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EARLY MESOZOIC ALKALINE MAFIC DYKES, SOUTHWESTERN NOVA SCOTIA, CANADA, AND THEIR BEARING ON TRIASSIC–JURASSIC MAGMATISM

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Abstract

Dykes of lamprophyre and alkaline olivine diabase cut the Cambro-Ordovician Goldenville Formation and the Carboniferous Wedgeport Pluton near Plymouth, southwestern Nova Scotia. ^{40}Ar/^{39}Ar geochronology yielded hornblende–biotite ages ranging between 231 ± 3 and 222 ± 3 Ma (mean 227 Ma) for the lamprophyres, and biotite ages of 209 ± 6 and 203 ± 15 Ma for the olivine diabase. Minerals present in the dykes include olivine (Fo_{83}), augite with a rim of titanaugite, kaersutite and titaniferous phlogopite. The whole-rock composition of both the lamprophyre and olivine diabase shows greater *LILE* and *HFSE* enrichment in the lamprophyres, but the relative abundances of these elements are remarkably similar in the two rock types, suggesting that they are comagmatic. Values of ε_{Nd} (~+4) and ε_{Sr} (~+5) are much more primitive than values for the widespread early Jurassic tholeiites. Pb isotope compositions for the lamprophyres fall near the Northern Hemisphere Reference Line; those of the olivine diabase are intermediate between the lamprophyres and more radiogenic Pb compositions typical of the Triassic alkaline dykes at Seabrook, New Hampshire, and the early Jurassic tholeiites; they may have experienced some contamination in the lower crust. The lamprophyres resemble, in age and chemical composition, other alkaline rocks of the Coastal New England province. The olivine diabases, apparently synchronous with the main Eastern North American tholeiites, represent renewed partial melting of the same mantle source, triggered by the thermal effect of the regional tholeiitic magma.

Keywords: lamprophyre, diabase, dyke, Triassic, Jurassic, Nova Scotia.

Sommaire

Des filons de lamprophyre et de diabase alcaline à olivine recoupent la Formation de Goldenville, d'âge cambro-ordovicien, et le pluton de Wedgeport, d'âge carbonifère, près de Plymouth, dans le sud-est de la Nouvelle-Écosse. La géochronologie fondée sur les résultats ^{40}Ar/^{39}Ar sur hornblende–biotite a donné des âges entre 231 ± 3 et 222 ± 3 Ma (en moyenne 227 Ma) pour les lamprophyres, et sur la biotite, des âges de 209 ± 6 et 203 ± 15 Ma pour la diabase à olivine. Parmi les minéraux présents dans les filons se trouvent forstérite (Fo_{83}), augite avec un liseré de titanaugite, kaersutite et phlogopite titanifère. La composition de ces roches montre un plus fort enrichissement en éléments traces lithophiles à large rayon et en éléments à champ électrostatique élevé dans les lamprophyres que dans les diabases, mais les proportions relatives de ces éléments sont remarquablement concordantes, ce qui fait penser que ces deux types de roche seraient comagmatiques. Les valeurs de ε_{Nd} (~+4) et de ε_{Sr} (~+5) sont beaucoup plus primitives que dans le cas des tholéiites répandues d'âge jurassique précoce. Les rapports des isotopes de plomb dans les lamprophyres correspondent à la ligne de référence de l'hémisphère nord; en revanche, les valeurs de ces rapports dans le cas des diabases sont intermédiaires entre ceux des lamprophyres et des compositions plus fortement radiogéniques typiques des filons alcalins d'âge triassique à Seabrook, au New Hampshire, et des tholéiites d'âge jurassique précoce. Ces rapports témoigneraient d'une contamination dans la croûte inférieure. Les lamprophyres ressemblent, par leur âge et leur composition chimique, aux autres manifestations alcalines de la province côtière de la Nouvelle Angleterre. Les diabases à olivine, qui sembleraient synchrones avec l'épanchement principal des magmas tholéiitiques dans l'est du continent nord-américain, pourraient résulter d'un renouvellement de fusion partielle de la même source magmatique, déclenché par l'influence thermique de la mise en place à l'échelle régionale des magmas tholéiitiques.

(Traduit par la Rédaction)

Mots-clés: lamprophyre, diabase, filon, triassique, jurassique, Nouvelle-Écosse.

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INTRODUCTION

Early Mesozoic igneous rocks, associated with rifting in the north Atlantic Ocean, form two groups on the Atlantic margin of the U.S. and Canada. The middle to late Triassic alkaline rocks of coastal New England are coeval with early rifting, which began in the Anisian (early Middle Triassic). The widespread earliest Jurassic tholeiitic magmatism immediately underlies a major Hettangian (earliest Jurassic) unconformity on the continental margin, marking a fundamental change in rift tectonics (Pe-Piper *et al.* 1992).

This paper is concerned with the best-developed example of middle to late Triassic alkaline rocks in Atlantic Canada: the dykes and sills that cut the Wedgeport pluton and adjacent metasedimentary rocks in the Plymouth area of southwestern Nova Scotia. Our objective in this paper is: a) to describe the mineralogy and geochemistry of these alkaline dykes, (b) to document the mode of intrusion of the dykes that cut the granite, c) to date these dykes more accurately, and d) to review the alkaline Triassic rocks of Atlantic Canada and outline their significance in the regional tectonic evolution.

REGIONAL OCCURRENCE OF TRIASSIC ALKALINE MAGMATISM

Late Triassic alkaline rocks are widespread in New England but rare in Atlantic Canada (Fig. 1). In New England, the alkaline rocks include: (1) The mildly alkaline Seabrook diabase dykes in New Hampshire [*ca.* 212–236 Ma, K–Ar (whole rock): Bellini *et al.* 1982; McHone 1992] and nearby alkaline basalt dykes in southern New Hampshire (Sundeen & Huff 1992), (2) mafic dykes of the northern Boston platform, in northeastern Massachusetts [*ca.* 226 Ma, K–Ar (whole rock): McHone & Butler 1984], (3) at least some of the NE-trending olivine alkaline diabase dykes (Hermes *et al.* 1984, Ross 1992) in Rhode Island and adjacent parts of Massachusetts, (4) three syenite to alkaline granite plu-

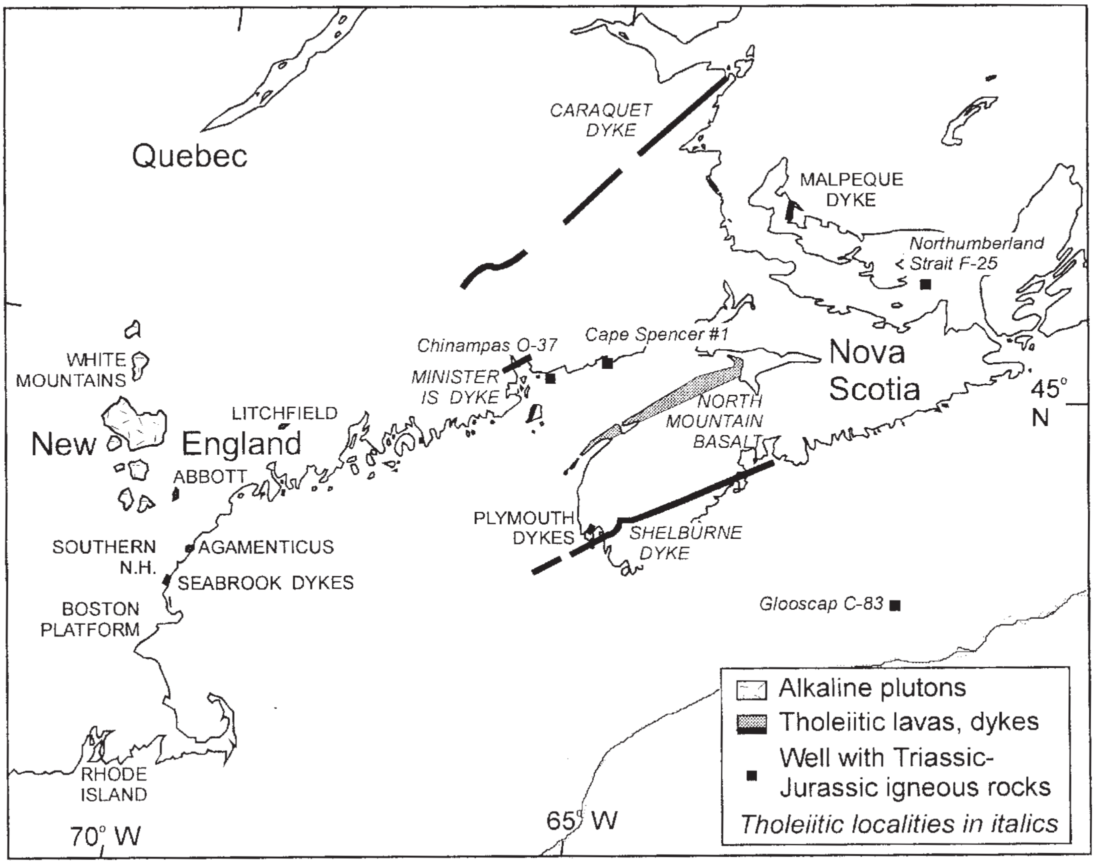

FIG. 1. Map showing distribution of early Mesozoic igneous rocks in eastern New England and western Atlantic Canada (modified from Pe-Piper *et al.* 1992).

tons in southern Maine (Litchfield, Agamenticus and Abbott plutons) that have yielded dates close to the Permian–Triassic boundary (Foland & Faul 1977, McHone & Butler 1984) and associated dykes (Swanson 1992). McHone & Butler (1984) referred to this suite of rocks as the Coastal New England (CNE) province. Several authors have suggested that this New England igneous activity was related to a mantle plume that later produced the Jurassic–Cretaceous White Mountain plutons (Eby 1987) and the New England Seamounts (Duncan 1984, de Boer *et al.* 1988), although this model has been criticised by McHone (1996). Early Cretaceous lamprophyric dykes and other minor alkaline intrusions are widespread in the Montreal region of Quebec and in northern New England (McHone 1992).

