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Mafic dike suites within Mesozoic igneous provinces of New England and Atlantic Canada

J. Gregory McHone
Graduate Liberal Studies Program, Wesleyan University, Middletown, Connecticut 06459

ABSTRACT

Complex swarms of mafic dikes extend across New England and Atlantic Canada. Radiometric dates, distributions and structural patterns, petrologic correlations, and geochemical analyses of the postmetamorphic dikes and related plutonic complexes are used to distinguish at least four petrogenetic groups, or igneous provinces, that span the Mesozoic. These groups are as follows. (1) The Early Cretaceous New England—Quebec igneous province, which contains thousands of lamprophyric dikes and at least 20 associated plutonic complexes in northern New England and southern Quebec. (2) The Early to Middle Jurassic White Mountain magma series in central and northern New Hampshire, which contains numerous alkalic diabase and lamprophyre dikes associated with large syenitoid-granitoid plutons. (3) Quartz tholeiitic dolerites of the Early Jurassic Eastern North America dike province, occur as scattered, large dikes that also fed flood basalts, remnants of which are found in the Mesozoic basins. (4) Olivine diabase dikes are present along southeastern coastal New England (CNE groups), for which K-Ar dates and an association with the Agamenticus complex in Maine indicate Triassic ages. The CNE dikes may be correlated with Triassic intrusions in parts of Atlantic Canada (AC groups) as well as with undated dikes in southern New England.

INTRODUCTION

Mafic dike swarms have intruded the Appalachian orogen as a function of several distinct, mainly extensional, tectonic events dating from the Late Proterozoic through the Mesozoic. The Precambrian and Paleozoic mafic dikes survive only with varying degrees of metamorphic overprint in the Appalachian orogen, and much more work is needed to define their overall distribution and petrology. Many of the very numerous and better known postmetamorphic dikes were produced during Early Jurassic and Early Cretaceous magmatic events in New England and elsewhere (McHone and others, 1987).

However, only a small portion of the thousands of dikes and other intrusions that are present in New England have been mapped, and relatively few of those mapped have been studied well enough to assign them to any particular igneous province or event. McHone (1984) presented a compilation map and table of radiometric dates for some of the northern New England Mesozoic intrusions, and additional work is underway by a handful of resolute petrologists who are represented in this volume.

Several authors in this volume discuss a new grouping of pre-Jurassic, postmetamorphic diabase dikes in New England, work which has recently been augmented by Canadian geologists in the Atlantic provinces. It is now possible to describe intrusive rocks that represent at least four distinct magmatic provinces, all apparently Mesozoic in age, in the Northern Appalachians of the United States and Canada. Because mafic dike swarms overlap across much of the region, it is necessary to find characteristics that distinguish the generations of magmas. Tectonic and magmatic evidences for similar or related events are present in areas of Africa and Europe that were once geographically adjacent, and which are also related to the rifting and spreading that formed the North Atlantic Ocean.

In this paper, the term "diabase" is used for a mafic dike rock that is appreciably altered (but not metamorphosed) from an originally fresh dolerite. Diabase and dolerite are considered to be chemical equivalents to common volcanic basalts, and so may also be classified using basaltic terms such as "quartz tholeiite." The various lamprophyre types can likewise be described with alkali basalt (volcanic) terminology, despite their shallow plu-

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tonic nature. Our understanding of mafic dikes in eastern North America, as discussed in this volume and elsewhere, will progress because we use a volcanic classification system in common with others who study the genesis of basalts worldwide. Although descriptions in this paper include all dikes and other Mesozoic intrusions, the discussions concentrate on the earliest of these diabase and dolerite dike swarms.

REGIONAL MAGMATIC GROUPS

Summary descriptions of magmatic events in eastern North America were presented elsewhere by de Boer and others (1988), McHone and Butler (1984), and others, including investigators represented in this volume. None of the New England summaries can be called complete or even very comprehensive, because there is still a bewildering mix of intrusive rocks to be sorted out, especially across large regions of New Hampshire and Maine. The following sections contain brief descriptions of four Mesozoic igneous provinces, shown in Figure 1, that are known because of considerable chemical, radiometric, and petrographic study over much of their areas. These provinces overlap and must be individually characterized before realistic petrogenetic models can be made.

Cretaceous dikes and plutonic complexes

Early Cretaceous igneous rocks of southern Quebec and northern New England are generally bimodal (syenite-gabbro) and alkalic, and include the classic Monteregian Hills intrusions (Philpotts, 1974) in Canada as well as several plutonic complexes in Vermont, New Hampshire, and southern Maine (McHone and Butler, 1984). Early Cretaceous (mainly 100–130 Ma) lamprophyre dikes are abundant across that region, mostly as camptonite with scattered groups of monchiquite, spessartite, and ultramafic types.

The lamprophyres form a continuous province that interconnects all of the Cretaceous plutons throughout northern New England and adjacent Quebec (McHone, 1978a). Dike rocks with felsic and intermediate compositions are locally abundant only near plutonic complexes, and are probably offshoots of differentiated magma chambers. McHone and Butler (1984) group these dikes and plutons under the name New England–Quebec (NEQ) igneous province. Some basalts that have been found in the Georges Bank basin, offshore from southeastern New England, show compositions and ages similar to the NEQ intrusions (Hurtubise and others, 1987). The NEQ rocks are also very similar to intrusions found at Notre Dame Bay in Newfoundland (Strong and Harris, 1974) and offshore from eastern Canada (Jansa and Pe-Piper, 1985).

