ALKALIC DIKES OF THE LAKE CHAMPLAIN VALLEY

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ABSTRACT

Over 250 Early Cretaceous lamprophyre and trachyte dikes have been mapped in the central Lake Champlain Valley of Vermont and New York. Two regional subdivisions are recognized: a smaller swarm of about 80 lamprophyre (mostly monchiquite) dikes in the Plattsburgh-South Hero-Milton area, and a larger swarm of over 150 monchiquite, camptonite and trachyte (mostly bostonite) dikes in the Willsboro-Shelburne-Charlotte area. Most of the dikes trend approximately east-west, but more diverse orientations are found near the syenitic Barber Hill stock in Charlotte, Vermont. The lamprophyres have basanitic compositions and mineralogies which include augite, kaersutite, olivine, phlogopite, andesine and analcime. The trachytes are mainly anorthoclase, with minor quartz, biotite and microcline. A new Rb-Sr age for seven trachyte dikes of 125 ± 5 m.y. enhances a cogenetic model for all the dikes. The Champlain magmas are part of the Monteregian-White Mountain igneous province, and may represent a mafic-felsic pair formed by an immiscible liquid mechanism from mantle-derived camptonitic magma.

INTRODUCTION

Mafic and felsic intrusives in the central Lake Champlain Valley of Vermont and New York have attracted attention for many years. Previous work includes papers by Thompson (1861), Kemp and Marsters (1893), Alling (1927), Hudson and Cushing (1931), Hawley (1956), Migliori (1959), Dimon (1962), Gillespie (1970) and Laurent and Pierson (1973). Our thesis work at the University of Vermont (Corneille, 1975; McHone, 1975) concentrated on petrographic and geochemical descriptions of the dike rocks. Our studies have been integrated with related work on the Mesozoic magmas of New England and Quebec (McHone and Butler, 1978). In this paper we shall describe the physical and chemical characteristics of the Champlain dikes, and follow with a discussion of petrogenetic models.

DESCRIPTION OF DIKES

Appearance

The lamprophyre dikes are fine-grained, dark gray rocks, with rusty-brown weathered surfaces. Fracture sets within the rocks are usually developed both perpendicular and parallel to the dike walls. Glassy chill margins are ubiquitous. Elongate black phenocrysts of amphibole and stubby pyroxene prisms are often visible, even without a hand lens. Most lamprophyres contain white amygdules in flow streams parallel to the dike contacts. Pink to gray ellipsoidal bodies 0.5 to 1 cm across, called ocelli, are found in many of the lamprophyres. Xenoliths have been noted in 22 examples, usually as small, rounded pieces of Paleozoic shales and carbonates, and Precambrian gneisses, marbles and anorthosite from the underlying Grenville basement. The trachyte dikes are buff to reddish-tan colored rocks, most with visible phenocrysts of alkali feldspar. Fifteen trachyte dikes contain xenoliths, usually larger and more angular than the inclusions found in lamprophyres but with similar lithologies. Several trachyte "breccia dikes" exposed on Shelburne Point have more than 90 percent xenoliths by volume (Hawley, 1956).

Distribution

Figure 1 shows the locations for most of the Mesozoic intrusions known in the Champlain Valley. The majority of the dikes are exposed along the bedrock shorelines of Lake Champlain, but many are also found in roadcuts and quarries away from the lake. A few sills are also known, including a large felsic intrusion in Willsboro, New York called the Cannon Point sill (Fig. 1). Few dikes can be traced far because of surficial cover, but Fisher (1968, p. 33) projects lengths up to a mile for dikes in the Plattsburgh area. Lamprophyre dikes may generally have width-to-length ratios of over 1:1,000 (McHone, 1978b).

The group of dikes southeast of Plattsburgh (Fig. 1) is separated from the dikes south of Burlington by barren shorelines in New York, and by a lack of dikes at North Burlington and Colchester Point, Vermont. Some dikes may be covered by the Winooski River delta. The Plattsburgh anomaly (Fig. 1) is most likely a magnetic and gravity expression of a shallow, unexposed mafic stock similar to several of the Monteregian plutons in Quebec (Diment, 1968). The northern dikes do not encompass the anomaly. No dikes have been reported along the rocky shores of Lake Champlain north of Grand Isle and Milton, Vermont, and dikes are very rare south of Vergennes, Vermont.

