Mesozoic Dyke Swarms of Eastern North America

J. Gregory McHone
Department of Geological Sciences, University of Kentucky, Lexington, Kentucky 40506, U.S.A.

Martin E. Ross
Department of Geology, Northeastern University, 360 Huntington Avenue, Boston, Massachusetts 02115, U.S.A.

John D. Greenough
Department of Geology, Mount Allison University, Sackville, New Brunswick E0A 3C0, Canada

McHone J. Gregory, Ross, Martin E., and Greenough, John D., Mesozoic dyke swarms of eastern North America; in Mafic dyke swarms, Editors: Halls, H.C., and Fahrig, W.F., Geological Association of Canada Special Paper 34, p. 279–288.

Abstract

Mesozoic mafic dykes vary by region within igneous provinces along the Atlantic margin of North America. The Early Jurassic Eastern North America (ENA) province comprises extensive swarms of quartz and olivine tholeiitic dolerites along 2000 km or more of the eastern side of the Appalachians. A newly recognized transitional to alkalic group of Triassic (?) dykes in eastern New England may be an early subprovince of ENA dykes. Abundant Early Cretaceous lamprophyres are associated with alkalic plutonic complexes, and trend across the Appalachian orogen in the New England-Quebec province and in the Notre Dame Bay province of north-central Newfoundland. Chemical, radiometric, and tectonic characteristics of the dykes indicate a history of distinct magmatic events and heterogeneous origins within regional groups. Different but nearly contemporaneous dyke trends are found as regional domains within province boundaries. The dyke generations are linked to sequential rifting events that also opened sections of the North Atlantic Ocean. The mafic dykes record a tectonic-magmatic pattern controlled by stresses from plate and mantle movements, acting upon lithospheric structural anisotropies.

Résumé

Les dykes mafiques du Mésozoïque varient selon les rédions à l'intérieur des provinces ignées situées le long de la bordure est de l'Amérique du Nord. La province orientale de l'Amérique du Nord (ENA: Eastern North America), du Jurassique inférieur, comprend des réseaux étendus de dolérites tholéiitiques à quartz et olivine couvrant plus de 2000 km le long du versant oriental des Appalaches. Un groupe de dykes d'âge triassique incertain, récemment identifié, de composition intermédiaire à alcaline et situé dans la partie orientale de la Nouvelle-Angleterre pourrait éventuellement constituer une ancienne sous-province de l'est de l'Amérique du Nord. De nombreux lamprophyres du Crétacé inférieur associés à des complexes plutoniques alcalins traversent les Appalaches dans la province de la Nouvelle-Angleterre et du Québec et celle de la baie de Notre-Dame, dans le centre-nord de Terre-Neuve. Les caractéristiques chimiques, radiométriques et tectoniques des dykes permettent d'identifier des événements magmatiques distincts et des origines hétérogènes à l'intérieur des groupes régionaux. Des directions différentes mais quasi concomitantes constituent des domaines régionaux à l'intérieur des provinces. Les diverses générations de dykes sont liées à la création ultérieure de rifts à l'origine de l'ouverture de certaines sections de l'Atlantique Nord. Les dykes mafiques présentent une configuration tectono-magmatique régie par les contraintes dues aux mouvements des plaques et du manteau, effectués selon les anisotropies structurales de la lithosphère.

INTRODUCTION

Mafic dyke swarms have been forming in the region of the Appalachian orogen since late Precambrian times, apparently in concert with tectonic events that opened the Iapetus Ocean during the Eocambrian, produced shearing and collisions of plates in the Paleozoic, and finally opened sections of the North Atlantic Ocean through the Mesozoic and early Cenozoic eras. The Precambrian and Paleozoic mafic dykes survive only with varying degrees of metamorphic overprint in the eastern Appalachian orogen, and little is known about their overall distribution and petrology. We describe the best known of the temporal groups — the Mesozoic dyke swarms.

The Mesozoic dykes are generally of two types: an extensive Late Triassic to Early Jurassic swarm of tholeiitic dolerites, followed in time by several smaller, local, and more-alkalic provinces of lamprophyres and associated plutonic complexes of Cretaceous and younger ages. In general, the Mesozoic dykes are easily distinguished from older intrusions by their post-metamorphic mineralogy and field appearance. Many, perhaps hundreds, of published and unpublished studies have been made on local and regional aspects of the intrusions. Despite these studies, details of the locations and thus sampling availability of mafic dykes have been variably neglected in bedrock mapping projects, greatly impeding new work that attempts to synthesize local dyke occurrences and petrology into a regional model.