NEQ lamprophyres have compositions (Table 1) similar to camptonite (basanite) and monchiquite (nephelinite) from many other localities (McHone, 1978a). They are characterized by high primary volatile contents, phenocrysts of Ti-augite and olivine (often as relicts), a lack of low-Ca pyroxenes, presence of brown amphiboles, and intermediate plagioclase that is confined to the groundmass.

Jurassic dikes and plutonic complexes

A few very large (widths 10–50 m; lengths to 400 km or more) quartz-orthopyroxene tholeiitic dikes of the extensive Early Jurassic dolerite of eastern North America (ENA province) (Weigand and Ragland, 1970) are known in Maine (McHone, unpublished work), New Brunswick (Greenough and Papezik, 1986; Stringer and Burke, 1985), Nova Scotia (Papezik and Barr, 1981; Dostal and Greenough, this volume), and Newfoundland (Papezik and Hodych, 1980). Their distribution has some similarity to that of the relatively few, but large, ENA dolerite dikes in Connecticut and Massachusetts, which apparently were feeders to the remnants of flood basalts now preserved in the Connecticut Valley (Philpotts and Martello, 1986).

The majority of northeastern ENA dikes that have been radiometrically dated show ages around 190 to 200 Ma (McHone, 1984; Hodych and Hayatsu, 1988). The dates are mostly in accord with de Boer's (1967) observation of Jurassic paleomagnetic poles for the dikes. Dolerite dikes of this age were sources for Early Jurassic basalt flows and sills in Newark Group sedimentary basins in eastern North America, including the Palisades Sill of New Jersey and the North Mountain basalts of Nova Scotia (Puffer and Philpotts, 1988).

Along the northern coast of Maine there are dikes with variable distribution and abundance, but little modern work has been done except in two areas. Some hundreds of dikes have been mapped in and around Mt. Desert Island, Maine (Acadia National Park), by Carlton Chapman and students (Chapman and Wingard, 1958; Wingard and Brookins, 1965). Several sets of both premetamorphic and postmetamorphic dikes are present. At Johns Bay (central coastal Maine), Bascom (1899) mapped several large "olivine" dolerite dikes that are similar to Early Jurassic dikes now known elsewhere in the study area. New samples of these dikes contain phenocrysts of very pale and clear hypersthene or bronzite that Bascom (1899) apparently mistook for olivine. Several other large postmetamorphic dolerite dikes have been mapped in northern and eastern Maine (Fig. 1), all of which appear to be quartz tholeiites with orthopyroxene phenocrysts, and which must also be members of the ENA dike province.

White Mountain Magma Series

The classic syenitoid-granitoid plutons of the White Mountain magma series (WMMS) in New Hampshire (Fig. 1) are also mainly Early Jurassic in age. It is difficult to correlate the generation of the mainly felsic plutonic complexes to dike swarms within the region. Many lamprophyre dikes (including the type locality of camptonite) and plagioclase-rich dolerites are found within the WMMS province; the few dates include both Early Jurassic and Early Cretaceous (McHone, 1984). Other diabase

