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LAMPROPHYRIC DIKES OF THE BURKE AREA, VERMONT

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ABSTRACT

The thirty-two dike occurrences examined may be divided into four groups on the basis of their mineralogical composition: (1) diabase, including alkali- and olivine-rich types, (2) camptonite, (3) rare monchiquite, and (4) rare kersantitic types. They have all undergone much deuteric alteration. Chemical analyses of five of the dikes show low silica. Magnesia and lime are high in the olivine-bearing types and alkalis are high in the camptonite and feldspar-rich types.

Origin of the lamprophyres would seem to be explained best by fractional crystallization of a basic, alkalic, volatile-rich magma with an accumulation of olivine and pyroxene crystals to form the more basic types and separation by filter pressing of liquids to form the more alkalic feldspar-rich types. There is no evidence whether assimilation was important in the production of the alkalic volatile-rich magma. The suite has close similarity to the lamprophyre dikes accompanying the early Jurassic White Mountain plutonic-volcanic series in New Hampshire and also to the basic dikes associated with the early Cretaceous Monteregian Hills intrusions of Quebec.

INTRODUCTION

During the course of field work in the Burke area of northeastern Vermont thirty-seven occurrences of basic dikes were noted. Specimens of thirty-two dikes were collected and thirty-seven thin sections were made, at least one from each dike. Samples from five dikes were selected for chemical analysis, which was carried out by standard silicate analysis methods, essentially following those described by Kolthoff and Sandell (1952).

The freshest, most extensive and most accessible dike outcrops are in new road cuts on East Haven Mountain, due east of the village of Hartwellville. Other accessible exposures are in the road cuts on Route 114 just south of the Newark-Brighton town line. The locations of the thirty-two dikes studied are shown in Fig. 1.

FIELD OCCURRENCE

The dikes intrude: (1) the Waits River formation, composed mainly of alternations of calcareous phyllite, pelitic and quartzose schist, and some amphibolite; (2) the Gile Mountain formation, composed mainly of pelitic and quartzose phyllite and schist and some amphibolite; and (3) granitic intrusions correlated with stocks and batholiths in New Hampshire referred to by Billings (1956) as the New Hampshire plutonic series. In nearly all cases the exposures are very poor and small, usually restricted to flat exposures in streams. Collection of unweathered samples was commonly difficult, particularly from the very thin dikes. In some cases only loose blocks were discovered.

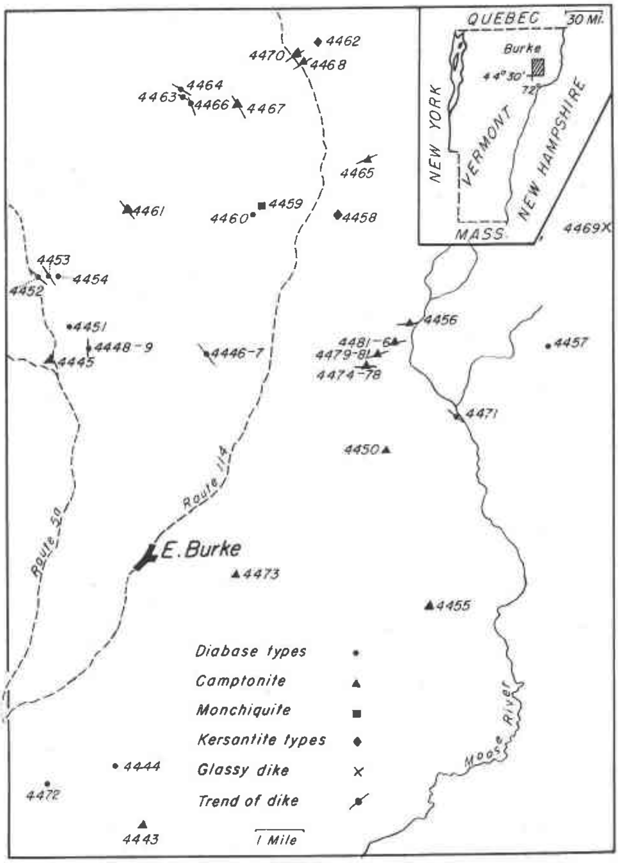

FIG. 1. Location of the Burke area, Vermont, and of the 32 dikes sampled. Numbers refer to specimens in the lithology collection (Li) at the Chicago Natural History Museum.

The dikes vary in thickness from a few inches to a few feet, and more rarely up to ten feet. They all appear to have steep to vertical dips; of the dozen which it was possible to measure not one has a dip of less than 72°. The strikes vary, but have a definite easterly trend (Fig. 1); thus nineteen of the twenty-four dikes measured have strikes which lie in the quadrant between N. 45° E. and N. 135° E. Cooke (1957) notes that the basic dikes of the Coaticook-Malvina area, Quebec, have steep to vertical dips and east to southeast strikes. Kemp and Marsters (1893) record that the many dikes they studied in the Lake Champlain area are nearly all vertical and have a stongly preferred east-west trend, that is, the strikes of over 75% lie between northeast and southeast.

General Appearance

Fresh surfaces are mainly dark gray to dark greenish gray with locally a suggestion of purplish gray color. In two thin dikes there are light- and dark-colored bands parallel to their contacts, whereas in another dike lighter, ovoid ocelli can clearly be seen against the darker groundmass. The dikes are invariably fine- to very fine-grained, and their immediate contacts with the country rock sometimes stand out as lighter colored aphanitic bands, 0.5 mm to 14 mm thick. Under the binocular microscope (×30) the rocks are generally too fine-grained for identification of their constituents. In some specimens feldspar laths and feldspar phenocrysts can be observed, and in others needles of black amphibole are prominent. Biotite, olivine and pyroxene phenocrysts are locally evident and rounded blebs of glassy analcite may be conspicuous. Amygdules of calcite (rarely chlorite) are present in some of the dikes and pyrite in many.