Two-thirds or more of the northern subgroup of dikes are monchiquite. Trachyte dikes are confined to the southern subgroup, being most abundant in the Shelburne and Charlotte areas of Vermont. Charlotte also contains the Barber Hill stock, a small syenitic complex (Fig. 1). Camptonite dikes are present throughout both subgroups, and are also found westward in the Adirondacks (Jaffe, 1953) and eastward through Vermont and much of New England (McHone, 1978b).

Orientation and size

Over 90 percent of the lamprophyre dikes trend within 20 degrees of east-west (Fig. 1), intruding a major fracture set in the Champlain Valley (Stanley, 1974). Whether the fractures are coeval with the dikes or predate them, this trend preference implies a north-south "least compression", or extensional orientation of crustal stresses in Early Cretaceous time. Tectonic implications of dike-stress relationships in New England have been discussed elsewhere (McHone, 1978a and 1978b). The trachyte dikes also tend to be east-west, but in addition many have orientations radial to the Barber Hill stock (Fig. 1), as noted by Gillespie (1970).

The great majority of the lamprophyre dikes are between 20 cm and 150 cm wide, while 1 to 3 m is more typical of the trachyte dikes. Apparently the mafic magmas, being less viscous, were able to flow more readily than the felsic magmas and are thus more likely to occur as narrow fracture fillings.