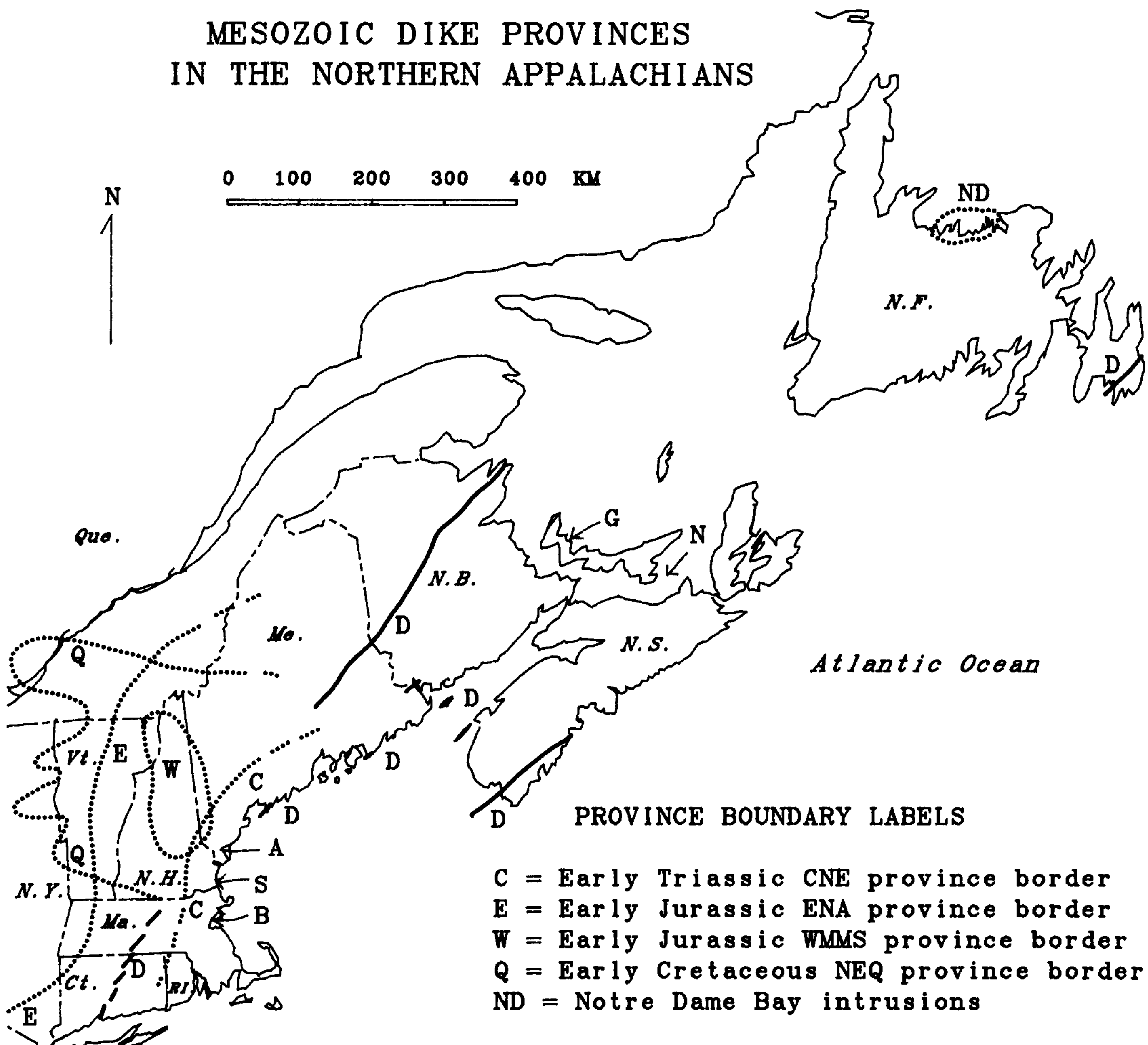

Figure 1. Locations of Mesozoic igneous rocks in New England and Atlantic Canada, and boundaries of Mesozoic igneous provinces after McHone and Butler (1984). Province boundary labels are explained in the figure; others mentioned in the text are: N = Northumberland Strait dikes; G = George Island dikes; D = major ENA dolerite dikes; A = Agamenticus complex; S = Seabrook, New Hampshire; B = Boston, Mass. CNE = coastal New England; ENA = eastern North America; WMMS = White Mountain magma series; NEQ = New England–Quebec.

dikes in western Maine appear to be transitional between camptonite and alkalic-basalt types, with a few early Jurassic dates (McHone and Trygstad, 1982). It also appears that pervasive hydrothermal effects from the large plutons have affected many dikes. For these reasons, mafic dikes of different generations are not well sorted out in inland New Hampshire and western Maine, although the same types are found as elsewhere.

Triassic dikes and plutonic complexes

In southermost Maine, intense swarms (several thousand dikes) have attracted interest since the early 1800s (Kemp, 1890). McHone (1984), McHone and Trygstad (1982), and Swanson (this volume) have discussed these dikes and summarized previous studies, which as yet include few chemical or radiometric

TABLE 1. COMPOSITIONAL MEANS OF MESOZOIC DIKE MAGMA GROUPS

Group*	1	2	3	4	5	6	7	8
Number†	14	35	41	37	10	4	4	9
Major Oxides (wt.%)								
SiO_2	38.60	43.07	52.19	48.38	47.62	42.02	47.80	44.04
TiO_2	2.73	2.80	1.04	0.69	1.95	2.74	1.62	2.09
Al_2O_3	12.30	13.89	14.57	15.98	16.28	9.34	16.64	13.58
Fe_2O_3§	4.23	4.30	2.54	2.19	3.45	4.24	3.12	3.59
FeO§	6.97	6.94	8.46	8.56	7.92	8.00	8.40	8.53
MnO	0.22	0.25	0.19	0.18	0.18	0.17	0.79	0.21
MgO	7.91	7.08	7.55	8.83	7.16	14.31	9.29	9.56
CaO	13.78	9.79	10.74	11.06	9.14	10.18	8.83	7.93
Na_2O	3.24	3.02	2.11	2.07	2.89	3.48	3.72	1.93
K_2O	1.91	1.93	0.60	0.40	1.09	0.83	0.27	0.92
P_2O_5	1.35	0.74	0.14	n.a.	0.30	0.88	0.12	0.41
LOI**	6.58	6.07	n.a.	n.a.	n.a.	2.98	n.a.	6.10
Total	99.88	99.81	100.05	98.12	98.01	99.23	100.29	98.89
Trace Elements (ppm)								
V	242	267	221	n.a.	n.a.	268	255	216
Cr	242	226	220	394	n.a.	348	227	325
Ni	128	109	78	116	n.a.	398	156	205
Cu	n.a.	n.a.	105	77	n.a.	68	188	49
Zn	n.a.	n.a.	78	84	n.a.	111	776	113
Rb	51	50	20	14	n.a.	10	10	28
Sr	1,470	1,003	176	120	n.a.	1,003	275	462
Y	38	29	24	n.a.	n.a.	26	24	24
Zr	326	275	86	60	n.a.	227	84	n.a.
Ba	1,264	762	156	n.a.	n.a.	646	352	491
M qtz	0.0	0.0	2.5	0.0	0.0	0.0	0.0	0.0
M hyp	0.0	0.0	23.4	14.3	8.0	0.0	0.0	19.1
M ol	5.7	10.6	0.0	8.9	9.2	20.4	20.9	7.3
M ne	14.9	5.8	0.0	0.0	0.0	10.6	1.6	0.0
M di	35.5	20.2	19.5	17.7	12.3	29.6	12.2	8.9
MG‡	0.67	0.65	0.61	0.65	0.62	0.76	0.66	0.67

*Groups: 1 = New England–Quebec monchiquites (McHone, 1978b); 2 = New England–Quebec camptonites (McHone, 1978b); 3 = Northern Appalachian ENA dolerites (see McHone and others, 1988); 4 = Southern Appalachian ENA dolerites (see McHone and others, 1987); 5 = Rhode Island diabase dikes (Hermes and others, 1984); 6 = George Island intrusion (Prest, 1972; Greenough and others, 1988); 7 = Northumberland Strait intrusions (Pe-Piper and Jansa, 1986); 8 = Seabrook diabase dikes (this chapter).