No thermal metamorphic effects on the wall rocks are visible in the field. Under the microscope a very narrow zone (less than 1 mm thick) is observed in a few cases where the minerals (quartz and calcite) are much reduced in size and recrystallized. In one case there are masses and streams of opaques close to the contact.

Petrography

For a consanguineous suite of basic dikes there is a relatively wide variation in mineralogical content and proportions. However, the rocks all have two features in common: (1) a notable content of carbonate, chlorite and sulfides and (2) alteration of the feldspars, pyroxene and olivine. These features are interpreted as late-stage or deuteric effects brought about by a high proportion of volatiles. Most, if not all, lamprophyric suites appear to have this characteristic.[1]

Although there are no sharp divisions, for descriptive purposes the Burke dikes have been grouped into four categories: (1) diabase and trachydiabase, (2) camptonite, (3) rare monchiquite, and (4) rare kersantite (Fig. 1). The fine grain size of the mesostasis and the extent of deuteric alteration of both microphenocrysts and groundmass make it difficult, if not impossible, to prepare reliable modes.

Diabase and trachydiabase

None of the rocks included in this group are typical diabase. Some dikes lack, or are nearly free of, the usual ferromagnesian minerals. One dike (Li 4446)[2] has phenocrysts of

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[1] In U.S.G.S. Prof. Paper 99 many of the analyses of lamprophyres are included in the group of altered rocks and tuffs, the norms of which have not been calculated.

[2] The numbers refer to specimens in the collection of the Geology Department, Chicago Natural History Museum.

plagioclase (andesine? based on the extinction angle against poor albite twinning) which are badly altered, in part to carbonate. They occur in a groundmass of plagioclase laths with interstitial chlorite, carbonate, abundant ilmenite (altered to leucoxene), magnetite and sulfides. Amygdules of spherulitic chlorite and calcite are common and some sub-rounded (corroded?) untwinned feldspar is present. In Li 4471 andesine laths, locally arranged variolitically, occur in an indeterminate base which includes carbonate, some weakly birefringent material (feldspar? or analcite), chlorite or serpentine, ores, apatite and some minute (*ca.* 0.01 mm) brown biotite and perhaps amphibole. Other examples have sparse microphenocrysts of colorless augite or slightly pleochroic titanaugite, commonly altered to carbonate, accompanied by labradorite microphenocrysts (Li 4466) or occurring in a base of altered plagioclase laths having a pilotaxitic texture (Li 4453; anal. 4, Table I). The chemical analysis of Li 4453 indicates the presence of notable alkali feldspar. The rock may thus be properly called a trachydiabase. A more alkalic specimen of trachydiabase (Li 4460) shows altered plagioclase mantled with alkali feldspar and accompanied by considerable clear euhedral sanidine along with the usual carbonate, chlorite (including some after biotite), opaques, apatite and sphene. Specimen Li 4457 has abundant large (up to 4 mm long) phenocrysts of plagioclase (*ca.* Ab_{48}) partly altered to carbonate in a base of plagioclase laths with interstitial carbonate, chlorite, serpentine, apatite, a little alkali feldspar, rare biotite, a little sphene, much magnetite and sulfides. There are scarce pseudomorphs of carbonate after pyroxene and of carbonate and serpentine possibly after olivine.

An increase of pyroxene leads to a more diabasic type (Li 4444) and an increase of olivine results in olivine diabase. In these rocks plagioclase (labradorite where identifiable) phenocrysts and laths are accompanied by carbonate and serpentine pseudomorphs after pyroxene and olivine in a mainly unresolvable base containing carbonate, chlorite and much opaque material, and perhaps some glass near the contact. Thin carbonate veins are in some cases present, which may even penetrate phenocrysts. One vein (Li 4464), 0.24 mm thick, has chlorite spherules lining its walls and calcite and serpentine in the interior. Augite may be absent and the feldspar reduced to microlites in a nearly isotropic base charged with opaques, carbonate and serpentine (Li 4454), and in some examples with analcite (Li 4451). Universal stage measurements on olivine fragments in pseudomorphs in Li 4451 give a (+) $2V = 85°–86°$, indicating a composition of Fo_{95-6} (Poldervaart, 1950). Inclusions are observed in some slices; in Li 4448 these include cognate xenoliths—aggregates of olivine pseudomorphs, rare pyroxene, carbonate, plagioclase, and opaques—and perhaps accidental rounded xenocrysts of feldspar.

Where analcite is more prevalent in the mesostasis the rock may be classed as an analcite diabase. Specimen Li 4452 has sparse altered plagioclase phenocrysts and rare olivine pseudormorphs in a groundmass of feldspar laths, chlorite, carbonate, ores, and small patches of analcite; amygdules of calcite and spherulitic chlorite are common. The opaques may have an unusual arrangement, *e.g.*, in Li 4449 they occur, in part, as rods or plates arranged in a rectangular meshwork.

