Maine Geological Survey
Studies in Maine Geology: Volume 4
1989

Geochemistry of the Granite-Gabbro Complex on Vinalhaven Island, Maine

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ABSTRACT

The bimodal granite-gabbro association on Vinalhaven Island, Maine has spectacular textural and structural relationships that are interpreted to have resulted from commingling of contemporaneous mafic and felsic liquids. During this process, the felsic and mafic magmas retained their identities and produced composite zones of chilled basaltic pillows in a granite matrix. Approximately 100 samples have been analyzed for whole-rock major and trace element abundances. These data have been used to classify the rocks and evaluate their relationships.

The granites are homogeneous, high SiO_2 (72.55-77.35 wt %), two-feldspar, biotite ± hornblende, I-type, crustal, minimum-melt granites, with similar compositions to other granites from the Maine coastal lithotectonic belt. The mafic rocks, medium-grained gabbros to diorites and fine-grained chilled basalt pillows, have a range in composition (MgO 4.09-11.11 wt %) that can be explained by varying amounts of crystal fractionation of the proposed parental magma composition accompanied by crystal accumulation and contamination by the surrounding granite melt. The parental composition calculated for the mafic rocks is similar to type I MORB that has been enriched in K, Sr, Rb, Ba, and Al. The mafic magma is probably the product of partial melting and was enriched in these elements during emplacement. A second group of mafic samples is enriched relative to the other mafic samples, in high field-strength elements TiO_2, Zr, Nb, along with Sr.

The physical differences in composition, temperature, and viscosity between the mafic and felsic magmas allowed the mafic magmas to chill as pillows, which helped prevent mixing between the basalt and the granite melt in the composite zones. The mechanical breakdown of some of the pillow-granite contacts has aided selective mixing, which has produced limited hybridization. These contaminated samples are not the result of simple two-component mixing of the observed granite and proposed parental basalt composition.

INTRODUCTION

The Island of Vinalhaven lies 15 miles east of Rockland, Maine at the southern end of Penobscot Bay. It is made up of a 361 ± 7 Ma Devonian granite-gabbro association, intruding the 393 ± 6 Ma Silurian-Early Devonian(?) Vinalhaven rhyolite and Thorofare andesite (Brookins, 1976). The intrusive rocks are the southwesternmost exposure of the Bays-of-Maine Igneous Complex (Chapman, 1962a).

The Bays-of-Maine Igneous Complex is a large, essentially bimodal Devonian granite-gabbro association that trends 280 km east-northeast, parallel to tectonic strike, from southern

Penobscot Bay along the coast of Maine into New Brunswick, Canada. According to Chapman (1962a) it consists of earlier gabbroic phases, closely followed by at least two later granitic phases. Chapman (1962a, 1968) has placed the granites of Vinalhaven into the younger group termed the Maine coastal plutons, cutting the earlier phases of the complex. He suggested that the Maine coastal plutons are post-orogenic and were emplaced in association with cauldron subsidence. These plutons straddle the proposed Acadian suture, and therefore must have been emplaced in the late stages of, or after, the Acadian orogeny (Berry, 1986). Both these conclusions are in accord with that of Loiselle and Wones (1979) who state that the coastal plutons are anorogenic or A-type granites. This study shows that the granites on Vinalhaven were closely associated with the emplacement of the "earlier" mafic phase and that intimate commingling of the two magmas took place during their emplacement (Mitchell, 1986).

The Association of Mafic and Felsic Magmas

The relationship between coexisting felsic and mafic magmas has been a long-standing controversy in geology (e.g. Holmes, 1931; Walker and Skelhorn, 1966; Yoder, 1973). Such associations have been explained through fractional crystallization of a parental basaltic magma, various degrees of partial melting of single or multiple sources, restite contamination, and magma-mixing. Each theory has prevailed at some time in the past, with magma-mixing receiving considerable attention in the current literature.

The intimate association of mafic and felsic magmas is well documented throughout the geologic record. These associations manifest themselves as mixed magma ejecta, net-veined complexes, composite dikes and sills, and dikes of incompletely mixed, commingled mafic "pillows" in granite hosts. Examples include commingling in the Precambrian Tigalak intrusion, Labrador, Canada (Wiebe and Wild, 1983), the Tertiary Marsco suite on the Isle of Skye, Scotland (Harker, 1904; Wager et al., 1965; Vogel et al., 1984), and mixed magma ejecta in the 1875 eruption of Askja, Iceland (Sigurdsson and Sparks, 1981).

Bunsen (1851) first recognized the association of basalt and rhyolite in the lavas of Iceland. He suggested that the mixing of these magmas could be responsible for the genesis of the range of igneous rocks of Iceland and other similar associations. In his classic work on the Tertiary igneous rocks of Skye, Harker (1904) interpreted the composite dikes, sills, and ring dikes as a consequence of the simultaneous intrusion of mafic and felsic magmas. Wager and Bailey (1953) examined the details of net-veined complexes and attributed the textures to the chilling of mafic magma against a cooler felsic magma, which produced chilled margins on the mafic unit. They called this incomplete mixing of compositionally distinct magmas "commingling."

Many subsequent studies support the commingling hypothesis (Gibson and Walker 1963; Blake et al., 1965; Wager et al., 1965; Walker and Skelhorn 1966; Wiebe 1973, 1974, 1979, 1980, 1984; Yoder, 1973; Gamble, 1979; Taylor et al., 1980; Reid et al., 1983; Marshall and Sparks, 1984; Cantagrel et al., 1984; Vogel et al., 1984; Whalen and Currie, 1984; Brown and Becker, 1986), suggesting that the textures formed are the result of interaction when both magmas were liquid or largely liquid at the same time. Despite the overwhelming field and petrographic evidence for the commingling of mafic and silicic magmas, attempts to document the degree of liquid-liquid interaction with geochemical data have failed to support simple two-component mixing processes (Gamble, 1979; Taylor et al., 1980; Vogel et al., 1984; Whalen and Currie, 1984).

Other alternatives such as fluidization have been suggested for net-veining of mafic and felsic magmas (Reynolds, 1954). Chapman (1962b) suggested that the composite dikes of Mt. Desert Island, Maine were formed by net-veining, with a granite liquid intruding a solid gabbro host. Taylor et al. (1980) examined the Mt. Desert dikes and interpreted those dikes as having formed through commingling.

The well developed textural relationships and spectacular shoreline exposures on Vinalhaven Island make this an excellent location to study the commingling of mafic and felsic magmas. The purpose of this study is twofold: first to describe the chemistry of the intrusive rocks on Vinalhaven Island in order to place them in the regional and tectonic setting, and second to relate the chemical variation in the zones of commingling to the massive granite-gabbro association that makes up the majority of the island.

Throughout this paper the term commingling will be used to describe magmas which have mechanically mixed, but have retained their compositional identity. The terms hybridized and contaminated will be used interchangeably to describe situations where the magmas have interacted in such a manner that their compositions have been changed.

Methods

During the summers of 1984 and 1985, over 100 samples were collected from the granite-gabbro complex on Vinalhaven. Sample size for chemical analysis was based on the guidelines of Clanton and Fletcher (1976) and ranged from approximately 100 grams for fine-grained mafic material to 2,000 grams for medium-grained granite. Samples were analyzed for bulk rock chemistry major (Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P) and trace (V, Cr, Ni, Zn, Ga, Sr, Y, Zr, Nb, Ba, La, Ce, Pb, Th, U) elements using X-ray fluorescence spectrometry (XRF) at the Department of Geology and Geography, University of Massachusetts, Amherst. Standard petrographic thin sections were examined for textural relations and mineralogical data.

Major elements analyses were done following modifications of the methods of Norrish and Hutton (1969). Trace-element abundances were determined using the methods of Norrish and Chappell (1967). Mass absorption coefficients for the

TABLE 1. REPRESENTATIVE ANALYSES FROM THE VINALHAVEN GRANITE-GABBRO ASSOCIATION.
MGAVG, average of 11 medium grained granites; FGAVG, average of 6 fine grained granites; M, representative granite matrix material (VH-62); E, representative evolved sample (VH-51); P, five-pillow average representing the starting liquid composition; C, representative cumulate sample (VH-49). Analytical precision estimates (1 σ) expressed as weight percentage or ppm. Complete Vinalhaven analyses are given in Appendix A, Table A1.

Sample	MCAVG	1-std	FGAVG	1-std	M	E	P	C	Analytical Precision
SiO_2	74.37	0.62	73.83	0.59	61.71	53.34	48.94	47.58	0.16
TiO_2	0.32	0.03	0.30	0.02	1.62	2.25	1.26	0.89	0.005
Al_2O_3	13.00	0.18	13.58	0.12	14.26	13.89	17.11	17.69	0.06
Fe_2O_3*	2.06	0.14	1.91	0.17	8.59	12.03	9.95	9.18	0.03
MnO	0.04	0.01	0.04	0.01	0.16	0.20	0.17	0.15	0.005
MgO	0.28	0.05	0.39	0.05	1.91	5.55	8.26	11.11	0.04
CaO	1.10	0.09	1.23	0.11	4.41	7.89	10.82	10.84	0.03
Na_2O	3.45	0.16	3.56	0.17	3.62	3.21	2.70	2.48	0.09
K_2O	5.07	0.07	5.08	0.15	3.10	1.48	0.54	0.18	0.003
P_2O_5	0.07	0.01	0.08	0.01	0.53	0.35	0.11	0.10	0.006
Total	99.86	0.33	99.84	0.32	99.90	100.20	99.90	100.18	---
Mg' val	0.26	---	0.29	---	0.31	0.48	0.62	0.71	---
A/CNK	0.99	---	1.00	---	0.82	0.65	0.69	0.74	---
Ba	227	28	357	18	219	140	41	2	6
Rb	230	15	251	13	116	58	27	5	0.26
Sr	47	5	59	2	168	298	202	228	1.7
Pb	23	2	25	5	16	1	4	3	0.1
Th	20	3	21	3	12	4	1	1	0.2
U	8	2	8	1	3	1	1	0	0.7
Zr	195	15	219	20	289	208	93	62	0.6
Nb	13.1	0.7	14.9	0.8	12.5	8.0	2.2	2.3	0.3
Y	48	6	39	3	59	44	26	15	0.3
V	17	2	17	2	101	254	190	125	2.5
Cr	4	1	6	1	5	198	243	252	2.0
Ni	2	2	5	1	3	40	127	251	1.0
Zn	32	4	27	5	96	113	74	62	0.6
Ga	17	0	16	1	21	22	17	15	0.5
Rb/Sr	5.0	---	4.2	---	0.7	0.2	0.1	0.0	---
K/Rb	183.9	---	168.1	---	221.8	212.0	178.0	334.0	---
Zr/Nb	15.0	---	14.7	---	23.1	26.0	42.8	27.0	---

*Total Fe expressed as Fe_2O_3
Mg'- value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{+3}/Total Fe as FeO = 0.1
A/CNK = mol. $Al_2O_3/(CaO + Na_2O + K_2O)$

samples were determined using a Compton scattering method modified after Reynolds (1967) and were used to correct for matrix differences between samples and standards. Calibrations were based on both natural rock and synthetic standards. Analytical precision for both major and trace element analyses are given in Table 1.

Fifteen samples, selected on the basis of the XRF data, were analyzed for rare earth elements REE (La, Ce, Nd, Sm, Eu, Tb, Yb, Lu) and additional trace elements (Hf, Ta, Th, U) by Instrumental Neutron Activation Analysis (INAA) at the Department of Geology and Geophysics, Boston College.