In Atlantic Canada, igneous rocks of Triassic age are rare. They include: (1) the alkaline Malpeque Bay (Georges Island) sill, Prince Edward Island [*ca.* 245 Ma, K–Ar (whole rock), early Triassic: Greenough *et al.* 1988], and (2) the mildly alkaline mafic dykes and sills near Plymouth, briefly described by Chatterjee & Keppie (1981). One of these dykes was dated at 226 Ma (Ar–Ar on biotite) by Reynolds *et al.* (1987).

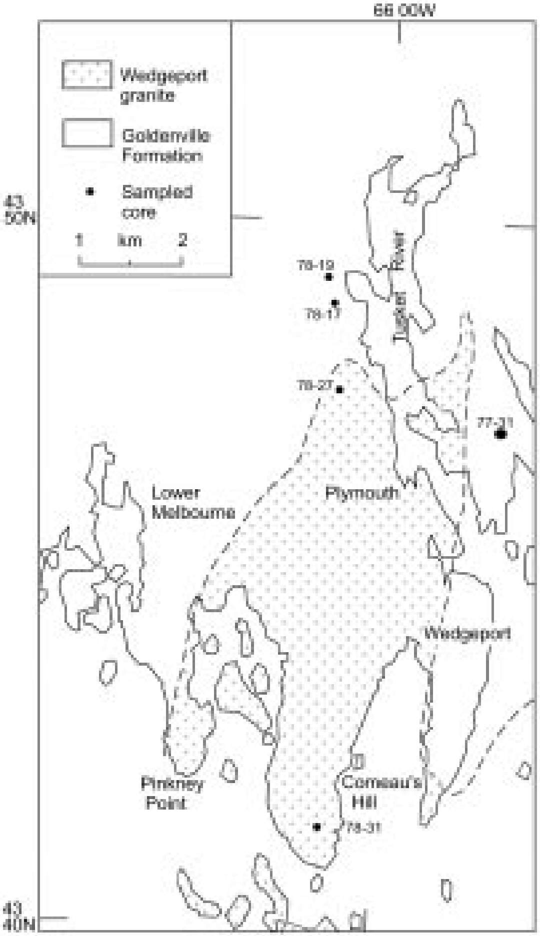

FIG. 2. Geological map of the Plymouth area, showing location of drillholes that intersect dykes (after Cullen 1983, Chatterjee & Keppie 1981).

THE TRIASSIC MAFIC DYKES OF THE PLYMOUTH AREA

In the Plymouth area of southwestern Nova Scotia (Fig. 2), the mid-Carboniferous Wedgeport Pluton (Cormier *et al.* 1988) and the surrounding Cambrian–Ordovician Goldenville Formation are cut by mafic dykes of lamprophyre and olivine diabase (Cant *et al.* 1978, Chatterjee & Keppie 1981). The dykes are poorly exposed in outcrop, but were sampled in a series of diamond drill-holes put down by Shell Canada Resources. They were also mapped on the basis of their magnetic signature (Cant *et al.* 1978). The dykes intruded the Wedgeport pluton along and across northeast–southwest-trending faults (Chatterjee & Keppie 1981) and the Goldenville Formation along pre-existing shear zones (Cullen 1983). The dykes have chilled margins (5–10 cm) and show little alteration or assimilation of the host rock. Wolfson (1983) and Cullen (1983) described the petrography of the mafic dykes that intrude the metasedimentary rocks.

Samples of olivine diabase dykes cutting the Wedgeport Pluton are available from drill core 7606–78–31 drilled for 76 m at an angle of 45° south of Comeau Hill (Fig. 2). The drillhole was put down to investigate a local magnetic anomaly. From 29 to 42 m, the core intersected several mafic dykes; two additional thin dykes were intersected at 51 m (3 cm) and 54 m (16 cm).

Samples of predominantly lamprophyric dykes that cut both the Goldenville Formation and the Wedgeport pluton have been examined from drill cores 78–19 and 78–27. Powdered geochemical samples from dykes in drillhole 77–31 also have been analyzed.

METHODS OF INVESTIGATION

Drill-core samples have been examined in hand specimen and, in the case of 78–31, logged in detail. Whole-rock geochemical analyses have been made by X-ray fluorescence and instrumental neutron-activation analysis (footnote, Table 1). Mineral analyses have been made by electron microprobe on the olivine diabase dykes; similar methods were used by Cullen (1983) in his study of the lamprophyres. Nd, Sr and Pb isotopes (Table 2) have been determined by Geospec Consultants Ltd. using methods summarized by Pe-Piper & Piper (1998). $^{40}Ar/^{39}Ar$ dating methods in the Dalhousie laboratory have been summarized by Dunn *et al.* (1998). Errors in estimated age are reported at the 2σ level and include the uncertainty in the irradiation parameter, J, but do not incorporate uncertainty in the age of the flux

TABLE 1. REPRESENTATIVE CHEMICAL COMPOSITION OF MAFIC DYKES FROM THE PLYMOUTH AREA, NOVA SCOTIA

	Lamprophyre				Olivine diabase (78-31)			
Dykes	78-27	78-19	77-31		Dyke 1		Dyke 2	
Sample no.			6	8	A	B	C	D
	Hol[1]	Hyp			GVF	M	HF	AM
Major elements (wt%) by XRF								
SiO_2	44.53	43.87	42.62	40.76	44.34	46.66	46.66	46.83
TiO_2	2.60	3.20	3.16	3.43	1.87	1.84	2.08	2.07
Al_2O_3	12.05	11.54	11.11	12.00	13.39	13.16	14.37	13.55
Fe_2O_3t	11.68	11.45	13.59	14.45	11.79	12.20	12.03	12.70
MnO	0.16	0.16	0.24	0.19	0.17	0.18	0.16	0.18
MgO	9.31	8.05	8.31	5.64	9.43	10.41	7.52	8.95
CaO	9.51	11.88	9.89	7.88	8.46	7.89	9.30	8.23
Na_2O	2.70	1.76	2.93	1.97	2.16	2.16	2.83	2.87
K_2O	2.34	3.52	1.91	2.89	0.83	1.05	1.25	1.29
P_2O_5	0.71	0.93	0.87	0.93	0.44	0.43	0.50	0.43
L.O.I.	3.3	3.4	5.0	10.1	6.7	5.1	4.4	4.0
Total	98.89	99.76	99.63	100.24	99.58	101.08	101.10	101.10
{Mg}	0.65	0.62	0.59	0.48	0.65	0.67	0.59	0.62
CIPW Norms[2]								
Or	14.65	17.43	12.10	19.26	5.35	6.55	7.74	7.96
Ab	10.39	-	9.25	12.17	19.93	19.29	24.04	25.01
An	14.67	13.86	12.35	17.33	26.60	24.39	23.89	21.16
Ne	7.48	8.47	9.39	3.59	-	-	0.56	0.18
Ol	20.74	13.71	19.85	20.92	20.16	17.86	20.89	25.14
Hy	-	-	-	-	9.66	15.57	-	-
Di	25.17	34.49	28.52	17.03	13.34	11.63	17.57	15.45
Ap	1.75	2.27	2.17	2.44	1.12	1.05	1.22	1.04
Il	5.23	6.38	6.43	7.34	3.87	3.69	4.14	4.10
Trace elements (ppm) by XRF								
Ba	680	994	815	870	303	365	421	400
Rb	107	108	78	66	24	39	32	57
Sr	804	817	848	754	545	562	599	584
Y	20	29	24	34	35	28	37	26
Zr	205	258	243	262	124	118	153	121
Nb	72	92	85	96	43	39	48	37
Pb	<10	12	13	44	12	10	13	11
Ga	22	19	20	23	18	18	21	20
Zn	95	121	104	206	127	102	121	100
Cu	43	47	56	64	50	57	50	62
Ni	243	113	286	185	171	287	114	210
V	169	216	224	274	200	156	182	196
Cr	266	196	304	349	274	277	216	243
REE and other trace elements (ppm) by INAA								
La	34	48	41	45	25	24	29	24
Ce	72	95	84	93	48	45	55	47
Nd	33	46	42	44	23	21	29	21
Sm	7.1	9.6	8.8	9.9	5.2	4.9	5.9	5.1
Eu	2.5	3.2	3.1	3.2	1.82	1.75	2.0	1.8
Tb	0.99	1.19	1.11	1.24	0.87	0.76	0.77	0.66
Yb	1.20	1.59	1.41	1.71	1.53	1.54	1.72	1.24
Lu	0.18	0.23	0.21	0.25	0.23	0.22	0.21	0.20
Cs	51	28	53	28	n.d.	n.d.	n.d.	n.d.
Hf	4.6	5.9	5.4	5.6	3.2	3.2	3.8	3.1
Sc	18.7	19.9	19.9	20.5	20.0	19.8	20.5	21.2
Ta	4.4	5.9	5.6	6.0	2.2	2.2	2.6	1.92
Th	4.6	6.4	5.2	5.3	3.4	3.2	3.9	3.5
U	1.08	1.76	1.06	6.9	0.69	0.85	0.65	0.66