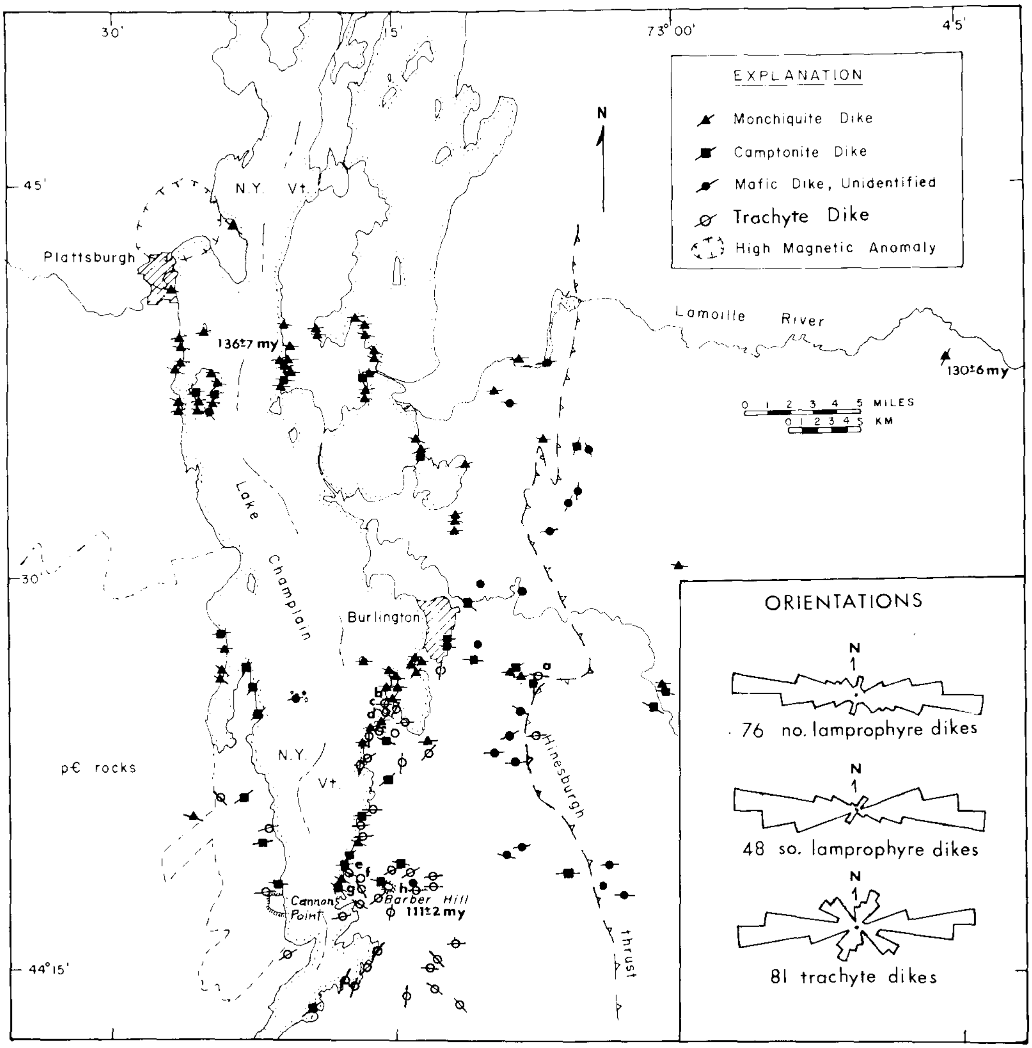

Figure 1. Alkalic dikes of the Lake Champlain Valley, New York and Vermont.

AGES OF DIKES

Zartman and others (1967) reported a K-Ar date of 136 ± 7 m.y. for biotite separated from a monchiquite dike on the western shore of South Hero, Vermont (Fig. 1). To the east, kaersutite (a basaltic hornblende) separated from a monchiquite dike near the Johnson-Cambridge town line (Fig. 1) yielded a similar date of 130 ± 6 m.y. (McHone, 1975). These dates are slightly younger than the 141 m.y. time boundary for the beginning of the Cretaceous Period (Van Eysinga, 1975). In southwestern Vermont, Zen (1972) reported an age of 105 ± 4 m.y. for a camptonite dike in West Rutland, Vermont (K-Ar on hornblende). Although younger than the Champlain dates, the Zen date falls within the 100 to 120 m.y. range of the Monteregian plutons (Philpotts, 1974) and of the younger group of alkalic plutons of the White Mountain magma series (Foland and Faul, 1977). Gillespie (1970) separated "slightly chloritized" biotite from syenite of the Barber Hill stock in Charlotte, Vermont (Fig. 1) which was dated by Armstrong and Stump (1971) at 111 ± 2 m.y., similar to the Monteregian ages.

Two monchiquite dikes are crosscut by trachyte dikes on the Shelburne lakeshore. If the trachyte dikes are cogenetic with the Barber Hill stock as suggested by Gillespie (1970), it would seem that the trachytes postdate the Champlain lamprophyres by around 20 m.y. However, both Welby (1961, p. 189) and Dimon (1962) report that a lamprophyre dike crosscuts the western side of Barber Hill. We could not locate this site during our field studies.

In order to help clarify the age relationships, eight trachyte dikes were selected for a whole-rock Rb-Sr isotopic age determination (sites a through h, Fig. 1). Four dikes were chosen from the Shelburne-South Burlington area, and four others were from the Barber Hill area of Charlotte. The results, listed in Table 1, form a reasonably good isochron except for sample "e" (Corneille's SPS-63) which has an anomalously high Sr87/Sr86 value relative to its Rb87/Sr86 (Fig. 2). This dike contains a variety of xenoliths that probably contaminated its chemistry, and was therefore disregarded in the isochron calculations.

The Rb-Sr date of 125 ± 5 m.y. for the trachyte is closer to the age of the lamprophyres than to Barber Hill. It seems likely to us that the 111 m.y. date for Barber Hill is erroneously young, possibly because of argon loss from the mica due either to alteration or to a prolonged cooling of the stock. If so, all of the lamprophyres, trachytes and syenites of the Champlain Valley may actually have intruded about 130 m.y. ago, satisfying both the geological relationships found by Gillespie (1970), and the crosscutting data.