Chondrite normalizing values are from F. A. Frey (pers. commun. to J. M. Rhodes, 1982). In all REE diagrams, samples are normalized to chondrites and Gd has been linearly estimated from Sm to Yb chondrite-normalized abundances to better define the Eu anomaly.

Geology of Vinalhaven Island

The most complete geologic study of Vinalhaven Island was made by Smith et al. (1907) in their description of the geology of the Penobscot Bay quadrangle. The geologic relationships from their map of the Vinalhaven area were transferred to the Vinalhaven 15' quadrangle and used as a base for this study. Figure 1 is a reproduction of their work with the addition of the contact for the fine-grained granite and the location of the zones of commingling of granitic and mafic magmas. Smith et al. (1907) did not map the fine-grained granite on Vinalhaven Island as a separate unit. The fine-grained granite was, however, well known during the early 1900's for its use as a building stone. Dow (1965) studied the Vinalhaven rhyolite, Thorofare andesite and Calderwood Formation on the northern portion of the island in conjunction with his work on North Haven Island. These units

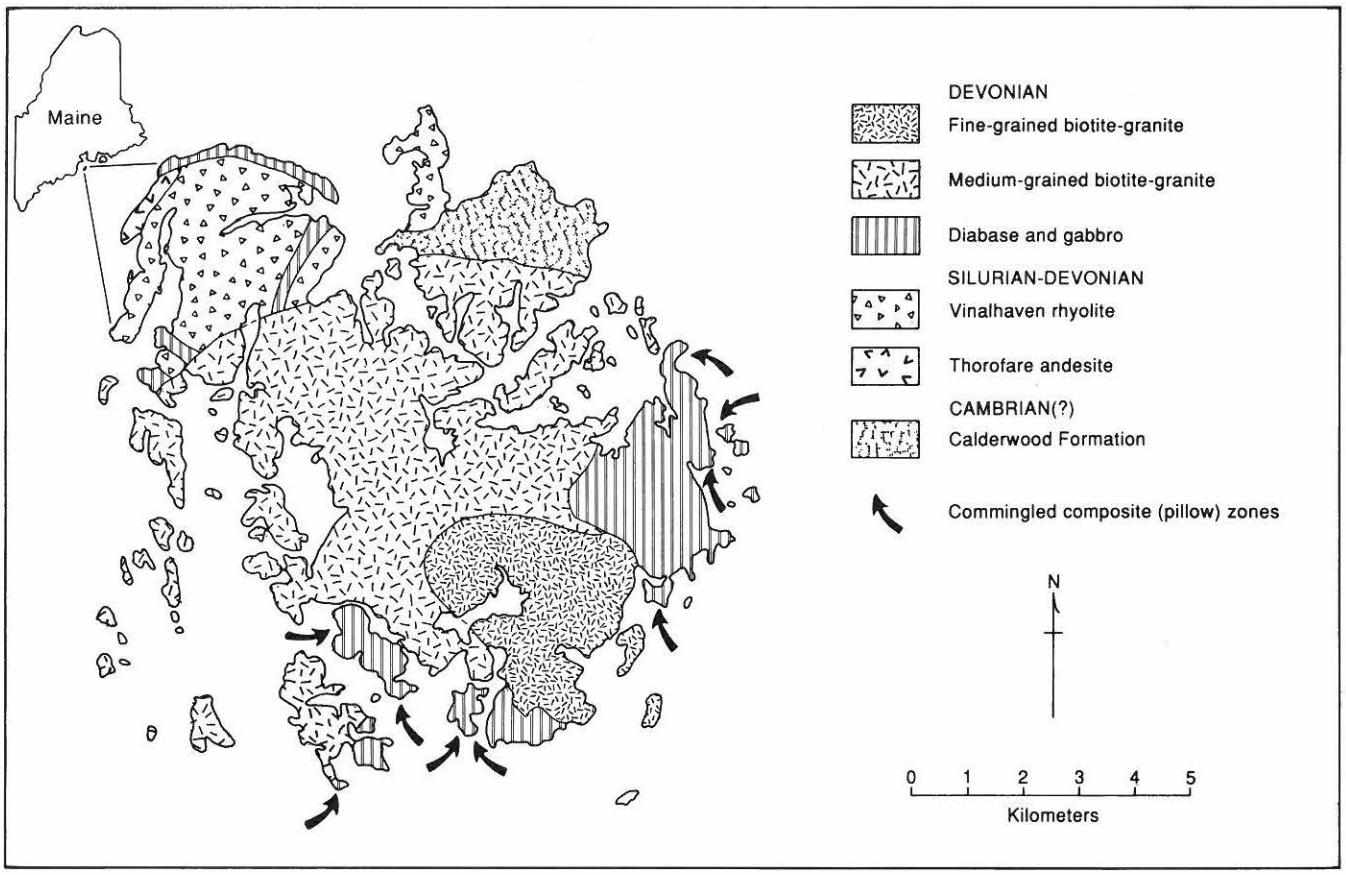


Figure 1. Generalized geologic map of Vinalhaven Island, Maine, after Smith et al. (1907), showing Cambrian(?) Calderwood Formation, Silurian-Early Devonian(?) Vinalhaven rhyolite and Thorofare andesite, Devonian granite-gabbro complex with early mafic phase, and later medium-grained hornblende-biotite granite cut by fine-grained biotite granite. Arrows indicate zones of commingled composite zones.

are intruded by the granite-gabbro association which makes up the southern three-quarters of Vinalhaven Island. Brookins (1976) dated a number of Devonian granites in Maine using Rb/Sr whole rock methods and obtained an age of 361 ± 7 for the medium-grained granite on Vinalhaven, with an initial $^{87}Sr/^{86}Sr$ value of 0.705 ± 0.001.

The intrusive rocks on Vinalhaven consist of early mafic phases ranging from olivine gabbro to diorite which are cut by a later medium-grained hornblende-biotite granite that is in turn intruded by a fine-grained biotite-granite. The association is bimodal in nature and does not show a continuous compositional gradation from basalt to granite (Fig. 2). During the emplacement of the medium-grained granite, commingling with the mafic phase occurred, producing many composite zones of basalt "pillows" and gabbro xenoliths in a granitic to granodioritic matrix. The locations of these zones are shown in Figure 1. Throughout this paper the term "pillow" will refer to the 10x10 cm to 1x5 m globules of basalt enclosed in granite; the term "matrix material" will refer to the granitic material interstitial to the basalt pillows. In addition to the granites and matrix material there are late-stage aplite dikes that cut all other intrusive units.

THE COMPOSITE ZONES

The intimate association of commingled felsic and mafic magmas on Vinalhaven Island has resulted in well developed basalt pillows which chilled within a granite matrix similar to those described by Wager and Bailey (1953). These composite zones range from large, 100 m x 20 m, sill-like sheets (Fig. 3a), to small, 5 m x 15 cm dikes that cut the gabbros. The pillows have a planar orientation that is parallel to the contact of the composite zones with the gabbro host. The extreme differences in composition, temperature, and viscosity between the mafic and felsic magmas have prevented them from thoroughly mixing together, allowing the pillows to retain their identity within the granite matrix (Fig. 3b-c).

Within these composite zones, the basalt pillows and granitic matrix material behaved in a very plastic manner. Pillows range from simple spheres to complex shapes with varying

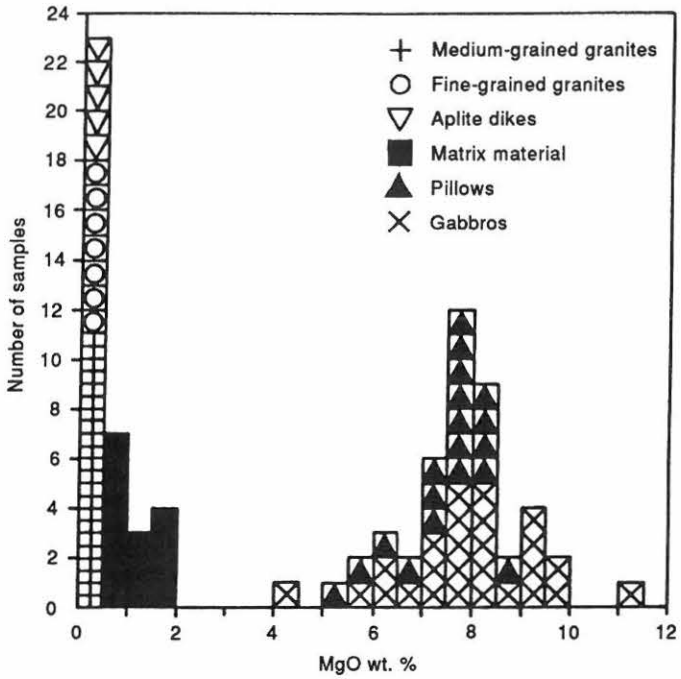
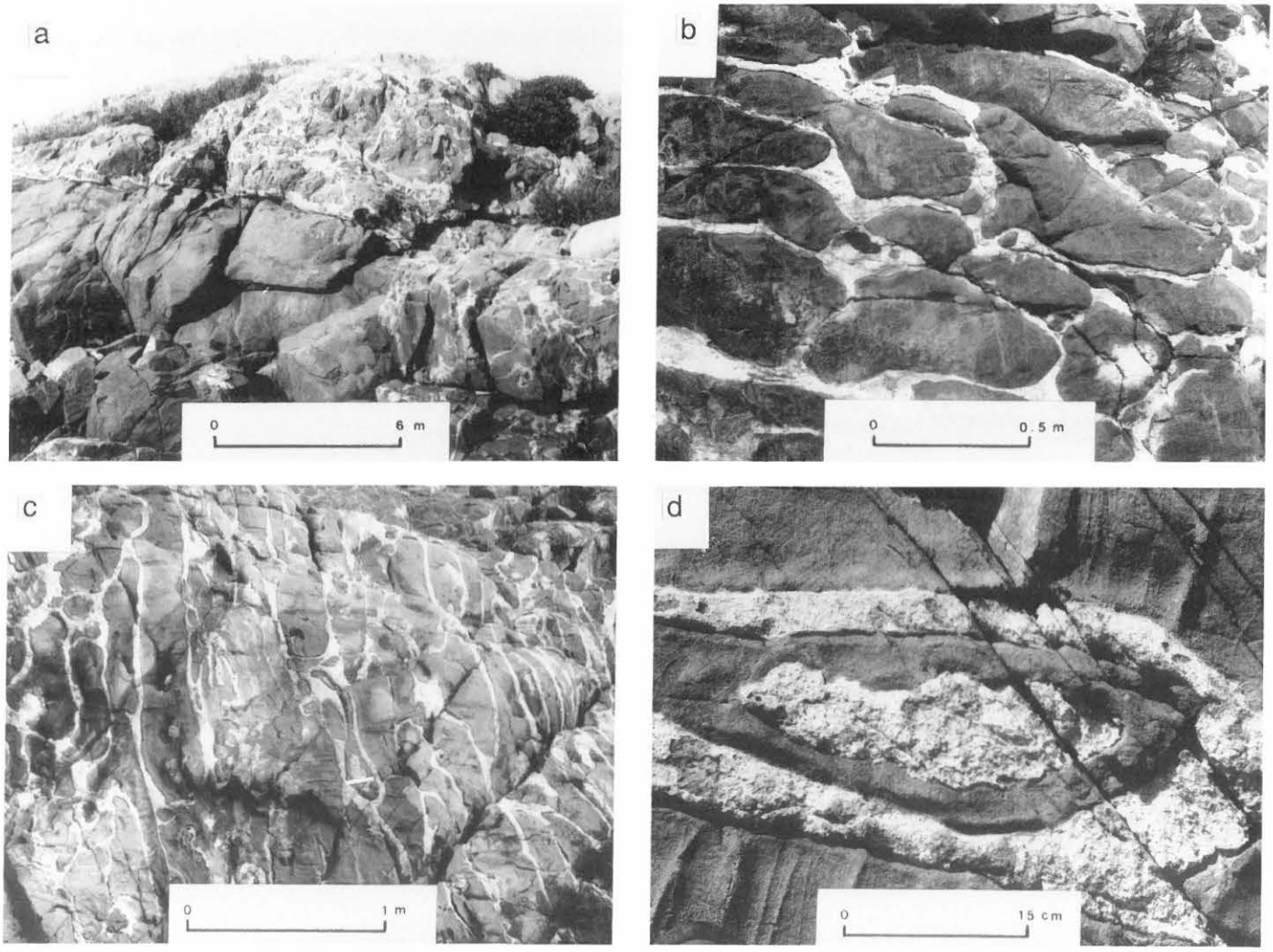


Figure 2 (at left). MgO histogram for all analyzed Vinalhaven samples, showing granites <0.5; matrix material 0.5-2.0; gabbro 4.0-11.8; pillows 5.5-8.9 (all wt. %). The gap in composition reflects the bimodal nature of the association. Data given in Appendix A.

