Compositional variations in pyroxenes and amphiboles of the Belknap Mountain complex, New Hampshire: Evidence for the origin of silica-saturated alkaline rocks

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Abstract

Compositions of amphibole and pyroxene in the various units of the Belknap Mountain complex of central New Hampshire indicate a diversity of parental magmas. Amphibole and pyroxene in camptonites and Moat Volcanic trachyandesite, and amphibole in the Vent Agglomerate dike, indicate crystallization from silica-undersaturated magmas similar to those of the Monteregian Hill intrusions. The Belknap Syenite, Cobble Hill Syenite, and Conway Granite are silica-saturated; amphibole and pyroxene from these rocks are typical of the White Mountain Magma Series.

Pyroxene in the camptonites, Gilford Gabbro, Vent Agglomerate dike, and the Endicott Diorite has similar $Mg/(Mg + Fe_{tot})$ values, but displays different [4]Al, Ti, Na, and Ca contents and zoning. These differences imply that even the units that may have had a common parent evolved independently from each other and are probably not related by shallow level processes.

Amphibole samples from the Conway Granite have higher $Mg/(Mg + Fe_{tot})$ values and are richer in Si and poorer in Al, Ti, and Na + K than those from the Vent Agglomerate dike. Amphibole from the Belknap Syenite forms a compositional continuum between amphibole in the Vent Agglomerate dike and Conway Granite. The nature of Belknap Syenite amphibole evolution, coupled with the presence of nepheline inclusions in oligoclase and interstitial quartz, suggests that the Belknap Syenite may have originated through mixing of a silica-poor magma similar to the Vent Agglomerate dike with a magma similar to the Conway Granite.

Underplating of the crust by strongly silica-undersaturated magmas similar to those in the Monteregian Hills may have partially melted lower crustal rocks to form the Conway Granite. Mixing of these two main magma types can account for the origin of the Belknap Syenite and may serve as a model for many of the alkaline, silica-saturated rocks of the White Mountain Magma Series.

Introduction

An aspect of alkaline magmatism of considerable interest is the origin of the Daly gap and the relationship between mafic, silica-undersaturated magmas and felsic, silica-saturated magmas. Bimodal associations of gabbro-diorite and syenite-granite occur at many ring-dike complexes throughout the world (Martin and Piwinski, 1972; Bonin, 1986), and there are three main schools of thought that explain these relationships: (1) Felsic magmas associated with such complexes are residual liquids resulting from extensive fractionation of mafic parents (Bonin and Giret, 1984; Foland et al., 1985, 1988a). Silica-undersaturated magmas with compositions close to the olivine-plagioclase-diopside thermal divide can fractionate to silica saturation, provided pressure and volatile content increase the stability of silica-poor minerals (Giret et al., 1980; Bonin and Giret, 1984, 1985a). (2) Felsic, anorogenic magmas are derived from anatexis of granulitic or other crustal rocks (Loiselle and Wones, 1979; Collins et al., 1982; Creasy and Eby, 1983; Eby and Creasy, 1983;

Eby, 1985; Woolley and Jones, 1987; Bailey, 1987). In this scenario, associated mafic rocks represent magmas that provide a heat source for melting (Loiselle and Hart, 1978; McHone and Butler, 1984; Bédard et al., 1987). (3) Crustal contamination or mixing with anatectic melts imposes silica saturation on initially silica-undersaturated parental magmas (Barker et al., 1975; Randall and Foland, 1986; Baker, 1987; Neumann et al., 1988; Foland et al., 1988a, 1988b).

This paper presents mineralogical data that constrain the above-mentioned possibilities for the origin of silica-saturated alkaline rocks of the Belknap Mountain complex of the White Mountain Magma Series.

Geological setting: The White Mountain Magma Series and the Monteregian Hill province

The Monteregian Hill and the White Mountain provinces of Quebec and northern New England contain numerous plutons that were emplaced between 240 and 90

Ma (Foland et al., 1971; Foland and Faul, 1977; Eby and Creasy, 1983; Eby, 1985, 1987). The Monteregian Hill intrusions define a west, northwesterly lineament in which the majority of plutons are composed of silica-undersaturated rocks (Fig. 1). Quartz-bearing rocks are abundant only in the eastern regions of the province. The Triassic-Cretaceous intrusions of the White Mountain province are called the White Mountain Magma Series (WMMS), and trend in a north-northwesterly direction in northern New England (Fig. 1; Billings, 1956). Intrusions of the WMMS were emplaced into the deformed Paleozoic rocks of the Appalachian orogen, whereas those of the Monteregian Hills were emplaced into the Grenville province and the flat-lying Cambro-Ordovician sediments of the St. Lawrence lowland. Intrusions of the WMMS were therefore emplaced into thicker Paleozoic sections than those in the Monteregian Hill province (Billings, 1956; Dooland et al., 1982; Eby, 1987). They consist primarily of silica-saturated rocks.

Several WMMS complexes consist of bimodal suites dominated by gabbro-diorite and syenite-granite: Ascutney, Pliny, Belknap, Ossipee, Merrymeeting Lake, Pawtuckaway (Billings, 1956; Czamanske et al., 1977; Loiselle, 1978; Carr, 1980; Randall, 1985; Foland et al., 1985; Eby, 1987). Geochemical studies of mafic rocks at these complexes indicate that WMMS parental magmas were slightly SiO_2-undersaturated to SiO_2-saturated mantle-derived magmas (Loiselle, 1978; Carr, 1980; Foland et al., 1985, 1988a), yet the relationship between mafic and felsic rocks of the WMMS remains tenuous. Because many of the WMMS rocks are at least of partly cumulate origin (Size, 1972; Loiselle, 1978; Foland et al., 1985), it is difficult to determine and isolate the effects of assimilation, mixing, and fractionation on liquid evolution and to elucidate the relationship between mafic and felsic rocks.

Based upon Sr isotopic evidence, Loiselle (1978) demonstrated that several units of the Belknap Mountain complex of the WMMS had experienced little or no upper crustal contamination, although he could not rule out contamination from lower crustal rocks with low Sr isotopic ratios. These units range from gabbro to granite and all have initial $^{87}Sr/^{86}Sr$ ratios of 0.70395. The Belknap Mountain complex was chosen for this study because upper crustal contamination could be eliminated as a hypothesis. Because coarse-grained WMMS rocks commonly do not represent liquid compositions (Size, 1972; Loiselle, 1978; Foland et al., 1985), mafic silicates were studied with the aim of deciphering the nature of liquid evolution. The compositions of amphiboles and pyroxenes in alkaline rocks vary widely as a function of magma composition, temperature, pressure, f_{H_2O}, and f_{O_2} (Czamanske and Wones, 1973; Thompson, 1974; Neumann, 1976; Larsen, 1976; Wass, 1979; Parsons, 1979, 1981; Giret et al., 1980; Stephenson and Upton, 1982; Bonin and Giret, 1984, 1985b), and their compositions can be used to evaluate potential relationships among rock units (Czamanske et al., 1977; Brooks and Gill, 1982; Lalonde and Martin, 1983; Bédard, 1988; Bédard et al., 1988).
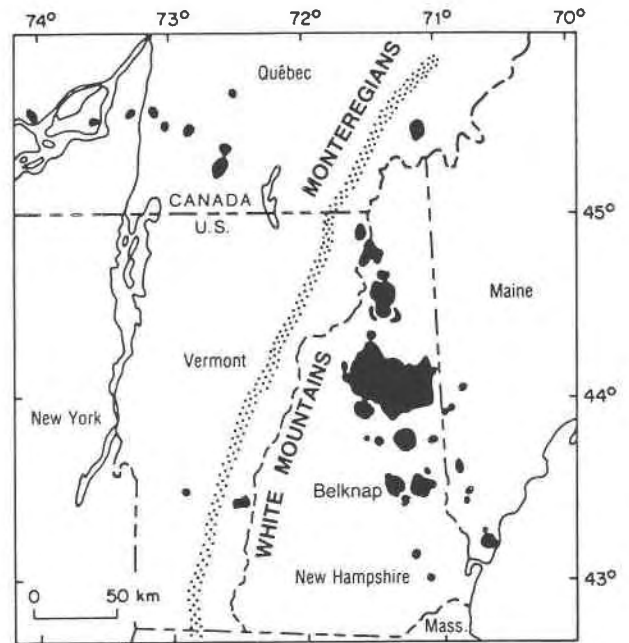

Fig. 1. Generalized map showing the Monteregian Hills and White Mountain provinces and the location of the Belknap Mountain complex (after Bédard, 1988). The stippled line represents the boundary line between the two provinces as proposed by Bédard (1988).

