and the absence of country rock blocks indicate that a granitic roof of the intrusion was established by this time. While granite accumulated in the west, mafic magma continued to be emplaced in the eastern portion of the intrusion (from section B to section F).

After this period of granite accumulation, mafic magma (presumably emplaced in the east) again spread westward dominantly as extensive accumulations of thin sheets, tubes and pillows in a granitic matrix (Fig. 16b); these are located on the peninsula SE of Old Harbor (OH in Fig. 1). Gravity data suggest they extend northward several kilometers at a shallow depth. Intrusive bodies of porphyry in granite exposed in the vicinity of Dog Point, Dyer Island and The Basin (Fig. 1) appear to be above these stratigraphically higher, thinner mafic sheets. Because this granite contains comparable evidence for crystal accumulation, these contact relations suggest that the mafic sheets spread westward within a crystal mush, rather than at a well-defined rheological transition between strong crystal mush and crystal-poor magma, and that the mafic sheets rejuvenated and remobilized the overlying crystal mush (Fig. 16b).

Mafic sheets continued to be emplaced at higher levels in the east (Fig. 16a). Country rock blocks are sparsely associated with the higher-level mafic sheets, suggesting that continued input of mafic magma in the east hindered establishment of a continuous solid granitic roof. These relations and the sparse occurrence of stopped country rock blocks suggest that the
last silicic magma chamber in coarse-grained granite existed near the top of the exposed country rock roof above the highest level of mafic input in the east. However, it is uncertain whether this chamber was younger or older than emplacement of the Vinal Cove complex and the fine-grained granite body.

CONCLUSIONS

The periodic influx of mafic and silicic magma into the evolving VIC provides a series of snapshots of the rheological conditions within the VIC through space and time. Basaltic dikes fed mafic sheets at subhorizontal rheological transitions from strong crystal mush to overlying crystal-poor magma. Felsic magma was emplaced as aphyric dikes that sharply cut solid plutonic rocks and mingled with and stirred into weak crystal mush and crystal-poor resident magma. Composite dikes of closely packed basaltic pillows in fine-grained granite also most probably fed significant volumes of crystal-poor silicic magma into contemporaneous silicic magma chambers. The absence of
intermediate dikes and the stratigraphy of the gabbro-diorite unit suggest that all hybridization occurred within VIC magma chambers.

The great extent of some mafic sheets (>10 km) suggests that the contemporaneous silicic magma chamber was of comparable extent. The consistently close association of country rock blocks with mafic sheets suggests that mafic input commonly led to roof collapse. The occurrence of country rock blocks all along the most extensive sheets and the likelihood that the height of the chamber was of the order of a few to several hundred meters suggest that mafic input may have triggered caldera-forming events.

Mafic magmas that fed the VIC appear to have been multiply saturated with ol + cpx + plag at middle to upper crustal pressures prior to emplacement as dikes into the subvolcanic VIC; within the VIC they underwent fractionation and hybridization with resident magmas, and provided heat that rejuvenated resident granite and silicic magma. Hybridization of mafic sheets occurred during and immediately following emplacement via interaction with both subjacent and the overlying compositionally zoned (perhaps via double-diffusive convection) mafic to intermediate to silicic magma. Rejuvenation of existing solid granite or strong crystal mush occurred at different times and locations and produced bodies of porphyry with strongly resorbed crystals. Much of this porphyry intruded and mingled with granite that preserves evidence for crystal accumulation in an earlier magma chamber. Multiple episodes of rejuvenation are supported by quartz CL and Ti zoning in coarse-grained granite (Wiebe et al., 2007) and recycled zircon antecrysts (Hawkins et al., 2009).

The history of multiple injections of magmas of contrasting compositions and episodes of rejuvenation and roof collapse over a time span of about 0.7–2.0 Myr, as recorded in the VIC, has much in common with the history of bimodal volcanic systems such as Long Valley (Simon et al., 2014) and the Okataina Volcanic Centre (Molloy et al., 2008). The VIC may be an analogue for the plumbing systems that underlie such volcanic centers.

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SUPPLEMENTARY DATA

Supplementary data for this paper are available at Journal of Petrology online.

REFERENCES