Figure 3 (below). Photographs of basalt pillows in granite matrix from zones of commingling. (a) Sheet-like nature of the composite sill in contact with the gabbro. (b) Close-up of a composite zone illustrating fluidity of interaction. (c) Compaction of pillows and matrix in a dike. (d) Rotated close-up of the spoon-like structure in lower center of (c); note the sharpness of the contact.



amounts of thinning, bending, and necking. This very fluid behavior has produced some spectacular structures (Fig. 3) with relationships suggesting that both the pillows and matrix were liquid, or largely liquid, at the same time (Mitchell, 1986).

The pillows have sharp, fine-grained margins containing biotite and hornblende that has partially replaced pyroxene within a plagioclase-rich matrix. The concentration of hornblende and biotite has produced a 2-3 centimeter green rind on the outer edges of the pillows. Grain size increases towards the center of pillows and is accompanied by an increase in the concentration of pyroxene and a concurrent decrease in the abundance of hornblende and biotite. This concentration of hydrous phases at the margins of the pillows is probably the result of contamination by the surrounding granite melt and is limited to the outer rind. The pillow centers show little to no evidence of contamination by the granite.

Some pillows have engulfed granite and contain quartz and microcline phenocrysts. These phenocrysts are very similar to those present in the granite except they are rimmed by biotite, hornblende, and some pyroxene, and are clearly out of equilibrium. Their presence suggests that the granite matrix contained phenocrysts prior to the commingling process. The pillows must have incorporated these phenocrysts while the basalt and granite were liquid and liquid plus crystals.

The granitic matrix material is fairly homogeneous. Chemically and petrographically, it is broadly similar to and probably is the equivalent of the medium-grained granite that crops out over most of the island. The contacts of the matrix with the pillows are fine-grained and the matrix appears to have remelted at the pillow interface, perhaps as the result of superheating by the basalt pillows. Most of the matrix material has seen very little contamination by the pillow material. The exception is in areas where there has been some deformation. Here the edges of the pillows have been mechanically broken and the mafic material comminuted into the granite matrix. This largely mechanical interaction results in matrix material with a slightly intermediate composition (see Fig. 2 and sample M, Table 1), accompanied by an increase in hornblende and biotite.

The clear-cut field relations on Vinalhaven suggest that the chemical variation in the composite zones should be the result of mixing of felsic and mafic magmas. In the following sections, detailed chemical analyses will be used to describe the intrusive rocks on Vinalhaven, and demonstrate that simple two component mixing of the observed mafic and felsic end members present in the composite zones is not solely responsible for the observed compositional variation.

THE GRANITES

The medium-grained granite on Vinalhaven, named "Vinalhaven Coarse" by the quarrymen of the late 1800's, is pink and medium-grained with about equal proportions of quartz, plagioclase (An_{12-22}), and microcline, and less than 10% mafic phases consisting of chiefly hornblende and biotite. Accessory

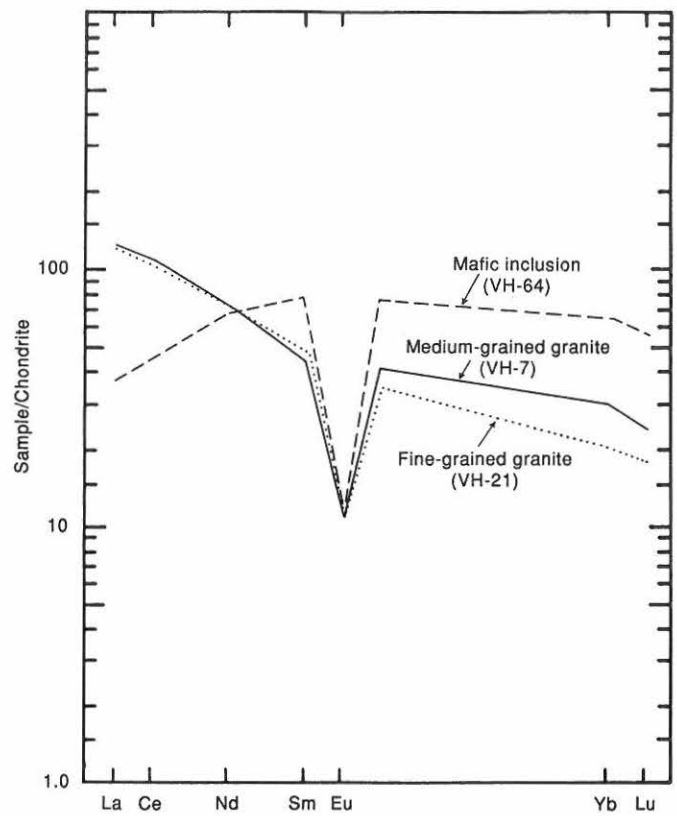


Figure 4. Chondrite-normalized REE plot for representative felsic samples. It is important to notice the difference between the pattern for the mafic inclusion (VH-64) and the mafic samples as in Figure 9.

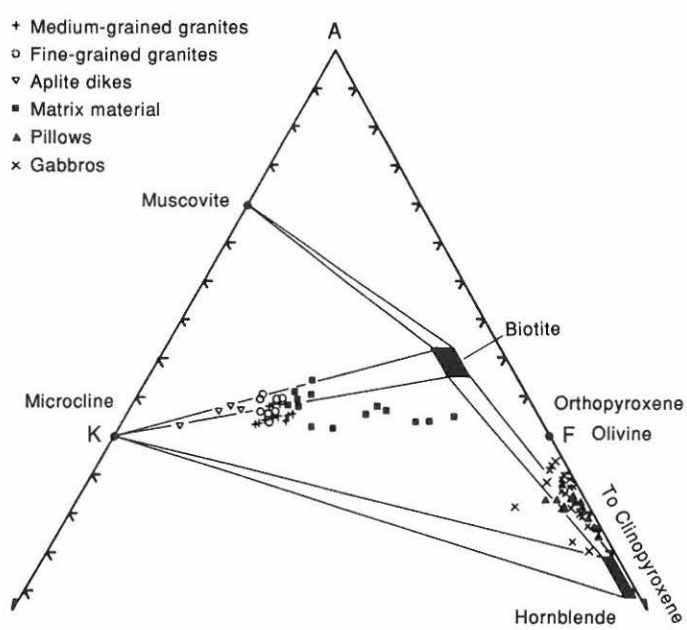


Figure 5. AKF projection from plagioclase and quartz with molar whole rock and mineral compositions. $A = Al_2O_3 + Fe_2O_3 + TiO_2 - Na_2O - K_2O - (CaO - 10/3\ P_2O_5)$, $K = K_2O$, $F = FeO + MnO + MgO - TiO_2$. Biotite and hornblende compositions from granites of similar composition (Deer et al., 1962; Rhodes, 1969).

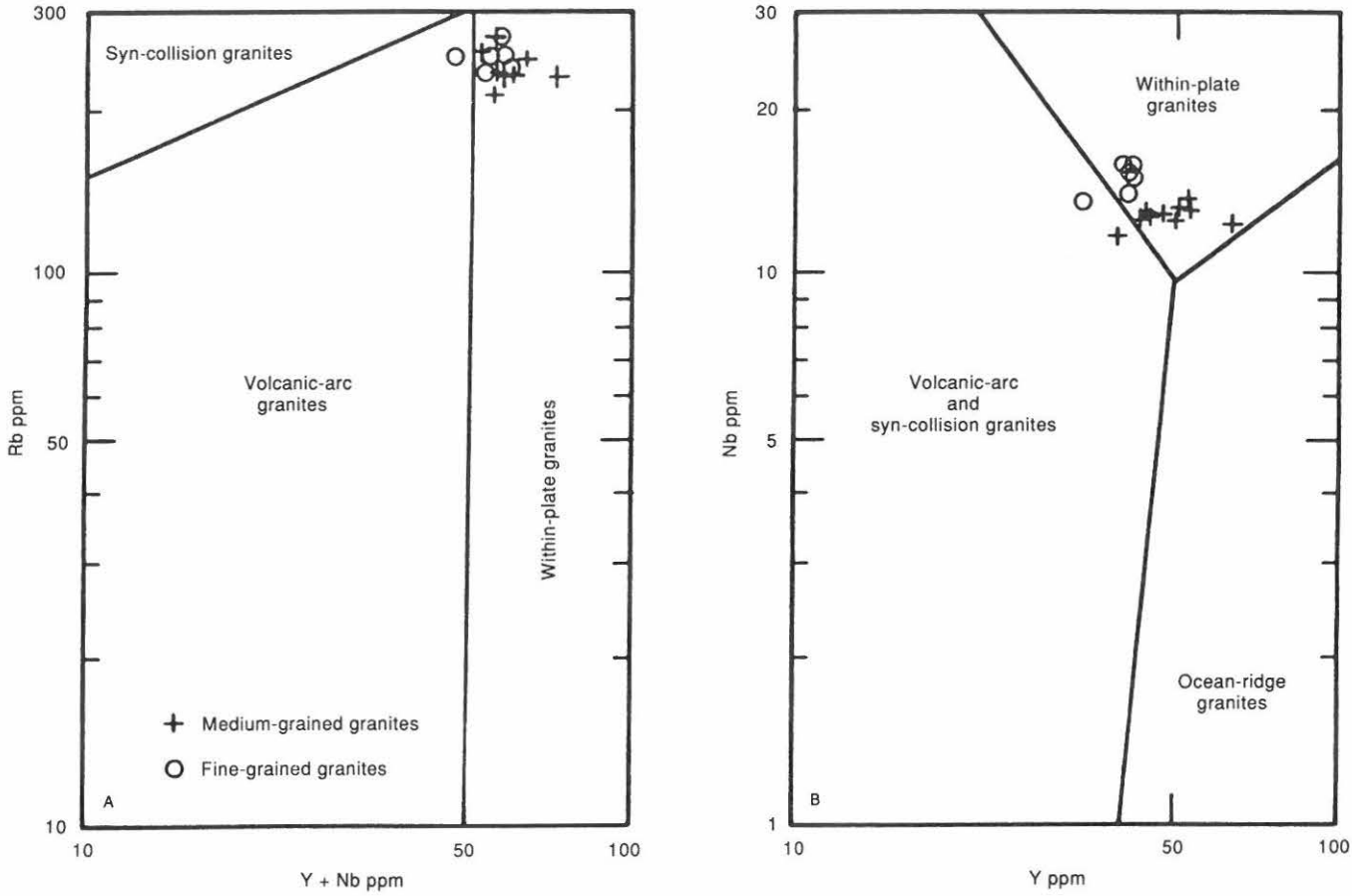


Figure 6. (a) Rb vs Y+Nb and (b) Nb vs Y tectonic discriminant diagrams after Pearce et al. (1984).

phases include magnetite, ilmenite, apatite, sphene, zircon, and allanite. Large alkali feldspar phenocrysts have exsolved to a fine-grained intergrowth of microcline and plagioclase. These are responsible for the rock's pink color. In rare samples these phenocrysts have plagioclase rims forming the so-called viborgite-type Rapakivi texture. There is some sericitization of the plagioclase and alteration of biotite to chlorite.