THE BELKNAP MOUNTAIN COMPLEX

The Belknap Mountain complex is dated at 168 ± 2 Ma by the Rb/Sr isochron method (Loiselle, 1978). The complex is exposed over 70 km² along the south shore of Lake Winnipesaukee in central New Hampshire. Modell (1936) originally mapped the complex and provided the first detailed petrologic descriptions of the various units. Subsequent remapping by Bothner and Gaudette (1971) and Bothner and Loiselle (1987) forms the basis of Figure 2. The units defined by these workers, listed from youngest to oldest, are Trap Syenite Breccia, Rowes Vent Agglomerate, Conway Granite, Albany Quartz Syenite, Lake Quartz Syenite, Sawyer Quartz Syenite, Belknap Syenite and Cobble Hill Syenite, Gilmanton Monzodiorite, Ames Monzonite, Endicott Diorite, (Gilford Gabbro), and (Moat Volcanics).

The relative ages of the Gilford Gabbro and the Moat Volcanics are uncertain. Based on whole-rock, major- and trace-element characteristics, Gaudette and Bothner (1969) and Bothner and Gaudette (1971) suggested that the Moat Volcanics are the extrusive equivalent of the Belknap Syenite. Mafic and felsic dikes are present throughout the complex but generally are of insufficient extent to determine their age relationships with units other than the unit into which they intrude. Many of these dikes are synplutonic, indicating coexistence of multiple magma types.

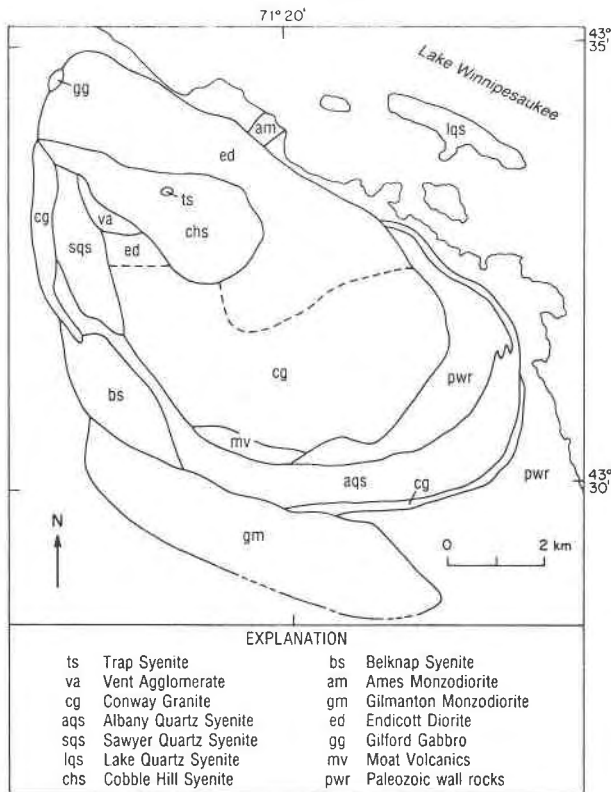Loiselle (1978) demonstrated that the Gilford Gabbro,

Fig. 2. Geologic map of the Belknap Mountain complex (after Bothner and Gaudette, 1971; Bothner and Loiselle, 1987).

Endicott Diorite, Belknap and Cobble Hill Syenites, Sawyer Quartz Syenite, and the Conway Granite define an isochron in the Rb-Sr system with a mantle-like initial $^{87}Sr/^{86}Sr$ ratio of 0.70395. This similarity in isotopic signature suggested consanguinity, but Loiselle was not able to confirm or deny this owing to the cumulus nature of several units, the wide compositional gaps among units, and uncertainties about the fractionating phases. The remaining units have higher $^{87}Sr/^{86}Sr$ values, suggesting crustal contamination, and are not considered further. (The Rowes Vent Agglomerate, the Trap Syenite Breccia, and the Moat Volcanics were not analyzed by Loiselle but are included in this study.)

This paper represents an attempt to understand the genesis of the isotopically homogeneous units through a study of their mineral and whole-rock compositions. The following section is a summary of the salient features of the units studied. Detailed field and petrographic descriptions are found in Modell (1936) and Bothner and Loiselle (1987).

Gilford Gabbro

The gabbro is poorly exposed along the northwest portion of the complex. The contact with the surrounding rocks is not exposed, so its age relative to other units is uncertain.

The gabbro is medium- to coarse-grained and consists of labradorite, two amphiboles, clinopyroxene, magnetite, and ilmentite. Brown, kaersutitic amphibole forms poikilitic knots up to 3 cm in diameter and encloses pyroxene, plagioclase, and oxides. Green amphibole commonly fringes brown amphibole and pyroxene.

Endicott Diorite

The Endicott Diorite is intensely brecciated by the Conway Granite. The bulk of the breccia consists of blocks of diorite ranging in size from centimeters to several meters in length. Many blocks appear unaltered and display sharp boundaries and angular morphologies. Some appear to fit together with their neighboring blocks, which suggests little movement during brecciation. Other blocks are rotated and highly altered. The unaltered diorite is medium-grained and consists of plagioclase (oligoclase–sodic andesine), amphibole (actinolitic hornblende), pyroxene (Fe-rich diopside), biotite, and minor quartz. Altered blocks have chloritized mafic silicates and an increase in proportions of biotite to amphibole.

Bothner and Loiselle (1987) describe a second type of block in the breccia that is fine-grained, is irregularly shaped, and displays cuspate margins. These blocks commonly contain orthoclase crystals similar to those in the Conway Granite matrix. Major-element analyses indicate that the blocks are chemically distinct from the diorites (Analyses B-22 and B-23, Table 1). They are richer in Fe_2O_3, MgO, and CaO and poorer in Al_2O_3 and K_2O at comparable SiO_2 contents, and are classified as hawaiites (Zanettin, 1984). The presence of identical blocks in the Sawyers Quartz Syenite suggests that they may be more appropriately viewed as exotic enclaves. Similar petrographic features in enclaves from other localities have been interpreted as evidence for magma mixing (Reid et al., 1983; Vernon, 1983; Dorais et al., 1990).

Belknap Syenite and dikes

The Belknap Syenite occurs as a small stock in the interior of the complex. It is medium- to coarse-grained and consists mainly of microperthite, oligoclase, and hornblende. Biotite, quartz, clinopyroxene, nepheline, magnetite, and ilmenite are minor constituents. Bothner and Loiselle (1987) observed that nepheline occurs as inclusions in oligoclase, whereas quartz is interstitial to feldspar. The two antithetic minerals are physically isolated from each other but occur in the same thin section.

Numerous dikes cut the Belknap Syenite. Some display a continuous intradike chemical variation between trachyandesite and trachyte (classification scheme of Zanettin, 1984); other dikes show limited variation within this same range. Most dikes are less than 30 cm in width. They are of limited lateral extent and generally pinch out after several tens of meters. Some dikes lack chilled margins and are synplutonic; others have chilled margins and were probably emplaced into solidified Belknap Syenite.

The trachyandesitic dikes are fine-grained, with phenocrysts of plagioclase, hornblende and Fe-Ti oxides. The

groundmass contains feldspar, hornblende, biotite, and Fe-Ti oxides. Trachytic dikes contain sanidine, plagioclase, hornblende, biotite, quartz, and Fe-Ti oxides.

Cobble Hill Syenite and dikes

The Cobble Hill Syenite is the only peralkaline unit in the complex (Table 1; Loiselle, 1978). It is medium-grained, and is composed of up to 90% perthitic feldspar. Amphibole crystals zoned from katophorite cores to richterite rims are the major mafic silicates, though they are not abundant. Minor plagioclase, quartz, biotite, and ilmenite are also present.

Trachytic and alkali trachytic dikes cut the Cobble Hill Syenite. The alkali trachytic dikes are compositionally distinct from the miaskitic dikes (mol $Na_2O + K_2O < Al_2O_3$; Sørensen, 1974) in the Belknap Syenite, and are even more peralkaline than the host Cobble Hill Syenite. Amphibole compositions in these dikes are more evolved than those of the host Cobble Hill Syenite, ranging from richterite to arfvedsonite (B-31). Aegirine is also present. The trachytic dikes (e.g., B-43) are the most primitive in the Cobble Hill system and are intermediate between the Belknap and Cobble Hill Syenites in composition. The rocks are more sodic than the Belknap Syenite dikes, the amphibole is more sodic (edenite vs. edenitic hornblende and hornblende), and the pyroxene is more Fe-rich (ferroaugite vs. augite).

Conway Granite

Conway Granite is abundant in most WMMS complexes. It forms the central core of the Belknap Mountain complex and is similar to other Conway exposures throughout the province. It contains perthite, oligoclase, quartz, biotite, sphene, magnetite, and, in some rocks, hornblende.

Rowes Vent Agglomerate

The Vent Agglomerate forms a small breccia pipe covering less than 1 km². It contains abundant xenoliths, rounded to angular and from <1 cm to 1 m in size, that are mainly pre-WMMS wall rocks, Belknap Syenite, Sawyer Quartz Syenite, and Conway Granite. The matrix is highly variable in texture and composition, typically consisting of fragmented grains of quartz and feldspar in a fine-grained groundmass. A synplutonic dike in the Agglomerate contains clinopyroxene grains with well-developed reaction rims of amphibole and biotite in groundmass oligoclase-albite. The rock is nepheline normative (sample B-68, Table 1); Vent Agglomerate mineral analyses are reported from this synplutonic dike.