Camptonite

Camptonite dikes are characterized by the presence of brown amphibole, two generations of ferromagnesian minerals, badly altered plagioclase in the groundmass, and abundant calcite, apatite and opaques. A typical specimen (Li 4456; anal. 3, Table I) is shown in Fig. 2. It contains common euhedral hornblende up to 3.7 mm long which sometimes exhibits zoning, simple twinning, and inclusion patches of fine unidentified aggregate material. The hornblende has the following optical properties—$\alpha = 1.670$, $\beta = 1.686$, $\gamma = 1.700$ (± 0.002), $Z \wedge c = 15°$; (−) $2V = 71°$; pleochroism and absorption are X-yellow $<$Y-brown$<$Z-very dark brown. These data are quite similar to those of brown hornblende in camptonite from Cape Palliser, New Zealand (Challis, 1960); Inland Kaikouras, New

TABLE I. CHEMICAL ANALYSES OF LAMPROPHYRE DIKE ROCKS FROM THE BURKE AREA, VERMONT

	1 Camptonitic Olivine Diabase (Li 4470)	2 Camptonite (Li 4468)	3 Camptonite (Li 4456)	4 Trachydiabase (Li 4453)	5 Kersantitic Type (Li 4462)	A Average Camptonite	B Diorite Dike (No. 2)	C Olivine Diabase Dike (No. 5)	D Augite Camptonite (No. 19)	E Camptonite (No. 22)
SiO_2	42.02	43.63	42.72	47.93	46.39	40.70	41.94	42.77	43.64	40.40
TiO_2	1.56	2.23	2.41	2.03	2.72	3.86	4.15	2.35	1.86	2.50
Al_2O_3	8.80	10.97	13.47	12.12	15.82	16.02	15.36	14.06	13.97	12.30
Fe_2O_3	4.10	5.28	4.89	2.77	2.63	5.43	3.27	2.72	4.58	4.62
FeO	7.04	6.93	6.42	7.77	8.83	7.84	9.89	8.34	6.94	6.94
MnO	0.18	0.18	0.17	0.15	0.16	0.16	0.25	0.15	0.07	0.24
MgO	13.08	10.13	7.19	4.00	3.07	5.43	5.01	9.72	9.65	12.08
CaO	11.42	10.83	10.98	8.15	5.97	9.36	9.47	11.47	11.97	12.19
Na_2O	1.74	2.21	3.02	3.02	6.10	3.23	5.15	1.89	1.75	0.42
K_2O	0.38	0.76	3.13	4.12	0.97	1.76	0.19	1.43	1.25	1.28
P_2O_5	0.44	0.51	1.10	1.03	1.13				0.61	0.74
H_2O+	4.82	3.19	2.73	3.82	3.36 }	2.62	3.29	2.74	2.70	4.40
H_2O-	1.36	0.85	0.42	0.96	0.36 }				1.09	1.36
CO_2	3.30	2.49	1.13	1.43	2.63	2.97	2.47	1.62	0.39	0.56
S	0.16	0.32	0.30	1.75	0.14				0.24	0.23
	100.40	100.51	100.08	101.05	100.28		100.44	99.26	100.71	100.57[1]
Less O for S	0.06	0.12	0.11	0.66	0.05				0.09	0.09
	100.34	100.39	99.97	100.39	100.23		100.44	99.26	100.62	100.48[1]

[1] Includes Cl, 0.02; Cr_2O_3, 0.06; BaO, 0.18; NiO, 0.05. Analyses 1–5—analyst, B. G. Woodland; A-average of 15 camptonites #133 Daly, 1933, p. 28); B, C, —Hawes (#2, 5, 1879, p. 150); D, E, —Poitevin and Cooke (#19, 22, 1946, p. 91).

C.I.P.W. Norms (CO_2 neglected)

	1	2	3	4	5	5a[2]
or	2.22	4.45	18.35	24.46	6.12	6.12
ab	14.15	18.34	4.45	22.53	38.25	51.35
an	15.29	18.07	15.57	7.51	12.79	5.84
ne	—	—	11.12	1.42	7.10	—
C	—	—	—	—	—	2.55
wo } di	16.12 }	13.34 }	13.11 }	11.14 }	3.94 }	—
en } di	12.00 } 30.63	10.10 } 25.29	9.90 } 24.86	6.90 } 21.60	1.80 } 7.85	—
fs } di	2.51 }	1.85 }	1.85 }	3.56 }	2.11 }	
en } hy	1.10 } 1.36	4.20 } 4.86	—	—	—	0.26 } 0.58
fs } hy	0.26 }	0.66 }	—	—	—	0.32 }
fo } ol	13.65 } 16.81	7.70 } 9.13	5.60 } 6.72	2.24 } 3.46	4.13 } 9.84	5.32 } 12.46
fa } ol	3.16 }	1.43 }	1.12 }	1.22 }	5.71 }	7.14 }
mt	6.03	7.66	7.19	4.18	3.71	3.71
il	3.04	4.26	4.56	3.80	5.17	5.17
ap	1.01	1.34	2.69	2.35	2.69	2.69
pr	0.30	0.60	0.56	3.27	0.26	0.26
cc	—	—	—	—	—	5.90
	(III)IV."2.2(3).2.2.	III".5.3(4).4".	III.6."3.3".	"III.5.2.3.	II".5(6).2.(4)5.	II."5."2.(4)5.

[2] CO_2 calculated as calcite.

	1	2	3	4	5
$\frac{FeO+Fe_2O_3\times 100}{FeO+Fe_2O_3+MgO}$	46.0	54.7	61.1	72.5	78.9
$\frac{Fe_2O_3\times 100}{FeO+Fe_2O_3}$	36.8	43.2	43.2	26.3	22.9
$\frac{K_2O\times 100}{Na_2O+K_2O}$	17.9	25.6	50.9	57.7	13.7
Location					
Lat.	44°44′18″N	44°44′12″N	44°39′36″N	44°40′12″N	44°44′42″N
Long.	71°53′W	71°52′54″W	71°50′W	71°59′30″W	71°52′30″W
	Roadcut on route 114, ca. 300 yds. south of Newark-Brighton town line.	Roadcut on route Route 114, 150 yds. south of No. 1.	Slope west of W. branch of Moose river.	In stream, 250 yds. east of Route 5a.	Near top of hill east of Route 114.