TABLE 1. RB-SR ISOTOPIC DATA FOR CHAMPLAIN TRACHYTE DIKES.					
Sample no.	Rb (ppm)	Sr (ppm)	Rb/Sr	Rb87/Sr86	(Sr87/Sr86)N
a (MWB)	229	47	4.896	14.2080	0.7326
b (SP41)	206	30	6.781	19.6990	0.7441
c (SP45)	103	1189	0.087	0.2508	0.7088
d (SP43)	226	33	6.868	19.9480	0.7410
e (SPS63)	127	73	1.741	5.0477	0.7235
f (SPS61)	95	438	0.217	0.6273	0.7090
g (SPS71)	251	358	0.701	2.0290	0.7108
h (MPMB)	43	205	0.210	0.6070	0.7078

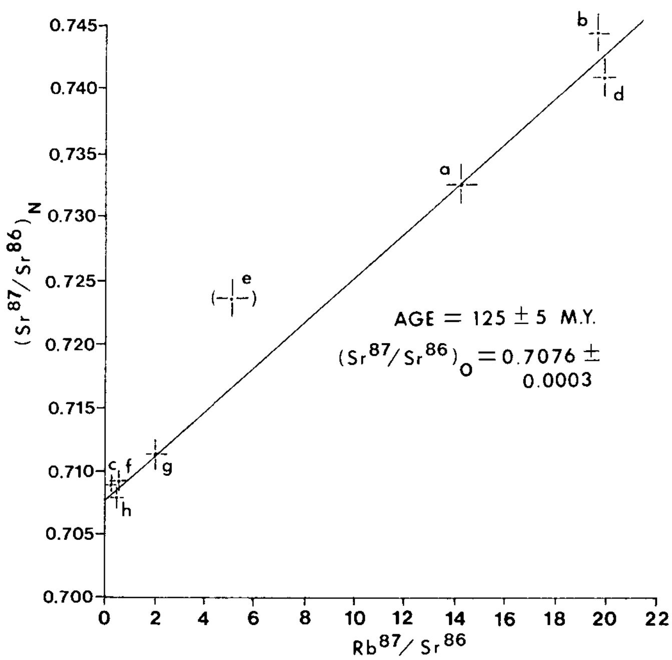

Figure 2. Rb-Sr isochron for Champlain Valley trachyte dikes.

PETROGRAPHY

Thin-section studies of the lamprophyres reveal microporphyritic textures in which both phenocrysts and matrix minerals tend to be euhedral (panidiomorphic). Both camptonite and monchiquite have similar mineralogies, except that monchiquite contains little or no feldspar, while camptonite has abundant andesine or labradorite in its groundmass. In extreme examples of monchiquite, mafic minerals (augite, olivine and minor calcite) constitute over 90 percent of the rock (dikes MT-1 and MT-4, Table 3). All phenocrysts are mafic minerals, usually augite or kaersutite (titaniferous hornblende). Optical data for the phenocrysts are listed in Table 2, and mineral chemistries will be discussed in the next section. Zoning is pronounced in the augites, with reddish Ti-rich rims, and rarely, green Na-rich cores. Augite, kaersutite and phlogopite are common groundmass minerals, in addition to lesser amounts of plagioclase, analcime, calcite, titaniferous magnetite and alkali feldspars. The ocelli have lobate boundaries which are crosscut by some kaersutite phenocrysts, and are rich in alkali feldspars, plagioclase, kaersutite, apatite, calcite and zeolites. Studies by Philpotts (1976) and others contend that ocelli are separated as immisible liquids in the lamprophyric magmas, based

TABLE 2. OPTICAL DATA FOR DIKE PHENOCRYSTS		
Dike type	Optical Data* (degrees)	Mineral
Trachyte	2Vx = 46 - 58	Anorthoclase
	2Vx = 58 - 60	Albite
	2Vx = 74 - 88	Microperthite
Camptonite	2Vz = 84 - 88	Olivine
	2Vz = 54 - 70	Augite
	Z∧c = 32 - 52	Augite
	2Vz = 44 - 48	Titanaugite
	2Vz = 70 - 85	Aegirine-augite
	2Vx = 66 - 82	Kaersutite
	Z∧c = 9 - 19	Kaersutite
	Z∧c = 17 - 36	Plagioclase
Monchiquite	2Vz = 84 - 88	Olivine
	2Vz = 50 - 70	Augite
	Z∧c = 35 - 48	Augite
	2Vz = 30 - 55	Titanaugite
	2Vx = 66 - 85	Kaersutite
	Z∧c = 4 - 15	Kaersutite