Moat Volcanics

The extrusive component of the WMMS has been called the Moat Volcanics (Billings, 1956). The volcanic rocks of the Belknap complex are mainly trachytic and rhyolitic tuffs (Modell, 1936; Bothner and Loiselle, 1987). The trachyte consists of plagioclase phenocrysts in a feldspar and chloritized biotite groundmass. A previously unreported trachyandesite is also present within the Moat Volcanics. This rock is highly altered, with chlorite forming pseudomorphs after what appears to have been pyroxene phenocrysts. Anhedral kaersutite grains are set in a fine-grained groundmass of sodic andesine, clinopyroxene, Fe-Ti oxides, and epidote. The rhyolitic tuff contains plagioclase, sanidine, and quartz phenocrysts in a quartz-feldspar groundmass.

Camptonite dikes

Lamprophyric dikes are common throughout the Belknap complex (Pirsson and Washington, 1905, 1906; Modell, 1936), but are most easily seen at the summits of Belknap, Gunstock, and Piper Mountains. Dikes sampled for this study cut the Belknap Syenite and the Gilmanton Monzodiorite. Most are less than 20 cm in thickness and extend for only a few meters before pinching out, but Pirsson and Washington (1906) describe several dikes that are 2 m thick.

The lamprophyres consist of phenocrysts of kaersutite and salite in a groundmass of fine-grained kaersutite, plagioclase (andesine), and magnetite with analcite- and calcite-bearing ocelli. Kaersutite phenocrysts typically have relatively Fe-rich cores mantled by more Mg-rich regions, which are normally zoned to the rims. Augite phenocrysts display sector, oscillatory, and normal zoning.

WHOLE-ROCK COMPOSITIONS

Major-element and normative compositions of representative rock samples are given in Table 1. All samples are miaskitic (mol $Na_2O + K_2O < Al_2O_3$; Sørensen, 1974), except the peralkaline Cobble Hill Syenite and dikes. The camptonites and Vent Agglomerate dike are nepheline-normative, as are the Endicott Diorite samples of Loiselle (1978). Most Belknap and Cobble Hill Syenites and dikes are quartz normative.

Figure 3 illustrates total alkali vs. silica contents for rocks of this study and those of Loiselle (1978). All samples plot in the alkaline field as defined by Miyashiro (1978). The alkali and silica contents increase from the camptonites through the syenites and trachytes. Camptonites are the only samples that plot in the strongly silica-undersaturated field to the left of the line labeled US-CS, which represents the boundary between magmas that, at low pressures, become more silica-undersaturated and those that become silica-saturated (Eby, 1987). Three Endicott Diorite samples from Loiselle (1978) straddle the boundary between the two fields. Conway Granite samples are relatively poor in alkalies and plot near the alkaline-subalkaline boundary.

The Gilford Gabbro has chemical characteristics that appear to indicate crystal accumulation. Loiselle (1978) observed that the Gilford Gabbro has high TiO_2, FeO_{tot}, and CaO contents, high CaO-Al_2O_3 ratios, and low SiO_2, Na_2O, and K_2O contents (Table 1) compared to alkali basaltic liquids, reflecting cumulus clinopyroxene, plagioclase, and ilmenite.

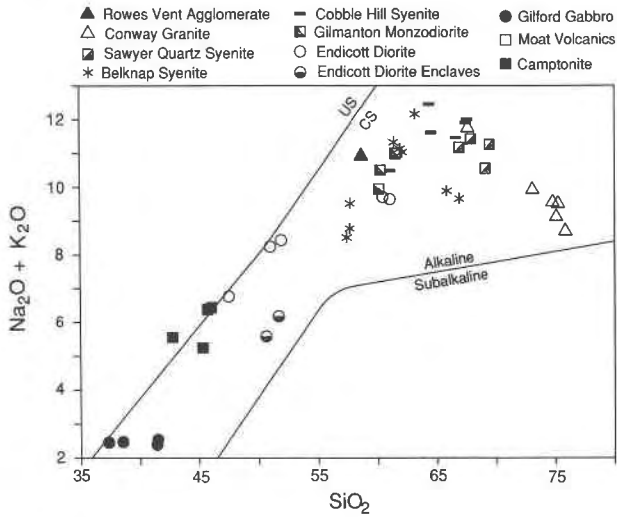Belknap Syenite dikes contain less Al_2O_3 than their

Fig. 3. Diagram of alkali vs. silica showing compositional diversity of Belknap Mountain complex rocks (after Miyashiro, 1978; Eby, 1987). Even though the diagram was devised for volcanic rocks, Eby has demonstrated that it is useful for classifying the plutonic rocks of the Monteregian Hills and the WMMS (Eby, 1987, his Fig. 3). The line labeled US-CS separates compositions that evolve to increasing silica undersaturation from those that evolve to critical saturation (Eby, 1987). All analysis samples, including the Conway Granite, plot within the alkaline field. Figure includes analyses from Loiselle (1978).
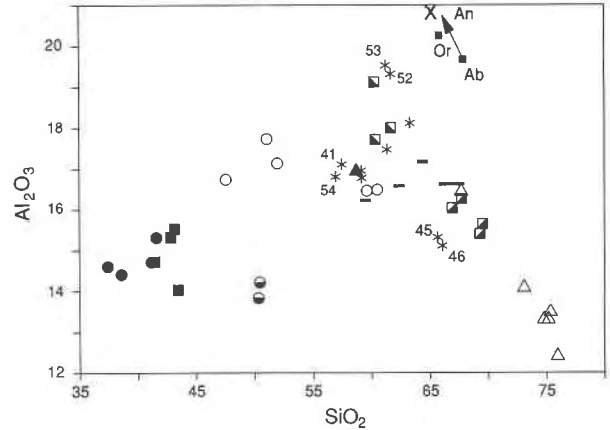

Fig. 4. Diagram of alumina vs. silica. Coarse-grained Belknap Syenite samples (B-52, B-53) are richer in Al_2O_3 than the trachyandesitic-trachytic dikes (B-45, B-46, B-54). The X marks the possible bulk composition of the feldspar component added to the inferred initial liquids, such as B-41 and B-54, to produce the Al_2O_3-rich, coarse-grained samples B-52 and B-53. The Endicott Diorite samples and the foreign enclaves that are also contained in the breccia are compositionally distinct. Figure includes analyses from Loiselle (1978).

coarse-grained host syenites (Fig. 4) and define a trend from 57% SiO_2 and 17% Al_2O_3 to 66% SiO_2 and 15% Al_2O_3. With the exception of one sample (B-41), coarse-grained Belknap Syenite samples define a vertical trend

between 60–63% SiO_2 and 17–19.5% Al_2O_3, suggesting feldspar accumulation. The similarity in composition of the coarse-grained sample B-41 to the trachyandesitic dikes indicates that B-41 might represent a slowly cooled equivalent of the dikes. Amphibole compositions and zoning are identical in the Belknap Syenite and dikes (see below), also suggesting that the dikes may represent the

TABLE 1. Representative analyses of Belknap Mountain complex rocks

	B-17	B-18	B-22B	B-23	B-26	B-27	B-31	B-34	B-40B	B-40C	B-41	B-43
SiO_2	59.80	60.90	50.30	51.35	41.20	41.60	63.95	66.20	43.10	43.45	57.40	60.04
TiO_2	1.37	1.32	3.42	2.96	5.74	6.32	0.22	0.31	3.07	3.02	1.42	0.89
Al_2O_3	16.40	16.40	13.80	14.60	14.70	15.30	16.05	16.60	15.50	15.80	17.10	16.40
Fe_2O_3	5.94	5.72	12.40	11.55	15.70	14.70	5.41	3.42	11.30	11.35	6.97	6.47
MnO	0.15	0.16	0.30	0.29	0.19	0.18	0.24	0.12	0.21	0.22	0.15	0.18
MgO	1.74	1.69	5.20	4.89	6.19	6.18	0.48	0.33	5.10	5.45	2.03	1.15
CaO	3.51	3.58	8.06	7.36	12.70	13.40	0.82	0.81	9.64	9.81	3.92	3.08
Na_2O	5.06	5.03	4.12	5.17	1.91	1.75	7.44	5.86	3.51	3.47	4.53	6.38
K_2O	4.57	4.53	1.43	1.03	0.63	0.64	4.46	5.57	2.78	3.00	4.96	4.35
L.O.I.	0.72	0.57	0.83	1.22	0.79	0.46	0.54	0.50	4.58	4.21	0.64	0.32
Total	99.26	99.90	99.86	100.42	99.75	100.53	99.61	99.72	98.79	99.78	99.12	99.26
Normative compositions												
qtz	4.02	5.39	—	—	—	—	0.96	8.13	—	—	1.82	—
or	27.41	26.95	8.57	5.80	3.79	3.81	26.39	33.18	17.50	18.24	29.67	25.23
ab	43.45	42.85	35.36	45.33	14.55	13.79	60.08	49.98	9.78	10.18	38.79	55.05
an	8.67	8.85	15.15	13.05	30.23	32.22	—	2.56	19.53	19.37	11.82	3.77
ne	—	—	—	—	1.03	0.60	—	—	11.84	11.40	—	—
ac	—	—	—	—	—	—	—	—	—	—	—	—
di	5.19	5.27	18.29	13.58	25.73	26.04	3.01	0.04	22.98	22.47	2.16	8.77
hy	4.72	4.41	7.75	4.83	—	—	4.55	3.31	—	—	7.68	1.37
ol	—	—	1.15	3.90	5.08	3.58	—	—	5.23	5.34	—	0.68
mt	2.97	2.85	6.20	5.70	7.90	7.30	1.02	1.70	5.95	5.87	3.48	3.20
il	2.64	2.52	6.59	5.69	11.10	12.08	0.47	0.59	6.21	6.11	2.73	1.68