FIG. 2

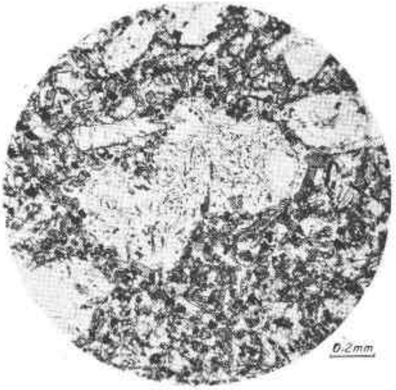

FIG. 3

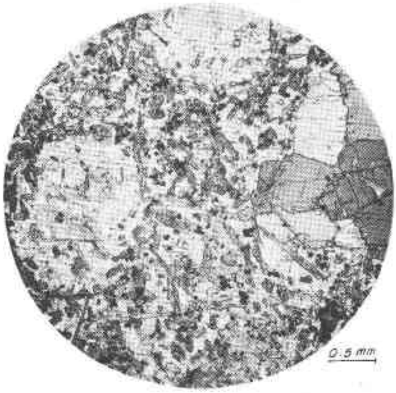

FIG. 4

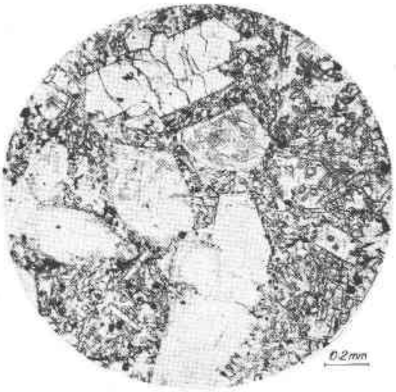

FIG. 5

FIG. 2. Photomicrograph of camptonite (Li 4456); phenocrysts of zoned euhedral brown hornblende and twinned euhedral and zoned pyroxene (very rare biotite occurs elsewhere in slice), in a very dense base of abundant ores, minute laths of feldspar, apatite and carbonate with tiny brown hornblende and pyroxene crystals.

FIG. 3. Photomicrograph of camptonite (Li 4468); phenocrysts of pyroxene and olivine altered to serpentine-carbonate or talc-carbonate aggregates in a groundmass of brown hornblende, pyroxene, plagioclase laths, iron ores, and carbonate. Ocelli are common and composed of feldspar laths, carbonate, serpentine, chlorite spherulites, a little brown hornblende and ores.

FIG. 4. Photomicrograph of camptonite (Li 4473); phenocrysts of brown hornblende and aggregates of serpentine-carbonate-sphene after (?) pyroxene, in a groundmass of abundant brown hornblende, plagioclase partly altered to carbonate, and (?) alkali feldspar, carbonate and iron ores. Ocelli are common and composed of feldspar, carbonate, a little brown hornblende and ores.

FIG. 5. Photomicrograph of camptonitic olivine diabase (Li 4470); phenocrysts of olivine, altered to serpentine and talc-carbonate and of pyroxene in a groundmass of small pyroxene and some brown amphibole, tiny feldspar laths, carbonate, much nearly isotropic interstitial material, including serpentine, chlorite, chlorophaeite and ores.

Zealand (Mason, 1958); Boulder Dam, Arizona (Campbell and Schenk, 1950); Skaergaard Peninsula, Greenland (Vincent 1953); and Mount Jo, New York (Jaffe, 1953). The brown hornblende of camptonite has been referred to as barkevikite (Poitevin and Cooke, 1946; Williams *et al.*, 1955, p. 89), titaniferous barkevikite (Ramsay, 1955), basaltic hornblende (Marsters, 1895) and kaersutite (Campbell and Schenk, 1950; Vincent, 1953; Challis, 1960). The relatively high titanium content of the analyzed rock (anal. 3, Table I) indicates that the hornblende may also be titaniferous and similar to those referred to above as kaersutite. Wilkinson (1961) has compiled data on brown amphiboles and notes that there is considerable overlap in optical properties of specimens referred to as oxyhornblende, kaersutite and barkevikite. He suggests that oxyhornblende should be limited to brown amphiboles with $\gamma-\alpha>0.04$. He further states that kaersutite has usually been recorded from analcite-bearing undersaturated rocks and barkevikite from nepheline-bearing ones, and that kaersutite has a higher content of titanium and a higher Mg/Fe^{2+} ratio than barkevikite.

Euhedral pyroxene phenocrysts (up to 1.35 mm long) are common; some are simply twinned and zoned and in part corroded. Their color is neutral to very slightly brownish, but some phenocrysts may have slightly pleochroic light green cores or patches. Inclusions of brown hornblende and carbonate patches occur sparsely within them. $Z\wedge c$ is 44°–45° and the (+) 2V is high, near 63°, which suggest that the pyroxene is diopsidic augite, perhaps slightly titaniferous. Scarce biotite phenocrysts are pleochroic from a light straw-yellow to brown. They have a (−) 2V of 5°–16° and β is 1.638 (± 0.002).

The groundmass contains small brown hornblende (up to 0.14 mm long) and pyroxene (up to 0.08 mm) set in an obscure base which in part appears to be composed of very fine plagioclase laths and the usual carbonate, apatite, and abundant iron ore grains and dust.

Brown hornblende is restricted to the groundmass in some examples. In Li 4468 (Fig. 3; anal. 2, Table I) pyroxene phenocrysts are accompanied by pseudomorphs of talc-carbonate and of serpentine after olivine. Ocelli in which the iron ores and ferromagnesian minerals are nearly absent are prominent. They are composed of plagioclase laths, carbonate patches, a little hornblende, and, in some instances, chlorite spherulites. Ocelli are also conspicuous in Li 4473 (Fig. 4), which has abundant hornblende of two generations and pseudomorphs of serpentine, carbonate and sphene, rarely enclosing pyroxene remnants. In a slice of another dike (Li 4455) fine white opaque aggregates occur in partly altered pyroxene and in carbonate-serpentine pseudomorphs. These are probably leucoxene and represent the original titanium content of the pyroxene. In other slices the pyroxene phenocrysts commonly have a purplish titanaugite rim around a neutral or light green core.