The fine-grained granite is gray, with equal proportions of quartz, plagioclase (An_{15-22}), and microcline, and less than 5% biotite. Accessory minerals include magnetite, ilmenite, apatite, zircon, sphene, and allanite. The principal petrographic difference between the two granites is one of grain size and the presence of hornblende in the medium-grained variety. On the basis of field and petrographic evidence, Stewart (1956) correlated the Vinalhaven medium- and fine-grained granites with the Sherwood granite on Deer Island and Crotch Island granite on Crotch Island respectively.

The medium- and fine-grained granites are both very homogeneous, have similar compositions, and appear to be the product of similar magmas with slightly different cooling histories. This would account for the presence of hornblende and increased grain size in the medium-grained granite. Table 1 gives the average chemical compositions for the two granites. They are metaluminous ($Al_2O_3/CaO + K_2O + Na_2O < 1$ molar) to mildly peraluminous, subalkaline, and correspond with the I-type classification of Chappell and White (1974) with <1% normative corundum, no modal aluminous minerals, and initial $^{87}Sr/^{86}Sr$ between 0.704-0.706 (Brookins, 1976).

Chondrite (CH) normalized rare earth elements (REE) patterns for the two granites are very similar (Fig. 4). They are enriched in light REE, 100-50 times CH, have large negative Eu anomalies, and an overall negative slope to their patterns. The medium-grained granite contains more Yb and Lu than the fine-grained granite. This relative enrichment of heavy REE is probably a function of hornblende content. Hornblende is enriched in the heavy REE relative to the granites (Hanson, 1978); thus, its presence in the medium-grained granite could be responsible for the observed differences in Yb and Lu in the two granites.

In order to examine the relationship between the whole rock chemistry and observed mineralogy, all Vinalhaven samples (felsic and mafic rocks) have been plotted on an AKF projection (Fig. 5). Average analyses of hornblende and biotite taken from the literature for rocks of similar compositions (Deer et al. 1962; Rhodes, 1969) have been plotted to show their general location on such a projection. Biotite is the key mineral composition

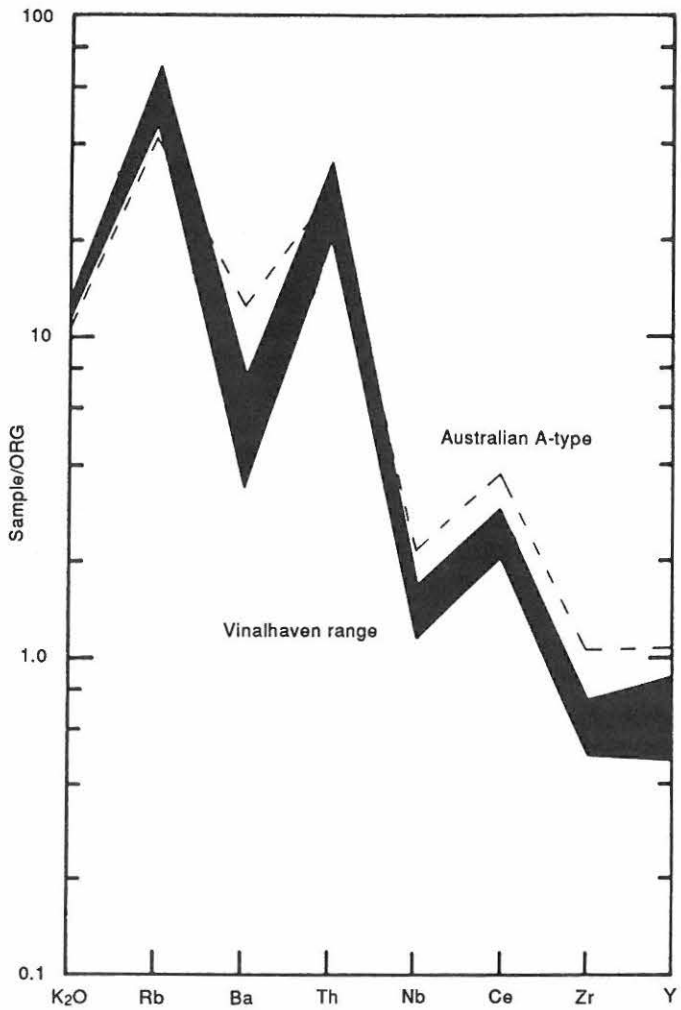


Figure 7. Modified "spider diagram" with samples normalized to Ocean Ridge Granites (ORG) after Pearce et al. (1984). Shaded field, range for medium- and fine-grained Vinalhaven granites; dashed line, average Australian A-type granites from White and Chappell (1983).

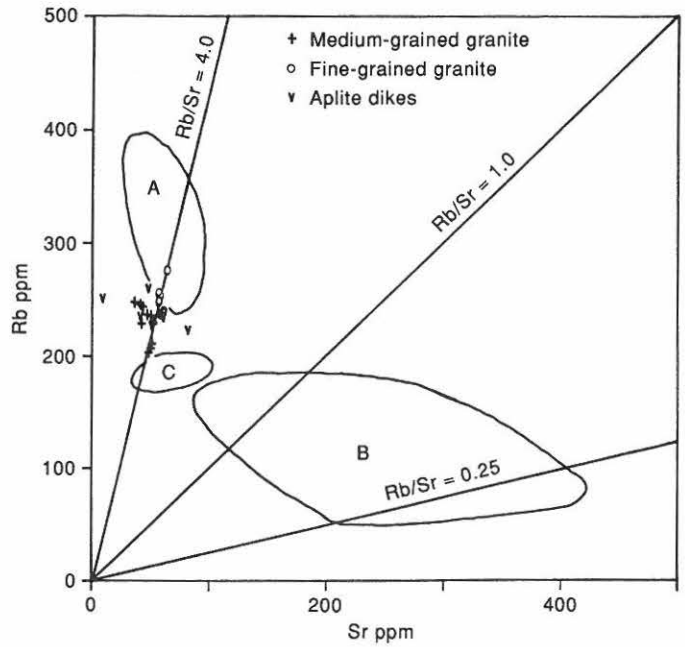


Figure 8. Plot of Rb vs Sr for granites from Vinalhaven. Fields A, B, and C for other Maine granites are taken from Loiselle and Ayuso (1980). Outlined fields include: A-Lucerne and Lead Mountain plutons; B-Bottle Lake complex, Center Pond pluton, and Seboeis foliated granitoid; C-Seboeis non-foliated granite and Katahdin pluton.

because its location controls the biotite-microcline tie line separating the muscovite-biotite-microcline-plagioclase field from the hornblende-biotite-microcline-plagioclase field. All Vinalhaven samples lack a primary aluminous phase and plot within the hornblende-biotite-microcline-plagioclase field, with some samples falling on or close to the inferred biotite-microcline tie line. S-type granites (Chappell and White, 1974) contain muscovite and other aluminous phases and would plot above the biotite-microcline tie line, whereas I-type granites lacking aluminous phases would plot along or below the biotite-microcline tie line.

The mineralogy, both essential and accessory (e.g. sphene), and the presence of mafic inclusions also support an I-type classification. In addition to their I-type characteristics, however, these granites show many of the compositional attributes of A-type, anorogenic granites (Barker et al., 1975; Loiselle and Wones, 1979; Collins et al., 1982; Anderson, 1983; White and Chappell, 1983; Whalen et al., 1987). Although there is some confusion over the definition of A-type granitoids, they tend to be subalkaline and metaluminous, with enrichment of incompatible elements (K, Zr, Nb) and depletion of compatible elements (Cr, Ni, Ba, Sr) relative to other granite types with comparable silica contents. The chemical characteristics of the granites from Vinalhaven are similar to those of proposed anorogenic suites.

In order to evaluate the tectonic environment in which these rocks were emplaced, they are compared to granites of known tectonic environment using trace element discriminant diagrams (Pearce et al., 1984). The granites on Vinalhaven plot in the field of within-plate granites on Nb vs Y and Rb vs Y+Nb diagrams (Fig. 6). This point is illustrated further using a modified "spider diagram" (Fig. 7), in which samples are normalized to an ocean ridge granite (Pearce et al., 1984). This multi-element pattern also compares closely with granites from within-plate environments. All are high in normalized Rb and Th, and are depleted in Ba, producing a substantial Ba anomaly. This anomaly is a common characteristic of granites of the within-plate suite. This pattern is also similar to granites from the post-orogenic suite (Pearce et al., 1984). The averages of 31 Devonian A-type granites from eastern Australia (White and Chappell, 1983) show a very similar pattern to those from Vinalhaven (Fig. 7). Thus, on the basis of their trace elements, both fine- and medium-grained granites on Vinalhaven show similar characteristics to

granites from known within-plate and post-orogenic environments.

In order to compare the granites of Vinalhaven to other Maine plutons, their Rb and Sr abundances have been plotted on Figure 8. Although the absolute abundances are transitional between groups A and C of Loiselle and Ayuso (1980), Rb/Sr ≥ 4.0 is consistent with group A, representing other plutons of the Maine coastal lithotectonic belt (Loiselle and Ayuso, 1980; Ayuso, 1986).

THE MAFIC SUITE

Characterization

The mafic rocks on Vinalhaven have been divided on the basis of their field occurrence. The intrusive rocks are grouped together as "gabbros" and the fine-grained rocks from the composite zones are referred to as "pillows." Each group shows a range in composition. The gabbros are medium-grained and range from true olivine two-pyroxene gabbros to hornblende-biotite diorites. The pillows are fine-grained basalts and contain varying amounts of olivine, clinopyroxene, plagioclase, biotite, and hornblende. Major and trace element abundances for the mafic suite show a wide range in composition (Appendix A). Compatible elements (CaO, Al_2O_3, Ni, Cr) decrease with decreasing MgO. Incompatible elements (TiO_2, K_2O, Na_2O, Zr, Nb, Y, Th) increase with decreasing MgO. The gabbros and pillows are very similar in composition, with the pillows showing a more restricted range within that of the gabbros (Fig. 2).

Samples with 8.9-11.8 wt% MgO are thought to have accumulated olivine and plagioclase crystals, are depleted in highly incompatible elements (60-79 ppm Zr, <2.5 ppm Nb, <3 ppm Th), and are low in moderately incompatible elements (0.85-1.56 wt% TiO_2, 15-25 ppm Y). They have flat chondrite normalized REE patterns approximately 10 times chondrite, which are depleted relative to other Vinalhaven samples (Fig. 9). These samples have Mg'-values of 0.64-0.71 and are enriched in compatible elements (169-355 ppm Cr, 177-251 ppm Ni). Most samples show little textural evidence of contamination or alteration.