Note: Samples B-17, B-18 = Endicott Diorite; B-22B, B-23 = Enclaves in Endicott Diorite; B-26, B-27 = Gilford Gabbro; B-31, B-43 = Cobble Hill dikes; B-34, B-44 = Cobble Hill Syenite; B-40B, B-40C, B-72, B-74 = Camptonites; B-41, B-52, B-53 = Belknap Syenite; B-45, B-46, B-49, B-54 = Belknap Syenite dikes; B-68 = Vent Agglomerate dike; B-59 = Sawyer Quartz Syenite. Analyses were performed on a Jerrall Ash Atom Comp II ICP utilizing Thermospec software.
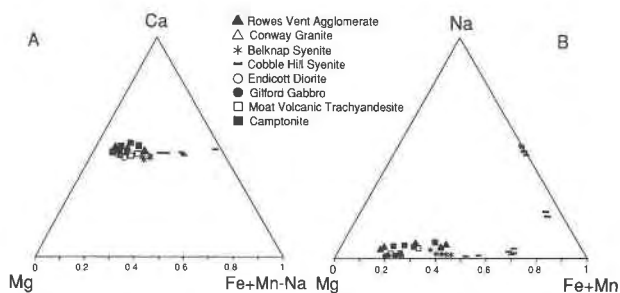
Fig. 5. (A) Ca–Mg–(Fe_{tot} + Mn − Na) and (B) Na–Mg–(Fe_{tot} + Mn). Pyroxenes in the camptonitic dikes, Gilford Gabbro, Moat Volcanic trachyandesite, and the Vent Agglomerate dike all span similar Mg/(Mg + Fe_{tot}), but Gilford Gabbro and Endicott Diorite pyroxenes are poorer in Na.

same types of liquids as those from which the Belknap Syenite crystallized.

The degree of feldspar enrichment in the Belknap Syenite can be estimated by comparing compositions of the coarse-grained rocks (B-52, B-53), synplutonic dikes (e.g., B-54) and end-member feldspars. Least-squares modeling indicates that Belknap Syenite samples B-52 and B-53 could have been derived by the addition of a feldspar component (represented by the X on the diagram) that is 1.5 wt% times that of the assumed original liquid B-54.

Whole-rock modeling of the different units is impractical because (1) petrographic and chemical evidence suggest that most units do not represent liquid compositions; (2) clinopyroxene xenocrysts in the Vent Agglomerate dike and foreign enclaves in the Endicott Diorite indicate open system behavior; (3) pyroxene and amphibole zoning in-
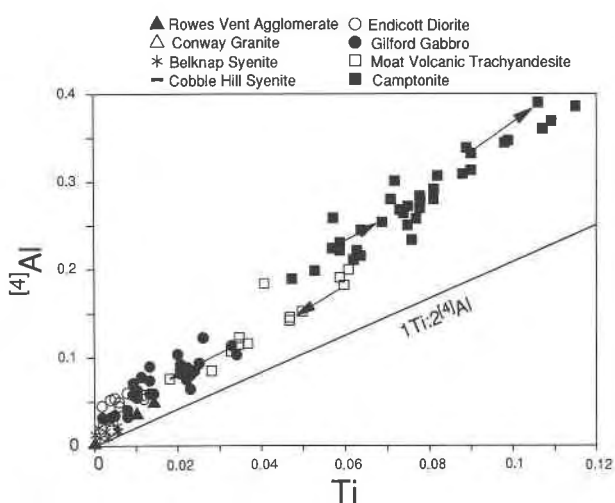

Fig. 6. Diagram of [4]Al vs. Ti. Belknap Mountain pyroxenes are richer in $CaAlSiAl_2O_6$ than $CaTiAl_2O_6$. Arrows connect cores and rims.

dicates that several units crystallized under differing silica, alumina, titania, and alkali activities, suggesting that even if some of the units were derived from a common parent, they evolved separately during ascent from depth (see below).

PYROXENE COMPOSITIONS

Representative pyroxene analyses are in Table 2. Pyroxenes in miaskitic rocks are diopside and hedenbergite (Fig. 5, Morimoto, 1988). Pyroxene evolution in these magmas terminated with crystallization of amphibole,

TABLE 1.—Continued

B-44	B-45	B-46	B-49	B-52	B-53	B-54	B-59	B-68	B-72	B-74	GSP-1 (sigma)
67.10	65.60	66.00	58.30	61.60	61.20	56.90	67.10	58.70	43.40	41.40	67.76(0.73)
0.19	0.76	0.63	1.58	0.60	0.58	1.51	0.26	1.29	3.46	3.80	0.66(0.03)
16.60	15.30	15.10	16.90	19.30	19.50	16.80	16.50	16.90	14.00	14.70	15.02(0.19)
2.65	4.30	4.36	7.95	3.12	2.77	7.78	2.88	6.30	11.70	12.80	4.41(0.06)
0.07	0.10	0.09	0.13	0.09	0.08	0.15	0.07	0.16	0.17	0.20	0.04(0.00)
0.14	0.88	0.72	2.28	0.65	0.60	2.22	0.23	2.25	7.28	6.56	1.01(0.03)
0.52	2.51	1.80	4.51	2.95	2.91	4.77	0.70	3.56	9.92	11.10	2.05(0.07)
6.61	4.93	4.58	4.36	6.17	6.25	4.55	5.79	5.96	2.88	3.17	2.76(0.04)
5.39	4.94	5.06	4.40	4.84	4.84	3.96	5.78	4.93	2.27	2.29	5.37(0.06)
0.62	0.46	0.67	0.81	0.32	0.41	0.58	0.53	0.87	4.07	3.64	
99.89	99.70	99.01	101.22	99.64	99.14	99.22	99.84	100.92	99.15	99.06	
					Normative compositions						
6.66	12.21	15.07	3.69	0.33	—	2.58	9.24	—	—	—	
32.82	29.42	30.44	25.71	28.79	28.95	23.76	34.38	29.16	14.70	14.04	
55.82	42.04	39.45	36.48	52.55	53.54	39.09	49.32	44.13	15.10	7.38	
—	5.07	5.80	13.40	10.74	10.99	13.93	1.97	4.80	18.71	19.83	
—	—	—	—	—	—	—	—	3.44	6.16	11.08	
0.49	—	—	—	—	—	—	—	—	—	—	
1.52	5.12	1.75	6.30	1.94	1.63	6.31	0.01	8.98	20.15	23.16	
1.67	2.09	3.65	6.50	2.37	0.86	6.66	2.62	—	—	—	
—	—	—	—	—	—	—	—	3.27	10.50	7.54	
1.07	2.13	2.18	3.89	1.55	1.38	3.90	1.43	3.12	6.01	6.56	
0.36	1.45	1.22	3.02	1.15	1.12	2.91	0.50	2.45	6.78	7.49	