Olivine, partly or entirely altered to serpentine or talc-carbonate aggregates, is very abundant in some of the dikes. In Li 4470 (Fig. 5; anal. 1, Table I) the altered olivine is accompanied by colorless pyroxene, which shows hour-glass structure and has a high (+) 2V near 60°. These minerals are set in a base of small pyroxene, brown hornblende, much serpentine or chlorophaeite, carbonate, opaques, chlorite spherulites and a little plagioclase locally aggregated in ocelli.

Generally it is not possible to determine the plagioclase but in a few slides extinction angles against albite twinning indicate andesine.

A little analcite is seen in some thin sections as patches in the groundmass and also in calcite-analcite amygdules.

Monchiquite

As recognizable feldspar diminishes, camptonite passes to monchiquite-camptonite and finally to monchiquite. One dike only (Li 4459) appears to qualify as a true monchiquite.

It has phenocrysts of pyroxene with titaniferous rims, of brown hornblende, of altered olivine and of a little biotite in a groundmass of pyroxene, brown hornblende, biotite, common analcite in patches and interstitially much calcite, chlorite, ores, apatite and perhaps some tiny feldspar.

Kersantite

A few Burke dikes have a notable content of biotite. One example (Li 4467), related to the camptonites, is composed of abundant considerably altered plagioclase in which a little albite twinning is discernible, sparse colorless pyroxene, brown hornblende, biotite (pleochroic from very light brown to very dark brown), interstitial chlorite and calcite, and abundant opaques. Biotite is the only ferromagnesian mineral present, apart from chlorite, in another dike (Li 4462), which is accordingly better classified as a kersantitic type (anal. 5, Table I). This rock contains many altered plagioclase laths (up to 0.5 mm long) and a little biotite (0.06 to 0.1 mm) in an obscure base which has much carbonate, chlorite, ores, abundant needles of apatite and probably alkali feldspar. Calcite-chlorite amygdules are abundant. A more typical kersantite dike (Li 4458) has much plagioclase, common biotite, sanidine and a little quartz as well as sparse pyroxene, sphene and the usual accessory and secondary minerals.

CHEMICAL COMPOSITION

Chemical analyses of five dikes are given in Table I together with some published analyses for comparison. The norms, also shown in Table I, were calculated ignoring the CO_2 content and counting in all the CaO, a procedure followed by Campbell and Schenk (1950) and one which permits a closer comparison with the tables of Washington (1917). If calcite is provided for and counted as femic, the classification of the five rocks remains the same, but the proportions of the normative mineral molecules obviously change. For example, in anal. 5 nepheline and diopside disappear and a little corundum and hypersthene appear (no. 5a), representing the biotite actually present. In anal. 4, when recalculated, nepheline also disappears and hypersthene enters. Each analysis falls into a different division of the C.I.P.W. classification, which is to be expected, since the rocks were chosen to represent a range of petrographic types. The norms do not correspond with the modes, for hornblende, biotite, chlorite, etc., are not represented.

The five analyses have a general similarity, but with notable fluctuations in the alkali, Al_2O_3, MgO, and CaO content; the percentage of silica is low in all. Lamprophyres in general have a considerable range of composition and even the members of a single suite of any particular area show relatively wide variations. In this respect the Burke examples are typical. The camptonites (anal. 2 and 3) may be compared with the "diorite" from Campton, New Hampshire, which was described by Hawes (1879) and which is the original camptonite of Rosenbusch, and compared with Daly's (1933) average camptonite. The olivine diabase of Hawes (1879) is also given in Table I for comparison with the melanocratic olivine-rich camptonitic diabase (anal. 1). The kersantitic type (anal. 5) is presumably a rare member of the suite, as this dike and one other were the only ones of that type discovered. It is distinct from the other analyzed rocks in having a high alkali and alumina content and a low CaO and MgO content. The most leucocratic of the analyzed dikes (anal. 4) has the highest silica and alkali content, low CaO and MgO, and the lowest total iron. The olivine-rich nature of the camptonitic diabase Li 4470 (anal. 1) and of camptonite Li 4468 (anal. 2) is indicated by their high MgO content.

PETROGENESIS

The origin of lamprophyres is still a disputed question and a number of suggestions have been made to explain various members of the group. Camptonite was associated with alkali syenite intrusions by Rosenbusch; but this association is by no means always the case, as camptonite commonly occurs in olivine basalt provinces. Bowen (1928) sought to explain the derivation of lamprophyres by the reaction of hornblende and/or biotite in hot olivine basalt magma. Another possible explanation is the assimilation of carbonate rocks by basaltic magma. Mica lamprophyres have been interpreted as the result of the reaction of basalt magma with granite (Turner and Verhoogen, 1960, p. 256). In recent years a number of studies have, however, concluded that camptonite represents the late alkaline fraction of a normal basaltic magma (Vincent, 1953; Ramsay, 1955; Challis, 1960).

The oxide percentages of the analyzed rocks have been plotted on an iron-magnesia variation diagram (Fig. 6). The resultant curves are relatively regular for the four rocks with iron-magnesia ratios from 46 to 72. The Na_2O, K_2O, Al_2O_3, SiO_2, TiO_2 and P_2O_5 curves show an increase in amount; the CaO and MgO curves a decrease. The FeO curve falls slightly to the camptonite plots and then rises, whereas the Fe_2O_3 curve behaves antipathetically to that of FeO. The plots for the kersantitic type (Li 4462) with an iron-magnesia ratio of 79 cause reversals in the slope of the curves of a number of oxides, which suggests that the kersantitic type does not bear the same close relationship of descent as the others.