*accuracy ± 2%

TABLE 3. GEOCHEMICAL DATA FOR CHAMPLAIN DIKE ROCKS AND MINERALS.

	1	2	3	4	5	6	7	8	9	10
SiO_2	38.0	35.4	36.85	36.20	46.0	44.57	46.9	41.2	62.1	69.0
TiO_2	2.97	3.80	1.78	2.25	1.83	2.16	2.40	2.01	0.45	0.24
Al_2O_3	11.0	11.7	9.78	11.87	13.6	13.71	14.2	12.1	19.5	16.5
Fe_2O_3	6.41	12.0*	11.75*	13.44*	5.67	2.30	4.44	1.62	2.4*	2.5*
FeO	6.92	-	-	-	6.88	7.18	4.87	8.71	-	-
MnO	0.22	0.26	0.18	0.26	0.19	0.18	0.13	0.16	0.21	0.20
MgO	11.6	5.97	11.59	8.24	7.28	8.39	4.58	8.71	0.16	0.06
CaO	12.8	18.0	15.57	15.11	10.7	10.44	8.00	11.4	0.18	0.50
Na_2O	1.81	3.31	2.59	2.04	2.81	2.94	3.68	2.38	6.5	4.3
K_2O	2.00	1.49	1.96	2.42	1.51	2.67	2.79	0.76	6.6	4.0
P_2O_5	0.94	1.19	1.26	2.68	0.56	0.55	0.60	0.45	0.07	0.10
H_2O^+	2.45	1.85	0.98	2.00	0.86	0.90	1.41	4.45	1.2	3.0
CO_2	1.84	4.84	6.61	2.62	1.35	3.41	4.89	7.70	-	-
H_2O^-	0.50	0.49	0.45	0.94	1.19	0.25	0.80	1.31	-	-
Total	99.46	100.28	100.46	100.07	99.43	99.65	99.69	100.27	99.37	100.40
Rb	54	50	67.6	77.4	41	79.6	61	11	229	43
Sr	1257	1443	1480	2030	830	1130	857	733	47	205
Y	-	-	34.2	53.7	-	25.2	-	-	-	-
Zr	335	492	272	254	279	230	471	192	-	-
V	-	-	225	254	-	189	-	-	-	-
Cr	-	-	331	111	-	444	-	-	-	-
Ni	-	-	258	101	-	168	-	-	-	-
Ba	1060	710	1950	1980	800	1150	943	665	-	-
Sr87/86	0.7040	0.7042	-	-	-	0.7046	-	0.7047	0.7326	0.7078

	11	12	13	14	15	16	17	18	19	20
SiO_2	41.24	39.21	35.57	43.12	45.87	39.66	50.18	52.51	34.39	55.32
TiO_2	0.22	5.36	4.54	2.30	2.63	2.52	0.96	0.02	0.11	0.15
Al_2O_3	0.00	12.70	16.38	16.77	6.90	14.15	7.66	24.91	15.87	28.08
FeO*	10.14	11.93	8.74	16.37	7.03	13.58	5.42	0.03	13.88	0.70
MnO	0.26	0.23	0.18	0.30	0.17	0.25	0.04	0.12	0.17	0.01
MgO	47.20	11.87	18.18	5.58	12.55	4.93	12.63	0.00	22.43	0.06
CaO	0.20	11.81	0.23	0.91	23.84	23.71	21.63	0.72	0.51	10.48
Na_2O	0.06	2.53	1.06	0.31	0.43	0.73	1.60	12.78	0.11	4.66
K_2O	0.00	1.38	8.45	6.48	0.00	0.02	0.00	0.18	0.32	0.38
Total	99.32	97.02	93.34	91.15	99.41	99.56	100.12	90.54	87.79	99.84

*total iron

Note: volatiles not analyzed in microprobe analyses.