	Olivine diabase (78-31)							
Dykes	Dyke 2			Dyke 4		Dyke 5		Dyke 6
Sample no.	E	F	H	I	J	K	L	M
	M	F-M	M-C	M	AM	VF	AF-M	F
Major elements (wt%) by XRF								
SiO_2	45.23	46.30	46.46	46.02	46.56	45.22	45.46	44.81
TiO_2	1.84	1.93	1.96	1.73	2.05	1.91	1.93	1.75
Al_2O_3	13.13	13.54	13.18	13.09	13.90	12.94	13.95	12.50
Fe_2O_{3t}	12.28	12.07	12.72	11.64	11.70	12.38	11.99	12.12
MnO	0.14	0.17	0.19	0.18	0.19	0.17	0.20	0.24
MgO	9.95	8.77	9.94	9.31	7.02	8.27	7.45	9.94
CaO	7.74	8.08	7.57	9.34	9.65	9.03	8.89	8.56
Na_2O	2.23	2.69	2.89	2.18	2.77	2.55	2.54	1.99
K_2O	1.21	1.25	1.21	0.89	1.07	1.09	0.92	0.75
P_2O_5	0.45	0.44	0.46	0.38	0.44	0.44	0.44	0.42
L.O.I.	5.60	4.40	4.20	6.30	5.80	6.10	6.20	7.20
Total	99.80	99.64	100.78	101.06	101.15	100.10	99.97	100.28
{Mg}	0.65	0.63	0.65	0.65	0.58	0.61	0.59	0.66
CIPW Norms								
Or	7.69	7.86	7.50	5.62	6.71	6.94	5.87	4.82
Ab	20.30	24.21	25.66	19.71	24.89	23.26	23.22	18.33
An	23.93	22.52	20.37	24.90	23.72	22.26	25.87	24.99
Ne	-	-	-	-	-	-	-	-
Ol	22.42	22.20	27.83	17.69	18.07	22.86	17.38	17.81
Hy	8.95	4.04	0.40	9.47	1.34	0.59	7.01	14.26
Di	11.87	14.22	13.23	18.19	20.09	19.11	15.62	15.13
Ap	1.12	1.09	1.12	0.94	1.09	1.10	1.10	1.06
Il	3.76	3.90	3.91	3.51	4.13	3.91	3.96	3.62
Trace elements (ppm) by XRF								
Ba	395	402	431	315	343	356	323	285
Rb	53	44	58	25	27	27	23	33
Sr	571	509	517	564	555	537	528	503
Y	30	31	28	28	32	29	46	31
Zr	139	145	133	101	125	135	128	114
Nb	40	44	40	31	40	40	37	38
Pb	12	12	13	10	10	10	<10	<10
Ga	18	17	18	15	19	20	17	18
Zn	110	140	124	78	76	110	82	114
Cu	48	47	55	48	53	46	57	49
Ni	216	197	250	255	134	266	144	344
V	137	171	176	184	191	194	208	174
Cr	217	248	268	307	244	293	289	298
REE and other trace elements (ppm) by INAA								
La	27	28	26	20.1	24	25	25	23
Ce	53	52	51	40	46	52	49	44
Nd	26	27	27	22	22	27	22	24
Sm	5.5	5.6	5.5	4.5	5.1	5.3	5.4	4.7
Eu	1.93	1.90	1.91	1.56	1.78	1.90	1.89	1.71
Tb	0.84	0.86	0.79	0.63	0.90	0.86	0.89	0.72
Yb	1.68	1.60	1.30	1.31	1.46	1.56	1.90	1.42
Lu	0.21	0.24	0.17	0.19	0.23	0.19	0.30	0.19
Cs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hf	3.7	3.7	3.1	2.8	3.3	3.5	3.3	3.1
Sc	18.9	19.2	19.5	20.9	20.5	20.0	20.7	18.9
Ta	2.3	2.3	2.1	1.68	2.1	2.2	2.2	2.1
Th	4.1	3.6	3.7	2.6	3.3	3.2	3.3	2.7
U	0.82	0.59	0.54	0.57	0.57	0.67	0.53	0.55

[1] Hol: holocrystalline, Hyp: hypocrystalline, VF: very fine-grained samples from contacts, either with granite (sample A) or with another dyke (sample K); F: fine grained, M: medium grained, C: coarse grained; H: sample with patches of variable grain-size; A: very pronounced amygdaloidal texture; G: glassy.

[2] The norms have been calculated assuming $Fe^{3+}/Fe(total) = 0.15$

Methods: The samples were analyzed for ten major- and minor-element oxides and fourteen trace elements on a Philips PW1400 sequential X-ray-fluorescence spectrometer using a Rh-anode X-ray tube. Major-element oxide determinations were carried out on fused glass discs, whereas trace elements were determined from pressed powder pellets. International standards were used for calibration. Analytical precision, as determined from replicate analyses, is generally better than 2%, except for MgO, Na_2O and Nb, where it is better than 5%, and Th, where it is better than 10%. Loss on ignition (L.O.I.) was determined by treating the sample for 1.5 h at 105°C in an electric furnace. The rare-earth-element concentrations were determined by neutron-activation analysis, with at least two standard reference materials chosen so as to roughly correspond to the compositions of the unknowns. The precision of the results, as determined on replicate analyses, is generally better than 5% for La, Ce, Tb, Yb, Lu, Th, Sc and Co, and better than 10% for Nd, Sm, Cs, Hf, Ta and U.

TABLE 2. ISOTOPIC DATA FROM REPRESENTATIVE SAMPLES OF THE AREAS STUDIED

	Sample	$^{87}Sr/^{86}Sr$ measured	initial	Nd ppm	Sm ppm	$^{143}Nd/^{144}Nd$ measured	ε_{Nd} init	T_{DM^*} Ga	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Age* Ma
Plymouth dykes												
Lamprophyre	78-19	0.70505	0.7045	46.263	6.259	0.512803	+4.95	0.5	19.334	15.560	38.958	228
Lamprophyre	78-27	0.70493	0.7044	62.057	13.89	0.512835	+5.57	0.5	19.661	15.579	39.262	228
Olivine diabase	78-31D			25.01	5.67	0.51276	+4.06	0.6	19.061	15.617	38.883	203
Olivine diabase	78-31I			20.84	4.75	0.51279	+4.62	0.6	19.047	15.615	38.874	203
Olivine diabase	78-31K			24.66	5.42	0.51278	+4.56	0.6				203
Comparative samples												
Seabrook dykes	B1	0.70464	0.7043	22.6	5.3				19.383	15.698	39.048	230
Seabrook dykes	B2	0.70517	0.7051	20.5	4.9	0.51279	+4.34	0.7	18.995	15.678	38.854	230
Shelburne dyke, center	SN13	0.70953	0.7089	17.74	4.07	0.51240	−3.29	1.4	18.380	15.646	38.527	202
Shelburne dyke, margin	SN14	0.70745	0.7072	12.30	2.94				18.790	15.642	38.918	202

* For T_{DM} age determinations, the equation used is that of Faure (1986). For ε_{Nd} determinations, we used the constants $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$.

monitor, the hornblende standard, MMhb–1. The accepted age of this standard is 520 Ma (Samson & Alexander 1987).

GEOCHRONOLOGY

A lamprophyric dyke cutting the Goldenville Formation from drillhole 77–17 (Fig. 2) was dated at 226 ± 10 Ma by the $^{40}Ar/^{39}Ar$ method on biotite (Reynolds *et al.* 1987). Five new $^{40}Ar/^{39}Ar$ age determinations are presented in the present study (see Fig. 3 for age-spectrum plots). Biotite and hornblende separates from a lamprophyric dyke in core 78–19 yielded plateau ages of 228 ± 2 and 222 ± 3 Ma, respectively. Observed $^{37}Ar/^{39}Ar$ ratios suggest only a minor amount of biotite contamination in the low-temperature steps of the hornblende spectrum. A hornblende separate also was obtained from a lamprophyre in core 78–27. Biotite contamination seems more extensive here. The spectrum is noisy, but there is no apparent gradient in age. The mean age is 231 ± 3 Ma. We also attempted to date biotite and hornblende in olivine diabase from drillcore 78–31, but only a very small pure biotite separate (~1 mg) could be obtained. The three largest steps in the resulting age-spectrum have identical ages, but with large uncertainties; the mean of these is 203 ± 15 Ma. The hornblende separate from this rock is very fine grained; a few adhering felsic grains are present, but no biotite was seen. However, the age spectrum is dominated by a low-$^{37}Ar/^{39}Ar$ phase, probably biotite. Apparent ages at high release-temperatures are lower, seemingly correlated with elevated $^{37}Ar/^{39}Ar$ values. The large second step, accounting for 54% of the ^{39}Ar released, has the lowest $^{37}Ar/^{39}Ar$ value; its age, 209 ± 6 Ma, may be a best estimate of the biotite age. The mean age of the entire spectrum (excluding some very small steps at the end of the release) is 202 ± 6 Ma.

PETROGRAPHY

Introduction

Dykes cutting Goldenville Formation have been studied in drillholes 78–19 and 77–31 (Fig. 2) and are lamprophyric (monchiquite). Dykes cutting granite have been studied in drillholes 78–27 and 78–31. The samples from drillhole 78–27 are very similar to the lamprophyric dykes cutting the Goldenville Formation, whereas the samples from drillhole 78–31 are olivine diabase.

Individual dykes vary in grain size (medium to fine grained), crystallinity (almost holocrystalline to hypocrystalline), phenocryst:groundmass ratio, and the percentage of biotite and other phenocrystic minerals.