Samples with MgO 4.1-7.5 wt%, have Mg'-values of 0.48-0.64 and show strong evidence for both crystal fractionation and contamination by the surrounding granite. Modal hornblende and biotite increase with decreasing MgO, as do the incompatible elements (122-294 ppm Zr, 4.4-8.0 ppm Nb, 1-7 ppm Th, 23-44 ppm Y, 0.97-2.51 wt% TiO_2). Their chondrite normalized REE patterns are enriched relative to the other mafic samples (Fig. 9). These patterns show varying amounts of fractionation and contamination relative to samples with lower MgO contents. The presence of large Eu anomalies in some samples suggest that they may have incorporated varying amounts of granitic material. The compatible elements decrease (40-114 ppm Ni, 136-248 ppm Cr) as MgO decreases. Although there is overlap, these samples show more evolved compositions for all elements compared to the other mafic samples.

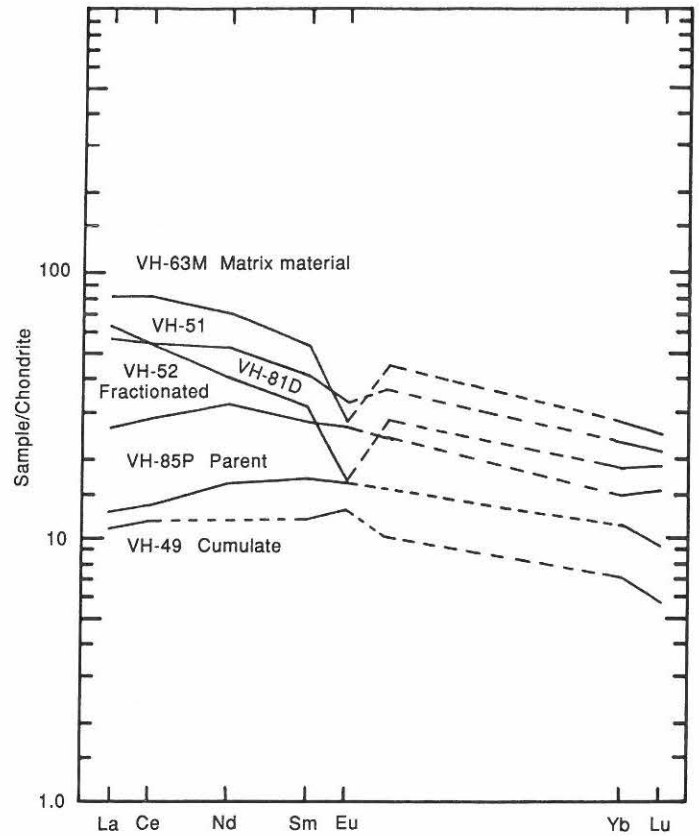


Figure 9. Chondrite-normalized REE diagram for selected mafic samples. VH-85P represents approximate parental composition. VH-49 is a cumulate sample. The other samples represent varying amounts of crystal fractionation and contamination. Samples with negative Eu anomalies have been contaminated by a granitic component.

Interpretation

Much of the compositional diversity of the mafic suite is thought to result from the combined effect of crystal accumulation and fractionation, and contamination by the surrounding granite magma. Samples with MgO between 7.5-8.5 are most abundant and are taken to represent compositions closest to the parental mafic magmas. Within this range, fine-grained pillow interiors are probably closest in composition to that of the mafic melt, since rapid cooling will have minimized the effects of crystal fractionation and accumulation. In addition, petrographic inspection shows that biotite and hornblende, possible evidence for granitic contamination, are restricted to the pillow rims. Thus pillow cores show little evidence of contamination by the granite matrix and should reflect a composition close to the original magma. The average of 5 such pillow cores with MgO between 7.5-8.5 has been taken to represent the

composition of the parental mafic magma. This five pillow average will be referred to as "P" and is given in Table 1. Pillow VH-85P has the composition closest to the calculated average. It has a flat chondrite-normalized REE pattern approximately 15 times chondrite. This pattern will be used to represent the parental REE pattern. The composition is similar to those reported for Type I mid-ocean ridge basalts (MORB) (Basaltic Volcanism Study Project, 1981), with the exception of enrichment in K, Sr, Ba, Rb, and Al relative to MORB. This enrichment could in part be the result of interaction with the granite.

In order to compare the Vinalhaven mafic suite to basalts from known tectonic environment, data have been plotted on a Zr/Y vs Zr diagram (Fig. 10). These samples fall into two distinct groups. Samples with Zr/Y <4 lie in the MORB field and samples with Zr/Y >4 plot in the within-plate field (Pearce and Norry, 1979). On the basis of their major element chemistry (except TiO_2) the group of samples with Zr/Y >4 could be produced by fractional crystallization of the proposed parental magma P. It is not possible, however, to explain some of their trace element abundances by either fractionation of low Zr/Y parental melts, or by contamination of such a melt by the associated granites. The high Zr/Y group is enriched in other high field strength elements Nb and TiO_2, and also in Sr. These samples are limited to a single area in the composite zone on the south-central portion of the island. On the basis of their field relations and trace element chemistry, these samples could represent a later phase of mafic activity that was enriched in incompatible elements and are correspondingly depleted in compatible elements relative to the proposed parental composition P. This enrichment would explain why these samples plot in the within-plate field on the Zr/Y vs Zr diagram. These compositions are evidence for a second mafic magma.

Figure 11 plots Zr vs Nb for all analyzed Vinalhaven samples. These two elements are highly incompatible with respect to basaltic and mantle mineralogy. Their concentrations and, particularly, their ratios are thought to be immobile and only slightly modified by alteration and secondary processes (Humphris and Thompson, 1978). Varying amounts of partial melting, crystal fractionation and crystal accumulation may change the abundances of Zr and Nb, but should not change their ratio. Thus a suite of rocks from the same source would have constant Zr/Nb ratios. The majority of the mafic suite, and in particular samples with high MgO content, have Zr/Nb ≥30. This ratio is comparable to many island arc tholeiites and Type I mid-ocean ridge basalts (Basaltic Volcanism Study Project, 1981). Although the enriched samples have higher Zr and Nb abundances than the other mafic samples, their Zr/Nb ratios are not significantly different. The consistent Zr/Nb ratio for the gabbros and pillows suggests that they were derived from the same source. The granites, on the other hand, have markedly different Zr/Nb ratios (<15) and large negative Eu anomalies which suggests that they were not differentiated from the mafic suite and were probably the result of crustal melting (Ayuso, 1986).

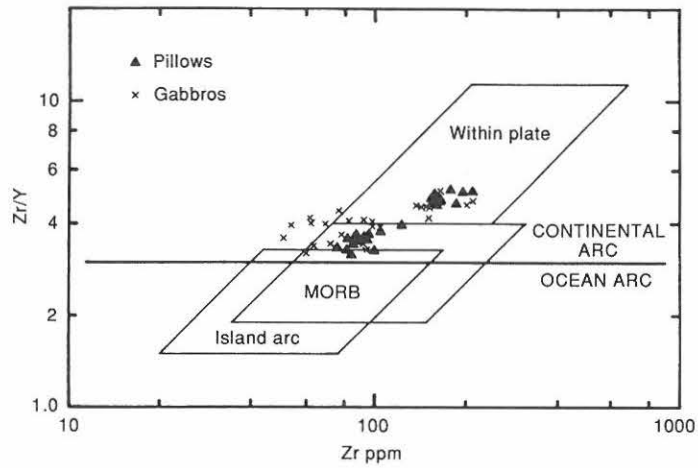


Figure 10. Zr/Y vs Zr tectonic setting discriminant diagram for basaltic rocks. Modified after Pearce and Norry (1979) and Pearce (1983).

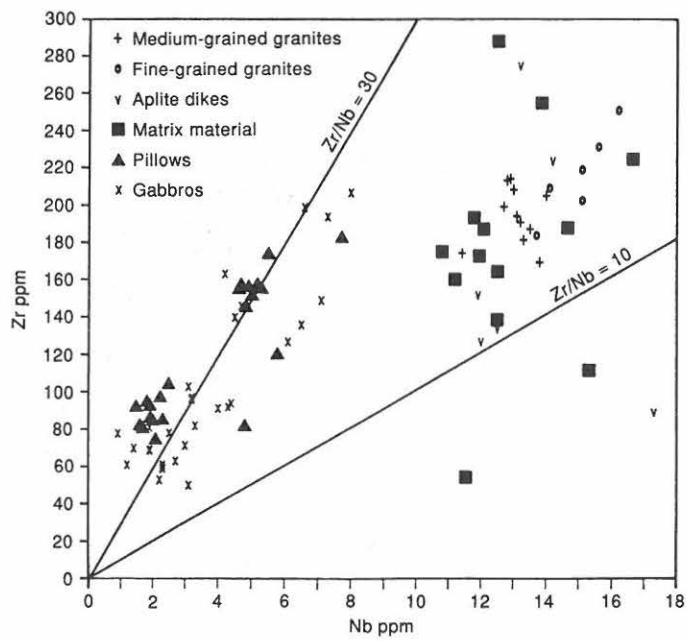


Figure 11. Zr vs Nb chemical variation diagram showing all analyzed Vinalhaven samples.

The Mafic Suite: Discussion

The wide range in composition for the mafic suite can be explained to a first approximation by a combination of crystal fractionation and accumulation from a parental basaltic magma modified by contamination. Figure 12 illustrates the interplay of crystal fractionation, accumulation, and contamination. The Vinalhaven samples have been projected from plagioclase onto the olivine-clinopyroxene-silica ternary diagram (Grove et al., 1982). The 1-atmosphere and inferred 1,000 bars P_{H2O} cotectics and reaction curves have been included for reference. The samples inferred to have accumulated olivine trend away from

P toward the olivine corner, whereas evolved samples trend toward more silica-rich compositions. Many of the evolved samples do not plot on or near the olivine-plagioclase-clinopyroxene saturation curve as they should if their composition is controlled solely by low pressure crystal fractionation. Instead, they trend directly towards the silica corner, or are intermediate between this trend and the three phase saturation curve. These samples are inferred to result from a combination of low pressure crystal fractionation and contamination by the granite along a proposed mixing line shown on Figure 12. These trends produce qualitative support for the idea that the range in composition in the mafic suite can be produced by varying amounts of crystal fractionation, crystal accumulation, and contamination by the granite. For a detailed discussion of the petrogenetic model of these samples see Mitchell (1988) and Mitchell and Rhodes (in prep).

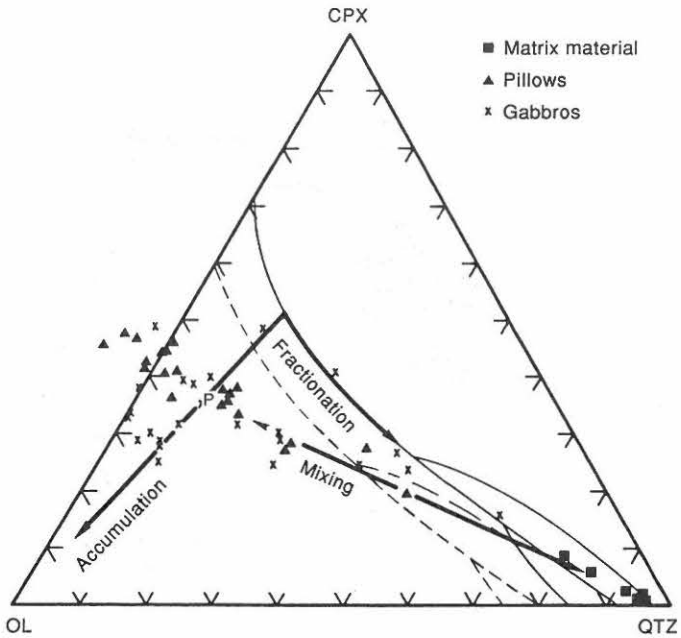


Figure 12. Projection from plagioclase onto the plane olivine (OL)-clinopyroxene (CPX)-silica (QTZ) after Grove et al. (1982). Solid phase boundaries modified from Grove et al. (1982), with the inclusion of data from Grove and Bryan (1983). Dashed curves are inferred phase boundaries for 1,000 bar P_{H2O} (Grove et al., 1982). P = parent composition; vectors indicate inferred fractionation, accumulation, and contamination trends.