TABLE 2. Representative pyroxene analyses, Belknap Mountains complex

	B-26 CPX-3B rim	B-31 CPX-1D core	B-41 CPX-2A core	B-43 CPX-1A rim	B-43 CPX-5B core	B-68 CPX-2C rim	B-74 CPX-4A core	B-74 CPX-4D rim	B-75 CPX-6B rim	B-75 CPX-6F core	B-86 CPX-3A rim
SiO_2	51.42	52.23	51.60	48.93	50.90	51.48	47.52	46.35	42.88	48.91	49.42
TiO_2	0.77	0.59	0.04	0.17	0.10	0.38	2.05	2.43	3.53	1.86	1.70
Al_2O_3	2.42	0.88	0.38	0.37	0.42	1.29	6.82	7.78	6.12	11.21	3.97
FeO_{tot}	8.30	29.46	14.06	23.35	15.82	13.26	7.99	7.97	7.20	6.07	7.33
MnO	0.18	0.22	0.92	1.30	1.13	0.78	0.12	0.18	0.23	0.19	0.29
MgO	14.45	0.03	10.60	5.59	8.61	10.16	13.05	11.89	11.54	14.53	14.15
CaO	21.93	0.64	22.39	19.63	22.44	21.96	21.75	21.74	21.61	21.92	21.82
Na_2O	0.28	13.04	0.18	0.29	0.12	0.88	0.73	0.72	0.74	0.68	0.32
Total	99.75	97.09	100.17	99.61	99.54	100.21	100.04	99.06	99.26	100.28	99.01
Calculated formulae											
Tetrahedral site:											
Si	1.913	1.998	1.970	1.956	1.981	1.953	1.759	1.740	1.601	1.791	1.850
[4]Al	0.087	0.002	0.017	0.017	0.019	0.047	0.241	0.260	0.399	0.209	0.150
Fe(3+)	—	—	0.013	0.027	—	—	—	—	—	—	—
M1 site:											
[6]Al	0.019	0.038	—	—	—	0.011	0.057	0.084	0.109	0.055	0.025
Fe(3+)	0.045	0.897	0.040	0.055	0.022	0.079	0.122	0.092	0.146	0.099	0.052
Ti	0.022	0.017	0.001	0.005	0.003	0.011	0.057	0.069	0.099	0.051	0.048
Mg	0.801	0.002	0.603	0.333	0.499	0.575	0.720	0.665	0.642	0.793	0.789
Fe(2+)	0.113	0.045	0.356	0.607	0.476	0.324	0.044	0.090	0.004	0.002	0.086
M2 site:											
Fe(2+)	0.100	—	0.040	0.091	0.017	0.018	0.081	0.068	0.075	0.085	0.092
Mn	0.006	0.007	0.030	0.044	0.037	0.025	0.004	0.006	0.007	0.006	0.009
Ca	0.874	0.026	0.916	0.841	0.936	0.893	0.863	0.874	0.865	0.860	0.875
Na	0.020	0.967	0.013	0.022	0.009	0.065	0.052	0.052	0.054	0.048	0.023

Note: All microprobe analyses were performed on an ETEC autoprobe with 15-KV accelerating voltage and 0.2-μA specimen current.

which replaced pyroxene on the liquidus. Further pyroxene crystallization occurred only in the peralkaline Cobble Hill Syenite dikes, whose pyroxenes are Na-rich, ranging from Fe-rich augite to aegirine (Fig. 5b).

Pyroxenes in the Belknap Mountain complex display a progressive decline in [4]Al and Ti contents (Fig. 6) from the camptonite through the Moat Volcanic trachyandesite, Gilford Gabbro, Endicott Diorite, and Vent Agglomerate dike to Belknap Syenite. The deviation of pyroxenes in these miaskitic units to the [4]Al-rich side of the 1Ti/2[4]Al line indicates that $CaAlAlSiO_6$ substitution is significant.

Pyroxenes in the camptonites, Gilford Gabbro, Endicott Diorite, Vent Agglomerate dike, and the groundmass of Moat Volcanic trachyandesite all have similar Mg/(Mg + Fe_{tot}) contents but display different [4]Al and Ti zoning patterns and Ca and Na concentrations (Figs. 5, 7). Most crystals in the camptonites and Gilford Gabbro are richer in [4]Al and Ti toward their rims (Figs. 7a, 7b), indicating increasing $CaTiAl_2O_6$ and $CaAlAlSiO_6$ substitution with crystallization. They eventually decline in [4]Al and Ti with decreasing Mg/(Mg + Fe_{tot}). Mg-rich pyroxene in the groundmass of the Moat Volcanic trachyandesite has similar Al and Ti contents to that in cores of pyroxene in the camptonites. Their zoning differs from that of the camptonite pyroxene, showing only minor initial increases in [4]Al and Ti at the most Mg-rich compositions, with overall declines in Al and Ti vs. Mg/(Mg + Fe_{tot}). Pyroxene in the remaining miaskitic units is relatively poor in Al and Ti and lacks any significant variation vs. Mg/(Mg + Fe_{tot}).

Pyroxene in the camptonites has high [6]Al/[4]Al values (Fig. 8). A microprobe traverse across a zoned pyroxene from a camptonite shows that with the exception of a small central region, relatively uniform ratios of [6]Al/[4]Al occur throughout the core. In contrast, the rims exhibit a sharp decrease (Fig. 9). Ti and Al concentrations continuously increase toward the rim, with minor decreases in the outermost rim.

Clinopyroxene in the camptonites, Moat Volcanic trachyandesite, and Vent Agglomerate dike is more Na-rich at comparable Mg contents than that in the Gilford Gabbro, Endicott Diorite, and the Belknap Syenite dikes (Fig. 5b, 10). Pyroxene in camptonite, Gilford Gabbro, Moat Volcanic trachyandesite, and Endicott Diorite shows Na enrichment with declining Mg/(Mg + Fe_{tot}), indicating increasing alkali activities with crystallization. Pyroxene in the camptonite and the Vent Agglomerate is also the richest in Ca (Fig. 5a).

DISCUSSION

Bédard et al. (1988) observed similar [4]Al and Ti enrichment with declining Mg/(Mg + Fe_{tot}) in pyroxenes of the Monteregian Hill dikes and suggested that three mechanisms could account for the zoning; i.e., kinetics, cooling and fractional crystallization, and polybaric crystallization. The studies of Grove and Bence (1979) and Gamble and Taylor (1980) indicate that rapid cooling increases the Ti and Al concentrations in pyroxenes, but because Ti and Al enrichment is common in the pyroxene in the camptonitic dikes, Moat Volcanics trachyandesite,
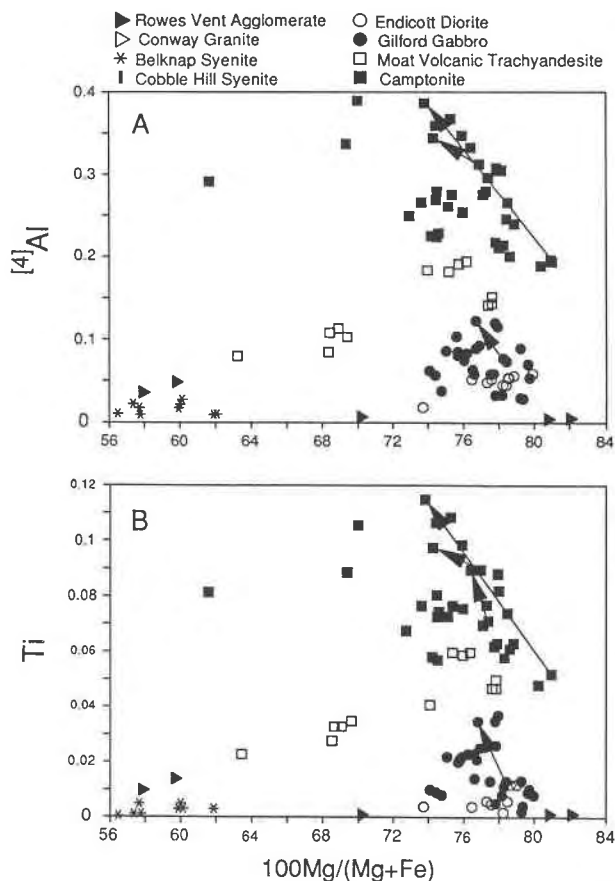
Fig. 7. (A) Pyroxene [4]Al, and (B) Ti contents vs. 100 Mg/ (Mg + Fe$_{tot}$). Arrows indicate zoning of individual crystals. See text for discussion.
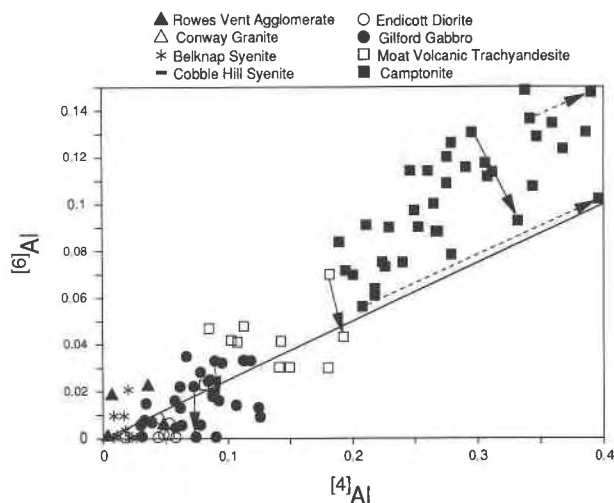

Fig. 8. Pyroxene [4]Al vs. [6]Al contents. Diagonal line separates pyroxenes that crystallized under high pressure from low pressure pyroxenes (after Wass, 1979). Solid arrows connect pyroxene cores and rims, dashed arrows connect compositions within cores.

and the Gilford Gabbro, it seems reasonable that the zoning is not the result of kinetic effects.