Lamprophyre dykes

The lamprophyres are all porphyritic rocks with an aphanitic groundmass showing alteration to calcite. The phenocrysts are euhedral and include: dark-brown pleochroic amphibole (10 to 15%), clinopyroxene (10–25%) and olivine pseudomorphs (4–10%). The groundmass makes up 50–55% of the rock and consists of the same minerals as the phenocrysts, in addition to microlites of skeletal plagioclase, as well as calcite and acicular apatite. In addition to the groundmass microlites, plagioclase also occurs as an intergranular mineral (5%, 0.1–0.5 mm) in some samples. The amphibole phenocrysts range in size from 0.18 to 1.3 mm; in addition, amphibole commonly overgrows clinopyroxene. The clinopyroxene crystals range in size from 0.04 to 4.3 mm and are typically zoned (brown rim, colorless core) and unaltered. They occur as individual grains and as radiating clusters forming a glomeroporphyritic texture with or without inclusions of olivine. Olivine pseudomorphs (0.16–1.2 mm) are euhedral and completely

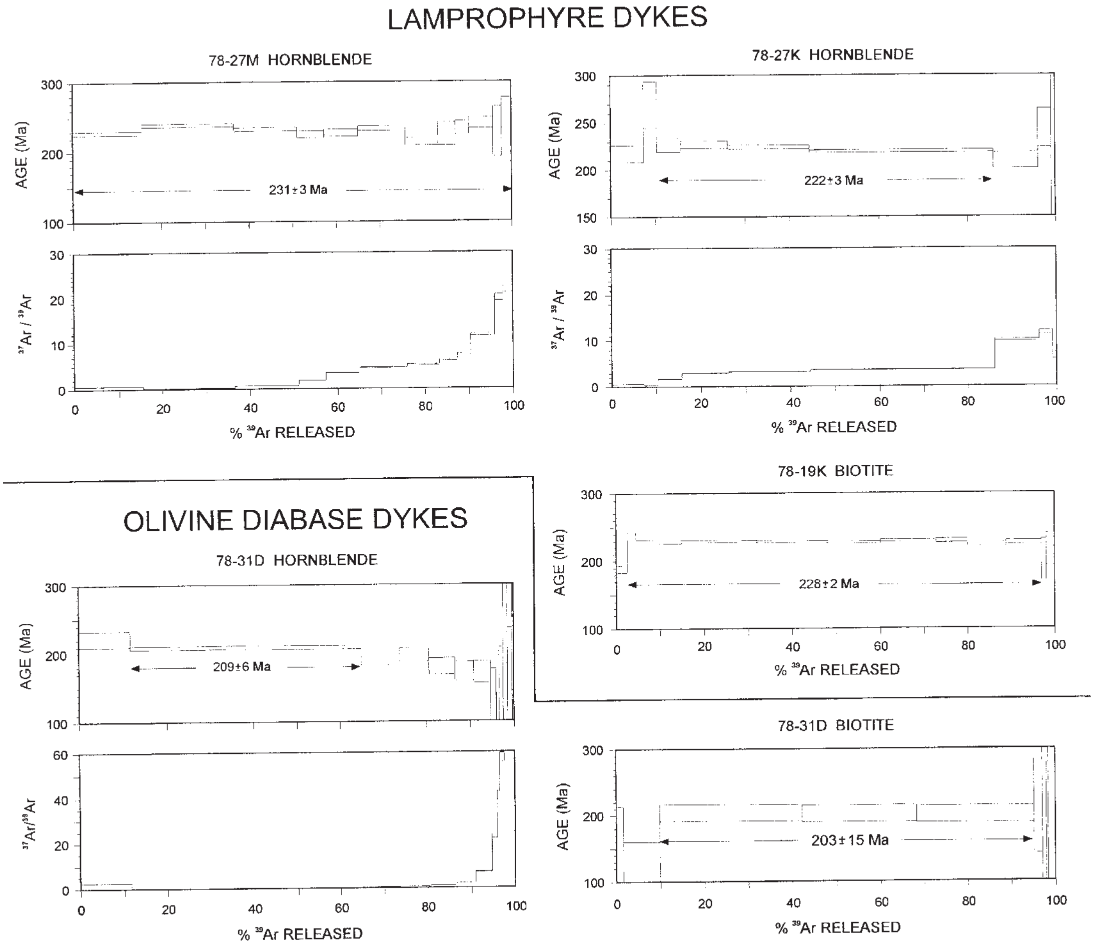

FIG. 3. $^{40}Ar/^{39}Ar$ age spectrum plots and $^{37}Ar/^{39}Ar$ spectra for hornblende separates. Half-heights of open rectangles indicate 1σ relative (between-step) uncertainties; otherwise, uncertainties are indicated at the 2σ level.

replaced by a serpentine-group mineral. Biotite has a similar habit to that of brown hornblende, and is found as euhedral to subhedral microphenocrysts (0.04–0.2 mm), typically associated with the outer margins of the clinopyroxene phenocrysts. Opaque minerals (3–5%, 0.04–0.5 mm) are anhedral to subhedral grains and occur in the groundmass and as inclusions in amphibole and olivine pseudomorphs. Traces of anhedral chlorite occur locally intergrown with the amphibole and opaque minerals. Acicular apatite (about 0.3 mm in length) is present in the groundmass.

Olivine diabase dykes

Four complex dykes have been sampled among the five dykes in the part of drillhole 78–31 illustrated in Figure 4. An additional sample (M) was taken from another thin dyke deeper in the drillhole. All the samples, with the exception of those close to contacts (*e.g.*, samples A and K), consist of olivine-phyric amygdaloidal diabase, although the percentage of amygdules is pronounced only in few samples, sample J in particular (Fig. 5A). The grain size of these samples ranges from very fine grained to coarse grained. The samples from the contacts are highly porphyritic, very fine grained with a high percentage of dusty glassy groundmass and a brownish glass just at the actual contact. There are textural discontinuities not only at the contacts, but also within a single sample over distances of a few centimeters (Fig. 5B) and on a thin-section scale. These textural discontinuities are accompanied by mineral discontinuities: the fine patches are rich in biotite, whereas the coarser ones are rich in olivine. These mineralogical discontinuities are shown in Figure 4,

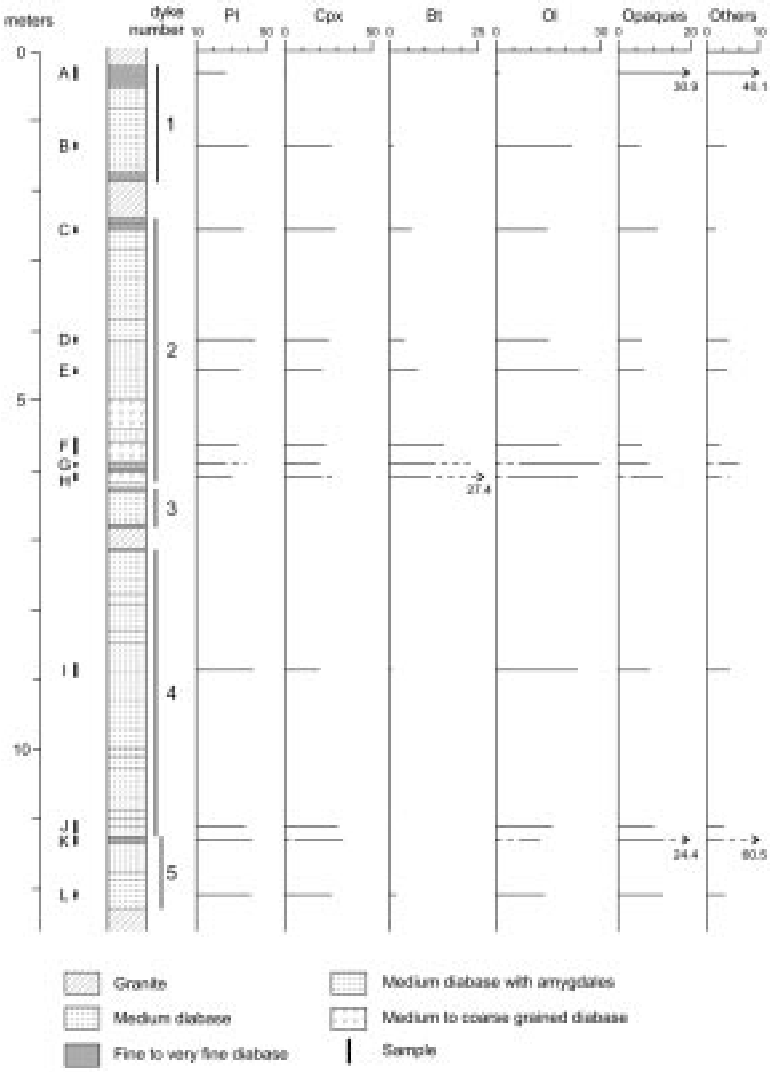

FIG. 4. Location and modal mineral variation (% by volume) of the multiple dykes in core 78–31. For samples with modal analysis for both fine- and coarser-grained patches (samples G, H), a solid line is used for the coarser patch and a dotted line is used for the fine one. The opaque phases include primary Fe–Ti oxide minerals and a very fine-grained mixture of opaque grains and glass. "Others" include calcite and other alteration minerals, where the primary mineral could not be identified. Note that a high percentage of samples A and K is made up of glassy groundmass that is not plotted.

where modal proportions in fine (dotted line) and coarse patches (solid lines) are given for samples G and H. There is also evidence for more than one injection. For example, dyke 5 has intruded dyke 4 (Fig. 5C). The part of sample K close to the contact with sample J contains large round crystals of clinopyroxene that show reverse zoning. These crystals seem to represent xenocrysts from dyke 5.