†N = number of analyses.

§Fe_2O_3 maximum calculated as TiO_2 + 1.5; FeO from remaining Fe.

**LOI = Loss on ignition (mainly H_2O + CO_2).

‡Mg = $Mg/Mg+Fe^{+2}$.

analyses. As in the Mt. Desert Island region, several groups of variably altered dikes are present, the youngest including Jurassic dolerites and Cretaceous lamprophyres.

Construction of the Seabrook nuclear power plant in southern coastal New Hampshire revealed numerous fine-grained olivine diabase dikes as much as 4 m thick, trending around N45°E. Maps of the cooling tunnels for the plant show 38 dikes in a distance of 4.8 km. Nine whole-rock K-Ar dates on the dikes at Seabrook and on others nearby range from 212 to 237 Ma (Bellini and others, 1982). The Middle to Late Triassic dates for these diabase dikes and three syenitic plutons in southern Maine (Foland and Faul, 1977) outline an elongate shape for an igneous province within about 75 km of the coasts of eastern Massachusetts, New Hampshire, and Maine (Fig. 1; McHone and Butler, 1984).

The Agamenticus syenitic complex in southern Maine (Fig. 1) has both an Rb-Sr date of 222 ± 3 Ma (Hoefs, 1967), and a K-Ar date of 228 ± 5 Ma (Foland and Faul, 1977). Two other plutons in southern Maine have single K-Ar Triassic dates: the Abbott syenite stock (221 ± 8; Foland and Faul, 1977) and the Litchfield syenitic complex (234 ± 5 Ma; Burke and others, 1969). A plagioclase-rich basaltic dike described by Hussey (1971) in the coastline just east of the Agamenticus complex contains abundant Agamenticus-type syenite xenoliths, and has yielded a whole-rock K-Ar date of 237 ± 9 Ma (N. W. McHone, 1984, personal commun.). The Agamenticus complex is crosscut by lamprophyre and diabase dikes (exposed in highway cuts), and it is geographically close to abundant dikes of the Seabrook type. Both Early Cretaceous and Early Jurassic camptonite and monchiquite dikes are also present in the area, and can often be recognized in the field by their distinctively lamprophyric textures (McHone, 1978a). At least three groups of postmetamorphic mafic dikes of differing ages are therefore known along coastal New England.

Thin sections of the Seabrook dike rocks show variable phenocryst concentrations of plagioclase, augite, and olivine pseudomorphs in a fine-grained matrix of plagioclase and pinkish (Ti-rich) clinopyroxene. Alteration products are common to very abundant, and include calcite, serpentine, chlorite, and clay minerals. Metamorphic products such as green amphiboles are not present. The alteration effects are interpreted as hydrothermal, and some dikes are silicified or bleached to a pale gray. Such effects have been observed elsewhere in the Appalachians, especially where dikes occur in fault zones, which were studied with great care at the Seabrook site. Nine whole-rock chemical analyses of the Seabrook dikes are presented in Table 2, and are discussed in a later section.

The suggestion of a Triassic group in New England had previously been made by Foland and Faul (1977). McHone and Butler (1984) used the name Coastal New England (CNE) for the province. Swanson (this volume) has conducted intensive mapping of dike swarms in southern Maine that are correlated with the Seabrook dikes, and presents a lucid tectonic model of their origins in concert with the Agamenticus plutonic complex.

Atlantic Canada subprovince

An offshore exploration well drilled into a Silurian to Carboniferous sequence crossed two intervals of basaltic rocks in Northumberland Strait, southeast of Prince Edward Island (Fig. 1; Pe-Piper and Jansa, 1986; Pe-Piper and others, this volume). The upper unit is formed by dikes considered to be intermediate in age; K-Ar dates are between 214 ± 9 Ma and 239 ± 10 Ma (Pe-Piper and Jansa, 1986). An average of four chemical analyses for this dike unit is given in Table 1. The rock is chloritized but contains pseudomorphs of olivine phenocrysts, as well as fresh augite and plagioclase. As discussed elsewhere in this volume, there are distinct differences between these and other Mesozoic intrusions in Atlantic Canada (AC); as in New England, such intrusions include Early Jurassic quartz tholeiites and Early Cretaceous lamprophyres.

A lamprophyric sill at George Island on the northern shore of Malpeque Bay, Prince Edward Island, was described by Prest (1972) and Greenough and others (1988). Part of the intrusion is a xenolithic breccia with inclusions of country rocks, lherzolites, and other mantle types. Five whole-rock K-Ar dates are clustered between 239 and 247 Ma (Middle to Early Triassic). The intrusion contains olivine phenocrysts and phlogopite in the matrix; plagioclase is only poorly developed. An average of four chemical analyses by Greenough and others (1988) is given in Table 1.

Boston platform subprovince

At least five dike swarms have been recognized among the estimated 1000 to 2000 mafic dikes intruded into Proterozoic to Silurian rocks of the northern part of the Boston platform in Massachusetts (Fig. 1). The swarms have general trends of northwest (two swarms), northeast, east-west, and north-south, in order of decreasing dike abundances. Seven petrographic varieties of dolerites and altered dolerites and three varieties of lamprophyres have been identified (Ross, 1984, and this volume). Field evidence and 11 published K-Ar dates suggest that the north-south and northeast-trending dolerites, and the northeast-trending lamprophyres range from Triassic to Early Jurassic in age, and that other swarms are Cambrian to Permian (Ross, 1984).