1 - Dike BU-2 (Monchiquite)
2 - " MM-1 "
3 - " MT-1 "
4 - " MT-4 "
5 - " BU-4 (Camptonite)
6 - " BU-8 "
7 - " BU-15 "
8 - PL-2 (Camptonite)
9 - " MWB (Trachyte)
10 - " MPMB "
11 - Olivine (MT-2)
12 - Kaersutite (BU-1)
13 - Phlogopite (BU-2)
14 - Biotite (MT-2)
15 - Augite (BU-2)
16 - " (MT-2)
17 - " (BU-2)
18 - Analcime (BU-1)
19 - Chlorite (BU-2)
20 - Feldspar (WR-8)

on their high-temperature mineralogy and forms indicative of liquid-liquid interfaces. Amygdules often coexist with the ocelli but are clearly distinguishable, being filled with calcite, zeolites, and rarely quartz; all are low-temperature infillings of former gas bubbles.

The trachyte dikes have traditionally been called bostonite, a term which was originally applied to non-porphyritic rocks with alkali feldspars texturally grouped into oriented "clumps" of grains. Many Champlain examples are porphyritic rocks with trachytic flow textures, and so the broader term trachyte is more appropriate for all of the felsitic dikes. Anorthoclase predominates both as phenocrysts and matrix grains, but quartz, biotite and microcline can also be present in minor amounts. The trachyte matrix is often partly altered, with carbonates and clay minerals obscuring the textures. Optical data for the trachyte minerals are listed in Table 2.

GEOCHEMISTRY

Selected whole-rock and mineral analyses of Champlain dikes are presented in Table 3. Analytical procedures are described elsewhere (McHone, 1978a). In general, the lamprophyres display very high volatile (CO_2, H_2O, P_2O), strontium and barium contents. The monchiquites reflect their feldspar-poor and augite-rich mineralogies with low silica and aluminum and high calcium values. The lamprophyres also tend to have high ferric/ferrous ratios, due to high oxygen fugacities during crystallization. Despite the high volatile contents, the lamprophyres show little alteration in thin section, except that olivine is generally replaced by calcite or serpentine minerals. The CO_2 and H_2O are present mainly in the primary micas and amphiboles, and in late-stage zeolites and calcite in the groundmass and amygdules. The trachyte analyses (nos. 9 and 10, Table 3), although incomplete, must be closely similar to the chemistries of their principal mineral component, alkali feldspar. Barber Hill syenites which were analyzed by Laurent and Pierson (1973) are chemically indistinguishable from the trachytes.

The forsteritic olivine analysis (no. 11, Table 3) is typical for most of the original lamprophyric olivines. Kaersutite (no. 12, Table 3) is distinguished from other pargasitic amphiboles by its high titanium content; most alkalic lamprophyres, including the type camptonite at Livermore Falls, New Hampshire, contain at least minor amounts of this amphibole. The chemistry of kaersutite is remarkably like many lamprophyre whole-rock analyses (compare nos. 1 and 12, Table 3). Augite chemistries (nos. 15, 16 and 17, Table 3) vary considerably in Champlain lamprophyre rocks, mainly a result of concentric zoning in the phenocrysts. Formula calculations indicate high Fe^{+3} contents, and the presence of ferric iron and titanium is coupled with charge-balancing substitutions in the crystal sites; mainly Al for Si, Fe^{+2} and Mg; and Na for Ca. The low silica contents of the magmas may promote such substitutions.