The modal composition of all samples from drillhole 78–31 is given in Figure 4. All the samples contain phenocrysts of olivine set in a matrix of colorless to brownish clinopyroxene, plagioclase, and opaque minerals,

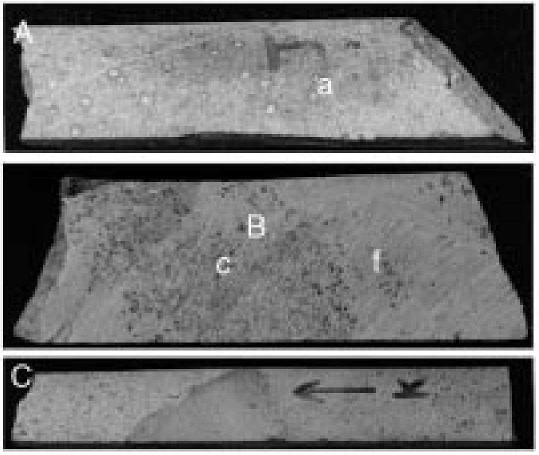

FIG. 5. Hand-specimen photographs of olivine diabase dykes. A. Amygdaloidal diabase with amygdules (a) filled with calcite (sample J). B. Sample with an inhomogeneous texture. The coarse-grained patches (c) are rich in olivine, whereas the fine-grained patches (f) are rich in phlogopite. C. Hand specimen showing the contact (arrow) of two dykes: dyke 4 (sample J) and dyke 5 (sample K) of Table 1.

and most contain reddish brown interstitial biotite. In samples close to contacts (Fig. 4), biotite is either absent or in traces amounts, whereas olivine and plagioclase are abundant, either as phenocrysts or in the very fine grained, formerly glassy groundmass (Fig. 4). The olivine is commonly altered to a serpentine mineral. The amygdules are filled with calcite. Accessory minerals include acicular apatite. The primary opaque phase is magnetite. Pentlandite, pyrrhotite and pyrite occur only as inclusions in olivine and in some samples in clinopyroxene. Some chlorite also is present.

GEOCHEMISTRY

Lamprophyre dykes

The lamprophyres have an alkaline basaltic composition (Fig. 6A) and contain nepheline in their norms (Table 1). Binary element-variation diagrams (not shown here) such as TiO_2 *versus* Zr, Ce *versus* Yb, Th *versus* U, and Cr *versus* Ni, show patterns that suggest the fractionation of olivine, clinopyroxene and plagioclase. The light rare-earth elements (*LREE*) show a strong enrichment ($La/Yb_N > 10$) and a slight positive Eu anomaly (Fig. 7). Plots of elements normalized to primitive mantle (Fig. 8) show typical "alkaline" trends, with strong enrichment in large-ion lithophile elements (*LILE*), Nb, Ta, *LREE* and high field-strength elements (*HFSE*). The rocks show less enrichment in Th and U than in other *LILE*.

Olivine diabase dykes

The olivine diabase from drillhole 78–31 is of mildly alkaline basaltic composition. The main geochemical variations among dykes and within single dykes involve MgO, CaO, Ni and TiO_2 (Fig. 9, Table 1). Comparison of Figures 4 and 9 suggests that these differences result from variation in the modal percentage of olivine, clinopyroxene and biotite. Binary element-variation diagrams (also not shown here) suggest clinopyroxene and plagioclase fractionation.

The olivine diabase dykes span the "alkaline" and "subalkaline" fields of Irvine & Baragar (1971) (Fig. 6A). Two samples contain normative nepheline (Table 2), whereas the remainder contain only olivine in their norms. Rare-earth-element variation is similar to that in the lamprophyres (Fig. 7), except that the *LREE* are slightly less enriched. Plots of element concentrations normalized to primitive mantle show a remarkably similar pattern to the lamprophyres (Fig. 8), except that olivine diabase shows a little less overall enrichment in *LILE* and *HFSE*. Rare-earth-element patterns are quite different from those of olivine-normative tholeiitic diabases elsewhere in eastern North America (*e.g.,* Warner *et al.* 1985). In their overall chemistry, the dykes are quite different from the widespread early Jurassic tholeiitic basalt and diabase, even those that are olivine-normative (e.g. Ragland *et al.* 1992), having higher alkalis and *HFSE* and lower iron and silica.

Sr, Nd and Pb isotopes

Strontium, Nd and Pb isotopic analyses have been made of both the lamprophyre and olivine diabase dykes. In addition, new Sr, Nd and Pb isotopic data are presented for the Seabrook dykes of New Hampshire and the early Jurassic Shelburne dyke of Nova Scotia, to provide comparisons with other occurrences of Triassic alkaline magmatism and with Jurassic tholeiitic magmatism.

Initial Sr isotope ratios for the lamprophyre dykes and the Seabrook dykes are similar, between 0.7043 and 0.7051, and correspond to ε_{Sr} of 0 to +15 (Fig. 10, Table 2). Both lamprophyre and olivine diabase dykes from Plymouth, together with the Seabrook dykes, have positive ε_{Nd}, ranging from +4.0 to +5.5 (Fig. 10). These ε_{Nd} values are substantially higher than any of the "Mesozoic Appalachian Tholeiites" in the U.S. analyzed by Pegram (1990). They imply a mantle source lacking major crustal contamination. Pb isotope data for the lamprophyre dykes at Plymouth fall near the mantle Northern Hemisphere Reference Line (Hart 1984). The low $^{207}Pb/^{204}Pb$ value at a high $^{206}Pb/^{204}Pb$ value (Fig. 11) indicates that there has not been important contamination by crust in these lamprophyres. In contrast, the Seabrook dykes fall close to many "Mesozoic Appalachian Tholeiites" analyzed by Pegram (1990), as does

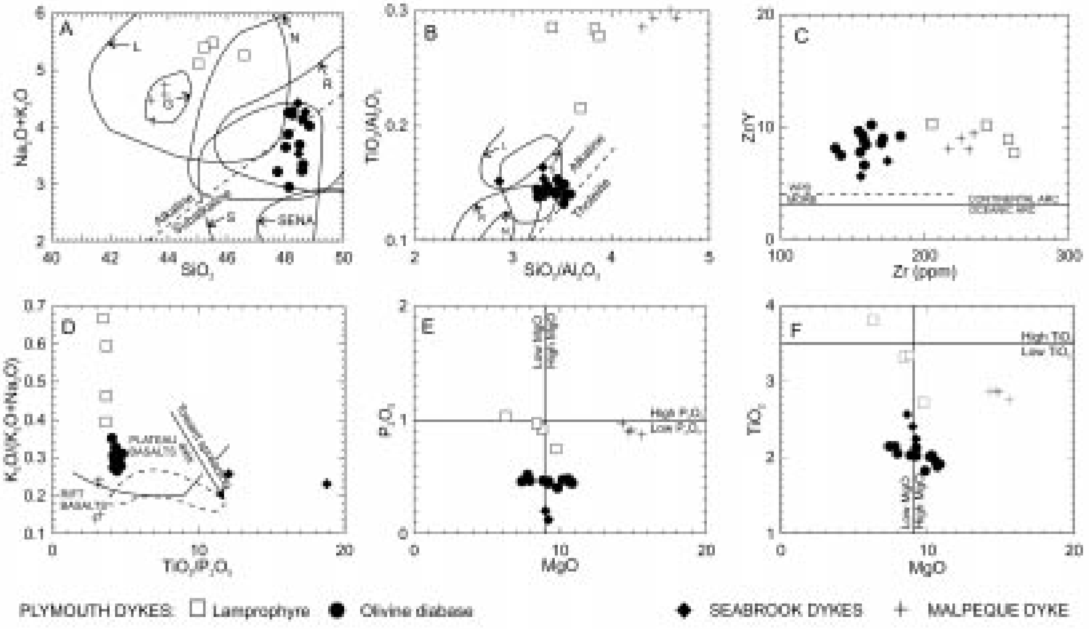

FIG. 6. Diagrams used by McHone (1992) and Ross (1992) to illustrate the chemical variation of the Plymouth dykes and comparative early Mesozoic rocks from New England and Atlantic Canada. All analytical data recalculated on a volatile-free basis. A. Total alkalis *versus* silica diagram using the discriminant of Irvine & Baragar (1971) (dashed line separates the alkaline from the subalkaline rocks). The fields SENA, G, L, N, R, and S are from McHone (1992) (SENA: Southern Appalachian Eastern North American province olivine tholeiite dykes, G: George Island sill (Malpeque dyke), L: early Cretaceous lamprophyres of northern New England, N: Northumberland Strait dykes, R: Rhode Island dykes, and S: Seabrook dykes). B. TiO_2/Al_2O_3 *versus* SiO_2/Al_2O_3 for dyke magmas, after McHone (1992). Field abbreviations as in (A). Dashed line separates tholeiitic groups from other groups of Mesozoic dykes (from McHone 1992). C. Zr/Y *versus* Zr diagram. WPB (within-plate basalt) and MORB (mid-ocean ridge basalt) fields are from Pearce & Norry (1979). Continental arc and oceanic arc fields are from Pearce (1982). D. K_2O/total alkalis *versus* TiO_2/P_2O_5 diagram of Charasekarem & Parthasarathy (cited in Solyon & Andreasson 1985). E. P_2O_5 *versus* MgO diagram. Boundary lines from Ross (1992). F. TiO_2 *versus* MgO diagram. Boundary lines from Ross (1992).

the Shelburne dyke. The Pb isotopic composition of the olivine diabase lies between that of the lamprophyres and that of the “Mesozoic Appalachian Tholeiites”. In contrast, the early Jurassic Shelburne dyke has high initial Sr isotope ratios (0.707 to 0.709; ε_{Sr} ~ +40 to +65), similar to those for the comagmatic North Mountain basalt (Jones & Mossman 1988), and negative ε_{Nd} (–3.3; see also Dostal & Durning 1998). These values are consistent with significant assimilation by the middle to lower crust, with fractional crystallization (AFC) involved in the petrogenesis of these magmas (Dostal & Dupuy 1984, Dostal & Durning 1998).