The Mesozoic dikes in the Boston platform area are described in this volume by Ross, including a group that is correlated with the CNE province. The geographic distribution, within the Avalon platform between Rhode Island and Maine, is also an argument for the continuity of the CNE igneous province through most of southeastern New England.

Rhode Island subprovince

Hermes and others (1984) described several dozen premetamorphic and postmetamorphic diabase dikes in Rhode Island and adjacent Massachusetts. The postmetamorphic dikes trend mainly north-northeast–south-southwest, are 1–2 m in width, and are considered to be Mesozoic in age (postdating Alleghanian metamorphism), but no radiometric dates for the diabase dikes have been reported. All show relicts of olivine phenocrysts, but no hypersthene phenocrysts; plagioclase and augite are present in the groundmass and as phenocrysts. Most examples show secondary alteration, some with groundmass biotite or calcite. Their chemistry (average of 10 analyses shown in Table 1) and petrography clearly separate these dikes from the Higganum dike and other quartz tholeiites to the west and north of Rhode Island. Because of these and other characteristics as shown in later diagrams, the Rhode Island dikes are likely to be a southern extension of the CNE province (Fig. 1).

Several ultramafic monchiquite dikes containing mantle-

TABLE 2. CHEMICAL ANALYSES OF SEABROOK DIKE ROCKS

Sample	HA-1	HA-5	HA-6	HA-7	HA-8	HA-9	HA-10	HA-12	HA-14
Oxides (wt %)									
SiO_2	43.70	42.91	45.00	45.64	43.44	46.39	43.23	42.34	43.67
TiO_2	2.30	2.30	1.69	2.17	2.09	1.84	2.10	2.24	2.06
Al_2O_3	13.13	14.41	13.29	13.33	13.41	14.43	13.86	13.03	13.31
Fe_2O_3*	3.80	3.80	3.19	3.67	3.59	3.34	3.60	3.74	3.56
FeO*	8.50	11.67	10.44	8.47	7.85	7.74	6.73	7.74	7.60
MnO	0.21	0.36	0.22	0.17	0.19	0.18	0.17	0.18	0.18
MgO	12.00	6.87	10.55	8.82	9.02	9.03	7.70	10.65	11.33
CaO	7.70	6.33	6.39	9.32	7.72	8.47	7.05	9.09	9.26
Na_2O	2.06	2.30	1.20	1.71	2.02	2.14	2.27	1.36	2.31
K_2O	1.19	0.99	0.28	0.69	1.06	0.92	1.23	1.00	0.92
P_2O_5	0.59	0.44	0.20	0.37	0.36	0.30	0.51	0.39	0.51
LOI†	4.12	6.47	5.86	3.60	8.58	4.01	9.64	7.34	5.27
Total	100.24	100.15	99.47	98.90	100.20	99.65	98.84	99.96	100.82
Trace elements (ppm)									
V	246	236	205	195	249	214	178	214	211
Cr	427	231	417	271	343	330	218	341	346
Ni	302	125	312	211	186	145	93	258	216
Cu	58	58	74	51	49	26	21	62	39
Zn	136	103	114	119	122	105	125	103	92
Rb	27	31	18	27	41	35	27	29	20
Sr	470	480	232	378	600	375	573	523	531
Y	26	26	22	24	22	25	27	23	25
Ba	855	384	186	230	1,074	429	441	426	395
Ce	66	50	13	39	42	38	65	45	58
Norms (mol %)									
AN	57.0	57.3	74.7	64.8	58.8	59.9	55.5	69.7	54.3
Q	0.0	0.0	1.7	0.5	0.0	0.0	0.0	0.0	0.0
Or	7.0	5.8	1.6	4.1	6.3	5.4	7.3	5.9	5.4
Ab	17.3	19.5	10.1	14.1	17.1	18.1	19.2	11.5	19.5
An	23.1	26.1	30.0	26.7	24.4	27.0	24.0	26.5	23.2
Di	9.0	2.0	0.3	13.8	9.3	10.5	6.1	12.8	15.5
Hy	9.0	19.2	40.3	24.5	16.9	20.8	18.9	15.0	0.5
Ol	18.4	8.8	0.0	0.0	6.8	3.9	2.6	9.4	20.2
Mt	5.5	5.5	4.6	5.3	5.2	4.8	5.2	5.4	5.2
Il	4.4	4.4	3.2	4.1	4.0	3.5	4.0	4.3	3.9
Ap	1.4	1.0	0.5	0.9	0.8	0.7	1.2	0.9	1.2
MG§	0.72	0.51	0.64	0.65	0.67	0.68	0.67	0.71	0.73

Analyses by J. Bédard, University of Montreal. For techniques, see Bédard and others (1987).
*Fe_2O_3 calculated as TiO_2 +1.5; FeO from remaining Fe.
†LOI = Loss on Ignition (H_2O +CO_2 combined).
§MG = Mg/Mg+Fe^{+2}.

type nodules are present near Westerly, in southwestern Rhode Island (Leavy and Hermes, 1979). A K-Ar date of 175 Ma (Hermes and others, 1984) and the isolation of the locality make it difficult to correlate the Westerly dikes with any of the above groups.

GEOCHEMISTRY

Many whole-rock chemical analyses have been published for dikes and plutonic complexes in eastern North America, although such data are still scarce in important areas such as Maine.