In this paper, we describe the distribution, ages, and petrology of Mesozoic mafic dykes as members of regional igneous provinces in eastern North America. In many ways we are limited by only partial (and perhaps therefore misleading) knowledge of several important features of the intrusions, not the least of which is their genesis in relation to the continent, the mantle, and the formation of the Atlantic Ocean crust. Many new studies of the Mesozoic dykes are underway, and will eventually provide one of the most comprehensive data bases ever assembled for a major igneous province. Models developed by this work emphasize the link between magmatism and tectonics during lithospheric rifting events.

We will first consider the enormous group of Early Mesozoic dolerite dykes comprising the Eastern North America (ENA) province, describing their distribution, orientations, ages, and petrography. A new compilation of major-element chemistry, by regional groups, is included. Smaller provinces of Early Cretaceous alkalic lamprophryre dykes in the Northern Appalachians are similarly treated. Finally, we point out some tectonic aspects that must be considered in models of the origins and relationships of the magmas.

EASTERN NORTH AMERICA DOLERITE PROVINCE

King (1961, 1971) first outlined the extensive system of tholeiitic dolerite dykes located throughout the entire eastern Appalachian region of the United States from Alabama through southern New England (Fig. 1). Weigand and Ragland (1970) studied their chemistry and provided the commonly used name of "Eastern North America (ENA) dolerite". Other than an important paper by Bertrand and Coffrant (1977), general descriptions of the dolerites of the ENA province rarely include examples in northern New England and the Atlantic Provinces of Canada. It is now known that alkalic to transitional dolerite dykes occur as a subset of the ENA province in eastern and northern New England, while large and widely separated tholeiitic dolerites are found in the easternmost provinces of Canada. New work on dykes of these Northern Applachian regions is discussed in this paper.

Petrographically, ENA dolerite grain sizes vary from fine to coarse, depending upon dyke thickness and thus cooling rates. All but the smallest dykes are subophitic and generally granular, rarely exhibiting porphyritic textures with phenocrysts of olivine in the olivine-normative varieties, labradorite, and glomeroporphyritic augite. Augite and labradorite or andesine dominate the groundmass, commonly with olivine, orthopyroxene (hypersthene or bronzite), and magnetite also present. The larger dykes of quartz-normative dolerite show interstitial "granophyre" zones of quartz and K-feldspar, derived as a fractionation product. The titaniferous dolerites (chemistry described below) contain augite phenocrysts with a distinctly rosy tint, especially toward grain margins.

Radiometric ages

The majority of ENA dykes that have been radiometrically dated show ages near 190 ± 10 Ma (Armstrong and Besancon, 1970; Sutter and Smith, 1979; Dooley and Wampler, 1983; McHone, 1984; Papezik and Barr, 1981; Ross, 1985). The dates are in accord with de Boer's (1967) observation of Jurassic paleomagnetic poles for the dykes. Dolerite dykes of this age are sources for Early Jurassic basalt flows and sills in Newark Group sedimentary basins in eastern North America, including the famous Palisades Sill (Dallmeyer, 1975; Puffer *et al.*, 1981; Puffer *et al.*, 1982; Philpotts and Martello, 1986). Dolerite dykes with apparent ages around 175 Ma are also observed across the Triassic-Jurassic Newart Group basins from Maryland through Connecticut (Sutter and Smith, 1979), and Deininger *et al.* (1975) noted an age near 170 Ma for a dolerite group in Albama. In southern New England, such dykes have been offset by the Middle Jurassic boundary faults of the Connecticut River basin (Philpotts and Martello, 1986).

As pointed out by Armstrong and Besancon (1970), Sutter and Smith (1979), de Boer and Snider (1979), and Dooley and Wampler (1983), K-Ar determinations for some of the intrusions are plagued by excess argon, increasing their apparent ages. However, present data (more than fifty radiometric dates) indicate no systematic variation in dyke ages along the Appalachian orogen of eastern North America.

Dyke trends and distribution

As seen in Figure 1, the ENA dolerite dykes show NW trends in the Southern Appalachians of the United States, an overlapping N-S group in the Carolinas through Pennsylvania, and NE trends from New Jersey through New England and the Atlantic Provinces of Canada. Detailed rose diagrams of the NW trends in the Southern Appalachians indicate a slight change in orientation of maxima, from N35°W in Alabama through South Carolina to N25°W in North Carolina and Virginia (Fig. 1). From New Jersey northward to Newfoundland, ENA dykes have a less-pronounced progression from around N30°E to N60°E, generally, from south to north (Fig. 1).