CONCLUSIONS

(1) The intrusive rocks on Vinalhaven are bimodal and consist of minimum-melt granites formed by crustal melting and a suite of mafic rocks probably derived by partial melting in the mantle.

(2) The medium- and fine-grained granites are closely similar in composition and represent magma from the same source, with slightly different cooling histories. Both are I-type granites that show compositional similarities to anorogenic granites. Their Rb/Sr ratio >4 is consistent with other granites of the Maine coastal lithotectonic belt.

(3) On the basis of their trace element compositions, both granites on Vinalhaven are similar to granites from within-plate and post-orogenic tectonic environments, suggesting they could have been emplaced during the late stages of, or after the Acadian orogeny.

(4) The mafic suite consists of medium-grained gabbros to diorites and fine-grained basaltic pillows with a wide range in composition that can be explained by varying amounts of crystal fractionation, crystal accumulation, and contamination by the associated granites. The proposed parental composition is similar to Type I MORB that have been enriched in K, Sr, Rb, Ba, and Al.

(5) Commingling of the mafic and felsic magmas has produced composite zones of basalt pillows in a granite matrix. The pillows retained their own identity because of differences in composition, temperature, viscosity, and lack of convective mechanical mixing. Shapes and structures formed during mingling of the mafic and felsic magmas, along with chilled margins on the pillows, suggest that they and the granites were liquid or largely liquid at the same time.

(6) These commingled magmas show limited chemical interaction. Samples with intermediate (hybrid) compositions are not the product of simple two-component mixing of the proposed mafic parent (P) and granite end members.

DEDICATION

This work is dedicated to the memory of Michael A. B. Stratton who through his work with dyslexic children at the Carroll School Bounders Program has given me and many other students the opportunity to believe in ourselves and our own abilities. He first took me to Vinalhaven when I was 12 years old, and let me climb on, throw, and carry rocks. He introduced me to the wonders of the Maine coastal islands, and his stories about the old quarry men and the lives they lived is what got me interested in rocks in general and granites in particular. Without his help, I would never have realized that it is possible to do anything you want as long as you try hard enough. This work would never have been possible without the self confidence and "can do" attitude that I gained by working with Mike over the years.

ACKNOWLEDGMENTS

This work was supported in part by grants from the Geological Society of America and Sigma Xi. We are grateful to J. W. Sparks and L. K. Autio for assistance with XRF analyses and discussion of the data, and to R. Hon and A. Sheardin for the INAA analyses. CBM would also like to thank S. A. Morse and Peter Robinson for their direction during this project.

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APPENDIX A. WHOLE ROCK MAJOR AND TRACE ELEMENT ANALYSES FOR THE VINALHAVEN GRANITE-GABBRO ASSOCIATION.

TABLE A1. VINALHAVEN WHOLE ROCK ANALYSES

	MEDIUM GRANITES										
Sample No.	VH-1	VH-2	VH-3	VH-4	VH-5	VH-6	VH-7	VH-8	VH-9	VH-10	VH-11
SiO_2	73.60	73.56	73.84	74.78	75.06	74.37	74.38	75.31	75.23	74.08	73.81
TiO_2	0.36	0.36	0.37	0.03	0.30	0.33	0.31	0.27	0.29	0.36	0.33
Al_2O_3	13.07	13.23	13.14	12.85	12.73	13.18	12.96	12.73	12.90	12.92	13.24
Fe_2O_3*	2.23	2.19	2.27	2.01	1.99	2.12	2.01	1.82	1.86	2.14	2.06
MnO	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.03	0.04	0.04
MgO	0.42	0.42	0.43	0.34	0.33	0.38	0.35	0.29	0.34	0.45	0.40
CaO	1.24	1.19	1.20	0.99	0.99	1.14	1.06	0.95	1.08	1.20	1.11
Na_2O	3.49	3.20	3.35	3.55	3.51	3.70	3.32	3.65	3.54	3.21	3.38
K_2O	5.05	5.23	4.98	5.09	5.04	5.01	5.11	5.00	5.10	5.05	5.16
P_2O_5	0.09	0.08	0.08	0.07	0.07	0.08	0.07	0.06	0.07	0.08	0.07
Total	99.60	99.49	99.70	100.01	100.04	100.34	99.60	100.14	100.43	99.53	99.59
Mg'-value	0.27	0.27	0.27	0.25	0.25	0.26	0.26	0.24	0.27	0.29	0.28
A/CNK	0.97	1.01	1.00	0.98	0.98	0.97	1.00	0.97	0.97	1.00	1.01
Ba	247	264	259	212	195	225	197	174	226	252	242
Rb	231	212	230	230	245	238	247	249	204	208	237
Sr	52	51	52	42	43	47	41	36	48	50	50
Pb	22	22	23	23	26	22	26	24	21	21	22
Th	19	17	19	22	28	19	23	25	17	19	18
U	8	6	12	5	7	8	10	9	7	7	7
Zr	215	209	214	192	182	206	188	170	175	200	195
Nb	12.9	13.0	12.8	13.2	13.3	14.0	13.5	13.8	11.4	12.7	13.1
Y	49	44	61	45	44	52	51	52	39	43	46
V	19	19	20	14	17	19	17	13	17	19	17
Cr	4	6	5	3	3	5	5	3	3	6	4
Ni	2	1	0	0	4	6	2	3	3	4	1
Zn	31	31	38	30	29	32	39	27	26	32	34
Ga	17	18	17	17	17	17	17	17	16	17	17
Rb/Sr	4.4	4.2	4.4	5.5	5.7	5.1	6.0	6.9	4.3	4.2	4.7
K/Rb	181.4	204.7	179.7	183.7	170.7	174.7	171.7	166.6	207.5	201.5	180.7
Zr/Nb	16.7	16.1	16.7	14.5	13.7	14.7	13.9	12.3	15.4	15.7	14.9
Zr/Y	4.4	4.8	3.5	4.2	4.2	4.0	3.7	3.3	4.5	4.7	4.2

*Total Fe expressed as Fe_2O_3

Mg'-value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{3+}/total Fe as FeO = 0.1

A/CNK = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$

TABLE A1. CONTINUED.

Sample No.	FINE GRANITES VH-20	VH-21	VH-22	VH-23	VH-24	VHL-26	APLITE DIKES VH-27	VH-28	VH-29	VH-30	VH-97	VH-102
SiO_2	74.72	72.79	73.53	73.79	73.46	74.28	74.23	76.55	72.55	77.35	75.48	75.28
TiO_2	0.31	0.35	0.27	0.28	0.32	0.28	0.30	0.17	0.37	0.07	0.18	0.23
Al_2O_3	13.38	13.78	13.64	13.63	13.58	13.46	13.57	12.74	14.13	12.58	13.26	13.18
Fe_2O_3*	1.99	2.18	1.77	1.74	2.10	1.77	1.82	1.27	2.00	0.81	1.23	1.55
MnO	0.04	0.05	0.03	0.03	0.04	0.03	0.03	0.02	0.03	0.02	0.01	0.02
MgO	0.38	0.48	0.35	0.33	0.44	0.36	0.39	0.22	0.48	0.04	0.18	0.27
CaO	1.27	1.38	1.12	1.08	1.33	1.10	1.30	0.72	1.47	0.50	0.75	0.98
Na_2O	3.58	3.35	3.36	3.48	3.61	3.68	3.88	3.45	3.70	3.46	3.54	3.44
K_2O	4.98	5.14	5.25	5.21	5.10	5.09	4.78	5.14	5.39	5.46	5.47	5.29
P_2O_5	0.08	0.08	0.08	0.07	0.08	0.09	0.07	0.05	0.10	0.01	0.04	0.06
Total	99.72	99.56	99.40	99.64	100.04	100.14	100.37	100.31	100.22	100.30	100.15	100.30
Mg'-value	0.27	0.30	0.28	0.27	0.29	0.29	0.30	0.25	0.32	0.08	0.22	0.26
A/CNK	0.98	1.02	1.03	1.02	0.98	0.99	0.97	1.02	0.97	1.01	1.01	1.00
Ba	341	370	350	376	326	361	377	221	611	17	298	280
Rb	242	278	258	255	239	250	236	237	225	253	262	229
Sr	61	64	57	58	58	57	61	41	82	9	48	51
Pb	22	22	32	25	19	32	21	23	23	27	27	23
Th	22	26	18	22	22	17	20	20	20	28	20	22
U	10	6	9	7	8	6	9	10	6	11	8	5
Zr	204	252	211	233	220	185	225	128	276	90	135	153
Nb	15.1	16.2	14.1	15.6	15.1	13.7	14.2	12.0	13.2	17.3	12.5	11.9
Y	42	41	40	41	40	34	37	32	35	43	34	36
V	19	18	18	13	21	17	16	9	24	3	7	11
Cr	6	7	5	6	5	5	4	4	7	2	1	3
Ni	3	5	5	4	6	5	3	5	7	1	1	5
Zn	31	29	20	30	31	18	27	18	28	16	11	15
Ga	17	17	17	16	17	16	15	14	17	16	17	17
Rb/Sr	4.0	4.3	4.5	4.4	4.1	4.4	3.9	5.8	2.7	28.1	5.5	4.5
K/Rb	170.8	153.4	168.9	169.6	177.1	169.0	168.1	180.0	198.8	179.1	173.3	191.7
Zr/Nb	13.5	15.6	14.9	14.9	14.6	13.5	15.8	10.7	20.9	5.2	10.8	12.9
Zr/Y	4.9	6.1	5.2	5.6	5.5	5.5	6.1	4.0	7.9	2.1	4.0	4.2

Sample No.	GABBROS VH-40	VH-41	VH-42	VH-43	VH-44	VH-45	VH-46	VH-47	VH-48	VH-49	VH-50	VH-51	VH-52
SiO_2	48.58	48.43	49.39	48.18	51.58	52.85	52.22	47.75	47.77	47.58	54.82	53.34	47.94
TiO_2	1.53	1.18	0.96	1.86	0.81	1.24	1.07	1.03	0.98	0.89	0.78	2.25	1.90
Al_2O_3	17.11	18.31	18.44	16.35	18.20	16.15	16.58	19.61	19.07	17.69	15.23	13.89	16.77
Fe_2O_3*	10.39	9.19	8.16	11.53	7.66	8.85	7.95	7.64	7.92	9.18	7.21	12.03	11.52
MnO	0.16	0.15	0.14	0.19	0.12	0.14	0.14	0.12	0.12	0.15	0.13	0.20	0.19
MgO	8.31	9.47	9.01	7.74	7.96	7.43	7.01	9.56	9.79	11.11	8.03	5.55	8.25
CaO	9.92	10.76	10.08	10.83	9.96	9.62	11.59	11.80	11.24	10.84	10.07	7.89	9.24
Na_2O	2.91	2.47	3.03	2.73	2.90	2.77	2.82	2.66	2.54	2.48	2.44	3.21	3.16
K_2O	0.64	0.26	0.46	0.44	0.85	0.96	0.64	0.12	0.15	0.18	1.05	1.48	0.48
P_2O_5	0.23	0.13	0.11	0.23	0.07	0.06	0.12	0.09	0.07	0.10	0.07	0.35	0.24
Total	99.77	100.33	99.77	100.06	100.10	100.06	100.12	100.36	99.64	100.18	99.84	100.20	99.68
Mg'-value	0.61	0.67	0.69	0.57	0.67	0.62	0.64	0.71	0.71	0.71	0.69	0.48	0.59
A/CNK	0.73	0.77	0.77	0.66	0.76	0.70	0.63	0.76	0.77	0.74	0.65	0.65	0.74

Total Fe expressed as Fe_2O_3
Mg'-value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{3+}/total Fe as FeO = 0.1
A/CNK = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$

TABLE A1. CONTINUED.