When the analyses are plotted on a silica variation diagram, the resultant curves are much more erratic in form than those in Fig. 6.

The triangular diagram FeO-MgO-Na_2O+K_2O (Fig. 7) shows that the FeO:MgO ratio increases with an increasing alkali proportion. Likewise, in the CaO-MgO-Na_2O+K_2O diagram (Fig. 7) the CaO:MgO ratio increases with an increasing alkali proportion, except for Li 4462, which shows a slight reversal in this trend. These relationships are in harmony

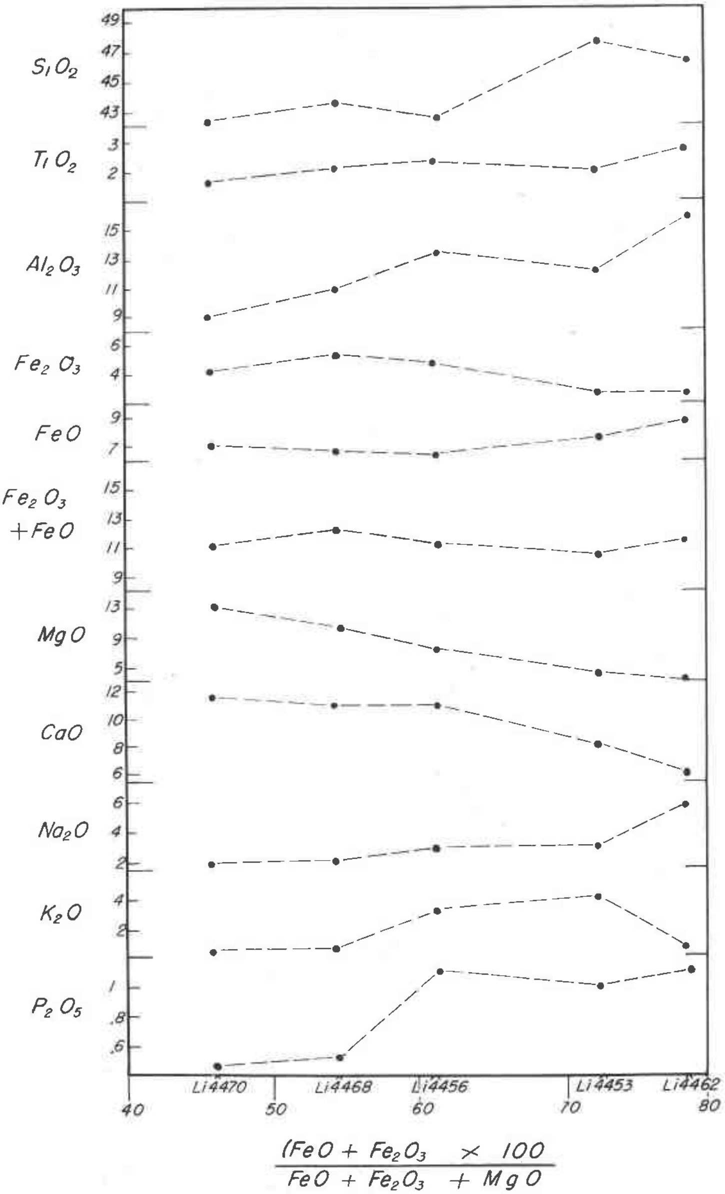

FIG. 6. Variation diagram of the five analyzed rocks plotted against the iron-magnesia ratio.

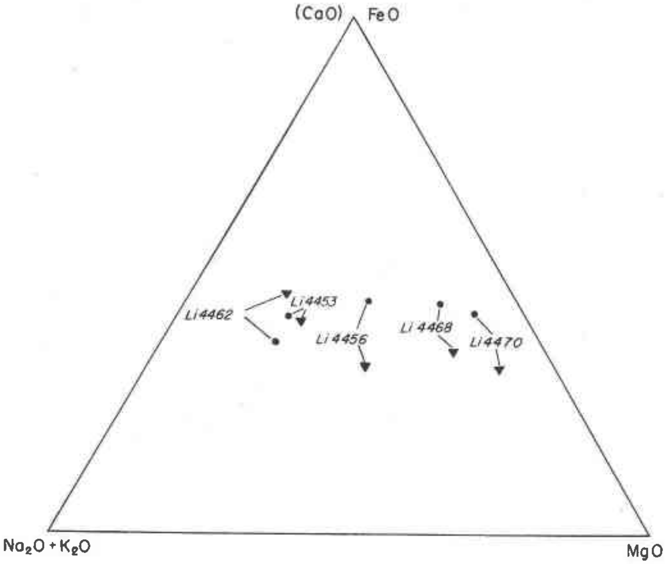

FIG. 7. Triangular diagram with plots of the five analyzed Burke rocks: CaO-Na_2O+K_2O-MgO shown as ●, FeO-Na_2O+K_2O-MgO shown as ▼.

with the results to be expected from differentiation of basaltic magma leading to an alkalic undersaturated late magma.