Major-element modeling of camptonite B-74 indicates that removal of 5–10% clinopyroxene (represented by a Ti-poor core composition of 1.68 wt% TiO$_2$) and 20–40% amphibole (average core composition of 5 wt% TiO$_2$), depletes the liquid from 3.80 to 3.47–2.60 wt% TiO$_2$, while enriching it by a factor of 0.5 to 1.5 wt% Al$_2$O$_3$. Alumina substitution in pyroxene produces a charge imbalance (Verhoogen, 1962; Campbell and Borley, 1974) that may be the controlling factor in the partitioning of Ti between pyroxene and liquid, an increase of which could preferentially incorporate Ti in the pyroxene in spite of its declining concentrations in the liquid. A greater uncertainty that hinders modeling is that Ti depletion in the modeled liquid requires amphibole fractionation; if the cores of the analyzed pyroxene grains had crystallized before amphibole saturation, then the Ti concentrations of the liquid would have increased, which could account for the observed Ti and [4]Al zoning.

Given the knowledge of liquid compositions, one can utilize the contents of [4]Al, [6]Al, and Ti in pyroxene as indications of magmatic P and T conditions (Wass, 1979;

Pe-Piper and Jansa, 1988; Bédard et al., 1988). Wass (1979) has suggested that [6]Al/[4]Al decrease with decreasing pressure of crystallization. The constant ratios of [6]Al/ [4]Al ratios of the camptonite pyroxene core (Fig. 9) could be taken to imply that the core crystallized at constant pressure, whereas the declining [6]Al/[4]Al ratios in the rim suggest that the rim grew under polybaric conditions during magma ascent. These suggestions are not unique, however, because of the uncertainties of liquid evolution, as discussed above. The CaTiAl$_2$O$_6$ and CaFe^{3+}AlSiO$_6$ contents of the pyroxene in Figure 9 increase toward the rim from 0.046 and 0.034 in the core to 0.096 and 0.115, respectively. The only pyroxene component with [6]Al in this pyroxene is CaAl$_2$SiO$_6$, which increases toward the rim, but only marginally so from 0.042 to 0.052. Enrichment in [4]Al is dominant over that of [6]Al, thereby giving an apparent decline in the ratio of [6]Al/[4]Al.

The solubility of Na in pyroxene declines with decreasing pressure (Kushiro, 1969; Thompson, 1974), whereas Ti solubility increases with declining pressure (Yagi and Onuma, 1967; Edgar et al., 1980), or with increasing temperature (Akella and Boyd, 1973; Gamble and Taylor, 1980). The enrichment in Ti toward the rim is compatible with either cooling and fractionation or polybaric crystallization, but because Na contents increase with declining Mg/(Mg + Fe$_{tot}$), it appears the overall zoning records a dominant effect of fractional crystallization.

Substitutions of Al and Ti in pyroxene are strongly influenced by magmatic silica activity (Kushiro, 1960; LeBas, 1962; Gupta et al., 1973; Akasaka and Onuma, 1980). Consequently, concentrations of these elements, Ca and Na in the pyroxenes of the Belknap Mountain units, and the normative minerals calculated from bulk analyses may be compared to determine the nature of the
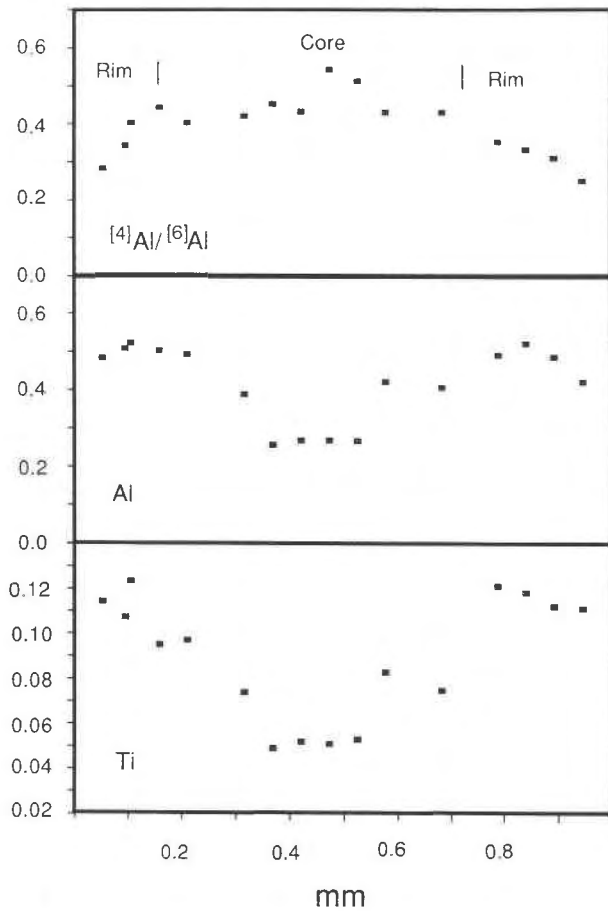
Fig. 9.   Microprobe traverse of diopside in a camptonitic dike showing $^{[6]}Al/^{[4]}Al$, Al, and Ti contents vs. distance. See text for discussion.

Fig. 10.   Pyroxene Na vs. Mg/(Mg + Fe$_{tot}$).

parental magmas. In general, the pyroxenes of the Belknap Mountain complex can be divided into two groups. The pyroxenes in the camptonite, the Moat Volcanic trachyandesite, and the Vent Agglomerate are relatively rich in Na compared to pyroxenes in the other units, suggesting that they crystallized from magmas with higher alkali contents. The pyroxene in the camptonites and the most Mg-rich pyroxene in the groundmass of the Moat Volcanic trachyandesite are also richer in Al and Ti than pyroxene in other units and most likely crystallized from strongly silica-undersaturated magmas. Bulk analyses of the camptonites and the Vent Agglomerate dike yield approximately 10% and 3% normative nepheline, respectively (Table 1). The lower Al, Ti, and Na concentrations in the Gilford Gabbro and Endicott Diorite pyroxenes indicate that their parental magmas were probably weakly to moderately silica-undersaturated. The Gilford Gabbro contains only 1% normative nepheline. The Endicott Diorite is poorly constrained; it varies from 2–5% normative nepheline (Loiselle, 1978) to 5% normative quartz (Table 1). Even though the Vent Agglomerate dike is
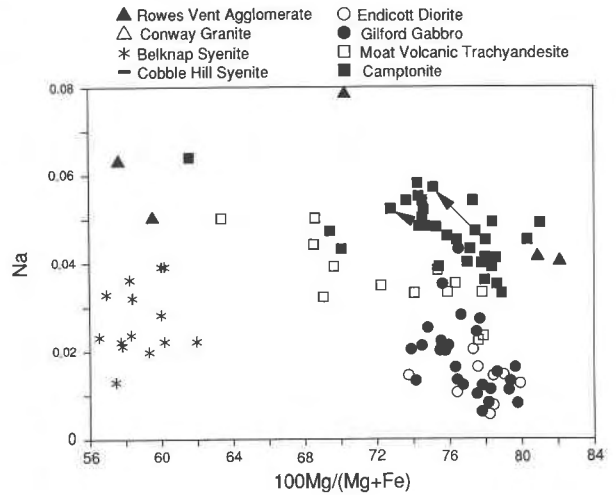
nepheline-normative, the pyroxene it contains is poor in $^{[4]}Al$ and Ti, implying either a higher magmatic silica activity than the bulk rock suggests, or previous precipitation of Ti- and Al-rich phases depleted liquid Ti and Al concentrations (Barberi et al., 1971; Gibb, 1973; Larsen, 1976; Tracy and Robinson, 1977). However, the well-developed reaction rims around pyroxene grains in the Vent Agglomerate indicate that they could be xenocrysts and consequently might not reflect the chemistry of the Vent Agglomerate dike magma. In summary, there seems to have been at least two general magma types for the rocks that contain pyroxene with overlapping Mg/(Mg + Fe$_{tot}$) contents: the parents of the camptonites, the Vent Agglomerate, and the Moat Volcanic trachyandesite were rich in alkalies and more strongly undersaturated than the relatively alakali-poor and weakly to moderately undersaturated parents of the Gilford Gabbro and Endicott Diorite.

AMPHIBOLE COMPOSITIONS

Amphiboles in the Belknap Mountain complex vary widely in composition (Table 3; classification after Leake, 1978). Amphibole in the camptonites, Gilford Gabbro, and the Moat Volcanic trachyandesite is kaersutite. The Vent Agglomerate contains hastingsitic hornblende; the Belknap Syenite and dikes contain hastingsitic hornblende, edenitic hornblende, edenite, and hornblende. The Conway Granite contains edenitic hornblende, hornblende, edenite, and actinolitic hornblende. Cobble Hill Syenite contains crystals zoned from katophorite to richterite; Cobble Hill dikes have amphibole ranging from richterite to arfvedsonite.