Sample No.	GABBROS (Cont.) VH-40	VH-41	VH-42	VH-43	VH-44	VH-45	VH-46	VH-47	VH-48	VH-49	VH-50	VH-51	VH-52
Ba	66	33	46	67	53	67	48	3	24	24	67	140	60
Rb	29	8	18	26	40	34	30	5	6	5	43	58	12
Sr	234	235	225	228	206	194	197	287	253	228	159	298	274
Pb	6	2	4	6	7	7	4	3	2	3	6	10	3
Th	2	2	2	1	3	2	2	0	0	1	4	4	1
U	1	1	1	1	2	1	1	0	0	0	2	1	1
Zr	93	79	71	141	83	72	97	79	62	62	92	208	164
Nb	4.3	2.5	1.4	4.5	3.3	3.0	3.2	0.9	1.2	2.3	4.0	8.0	4.2
Y	27	22	18	31	20	21	24	18	15	15	23	44	32
V	189	151	136	228	110	189	177	139	138	125	141	254	149
Cr	167	169	355	215	139	291	336	159	328	252	369	198	138
Ni	139	177	187	96	116	93	64	244	216	251	72	40	119
Zn	86	61	63	92	51	62	58	51	60	62	55	113	85
Ga	17	17	17	19	18	18	17	16	16	15	16	22	19
Rb/Sr	0.1	0.0	0.1	0.1	0.2	0.2	0.2	0.0	0.0	0.0	0.3	0.2	0.0
K/Rb	183.2	237.1	212.1	140.4	176.8	233.1	176.8	215.8	232.4	333.8	202.7	211.8	319.2
Zr/Nb	21.6	31.6	50.7	31.3	25.2	24.1	30.3	87.6	51.7	27.0	23.1	26.0	39.1
Zr/Y	3.4	3.6	3.9	4.5	4.1	3.4	4.1	4.4	4.0	4.1	4.0	4.7	5.2

Sample No.	GABBROS (Cont.) VH-53	VH-54	VH-56	VH-57	VH-58	VH-80D	VH-81D	VH-87D	VH-88DU	VH-92D	VH-93D	VH-94D	VH-200D
SiO_2	55.56	48.83	56.93	53.74	53.75	49.59	61.10	49.10	49.03	49.80	55.88	51.23	50.82
TiO_2	1.17	2.51	1.04	0.32	0.33	2.44	0.97	1.81	1.21	1.16	0.88	1.15	1.00
Al_2O_3	15.73	15.82	15.56	17.76	18.09	14.34	14.91	16.05	17.35	16.78	15.72	16.12	17.00
Fe_2O_3*	8.22	12.83	7.87	6.78	7.35	12.66	6.75	11.39	9.58	9.48	7.69	9.36	9.06
MnO	0.15	0.21	0.16	0.12	0.11	0.22	0.12	0.19	0.17	0.16	0.16	0.17	0.15
MgO	5.35	6.48	5.37	7.82	7.75	6.20	4.09	7.37	8.87	8.44	6.94	7.83	8.18
CaO	8.80	8.84	7.98	9.47	8.79	9.87	5.71	10.26	10.25	10.40	8.45	9.65	10.21
Na_2O	3.49	3.48	2.53	3.02	2.51	3.27	4.06	3.31	2.45	3.11	3.03	3.14	2.90
K_2O	1.41	0.89	2.15	1.11	1.15	0.84	2.60	0.63	1.14	0.51	1.36	0.83	0.76
P_2O_5	0.20	0.36	0.19	0.03	0.03	0.32	0.10	0.21	0.09	0.10	0.09	0.11	0.06
Total	100.07	100.24	99.78	100.17	99.86	99.75	100.40	100.30	100.04	99.93	100.21	100.17	100.12
Mg'-value	0.56	0.50	0.58	0.70	0.68	0.49	0.55	0.56	0.65	0.64	0.64	0.62	0.64
A/CNK	0.68	0.69	0.74	0.76	0.85	0.59	0.75	0.65	0.73	0.68	0.72	0.68	0.70
Ba	116	96	225	71	72	104	134	84	47	62	112	96	60
Rb	52	29	108	51	51	42	131	28	94	20	58	35	35
Sr	222	282	448	214	226	231	152	222	225	197	160	188	194
Pb	7	7	7	8	8	6	14	5	0	5	9	6	3
Th	5	2	5	3	3	2	11	2	1	1	5	3	3
U	1	1	3	2	2	1	8	0	1	1	3	2	1
Zr	128	195	137	51	54	200	150	147	82	98	95	104	64
Nb	6.1	7.3	6.5	3.1	2.2	6.6	7.1	4.7	1.9	3.2	4.4	3.1	2.7
Y	33	39	30	14	14	44	37	33	23	25	29	26	19
V	154	246	157	57	47	305	135	222	163	173	145	166	158
Cr	62	151	130	178	98	153	112	194	243	276	248	219	227
Ni	19	70	40	119	124	46	51	84	166	133	100	159	123
Zn	70	107	72	63	50	107	58	89	72	70	80	74	76
Ga	19	22	18	15	15	22	17	19	16	19	16	17	16
Rb/Sr	0.2	0.1	0.2	0.2	0.2	0.2	0.9	0.1	0.4	0.1	0.4	0.2	0.2
K/Rb	225	225.6	165.2	180.6	187.1	166.0	164.7	186.7	100.6	211.6	194.6	196.8	180.2
Zr/Nb	21.0	26.7	21.1	16.5	24.5	30.3	21.1	31.3	43.2	30.6	21.6	33.5	23.7
Zr/Y	3.9	5.0	4.5	3.5	4.0	4.6	4.1	4.5	3.6	4.0	3.3	4.0	3.4

*Total Fe expressed as Fe_2O_3
Mg'-value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{3+}/total Fe as FeO = 0.1
A/CNK = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$

TABLE A1. CONTINUED.

Sample No.	GABBROS (Cont.) VH-201D	VH-203D	GRANITE MATRIX MATERIAL VH-62M	VH-63M	VH-74M	VH-75M	VH-68M	VH-69M	VH-86M	VH-91M	VH-95M	VH-98M	VH-99M
SiO_2	49.57	49.61	61.71	63.95	71.62	68.77	72.78	73.41	73.25	73.10	74.65	69.63	67.69
TiO_2	0.99	0.85	1.62	1.28	0.55	0.68	0.39	0.38	0.38	0.89	0.38	0.80	1.03
Al_2O_3	17.60	17.85	14.26	14.47	13.49	14.19	13.29	13.35	13.68	13.39	12.55	13.12	14.32
Fe_2O_3*	8.87	8.36	8.59	6.81	3.13	4.17	2.55	2.37	2.21	2.44	2.30	4.82	4.98
MnO	0.14	0.13	0.16	0.11	0.07	0.07	0.04	0.04	0.02	0.04	0.03	0.08	0.08
MgO	9.89	9.40	1.91	1.63	0.84	1.36	0.73	0.66	0.68	0.69	0.58	1.69	1.11
CaO	9.54	9.99	4.41	3.81	1.87	2.60	1.67	1.52	1.60	1.50	0.93	3.14	2.88
Na_2O	3.01	2.83	3.62	3.65	3.66	3.17	3.51	3.30	3.21	3.55	2.76	2.99	3.79
K_2O	0.56	0.81	3.10	3.51	4.61	4.31	4.76	4.55	4.44	4.76	5.82	3.53	3.91
P_2O_5	0.08	0.07	0.53	0.29	0.10	0.12	0.08	0.07	0.07	0.07	0.08	0.19	0.24
Total	100.25	99.90	99.90	99.50	99.95	99.46	99.80	99.64	99.54	99.94	100.09	99.98	100.02
Mg'-value	0.69	0.69	0.31	0.32	0.35	0.39	0.36	0.36	0.38	0.36	0.33	0.41	0.31
A/CNK	0.77	0.75	0.82	0.86	0.94	0.97	0.95	1.02	1.05	0.98	1.00	0.91	0.91
Ba	59	48	219	267	209	338	218	222	243	227	299	240	247
Rb	21	39	116	118	212	141	194	180	155	193	214	99	135
Sr	213	215	168	130	64	98	58	61	73	60	56	109	139
Pb	5	5	16	17	22	20	24	22	18	22	23	14	16
Th	2	2	12	11	21	12	18	20	13	20	21	15	13
U	1	1	3	3	4	3	4	5	5	4	10	6	5
Zr	60	70	289	256	187	226	172	165	176	173	189	491	139
Nb	2.3	1.9	12.5	13.8	12.1	16.6	11.9	12.5	10.8	11.9	14.6	10.9	12.5
Y	18	18	59	53	48	48	40	43	34	41	46	58	45
V	138	127	101	96	48	62	28	28	31	28	27	74	90
Cr	298	342	5	13	11	22	15	13	15	12	6	17	4
Ni	195	180	3	7	4	11	6	7	8	5	3	5	3
Zn	61	60	96	76	45	52	39	30	23	34	24	54	45
Ga	17	17	21	19	18	19	17	16	17	17	16	16	19
Rb/Sr	0.1	0.2	0.7	0.9	3.3	1.4	3.4	3.0	2.1	3.2	3.8	0.9	1.0
K/Rb	220.1	171.3	221.8	246.9	180.5	253.7	203.6	209.8	237.7	204.7	225.7	295.9	240.4
Zr/Nb	26.1	36.8	23.1	18.5	15.5	13.6	14.5	13.2	16.3	14.5	13.0	45.0	11.1
Zr/Y	3.3	4.0	4.9	4.9	3.9	4.7	4.3	3.9	5.1	4.2	4.1	8.4	3.1

Sample No.	GRANITE MATRIX MATERIAL (Cont.) VH-200M	VH-201M	VH-202M	VH-203M	BASALT PILLOWS VH-60P	VH-68P	VH-69P	VH-80P	VH-81P	VH-84P	VH-85P	VH-86P	VH-91P
SiO_2	70.22	72.37	68.25	72.93	48.54	48.43	48.65	48.14	48.80	49.28	48.92	50.15	48.67
TiO_2	0.66	0.33	0.76	0.35	1.31	1.35	1.29	1.92	1.29	1.36	1.13	1.24	1.30
Al_2O_3	13.99	14.40	14.34	13.79	16.99	17.00	16.99	16.35	17.00	17.78	17.81	16.75	16.91
Fe_2O_3*	3.79	1.98	4.44	2.19	10.14	10.33	10.09	11.54	10.11	9.45	9.42	9.77	10.09
MnO	0.07	0.03	0.08	0.03	0.17	0.17	0.17	0.18	0.16	0.16	0.15	0.17	0.16
MgO	1.26	0.70	1.88	0.76	8.14	8.32	8.37	7.48	8.11	7.62	8.46	7.99	8.37
CaO	2.29	1.74	3.49	1.73	10.81	10.96	11.05	10.55	11.14	10.36	10.99	10.28	11.10
Na_2O	3.50	3.85	3.95	3.84	2.90	2.74	2.46	2.64	3.01	2.91	2.90	2.49	2.51
K_2O	4.46	4.66	2.94	4.24	0.44	0.68	0.55	0.57	0.28	1.32	0.27	0.78	0.31
P_2O_5	0.13	0.10	0.15	0.10	0.14	0.11	0.09	0.25	0.10	0.11	0.09	0.10	0.09
Total	100.36	100.16	100.28	99.94	99.84	100.08	99.70	99.61	100.0	100.35	100.14	99.72	99.50
Mg'-value	0.40	0.41	0.46	0.41	0.61	0.61	0.62	0.56	0.61	0.61	0.64	0.62	0.62
A/CNK	0.95	0.99	0.89	0.98	0.68	0.68	0.69	0.68	0.67	0.71	0.71	0.71	0.69

*Total Fe expressed as Fe_2O_3
Mg'-value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{3+}/total Fe as FeO = 0.1
A/CNK = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$

TABLE A1. CONTINUED.