The compositions of specimen Li 4470, particularly, and, to a lesser extent, specimen Li 4468 are more basic than would be expected from crystallization of a magma fraction. Either a less basic residuum has been squeezed away or else these rocks contain an accumulation of early formed crystals. Specimen Li 4470 has an abundance of altered olivine and pyroxene phenocrysts, some in clumps. Specimen Li 4468 contains olivine pseudomorphs and pyroxene. The olivine is more prevalent towards the dike contact, while a very thin (0.54 mm) offshoot of the dike contains both olivine and pyroxene in notable amount. Optical determination of the pyroxene phenocrysts of Li 4470 has shown them to be diopsidic-rich and the olivine phenocrysts in the associated dikes to be forsterite-rich (Fo_{90}). These are compositions of minerals of early crystallization. They, therefore, may represent an accumulation from an earlier magma. However, the olivine is almost always altered, so the evidence is obscured. A proportion of the olivine may have been precipitated early from the dike magma itself. The pyroxene phenocrysts also are commonly altered; in addition, they sometimes show strong zoning and the development of a rim of distinctly titaniferous augite. In one thin section the pseudomorphs after pyroxene contain blebs of sphene, indicating an originally high titanium content of the phenocrysts. This suggests that much of the pyroxene crystallized from the alkalic dike magma rather than having been added to the magma as crystals.

Hornblende began to crystallize as phenocrysts early in some of the dike magmas which produced camptonite. In such cases crystallization was contemporaneous with that of pyroxene and in one slice (Li 4456) the two are intergrown in places. Simultaneous crystallization continued into the later stages, as minute pyroxene and amphibole are commonly found together in the groundmass. In rare cases the hornblende mantles the pyroxene phenocrysts. What conditioned the appearance of hornblende only in some of the dikes is difficult to say, particularly from the chemical data. The amount of volatiles was high in all of the dike magmas, so that chemical composition presumably controlled its formation.

Biotite is present in almost half of the Burke dikes, although usually in small amounts and as tiny grains. It occurs mainly in the diabasic types, particularly the more alkalic ones, and in the monchiquitic camptonites, as well as in the rare kersantitic dikes. The biotite presumably crystallized late from increasingly alkalic late liquids.

Ocelli have been reported in basalt, diabase, and more frequently in camptonite and related rocks (Vincent, 1953; Ramsay, 1955; Challis, 1960). In the Burke area it is the camptonitic dikes that commonly have them. Some ocelli are of feldspar only; others also contain hornblende; and other have calcite, analcite, serpentine and some ferromagnesian minerals. The ocelli must represent the last alkali- and volatile-rich residual fluids.

In a few cases plagioclase laths and even hornblende have a parallel arrangement, but only in part of the thin sections. This indicates that there was still some directional movement even at a late stage of what must have been a viscous crystal mush lubricated by a volatile-rich residuum. The last stages in crystallization and the post-crystallization effects are development of amygdules, deposition of calcite, analcite and sulfides, and attack on the phenocrysts by the carbon dioxide-rich volatiles. Olivine is usually completely or largely altered to carbonate, talc-carbonate, or serpentine. The alteration to talc presumably took place above about 500° C. and perhaps below 700° C., while serpentine appeared below about 500° C. (Bowen and Tuttle, 1949). The pyroxene is commonly altered, mainly to carbonate. The sphene blebs already mentioned suggest that the products of breakdown of the pyroxene were dispersed into the mesostasis so that reaction took place while some mobility remained. This may also apply to the breakdown of olivine and may account for the occurrence of interstitial and vein serpentine. Thin veins of carbonate and serpentine which cut some of the rocks and

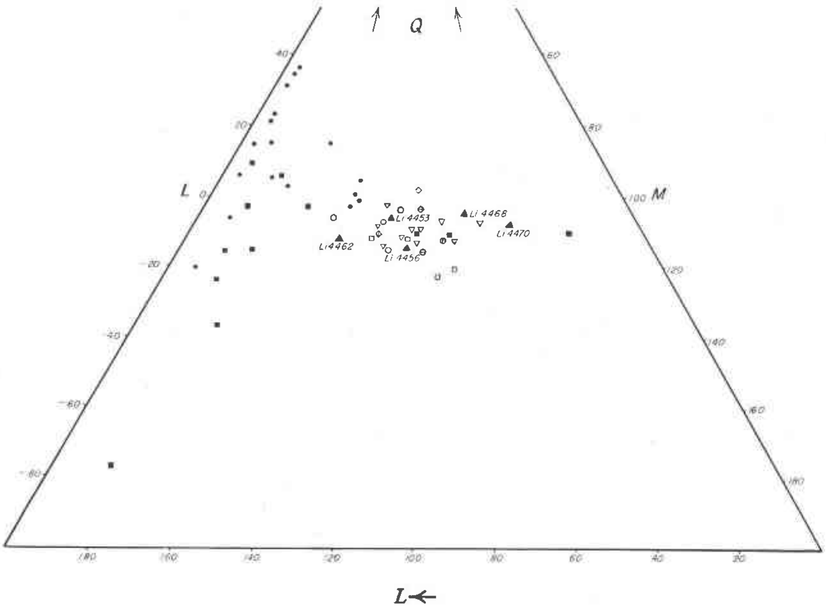

FIG. 8. Von Wolff diagram showing the five analyzed Burke dikes—▲; various camptonites from the literature—▽; selected analyses of rocks of the White Mountain plutonic-volcanic series—●; camptonites of the White Mountain series—○; Hawes (1879), diabase—⊖; Hawes (1879), olivine diabase—⦶; selected analyses of rocks of the Monteregian Hills—■; camptonites of the Monteregian Hills—□; Daly's average camptonite—◈; average of two analyses of Mount Holyoke, Massachusetts, diabase—◇; average of three analyses of olivine basalt of plateau type, Mull—⟠.

penetrate the phenocrysts represent the final acts after the rock was completely solidified.