Amphibole compositions are illustrated in Figure 11, which shows Si + Na + K vs. Ca + $^{[4]}Al$ contents. Amphiboles in the silica-undersaturated camptonites, the Moat Volcanic trachyandesite, and the Vent Agglomerate dike display limited Ca + $^{[4]}Al$ vs. Si + Na + K substi-

TABLE 3. Representative amphibole analyses, Belknap Mountain complex

	B-C AMPH-2A core	B-26 AMPH-1B core	B-31 AMPH-3B core	B-41 AMPH-1D rim	B-43 AMPH-4A core	B-46 AMPH-1C core	B-52 AMPH-1A core	B-54 AMPH-4B core	B-68 AMPH-2A core	B-75 AMPH-1C rim	B-86 AMPH-1B rim
SiO_2	45.14	40.43	47.29	45.14	44.19	41.52	40.60	44.00	39.53	38.13	37.70
TiO_2	1.00	4.55	0.74	1.25	1.07	1.43	3.13	1.35	1.79	6.34	5.83
Al_2O_3	5.52	12.78	2.48	6.73	6.10	7.42	9.73	6.32	11.12	14.78	13.74
FeO_{tot}	19.68	12.63	33.53	20.27	21.66	26.18	22.15	24.73	22.30	9.52	11.84
MnO	1.07	0.28	2.02	1.25	1.04	0.73	0.79	0.63	0.55	0.14	0.19
MgO	10.99	12.56	0.49	9.54	8.32	6.11	7.44	7.42	6.75	13.38	12.15
CaO	10.98	11.30	1.27	11.41	11.08	10.88	10.82	10.63	10.53	12.43	12.18
Na_2O	1.96	1.93	7.67	1.49	2.70	2.00	2.29	1.64	3.04	2.04	2.44
K_2O	0.74	1.11	1.68	0.77	1.26	1.19	1.39	0.73	1.57	1.39	1.19
Total	97.07	97.56	97.16	97.31	97.42	97.47	98.34	97.45	97.18	98.15	97.35
Calculated formulae (tetrahedral + octahedral cations = 13)											
Si	6.812	5.943	7.566	6.804	6.873	6.506	6.231	6.750	6.179	5.611	5.669
Al	0.982	2.057	0.434	1.196	1.119	1.371	1.760	1.143	1.821	2.389	2.331
Fe(3+)	0.206	—	—	—	0.008	0.123	0.009	0.107	—	—	—
	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
Al	—	0.158	0.034	—	—	—	—	—	0.228	0.175	0.105
Ti	0.113	0.503	0.089	0.142	0.125	0.169	0.361	0.156	0.210	0.702	0.659
Fe(3+)	0.694	0.575	1.064	0.643	0.119	0.781	0.534	0.813	0.409	0.048	0.043
Mg	2.472	2.752	0.117	2.143	1.929	1.427	1.702	1.696	1.573	2.934	2.723
Fe(2+)	1.584	0.978	3.422	1.913	2.690	2.650	2.300	2.253	2.507	1.124	1.446
Mn	0.137	0.034	0.274	0.159	0.137	0.096	0.103	0.082	0.073	0.017	0.024
	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
Mn	—	0.001	—	0.001	—	0.001	—	—	—	—	—
Ca	1.775	1.780	0.218	1.843	1.847	1.827	1.779	1.747	1.764	1.960	1.962
Na	0.225	0.219	1.782	0.156	0.153	0.172	0.221	0.253	0.236	0.040	0.038
	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.349	0.331	0.597	0.279	0.661	0.436	0.466	0.235	0.685	0.542	0.673
K	0.142	0.208	0.343	0.148	0.250	0.238	0.272	0.235	0.685	0.542	0.673
	0.491	0.539	0.940	0.427	0.911	0.674	0.732	0.378	0.998	0.803	0.901

tution and plot in the field of Monteregian Hill amphibole defined by Bédard (1988; Field I). This amphibole is richer in Ca + [4]Al than that from the nepheline-normative Gilford Gabbro or the silica-saturated, Belknap Syenite and Conway Granite amphibole (Fields II and III). Amphibole from the latter units (Fields II and III) exhibits greater Ca + [4]Al variability and relatively minor Si + Na + K variation. Amphibole from the peralkaline Cobble Hill Syenite and dikes displays a wide range in Si + Na + K substitution and has low Ca + [4]Al contents (Field IV).

Figures 12a–12d illustrate cationic Si, Al, Ti, and Na + K vs. Mg/(Mg + Fe_{tot} + Mn) of the Belknap Mountain complex amphiboles. Amphibole in Si-undersaturated camptonites, Moat Volcanic trachyandesite, and the Vent Agglomerate dike is relatively poor in Si and rich in Al, Ti, and Na + K compared to other amphiboles in the complex (Field I). The kaersutite phenocrysts in the Moat Volcanic trachyandesite are identical to those in the camptonites. Gilford Gabbro kaersutite is poorer in Al, Ti, and Na + K and richer in Si than kaersutite in the camptonites and Moat Volcanic trachyandesite of equivalent Mg/(Mg + Fe_{tot} + Mn) (Field II), suggesting crystallization from a magma of higher silica activity and lower alkali contents. Belknap Syenite amphibole, regardless of whether it is from coarse-grained rocks or dikes, defines trends between the amphibole from the Vent Agglomerate and Conway Granite and shows increasing Si

and decreasing Al, Ti, and Na + K with increasing Mg(Mg + Fe_{tot} + Mn) (Field III). Amphibole in the Cobble Hill Syenite and dikes shows very low Mg values, low Al and Ti contents, and high Si and Na + K contents (Field IV).

DISCUSSION

The systematic amphibole compositional variations with host-rock composition (Fig. 11) are consistent with the observations of Bédard (1988), who was able to discriminate between amphiboles from nepheline-normative rocks of the Monteregian Hills and silica-saturated WMMS rocks because they plot in distinct fields with very little overlap in Si + Na + K vs. Ca + [4]Al. The Belknap Mountain amphiboles that plot in Field I (e.g., camptonites, Moat Volcanic trachyandesite, Vent Agglomerate dike) appear to have crystallized from silica-undersaturated magmas similar to those of the Monteregian Hills.

The increase in Mg/(Mg + Fe_{tot} + Mn) values of the Belknap Syenite amphiboles towards those of the Conway Granite could simply be a consequence of increasing f_{O_2} within the Belknap Syenite magma (Czamanske and Wones, 1973). In this scenario, the continuum of amphibole compositions from the Vent Agglomerate dike through the Belknap Syenite to the Conway Granite would be coincidental. But the presence of nepheline inclusions in oligoclase and interstitial quartz in the Belknap Syenite suggests a drastic change in magmatic silica activity that
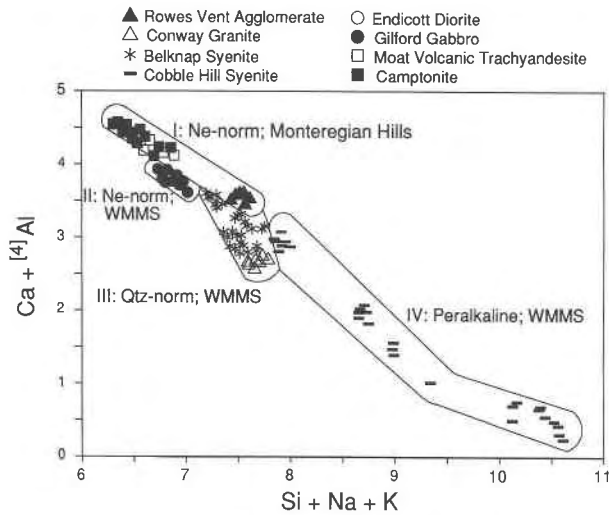
Fig. 11. Diagram of Ca + [4]Al vs. Si + Na + K after Giret et al. (1980). Bédard (1988) showed that Monteregian Hill and WMMS amphiboles plot in distinct fields with very little overlap. Field 1 represents amphibole compositions from nepheline-normative rocks of the Monteregian Hills (Bédard, 1988). Compositions of amphibole from the camptonites, Moat Volcanic trachyandesite, and Vent Agglomerate dike plot within the same compositional space as do those from the Monteregian Hills. Field III and IV are Bédard's compilations of WMMS amphibole. Field II represents amphibole from the Gilford Gabbro. Field III includes amphibole from the Belknap Syenite and dikes, and the Conway Granite. Field IV includes amphibole from the peralkaline Cobble Hill Syenite and dikes.

is difficult to reconcile with in situ fractional crystallization. The Belknap Syenite contains low modal proportions of silica-poor phases such as amphibole and magnetite, crystallization of which can possibly force a critically undersaturated liquid across the alkali-feldspar thermal divide in petrogeny's residua system (Tilley, 1957; Giret et al., 1980). Another possible explanation of the amphibole compositions and the modal quartz and nepheline is that the Belknap Syenite formed through mixing

an alkali-rich, nepheline-normative magma similar to the Vent Agglomerate dike with an alkali-poor, silica-saturated magma similar to the Conway Granite.