A partial compilation is available from me in the form of microcomputer data files using IGPET, a petrologic analysis program by Michael J. Carr (Rutgers University at New Brunswick).

Nine whole-rock chemical analyses of dike samples from Seabrook Station were done by Jean Bédard at the University of Montreal (Table 2). The high volatile contents are mostly due to hydrothermal alteration products, which may also lead to inaccurate mobile element concentrations. Important components that probably characterize the original (as cooled) dike magmas include the Si, Ti, Al, and Mg oxides, and trace elements Cr and Ni. Averages of the Seabrook analyses and of other dike groups discussed in this paper are given in Table 1.

Of the tholeiitic dolerites (columns 3 and 4 of Table 1), the Northern Appalachian (Connecticut–Atlantic Canada) examples are clearly richer in Si, Ti, and K compared to Southern Appalachian (Alabama–Georgia–South Carolina) dolerites. Such chemical values may vary with involvement of subcrustal continental lithosphere, apparently by partial melting and mixing (Pegram, 1990). The Rhode Island dikes are more aluminous than are Seabrook dikes or ENA tholeiites, but except for the mobile alkalies, are very similar to the average Northumberland Strait rocks. Lamprophyres, including the George Island intrusion, are generally poorer in Si but richer in K than the other dike types.

An alkali vs. SiO_2 graph (Fig. 2) shows the overlap of Seabrook, Rhode Island, and Northumberland compositions with the alkali basalt–tholeiite discriminant line of Irvine and Baragar (1971). Lamprophyres, including the George Island intrusion, are more strongly alkalic. Because of problems with mobile elements such as the alkalies, ratio diagrams of more immobile elements such as TiO_2/Al_2O_3 vs. SiO_2/Al_2O_3 may be more reliable for showing original magmatic characteristics (Fig. 3). A line from X:Y = 2.1:0 to X:Y = 4.1:0.2 (Fig. 3) separates both olivine and quartz tholeiites of the ENA province from most of the CNE-AC dike compositions. In addition, fractionation trends of the tholeiites show mainly in SiO_2/Al_2O_3, whereas the CNE types vary both with the SiO_2/Al_2O_3 and TiO_2/Al_2O_3 ratios: these trends probably are related to phenocryst fractionation controls of olivine or orthopyroxene and plagioclase in ENA magmas, vs. olivine and Ti-rich clinopyroxene in CNE magmas. Such controls are also seen on a Cr vs. Ni diagram (Fig. 4), where Ni varies with olivine-hypersthene and Cr more with clinopyroxene fractionation.

Pseudo-liquidus diagrams such as the constructions of Elthon (1983) are designed for idealized basalts that are unlike alkalic compositions; nevertheless, there is an indication of equilibrium of CNE-type magmas at greater depths than ENA dikes of the Northern Appalachians (Fig. 5). This is in accord with models for producing alkalic basalts at greater mantle depths than tholeiites, as proposed by many petrologists.

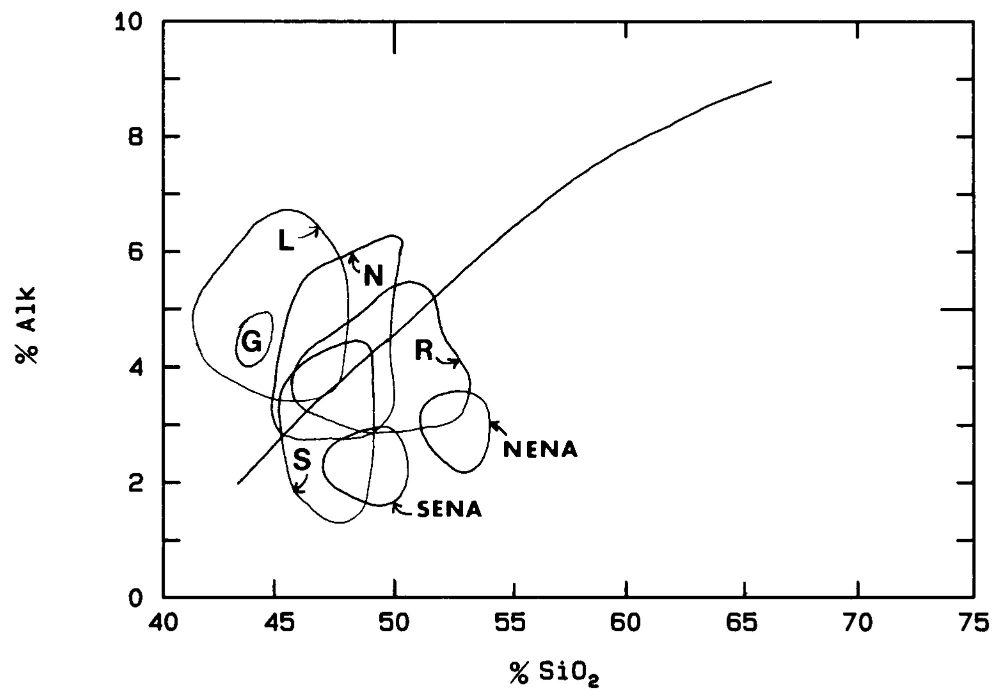

Figure 2. Alkalies (K_2O + Na_2O) vs. SiO_2 for dike magma types. Labels for dike groups: SENA = Southern ENA dikes (Alabama-Georgia-South Caroline); NENA = Northern ENA dikes (Connecticut–Atlantic Canada); L = lamprophyres of northern New England; G = George Island sill; N = Northumberland Strait dikes; R = Rhode Island dikes; S = Seabrook dikes. (See text for abbreviations; Table 1 for references). The alkali basalt–tholeiitic basalt discriminant line is after Irvine and Baragar (1971). Chemical values in this and following figures have been normalized as volatile-free.