The simplest interpretation of the isotopic data is that the Sr and Nd isotopes of the Plymouth and Seabrook dykes reflect principally their mantle source. The Plymouth lamprophyres also have a mantle Pb isotopic signature, but the Pb isotopes at Seabrook resemble those of the “Mesozoic Appalachian Tholeiites”. There are two competing hypotheses for the Pb isotopic composition of these tholeiites. Pegram (1990) interpreted the “crustal” signature of the Mesozoic Appalachian Tholeiites as derived from subcontinental lithospheric mantle metasomatized during Proterozoic subduction. Following this hypothesis, the Seabrook data would require magma from more pristine mantle to be contaminated by Pb from the metasomatized mantle. On the other hand, many authors (*e.g.*, Dostal & Dupuy 1984) have argued that the “Mesozoic Appalachian Tholeiites” experienced significant evolution in a base-of-crust magma chamber. Mean concentrations of Pb (7 ppm), Nd (13 ppm) and Sr (230 ppm) in the lower crust (Taylor & McLennan 1985) suggest that in the rocks studied, the effect of contamination by crust will be much greater for Pb than for the other two elements. In this hypothesis, it would be expected that the Plymouth olivine diabasic magmas (with 5 ppm Pb, 25 ppm Nd and 500 ppm Sr) would show more contamination by crust Pb than the Seabrook magmas (with 11 ppm Pb, 20 ppm Nd and 350 ppm Sr), but both would have substantially less crustal contribution to Nd and Sr isotopes. In fact,

TABLE 3. REPRESENTATIVE ELECTRON-MICROPROBE COMPOSITIONS OF CLINOPYROXENE FROM OLIVINE DIABASE DYKES IN DRILLHOLE 78-31

Sample	B		J				K			
			Ph	Ph	Ph	Ph	Ph FGP-C	Ph FGP	Mph CGP	Mph CGP
	c	r	c	r	c	r	c	r	c	r
SiO_2	52.35	47.32	48.41	50.77	49.04	48.75	51.59	49.78	52.40	48.73
TiO_2	0.70	2.11	1.61	1.02	1.30	1.65	1.00	1.18	0.50	1.72
Al_2O_3	2.62	4.99	5.84	2.50	5.13	4.58	2.70	4.75	2.15	4.32
Cr_2O_3	0.42	0.00	0.32	0.00	0.18	0.09	0.00	0.66	0.31	0.00
FeO_t	6.87	11.09	7.96	11.17	8.23	10.04	8.50	6.79	6.29	10.31
MnO	0.09	0.32	0.17	0.39	0.14	0.19	0.14	0.11	0.00	0.23
MgO	16.14	11.38	13.77	12.28	13.57	12.54	14.37	14.35	15.98	12.09
CaO	20.43	20.99	20.63	20.46	20.74	20.44	21.07	21.72	21.83	20.91
Na_2O	0.45	0.76	0.56	0.73	0.49	0.63	0.46	0.51	0.51	0.71
Total	100.07	98.96	99.27	99.32	98.82	98.91	99.83	99.85	99.97	99.02
Structural formulae based on O=6										
Si	1.926	1.816	1.816	1.927	1.848	1.852	1.921	1.850	1.933	1.855
Ti	0.019	0.061	0.045	0.029	0.037	0.047	0.028	0.033	0.014	0.049
Al	0.114	0.226	0.258	0.112	0.228	0.205	0.119	0.208	0.093	0.194
Cr	0.012	0.000	0.009	0.000	0.005	0.003	0.000	0.019	0.009	0.000
Fe	0.211	0.356	0.250	0.355	0.259	0.319	0.265	0.211	0.194	0.328
Mn	0.003	0.010	0.005	0.013	0.004	0.006	0.004	0.003	0.000	0.007
Mg	0.885	0.651	0.770	0.695	0.762	0.710	0.797	0.795	0.878	0.686
Ca	0.805	0.863	0.829	0.832	0.837	0.832	0.841	0.865	0.863	0.853
Na	0.032	0.057	0.041	0.054	0.036	0.046	0.033	0.037	0.036	0.052

Electron-microprobe data. Compositions reported in wt.% oxides. Ph: phenocryst, Mph: microphenocryst, c: core, r: rim, FGP: fine-grained patch, CGP: coarse-grained patch, FGP-C: fine-grained patch close to contact with the coarse-grained patch.

TABLE 4. REPRESENTATIVE RESULTS OF ELECTRON-MICROPROBE ANALYSES OF OLIVINE AND PHLOGOPITE FROM OLIVINE DIABASE DYKES IN DRILLHOLE 78-31

	Forsterite		Phlogopite			
Sample	K	K	B	C	G	G
SiO_2 wt%	39.64	39.61	39.73	35.90	37.60	36.13
TiO_2	0.00	0.07	2.62	4.58	4.29	4.08
Al_2O_3	0.00	0.11	9.36	12.86	12.33	11.80
FeO_t	15.81	17.08	19.39	20.11	16.00	22.60
MnO	0.21	0.25	0.15	0.14	0.00	0.17
MgO	43.64	42.46	13.71	10.05	13.42	9.14
CaO	0.22	0.22	0.33	0.00	0.00	0.14
Na_2O	0.28	0.21	0.64	1.06	0.98	1.01
K_2O	0.00	0.00	6.33	8.24	7.92	7.82
NiO	0.37	0.14	-	-	-	-
Cl	-	-	0.06	0.04	0.04	0.06
Total	100.17	100.04	92.32	92.98	92.58	92.92
Structural formulae						
[O]	[4]	[4]	[22]	[22]	[22]	[22]
Si *apfu*	1.002	1.003	6.167	5.656	5.791	5.758
Ti	0.000	0.001	0.306	0.543	0.497	0.489
Al	0.000	0.003	1.713	2.389	2.239	2.217
Fe	0.334	0.362	2.517	2.650	2.061	3.012
Mn	0.004	0.005	0.020	0.019	0.000	0.023
Mg	1.644	1.602	3.171	2.360	3.080	2.171
Ca	0.006	0.006	0.055	0.000	0.000	0.024
Na	0.014	0.010	0.193	0.324	0.293	0.312
K	0.000	0.000	1.253	1.656	1.556	1.590

it is the Seabrook dykes that show a more "crustal" Pb isotopic signature. We conclude that our data cannot discriminate between the two hypotheses.

Mineral compositions

The clinopyroxene present in both the olivine diabase (Table 3) and the lamprophyre dykes (Cullen 1983) is augite (Fig. 12) with a titaniferous augite rim, and it exhibits normal zoning. Forsterite is sufficiently fresh to analyze only in the olivine diabase dykes, where it is $Fo_{82–83}$. In the olivine diabase, the biotite is a normally zoned, titaniferous phlogopite (Table 4), similar in composition to the mica described as phlogopite from the

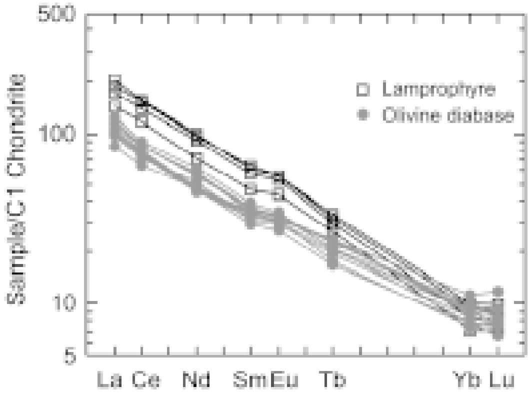

FIG. 7. *REE* variation for analyzed samples of lampropyhre and olivine diabase.

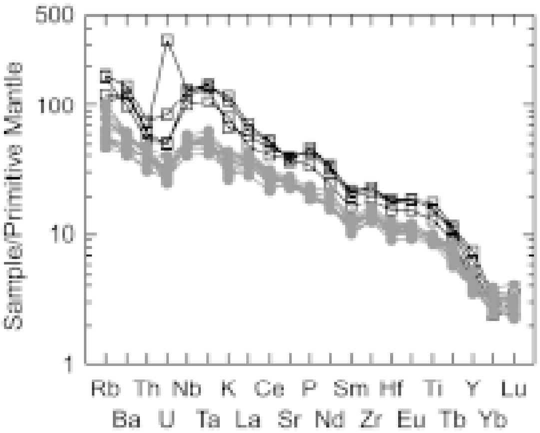

FIG. 8. Plots of selected trace-element variations normalized to primitive mantle (Sun & McDonough 1989). Symbols as in Figure 7.