If the Belknap Syenite does result from mixing, the sequence of emplacement of the Belknap Syenite and Conway Granite before the camptonites and Vent Agglomerate shows that the Vent Agglomerate dike and the Conway Granite cannot be the true components involved in the inferred mixing process. However, the presence of kaersutite and Al- and Ti-rich pyroxene in the Moat Volcanic trachyandesite indicates that nepheline-normative magmas were also present at the time the Belknap Syenite was emplaced. If the Moat Volcanics are in fact the oldest unit in the complex (Modell, 1936), the nepheline-normative magmas were probably present throughout the lifetime of the complex, and these magmas or their differentiates would have been available for mixing. Thus silica-undersaturated magmas similar to those of the Monteregian Hills province may have been influential in the genesis of the WMMS. Magmas such as those that crystallized to form rocks in the Monteregian Hills may have underplated the White Mountain province crust, melted lower crustal rocks, and mixed with these anatectites to form silica-saturated rocks such as the Belknap Syenite.

SUMMARY AND CONCLUSIONS

Implications for magmatic alkali and Mg contents and silica activities based on pyroxene and amphibole compositions are summarized in Table 4. Notwithstanding that pyroxenes in the camptonite, Moat Volcanic trachyandesite, Gilford Gabbro, Vent Agglomerate dike, and Endicott Diorite have similar $Mg/(Mg + Fe_{tot})$ values, differences in [4]Al, Ti, Ca, and Na contents indicate that they crystallized from different magmas. If several of these magmas once had a common parentage, they evolved independently to different magmatic conditions where pyroxene and amphibole subsequently crystallized with unique zoning patterns. The camptonites and Moat Volcanic trachyandesite may have had a more direct relationship, but the enrichment in Al and Ti with evolution

TABLE 4. Implications for parental magmas based on pyroxene (+) and amphibole (×) compositions

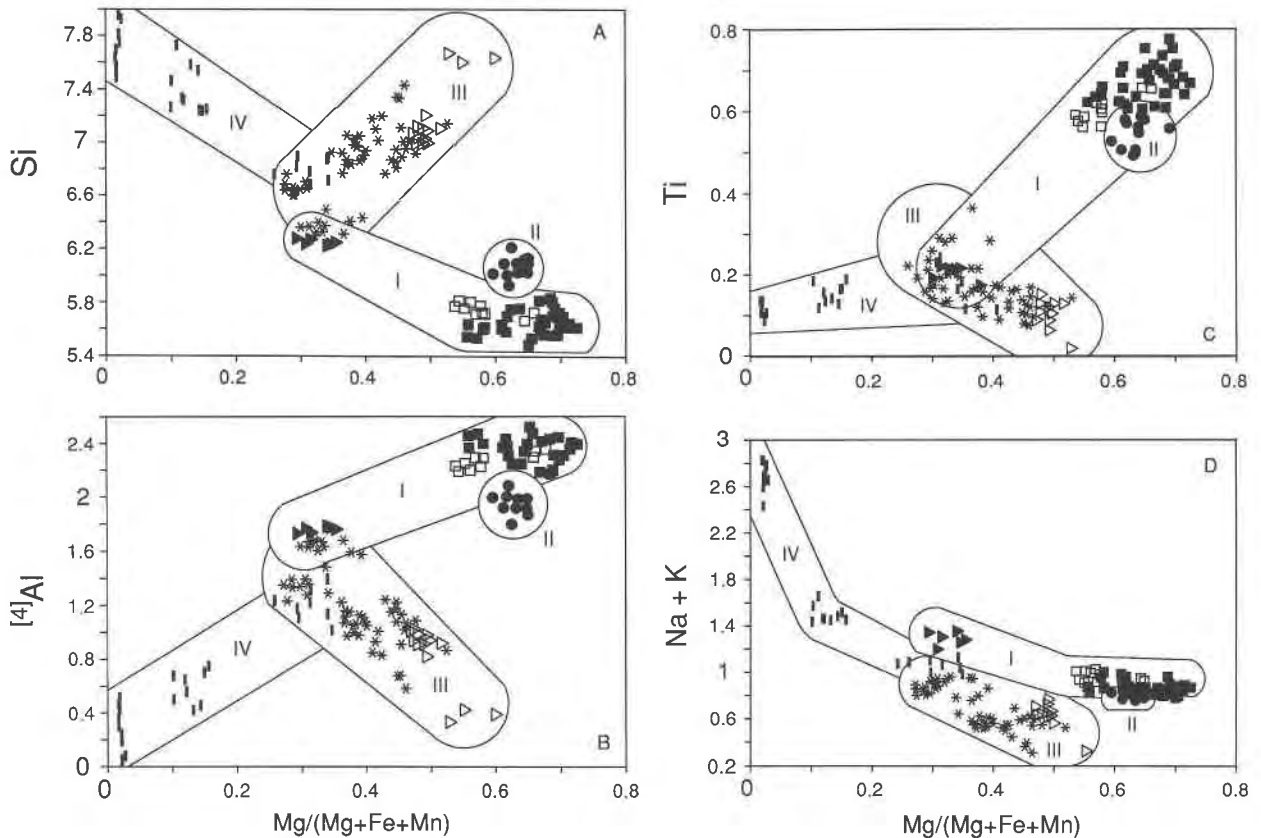| Parental magma characteristics	Mg-rich	Intermed. Mg-rich	Fe-rich	Strongly to moderately undersaturated	Mildly under-saturated	Silica saturated	Alkali-rich
Camptonite	+			+			+
	×			×			×
Moat Volcanic trachyandesite	+			+			+
	×			×			×
Gilford Gabbro	+				+		
	×				×		
Endicott Diorite	+				+		
Vent Agglomerate dike	+				+		
		×		×			×
Belknap Syenite		+				+	
		×			× ——— ×		
Cobble Hill Syenite			+			+	+
		×				×	×
Conway Granite		×				×	

Fig. 12. Amphibole Si, [4]Al, Ti, and Na + K contents vs. Mg/(Mg + Fe$_{tot}$ + Mn). Field I includes amphibole from the nepheline-normative camptonites, Moat Volcanic trachyandesite, and Vent Agglomerate dike. Field II contains amphibole from the Gilford Gabbro. Compositions of amphibole from the Vent Agglomerate dike, Belknap Syenite, and the Conway Granite form a continuum in Field III. Field IV includes amphibole from the Cobble Hill Syenite and dikes. Symbols as in Figure 7.

of camptonite pyroxenes vs. the depletion shown by pyroxenes in the Moat Volcanic trachyandesite indicates that they grew at different stages of crystallization. Pyroxene was an early crystallizing phase in the camptonites, whereas the pyroxene in the Moat Volcanic trachyandesite is a groundmass phase; presumably, Al and Ti would have been largely consumed by prior fractionation of kaersutite and plagioclase and by crystallization of Fe-Ti oxide (Bédard et al., 1988).

Pyroxene in the Endicott Diorite and some in the Gilford Gabbro have similar characteristics, but the amphibole in the two rocks is distinct. The amphibole in the Gilford Gabbro is kaersutite; that in the Endicott Diorite is edenitic, ferro-edenitic, and actinolitic hornblende.

Amphibole compositions in the Belknap Syenite and dikes could either reflect an increase of f_{O_2} in an otherwise closed system or be the result of mixing of nepheline- and quartz-normative magmas. The nepheline-normative magma involved in this inferred mixing process is similar to the suite represented by the camptonites, Moat Volcanic trachyandesite, and the Vent Agglomerate dike. The Conway Granite may be representative of the silica-sat-

urated end-member, and could have formed at depth as a cap on the roof of the main chamber (Chapman, 1976; McBirney, 1980; McBirney et al., 1985; Bédard et al., 1987).

An unresolved problem is the origin of the Conway Granite. In spite of isotopic data on the granite from several WMMS complexes, no consensus exists on its origin and its relationship to other units of the WMMS (Foland and Friedman, 1977; Foland et al., 1985, 1988a; Loiselle, 1978; Eby and Creasy, 1983). If the Belknap Syenite owes its silica saturation to mixing with Conway Granite, then it is crucial to determine whether the granite is an anatectic melt or residual liquid from fractionation. The latter interpretation requires silica saturation in felsic alkaline rocks to be independent of crustal contamination (Foland et al., 1985; 1988a).

Amphiboles in the camptonites, Moat Volcanic trachyandesite, and Vent Agglomerate dike are very similar to those in the Monteregian Hills and plot in the fields that characterize silica-undersaturated rocks as defined by Giret et al. (1980). This similarity in amphibole compositions suggests that magmas like those parental to the

Monteregian Hills were also present in the WMMS province, and may have been involved in the generation and evolution of WMMS silicic melts. Crustal contamination of these melts or mixing with anatectic melts (i.e., Conway Granite?) or both may have contributed to the dominance of silica-saturated rocks in the WMMS.

Variable pyroxene and amphibole zoning within several rock types indicate that whole-rock models permitting consanguinity of various units in the complex should be evaluated cautiously. Each of these liquids evolved independently of the others once they separated from an assumed main reservoir at depth, hence their crystalline products exposed at the surface now have compositions that are a major step removed from the primary processes that generated their initial chemical characteristics.

ACKNOWLEDGMENTS

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