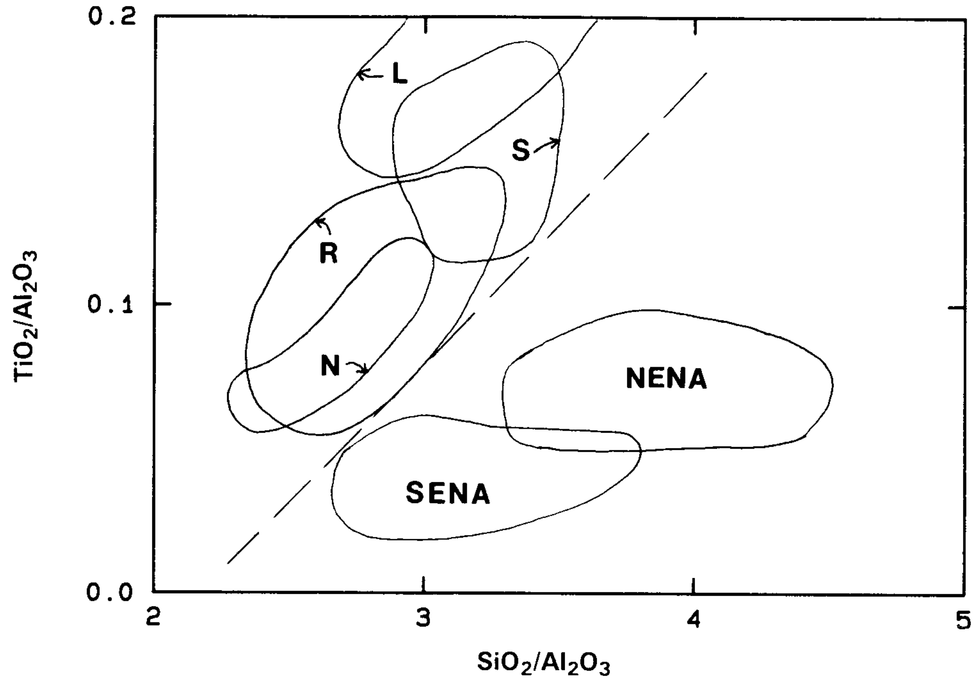

Figure 3. TiO_2/Al_2O_3 vs. SiO_2/Al_2O_3 for dike magma types. Labels as in Figure 2. Dashed line separates ENA tholeiitic groups from other Mesozoic dike groups.

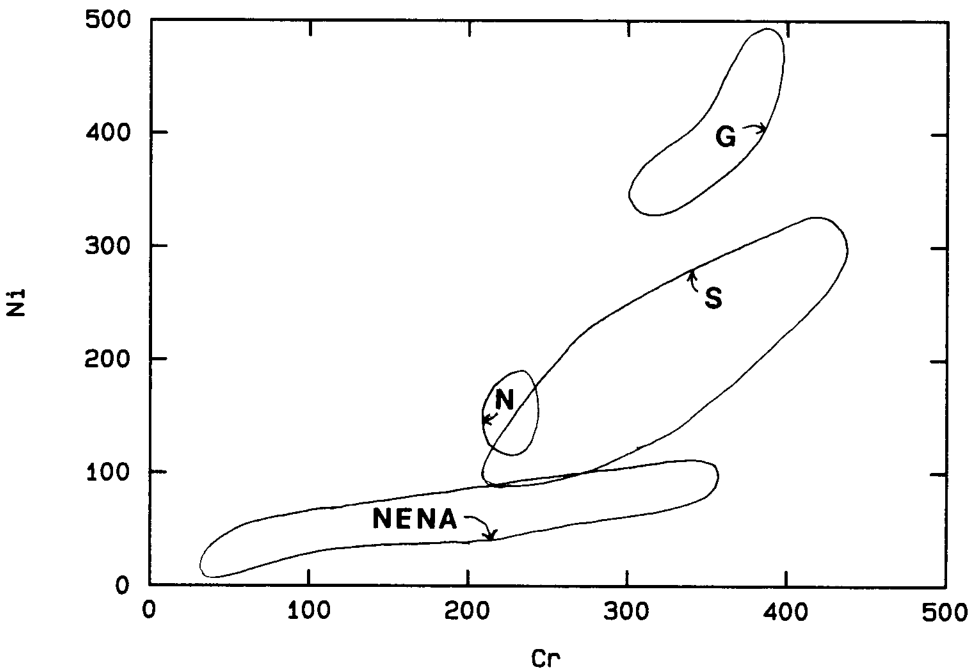

Figure 4. Ni (ppm) vs. Cr (ppm) for dike magma types. Labels as in Figure 2.