It is impossible to come to a definite conclusion as to whether this suite of alkalic differentiates was produced entirely by fractional crystallization of an olivine basalt magma or whether some assimilation of hornblende or hornblende-bearing rock, for example, or of limestone has taken place. The uncommon occurrence of corroded xenocrysts suggests that some assimilation may have taken place. There is no apparent correlation, however, between dike type and wall rock. The camptonites, for example, intrude the calcareous Waits River formation, the pelitic and quartzose Gile Mountain formation, and granite. If important assimilation took place, it must have done so at depth. It seems probable that the most melanocratic olivine-rich dikes formed from an alkalic magma enriched with earlier-formed phenocrysts. Removal of some or all of these phenocrysts would produce an increase of the FeO:MgO and the alkali:CaO ratios. Further fractionation of the alkalic magma would be necessary to produce the FeO- and alkali-rich (that is, the felspar-rich) dikes.

The five rock analyses have been plotted on a von Wolff diagram in Fig. 8 together with a number of other camptonites, Daly's average camptonite (1933, p. 28), the average of two diabases from Mt. Holyoke, Massachusetts (Emerson, 1917, p. 271), and the average basalt of plateau type, Mull (Turner and Verhoogen, 1960, p. 226). As expected from the norms, all of the five Burke analyses fall into the undersaturated field, the three more basic ones into the nepheline basanite field and the two more alkalic ones into the trachydiabase field. The curve joining the plots shows a distinct alkalic trend. The average Mull plateau basalt lies near the center point of the curve, suggesting that the parent magma of the Burke dike rocks may have been an olivine basalt. It also suggests that the rocks represent firstly a more basic trend, possibly due to accumulation of earlier-formed crystals or perhaps to squeezing out of some of the differentiated alkalic magma, and secondly an alkalic trend leading to camptonite (Li 4456) and to the other more alkali-rich differentiates. The plots of all the camptonites are quite closely grouped and the main variations lie in the relative amounts of alkalic and femic components rather than in the degree of undersaturation.

Age and Relationship to Other Magmatic Activity

Examination of the history of magmatic activity of the New England-Quebec region suggests that the Burke alkalic basic dikes can perhaps be related to one of three magmatic series: (1) the intrusive necks of the Monteregian Hills of Quebec, (2) the White Mountain plutonic-volcanic series of New Hampshire, or (3) the upper Triassic basalts and diabases of the Newark fault troughs of Connecticut, Massachusetts, and Nova Scotia.

The Monteregian Hills are comprised of an alkalic suite of stocks and necks which extends from Montreal 50 miles southwest to Brome and which includes many camptonite dikes. The most southeasterly occurrence is in Mt. Megantic, which has recently been shown to belong to this suite (Lowden, 1961; Larochille, 1961; Fairbairn *et al.*, 1961). Poitevin and Cooke (1946) describe camptonite dikes from the Sherbrooke, Quebec, area and consider them to belong to the Monteregian Hills. Cooke (1957) reports camptonite dikes in the Coaticook area, immediately north of the international boundary and north of the Burke area. Potassium-argon and rubidium-strontium age determinations indicate an early to middle Cretaceous age, between 95 and 126 my., for the intrusions (Lowdon, 1961; Fairbairn *et al.*, 1961).

Age determinations on the White Mountain plutonic-volcanic series have produced results of a mean age of 186 ± 14 my. (Lyons *et al.*, 1957) and 185 my. (Tilton *et al.*, 1957). In the new geologic time scale (Holmes, 1959; Kulp, 1961) these ages place the magma series in the late Triassic or early Jurassic period.

The Newark basalt flows and diabase dikes have long been dated as late Triassic on the basis of the fauna of the accompanying sediments. Thus the age of the dikes would appear to be between late Triassic and early Cretaceous time. Chemically and mineralogically they show affinities more to the alkalic suites than to the Triassic diabase, which is tholeiitic in type. The plot on the von Wolff diagram (Fig. 8) of the average of two analyses of Mount Holyoke diabase falls outside the field of the five dikes analyzed and of all camptonites and of olivine basalt. Compare, however, the trends of the Monteregian Hills and the White Mountain plutonic-volcanic series which are plotted on the same diagram from a representative series of analyses of the two groups (Chapman and Williams, 1935; Dresser and Denis, 1944). The Burke dikes as well as those described by Kemp and Marsters (1893) from the Lake Champlain region and by Marsters (1895) from the Lake Memphremagog area are closely similar to the suite described by Hawes (1879) from Livermore Falls, New Hampshire.

Throughout northern Vermont and at least the Coaticook region of Quebec basic dikes have a preferred easterly strike. King (1961) notes that Triassic dikes in Connecticut and Massachusetts have a northeasterly trend. However, this difference is insufficient to draw any conclusions about relationship.

It thus seems that the tectonic activity of late Triassic times/which produced fault troughs parallel to the trend of the Appalachian orogenic belt and which was accompanied by considerable volcanic activity was succeeded by a period of different tectonic stresses in the basement. The latter is manifest by the magmatic activity in the early Jurassic in New Hampshire which is characterized by ring dikes and cauldron subsidences of the alkalic White Mountain plutonic-volcanic series, which extends in a north-northwesterly and south-southeasterly direction from York, Maine, to Mount Monadnock in northeastern Vermont. The latter is only some 38 miles south of the early Cretaceous intrusions of Mount Megantic, Quebec, a member of the Monteregian Hills group. The White Mountain plutonic-volcanic series and the Monteregian Hills when taken together cut across the trend of the Acadian orogenic belt and they may be, in general, younger in age to the northwest.

Lamprophyre dikes were intruded throughout the period of magmatic activity but perhaps those of northern Vermont are more closely related to the period of the Monteregian Hills intrusions than to the earlier White Mountain series. The dikes of northern Vermont were intruded under conditions when tensional stresses were operating approximately in a north-south direction.

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