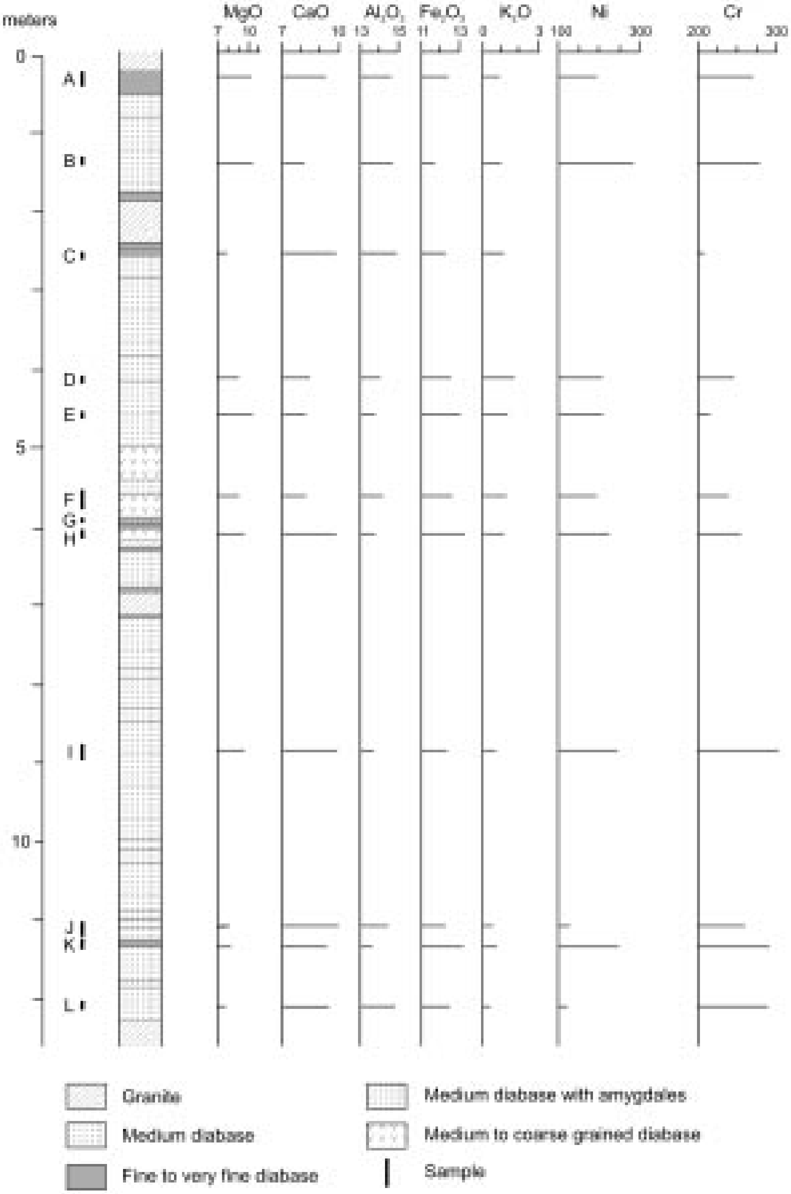

FIG. 9. Geochemical variations in the analyzed samples from multiple dykes in core 78–31.

Malpeque Bay sill (Greenough *et al.* 1988). The amphibole is strongly zoned kaersutite, which generally shows normal zoning, although reverse zoning also has been found. Plagioclase phenocrysts in the olivine diabase dykes have a core ranging from An_{25} to An_{53}. Most small laths of plagioclase and rims of phenocrysts have compositions between An_{55} and An_{65}.

DISCUSSION

Origin of internal discontinuities in the olivine diabase dykes

As described above, the interior of the olivine diabase dykes show macroscopic discontinuities (Fig. 4),

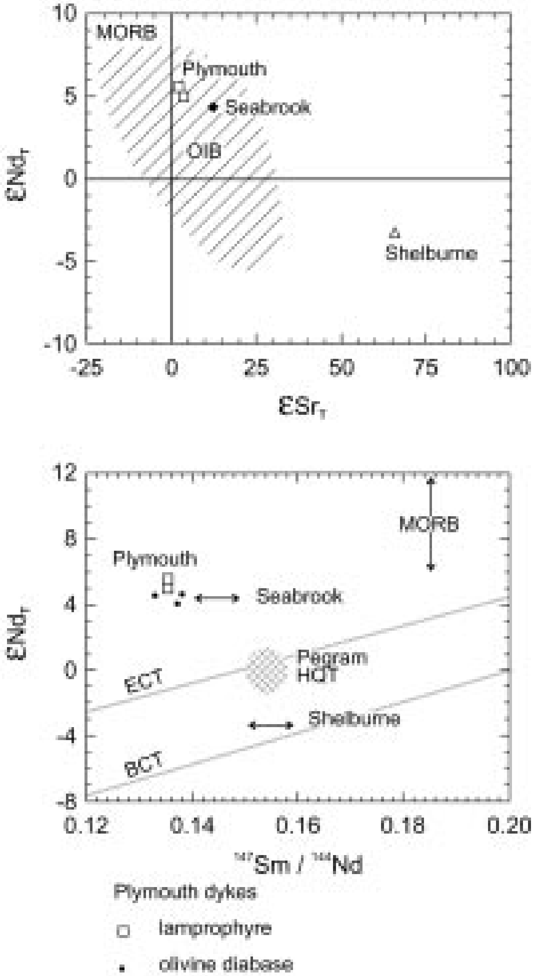

FIG. 10. (A) Plot of εNd_T *versus* εSr_T for the Plymouth lamprophyres, Seabrook dykes and Shelburne dyke. Hatched area is field for Ocean Island Basalt (OIB), from Wilson (1989). (B) Plot of εNd_T *versus* $^{147}Sm/^{144}Nd$ for the Plymouth dykes and other Triassic–Jurassic igneous rocks. Arrows for Seabrook and Shelburne dykes indicate $^{147}Sm/^{144}Nd$ not reported. HQT are high-Ti quartz tholeiites of Pegram (1990), BCT and ECT are, respectively, the trends of the basinal and extrabasinal Carolinas tholeiites of Pegram (1990).

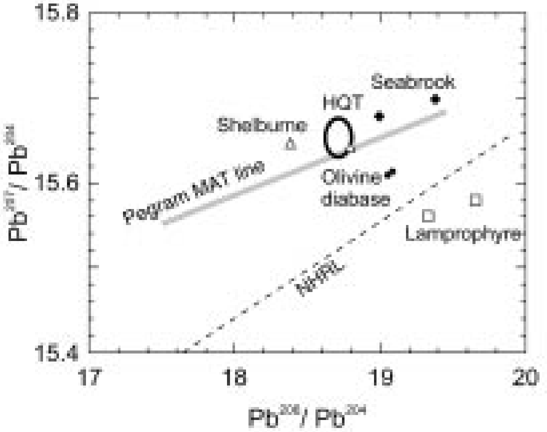

FIG. 11. Plot of measured $^{207}Pb/^{204}Pb$ *versus* $^{206}Pb/^{204}Pb$ for Plymouth dykes and other Triassic–Jurassic igneous rocks, compared with data of Pegram (1990). We follow Pegram (1990) in not applying an age correction for post-crystallization decay of U and Th. HQT are high-Ti quartz tholeiites of Pegram (1990), and his MAT line is the general trend of the Mesozoic Appalachian Tholeiites. NHRL is Northern Hemisphere Reference Line (for mantle) after Hart (1984).

picked out by abrupt changes in crystal size (coarse to fine), mineralogy (forsterite-rich to phlogopite-rich, Fig. 4) and geochemistry (*e.g.*, MgO, Ni, K_2O, Fig. 9). We list here important observations that may help explain the origin of these discontinuities. a) There is a lack of evidence of interior chilling at these discontinuities. b) Fine patches rich in phlogopite seem to be concentrated in the thicker dyke (samples C–H) and toward lower part of the drillhole. c) No olivine fractionation is suggested by element–element plots. d) Forsterite was precipitated at the time of intrusion, as indicated by the presence of forsterite phenocrysts close to the glass-bearing contacts. e) No preferred orientation of individual crystals is evident. f) The magma was volatile-rich (high loss on ignition).

Various mechanisms have been proposed that could account for these discontinuities, including: gravitational sinking, multiple injection, olivine fractionation and flow differentiation (*cf.* Simkin 1967, Bébien & Gagny 1979, Husch 1990). Sharp contacts and the presence of xenocrystic clinopyroxene suggest that some features result from multiple injection of magma (*e.g.*, dyke 5 has intruded dyke 4, Figs. 4, 6). The rapid changes in size of crystals, rock composition and mineralogy over a few centimeters but without any sharp contacts are most readily explained by flow differentiation. The abundance of phlogopite in finer-grained patches suggests that these may be later-crystallizing zones within which volatile constituents were concentrated.