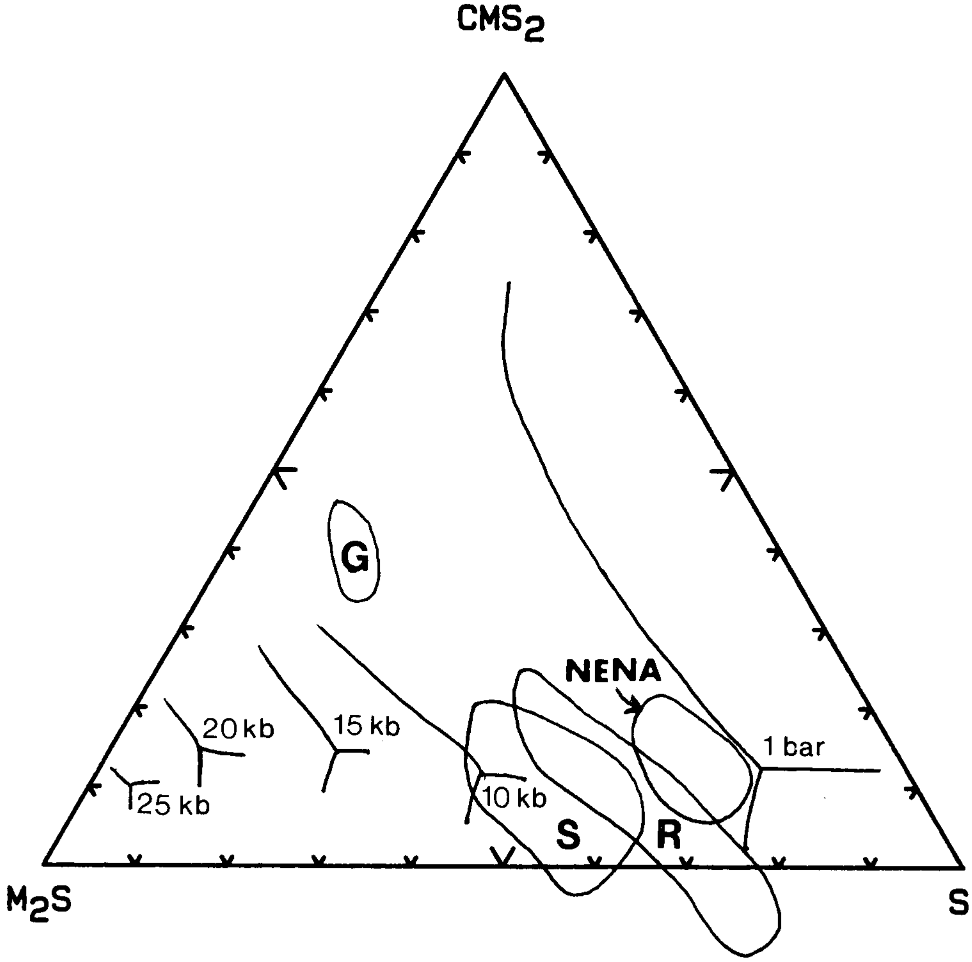

Figure 5. Diopside-forsterite-silica (CMAS) projection (from Ca-plagioclase) for basalt pseudo-liquids compositions at various pressures (Elthon, 1983). Labels as in Figure 2.

DISCUSSION

The distribution, age, and chemistry of the ENA dikes are related to the Jurassic breakup of Gondwana and the formation of the North Atlantic Ocean basin. As discussed by Weigand and Ragland (1970), Bryan and others (1977), and Philpotts and Martello (1986), among others, the dolerite magmas were precursors of the developing mid-ocean ridge basalts that formed the initial Atlantic Ocean crust. The extensive ENA dikes form three or more swarms within eastern Appalachian terrains (King, 1971), and it is now clear that ENA swarms extend from the major anticlinoria axes of the Appalachian highlands eastward to the continental margin. The structure responsible for this boundary may be a relict basement terrane boundary that also functioned as a Mesozoic strain limit (McHone, 1988). By Early Jurassic time, these dolerite dikes surrounded the incipient central Atlantic basin.

Triassic rifting events are now recognized in several areas of Europe and northwestern Africa. These include the Norwegian-Greenland Sea, the Bay of Biscay and Gibralter (Iberian Peninsula), and the Atlas rifts of Morocco and Algeria (Ziegler, 1988). In most of the rifts, volcanism remained minor until Late Triassic and Jurassic time, as in the northern North Sea (Fall and others, 1982). Major fault zones developed along Triassic graben that extended from the Iberian rifts into the present Nova Scotian shelf and Grand Banks (Sopeña and others, 1988). In Morocco, basalts dated at 211 Ma are interbedded with Middle Triassic sedimentary rocks, and are distinctly more alkalic than the younger tholeiites (Manspeizer, 1988).

Triassic rift basins in the Grand Banks have been disrupted by later Jurassic rifting, but a thick Middle to Late Triassic stratigraphic sequence is indicated by seismic data (Tankard and Welsink, 1988). Because this sequence has not yet been sampled by drilling, the presence of volcanic rocks is undetermined.

Although quite different from one another, the Triassic intrusions in Atlantic Canada are significant local precursors to more abundant magmatism later in the Mesozoic. As discussed by Pe-Piper and Jansa (1986) and Pe-Piper and others (this volume), the olivine-transitional to alkalic nature of the Triassic magmatism may be related to early attenuation of the continental crust during an initial rifting stage. Small amounts of mantle melts escaped only in specific rift zones during this period; the chemical makeup reflects more primitive mantle compositions. By Early Jurassic time, mantle upwelling had developed under the incipient ocean borders to produce the much-larger volumes of tholeiitic basalts, including a greater interaction of continental lithosphere.

A similar precursor event in coastal New England was much more pronounced, and included at least one large syenitic complex (Agamenticus) as well as the extensive swarms of olivine dolerite dikes that form the Coastal New England igneous province. It seems likely that rift activity, perhaps in the Gulf of Maine, could have accompanied the CNE intrusions, but is masked by Carboniferous and Jurassic structures.

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