The lamprophyre and mineral analyses of Table 3 are similar to rock and mineral analyses of many alkalic basalts, in particular basanites and nephelinites, from both oceanic and continental volcanic suites (see summary values by Carmichael and others, 1974, and LeMaitre, 1976). However, most chemical analyses published for alkalic basalts show very low CO_2 and H_2O contents, in contrast with the lamprophyres. Much of this difference could be due to low-pressure degassing of magmas in the volcanic extrusions, the most commonly studied regime of basaltic rocks. Unlike volcanics, the dikes preserved volatiles because they crystallized under confinement, sealed by chilled, glassy margins. The effect of these primary volatiles was to delay the crystallization of feldspar while encouraging the growth of H_2O and CO_2-rich minerals. Lamprophyres are therefore members or at least equivalents of the alkali olivine basalt series, a fact not emphasized by the literature.

PETROGENETIC MODELS

The trachyte dikes of the Champlain Valley are closely associated with the Barber Hill stock, and are chemically similar. In general, trachytes world-wide are believed to be offshoots from syenitic magmas, either from volcanic complexes or from alkalic plutons (often radiating from the parent body). The origin of trachyte magmas, then, is only a small step from the origin of syenites in alkalic complexes.

Lamprophyre dikes are most commonly identified in continental areas, and are enriched in lithophilic elements like alkalies and volatiles. Along with a supposed association with granites (see Hyndman, 1972, p. 192), this relationship has led many geologists to speculate that lamprophyres were originally "normal" magmas which became contaminated through assimilation or leaching of granitic rocks. In fact, however, only the felsic varieties of lamprophyres (spessartite, kersantite, minette) are often associated with granites. The alkalic, more mafic lamprophyre called camptonite is found either in independent regional dike swarms or with some general overlap of dikes with alkalic pluton distributions. It is significant that monchiquite, despite petrologic characteristics which appear to be gradational with camptonite, is never abundant except when near a gabbro-rich pluton. As discussed earlier, the alkalic lamprophyres are mineralogically, chemically and isotopically similar to many oceanic intraplate basalts (basanite and nephelinite). We believe their origins are also similar; that is, derivation by partial melting of relatively "undepleted" mantle rocks followed by magmatic differentiation.

In petrology, the "Daly gap" refers to the paucity of rock types intermediate between rhyolite and basalt in many alkalic volcanic suites. This bimodal distribution is not easily explained using schemes of differentiation by crystal fractionation. The Daly gap is evident in the Cretaceous rocks of the Monteregian and White Mountan magma series (McHone and Butler, 1978), and is reflected in the Champlain region by the presence of only trachyte and lamprophyre dike types. Yoder (1973) suggested a model in which trachyte is fractionally melted from a parental material (the mantle?) at one "invariant point", followed by basalt at a later invariant stage. One problem with his model is the sequence of magmas, for many volcanic complexes have the contrary order of basaltic before trachytic eruptions.

Currie (1972) and Philpotts (1974) have proposed that liquid immiscibility is a major mechanism for the Daly gap in the Monteregian plutonic rocks. The production of ocelli in lamprophyres is critical evidence for this process (Philpotts, 1976). According to the scheme, a lamprophyric magma would split much more completely while cooling slowly in a large chamber than it can in a rapidly cooled dike. The felsic phase may then separate as an independent pluton, or remain associated with its mafic complement. Fractional crystallization and/or wall-rock assimilation within each magma body could produce the other varieties of observed rock types. Chemical studies and other evaluations of this model are still in progress, but we favor it as a reasonable if unorthodox explanation.

In the Champlain Valley and elsewhere, ocelli are much more common in camptonite than in monchiquite. Camptonite is also compositionally intermediate between trachyte and monchiquite, which we therefore suggest are derived from the immiscible separates. If camptonite represents a "primitive" magma as generated in the upper mantle, the occurrence of camptonite in wide-ranging dike swarms independent of plutons makes an origin as plutonic offshoots unlikely. Monchiquite dikes may be expected to be adjacent to a cogenetic alkali gabbro pluton, possibly indicated in our area by the Plattsburgh anomaly, since they represent a plutonic differentiate. Finally, trachyte dikes, formed by magmas more viscous than those which make up lamprophyre dikes, can never be far from a syenite body. In this area, the Barber Hill stock forms one source, while perhaps another may be expected to be present beneath Shelburne Point.

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