Sample No.	GRANITE MATRIX MATERIAL (Cont.) VH-200M	VH-201M	VH-202M	VH-203M	BASALT PILLOWS (Cont.) VH-60P	VH-68P	VH-69P	VH-80P	VH-81P	VH-84P	VH-85P	VH-86P	VH-91P
SBa	230	429	190	331	39	29	26	71	32	63	37	73	32
Rb	175	168	111	163	22	38	27	31	12	120	10	36	12
Sr	80	99	99	85	206	197	203	233	203	190	214	193	211
Pb	19	17	14	20	2	6	6	3	5	3	4	1	3
Th	17	18	12	20	1	0	1	1	1	0	2	1	1
U	7	4	3	3	0	1	1	1	1	1	0	1	0
Zr	193	55	112	161	87	99	86	158	93	96	87	106	76
Nb	11.8	11.5	15.3	11.2	2.3	2.2	2.0	4.9	1.5	1.8	1.9	2.5	2.1
Y	43	31	42	29	25	30	25	33	26	26	24	28	22
V	57	30	84	30	189	204	200	230	189	201	166	194	188
Cr	20	11	41	12	228	259	261	212	239	274	211	257	254
Ni	14	10	17	9	129	126	127	89	127	148	129	126	106
Zn	40	24	54	25	72	84	76	81	73	67	66	77	84
Ga	17	17	17	16	16	18	16	20	17	18	18	16	17
Rb/Sr	2.2	1.7	1.1	1.9	0.1	0.2	0.1	0.1	0.1	0.6	0.0	0.2	0.1
K/Rb	211.5	230.2	219.8	215.9	171.4	148.5	169.7	151.4	193.6	91.3	220.8	179.8	212.3
Zr/Rb	16.4	4.8	7.3	14.4	37.8	45.0	43.2	32.3	62.1	53.3	45.8	42.3	36.1
Zr/Y	4.5	1.8	2.7	5.6	3.5	3.3	3.4	4.8	3.6	3.7	3.7	3.8	3.4

Sample No.	BASALT PILLOWS (Cont.) VH-95P	VH-96P	VH-98PI	VH-98PO	VH-99PI	VH-99PM	VH-99PO	VH-100PI	VH-100PO	VH-101P	VH-200P	VH-201P	VH-202P	VH203P
SiO_2	55.59	47.85	52.32	52.33	52.58	49.11	48.46	47.62	47.97	48.02	48.51	51.93	48.23	48.61
TiO_2	1.04	1.92	2.07	2.01	1.26	1.84	1.84	1.92	1.91	1.91	1.33	1.42	1.24	1.28
Al_2O_3	15.89	16.47	15.43	15.22	16.64	16.26	16.43	16.34	16.49	16.59	16.72	16.43	17.29	17.36
Fe_2O_3*	7.88	11.76	11.10	11.05	8.73	11.19	11.31	11.68	11.63	11.57	10.56	9.65	9.97	9.17
MnO	0.15	0.19	0.22	0.18	0.15	0.19	0.18	0.19	0.19	0.19	0.18	0.20	0.17	0.16
MgO	6.05	7.87	5.70	5.46	7.34	7.49	7.63	7.90	7.76	7.81	8.24	6.63	8.94	8.39
CaO	7.91	10.74	8.67	9.07	9.02	10.19	10.39	10.70	10.71	10.71	11.24	9.08	11.48	11.81
Na_2O	3.19	2.72	3.50	3.68	3.14	3.01	2.65	3.02	2.96	2.80	2.93	3.53	2.57	2.66
K_2O	1.76	0.43	0.71	0.64	1.40	0.57	0.68	0.41	0.56	0.52	0.22	1.29	0.45	0.44
P_2O_5	0.10	0.26	0.27	0.29	0.11	0.24	0.24	0.24	0.26	0.25	0.10	0.18	0.09	0.10
Total	99.55	100.19	99.98	99.93	100.36	100.28	99.81	100.02	100.43	100.38	100.01	100.32	100.44	99.97
Mg'-value	0.60	0.57	0.50	0.49	0.62	0.57	0.57	0.57	0.57	0.57	0.61	0.58	0.64	0.64
A/CNK	0.74	0.67	0.69	0.65	0.72	0.67	0.68	0.66	0.66	0.67	0.66	0.69	0.68	0.66
Ba	126	67	59	67	85	88	80	60	65	63	22	153	18	24
Rb	121	14	48	34	65	38	40	9	21	19	8	57	17	25
Sr	164	245	205	203	210	233	236	240	238	239	204	187	188	185
Pb	11	3	12	5	8	5	3	4	6	9	3	8	4	3
Th	7	1	4	3	4	2	2	1	1	1	0	4	1	1
U	7	0	2	2	1	1	1	0	0	0	0	1	0	1
Zr	122	157	185	208	83	147	158	154	159	159	94	176	82	84
Nb	5.8	4.6	7.7	7.4	4.8	4.8	5.3	5.0	4.7	5.2	1.9	5.5	1.7	1.6
Y	31	34	40	41	23	32	33	32	33	34	26	34	25	26
V	154	231	263	237	168	217	224	230	228	232	203	185	204	204
Cr	186	209	136	126	200	195	205	210	211	215	263	161	292	286
Ni	91	97	44	45	114	95	103	98	102	105	111	97	154	158
Zn	70	86	91	91	68	88	82	85	89	92	73	89	85	69
Ga	18	19	22	20	17	20	18	19	18	19	18	18	17	16
Rb/Sr	0.7	0.1	0.2	0.2	0.3	0.2	0.2	0.0	0.1	0.1	0.0	0.3	0.1	0.1
K/Rb	120.7	255.5	123.4	156.7	178.7	124.5	141.5	373.5	219.3	228.4	225.1	187.8	219.7	146.1
Zr/Nb	21.1	34.1	24.0	28.1	17.3	30.6	29.8	30.8	33.8	30.6	49.5	32.0	48.2	52.5
Zr/Y	3.9	4.7	4.7	5.1	3.6	4.6	4.9	4.8	4.8	4.7	3.6	5.1	3.2	3.2

*Total Fe expressed as Fe_2O_3
Mg'-value = mol. prop. Mg/(Mg+Fe) after adjusting Fe^{3+}/total Fe as FeO = 0.1
A/CNK = mol. $Al_2O_3/(CaO+Na_2O+K_2O)$

TABLE A2. VINALHAVEN WHOLE ROCK ANALYSES (INAA).

Sample No.	VH-7	VH-21	VH-41	VH-49	VH-51	VH-52	VH-81D	VH-62M	VH-63M	VH-95M	VH-68P	VH-85P	VH-95P	VH-64
La	40.8	41.0	4.4	3.6	17.9	8.4	19.8	34.0	26.2	30.0	26.0	4.0	14.0	12.2
Ce	94.6	93.4	13.3	10.0	46.4	24.5	46.2	82.9	70.3	67.5	27.9	11.4	33.8	40.4
Nd	43.4	43.5	9.5	5.7	30.7	18.8	23.4	47.4	40.9	31.0	22.5	9.6	18.7	36.5
Sm	8.47	8.16	3.01	2.15	7.28	4.88	5.60	10.34	9.10	7.42	4.57	3.00	4.64	14.16
Eu	0.64	0.80	1.19	0.89	2.20	1.79	1.08	2.44	1.82	0.70	1.31	1.14	1.15	0.75
Tb	1.79	1.70	0.45	0.30	1.12	0.68	1.10	1.60	1.46	1.64	0.54	0.55	0.83	2.87
Yb	5.82	4.15	2.06	1.44	4.48	2.90	3.67	5.85	5.45	5.03	2.28	2.23	3.00	12.87
Lu	0.80	0.63	0.34	0.20	0.71	0.51	0.55	0.93	0.82	0.73	0.40	0.33	0.46	1.92
Hf	6.3	7.3	2.3	1.6	6.5	4.2	4.5	8.0	7.7	6.6	2.6	2.2	3.6	6.1
Ta	3.6	3.6	0.5	0.3	1.0	0.6	1.2	2.3	2.4	4.4	0.6	0.5	1.0	2.9
Th	24.8	25.7	0.5	0.2	4.9	0.7	11.3	11.8	11.1	24.9	0.5	0.6	6.5	19.8
U	7.2	5.1	-	-	-	-	6.6	2.2	1.8	8.4	-	-	6.3	5.9
Zr/Hf	29.7	34.5	34.7	38.1	31.8	39.4	33.1	36.2	33.2	28.9	38.4	38.9	34.0	33.6
Ta/Nb	0.3	0.2	0.2	0.1	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3	0.2	0.1
Sample/CH														
La	123.7	124.4	13.4	10.8	54.3	25.5	59.8	103.2	79.3	90.9	78.6	12.2	42.3	37.0
Ce	107.5	106.1	15.1	11.4	52.7	27.8	52.5	94.2	79.8	76.7	31.7	13.0	38.4	46.0
Nd	72.3	72.5	15.8	9.5	51.2	31.3	38.9	79.1	68.2	51.7	37.4	16.0	31.1	60.9
Sm	46.8	45.1	16.6	11.9	40.2	27.0	30.9	57.1	50.3	41.0	25.2	16.6	25.6	78.2
Eu	9.3	11.6	17.2	12.9	31.9	25.9	15.7	35.4	26.3	10.1	19.0	16.5	16.7	10.8
Tb	38.1	36.2	9.6	6.4	23.8	14.5	23.4	34.0	31.1	34.9	11.4	11.7	17.7	61.1
Yb	29.1	20.8	10.3	7.2	22.4	14.5	2.8	29.3	27.3	25.2	11.4	11.2	15.0	64.6
Lu	23.6	18.5	10.0	5.9	20.9	15.0	133.2	27.4	24.1	21.5	11.7	9.7	13.5	56.5
(La/Sm)CH	2.6	2.8	0.8	0.9	1.4	0.9	1.9	1.8	1.6	2.2	3.1	0.7	1.7	0.5
(Yb/Sm)CH	0.6	0.5	0.6	0.6	0.6	0.5	0.1	0.5	0.5	0.6	0.5	0.7	0.6	0.8