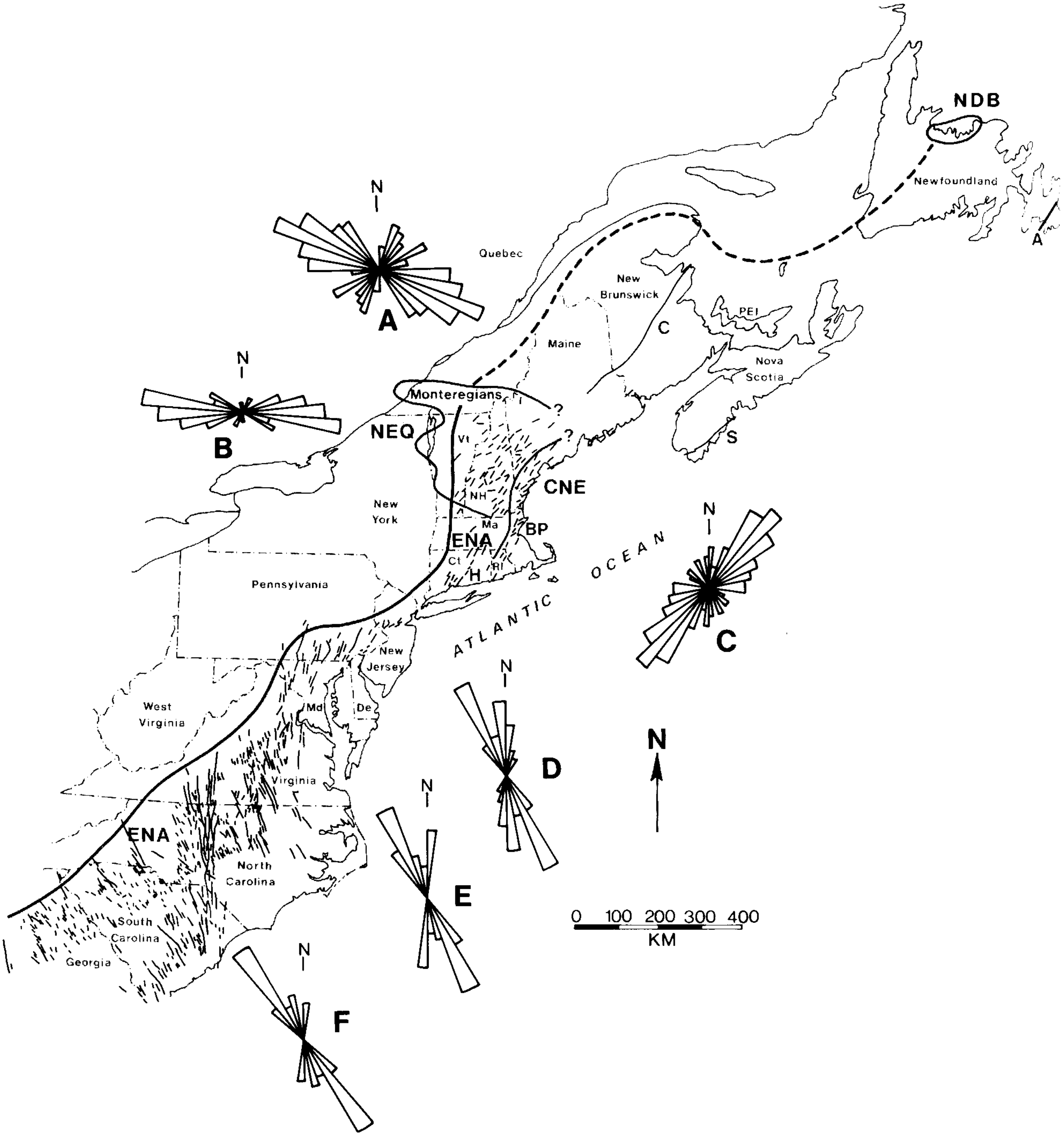

Figure 1. *General locations and province boundaries of Mesozoic dyke swarms in eastern North America. Heavy lines are province boundaries, dashed where conjectural. Abbreviations: ENA = Eastern North America dolerite province; NDB = Notre Dame Bay province; CNE = Coastal New England province; NEQ = New England-Quebec province; BP = Boston Platform area; C = Caraquet dyke; S = Shelburne dyke; A = Avalon dyke; H = Higganum dyke. Rose diagrams A-F are constructed from mafic-dyke trends as follows: A = 129 NEQ lamprophyre dykes of the Monteregian area of Quebec; B = 155 NEQ lamprophyre dykes of western Vermont and adjacent New York; C = 239 ENA dolerite dykes of the Appalachians north of New Jersey; D = 211 ENA dolerite dykes of Pennsylvania, Maryland, and Virginia; E = 184 ENA dolerite dykes of North Carolina; and F = 179 ENA dolerite dykes of South Carolina, Georgia, and Alabama.*

The large dolerite dykes of the Southern Appalachians are partially mapped under the Coastal Plain sediments in the Southern Appalachians by their aeromagnetic lineaments (Daniels *et al.*, 1983). With aeromagnetic data and a detailed map of dykes in North Carolina, Burt *et al.* (1978) first pointed out the existence of the major N-S dyke set in the SE Appalachians. Ragland *et al.* (1983) compiled maps to show that the N-S dyke set overlaps NW-trending dykes from South Carolina northward through North Carolina and Virginia (Fig. 1). A few limited examples appear to show that the N-S set crosscuts the NW-trending dykes.