Geochemical comparison with New England dykes

We use a variety of geochemical discrimination diagrams to compare the Plymouth dykes with various Mesozoic mafic dykes of New England, using the classification of McHone (1992). In the $Na_2O + K_2O$ *versus* SiO_2 plot (Fig. 6A), the Plymouth lamprophyric dykes

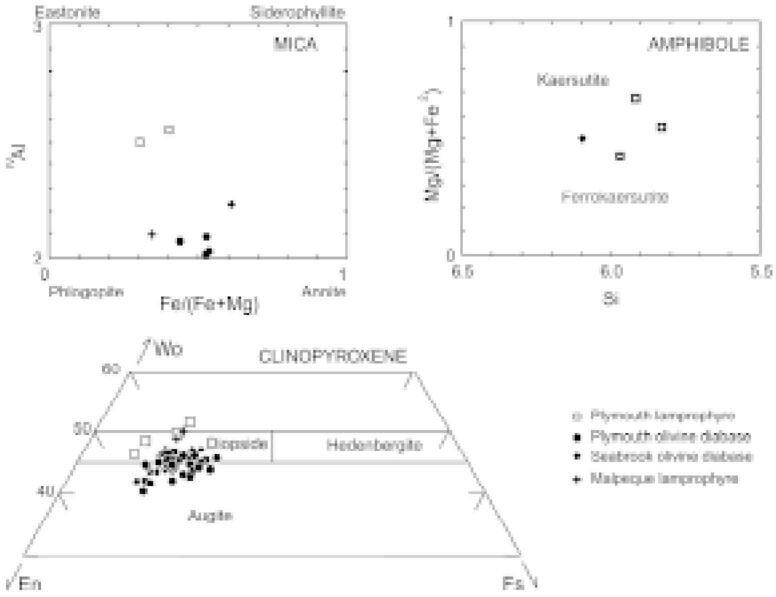

FIG. 12. Plots of mineral compositions of mica, amphibole and clinopyroxene showing comparison of the Plymouth dykes with the Seabrook and Malpeque dykes. Data on the Plymouth lamprophyric dykes are taken from Cullen (1983); those from the Malpeque dyke are from Greenough *et al.* (1988).

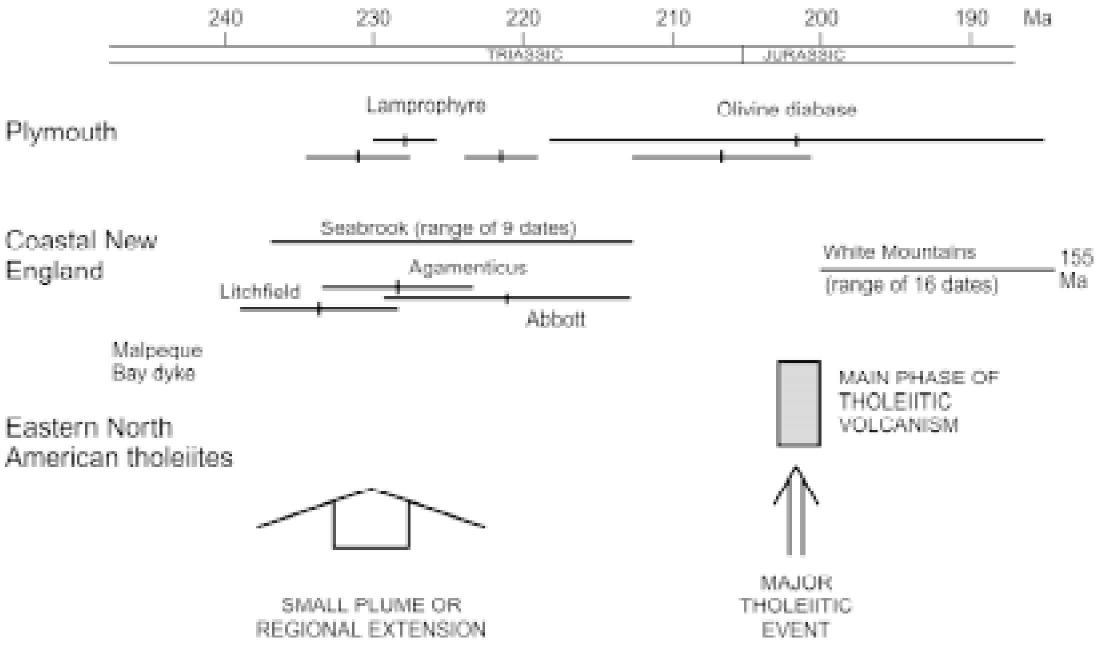

FIG. 13. Schematic representation of the geochronology of the Plymouth dykes and the Coastal New England igneous province, in relationship to large-scale tectonomagmatic events.

plot within the Cretaceous lamprophyre field (L), and the Plymouth olivine diabase dykes within the part of the field for the Seabrook dykes (S) that overlaps with that for the Rhode Island dykes (R). To overcome problems with mobile elements, such as the alkalis, McHone (1992) used ratios of more immobile elements, such as Ti/Al *versus* Si/Al as better indicators of original magmatic characteristics. He defined a field boundary between both olivine and quartz tholeiites of the eastern North America (ENA) province from most of the Coastal New England (CNE) dyke compositions. In such a diagram, all the analyzed rocks from Plymouth plot within the field for the CNE province (Fig. 6B). In particular, many of the olivine diabase dykes plot in the Seabrook dyke field, whereas the lamprophyric dykes fall in the Cretaceous lamprophyre field (Fig. 6B). McHone (1992) also used a plot of Ni *versus* Cr for discrimination of magma types. Although some of the analyzed samples fall within the Seabrook dyke field in such a plot (not shown here), both the lamprophyric and olivine diabase dykes show considerable scatter, and most of them plot outside the Seabrook dyke field. This scatter may result from the influence of the mineralogical discontinuities we have described in these samples.

Ross (1992) presented several element–element diagrams in an effort to discriminate the Mesozoic diabases (“dolerites”) of eastern Massachusetts. A Nb *versus* Zr diagram discriminates these diabases into an alkaline and a tholeiitic and transitional group (not shown). All the Plymouth dykes plot in the alkaline field. A P_2O_5 *versus* MgO plot discriminates the diabases into low- or high-MgO and into low- or high-P_2O_5 groups. The lamprophyric dykes span from low to high P_2O_5 and low to high MgO, whereas the olivine diabase dykes are all low in P and span the range from low to high MgO (Fig. 6E). In a similar diagram of TiO_2 *versus* MgO (Fig. 6F), the lamprophyric dykes span from low to high TiO_2 and low to high MgO, whereas all olivine diabase dykes are low in TiO_2, but range from low to high MgO. These element variations indicate that the lamprophyric dykes are more strongly alkaline than the olivine diabase dykes, and that there is a large change in MgO concentrations, probably due to flow differentiation and inhomogeneous dispersion of a volatile phase, since analyzed samples even within the same dyke range from the low- to the high-MgO group.

Relationship to the early Jurassic tholeiites and regional tectonics

The lamprophyre dykes at Plymouth appear to be small-volume partial melts of enriched mantle. Mantle of rather similar isotopic composition produced the magma that formed the Seabrook dykes and probably other dykes of the Coastal New England province in the middle to late Triassic. The limited geographic extent of these alkaline rocks on the eastern North America margin suggests that they may have been derived from a small mantle plume that later evolved to produce the White Mountain plutons (Fig. 13) and the New England Seamounts (de Boer *et al.* 1988, Pe-Piper *et al.* 1992), although this interpretation has recently been criticised by McHone (1996). We have no new data to contribute to the issue of whether the alkaline magmatism resulted from plume activity or tectonic reactivation of old structures.

The olivine diabase dykes at Plymouth appear to be derived from mantle with the same trace-element and isotopic characteristics as were the lamprophyres. The lesser enrichment in incompatible elements compared with the lamprophyres is probably evidence of a greater degree of partial melting, although the Pb isotopes also suggest some contamination by subcontinental lithosphere or crust. The argon geochronology, although based on only two small samples, suggests that these dykes are synchronous with the widespread, voluminous, and short-lived extrusion of tholeiites on the eastern North American margin (Fig. 13), including the nearby North Mountain Basalt and Shelburne dyke (Fig. 1), which have been dated at 201–203 Ma (Dunning & Hodych 1990, Hodych & Dunning 1992, Greenough 1996, Dunn *et al.* 1998). The origin of the tholeiites is disputed, but it is clear that they involved (a) large amounts of partial melting at elevated temperatures and (b) substantial contamination by “crust”, probably in base-of-crust magma chambers (*e.g.*, Puffer 1992, Dostal & Durning 1998). Several authors have argued that melting was initiated at the triple junction of Africa, South America and North America (*e.g.*, Wilson 1997), on the basis of radiating patterns of dykes (Cummins *et al.* 1992). Oyarzun *et al.* (1997) have suggested that the plume-head magmas were channelled into areas of lithospheric thinning. This hypothesis is attractive because it provides a mechanism whereby locally derived magma, which crystallized as olivine diabase, was emplaced in close proximity to a more distantly derived tholeiitic magma. Whether the renewed partial melting of the Plymouth source mantle was triggered by the thermal effects of tholeiitic magmatism or the decompression effect of the widespread earliest Jurassic extension is not clear.

CONCLUSIONS

1. Triassic alkaline igneous rocks, common in New England, are also found in southwestern Nova Scotia. Lamprophyres date from *ca.* 227 Ma and are synchronous with the Coastal New England igneous province. Alkaline olivine diabase was emplaced *ca.* 203–209 Ma, probably synchronously with the widespread early Jurassic tholeiites.

2. The alkaline mafic rocks of southwestern Nova Scotia contain forsterite (Fo_{83}), augite to titanaugite, kaersutite and titaniferous phlogopite. The olivine diabase occurs in multiply injected dykes that also show signs of flow differentiation.

3. The lamprophyre and olivine diabase show very similar relative trace-element abundances, suggesting that they were derived from the same source. They have mantle-like ε_{Nd} (+4) and ε_{Sr} (0 to +15). Pb isotopes suggest some contamination by crustal material, either from the lower crust or from mantle that was metasomatized during earlier subduction. In both chemical composition and radiogenic isotopes, these rocks are quite distinct from the early Jurassic tholeiites of eastern North America.

4. The lamprophyres were probably formed by a small degree of partial melting of enriched mantle. Further melting of this source was triggered by either the thermal effects of the emplacement of widespread early Jurassic tholeiite magma or the decompression effects of the synchronous extension.

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