May (1971) correlated these trends with pre-North Atlantic dolerite dykes in NW Africa and northern South America (Fig. 2), hypothesizing a single radial stress system centred on the present south-central Atlantic Ocean. Other discussions of Mesozoic stress patterns have been made by de Boer (1967) and Swanson (1982), in which shear strains are used to explain the trends and distribution of the dykes.

ENA dolerites seem to vary in abundance along the province, but not all blank areas in Figure 1 record a lack of dykes. Post-Jurassic sediments of the Atlantic Coastal Plain conceal many dykes whose extent is poorly known on the basis of magnetic data. Likewise, extensive glacial drift covers much of the Northern Appalachians. Closely spaced and sensitive aeromagnetic surveys are needed to outline even the large (>10 m wide) ENA dykes beneath surficial cover, and such surveys are lacking for much of the province. A reasonable approximation of dyke abundances shows some increase from inland toward the continental edge. Northern Maine and the Atlantic Provinces also show a comparatively low dyke-frequency throughout their areas.

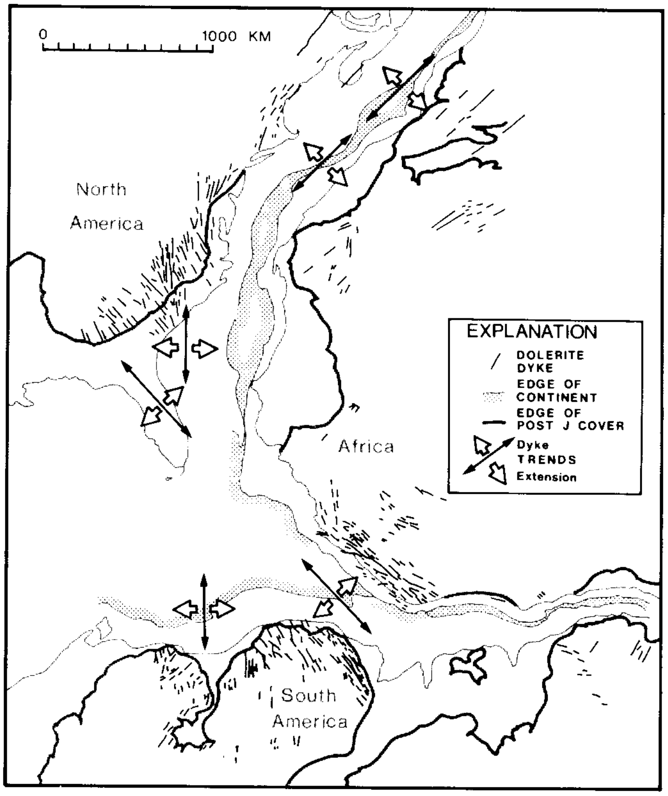

Figure 2. *General locations and trends of Early Jurassic dolerite dykes around the initial central Atlantic Ocean basin, modified from May (1971), with additions from Ragland* et al. *(1983), McHone (1984), Ross (1985), Papezik and Greenough (1985), H. Bertrand (personal communication, 1986), and Gibbs (this volume).*

ENA dolerite dykes of Atlantic Canada

The best known early Mesozoic dykes in the Atlantic coastal provinces of Canada (Fig. 1) are the Caraquet dyke of New Brunswick and northern Maine (Burke *et al.*, 1973), the Shelburne dyke of Nova Scotia (Papezik and Barr, 1981), and the recently discovered Avalon dyke of Newfoundland (Papezik and Hodych, 1980). Stringer and Burke (1985) have located and dated a smaller ENA dolerite dyke near the coast of SW New Brunswick, with no report of composition.

The Caraquet dyke is the largest, measuring at least 40 m wide and 390 km long through its mapped area, with perhaps another 150 km indicated by magnetic surveys in Maine (Boucot *et al.*, 1964). The Caraquet dyke is roughly on line with the large Higganum dyke system of southern New England (Fig. 1; Philpotts and Martello, 1986). Other large dyke segments are mapped in New Hampshire (the Onway dyke of Dye *et al.*, 1985), in SW Maine (the Hiram Station dyke of Merrill and Perkins, 1930), and in SE Maine (the Harpswell Neck dyke of Hussey, 1971). If connected with the Higganum dyke, the Caraquet megadyke would stretch at least 950 km. The Shelburne and Avalon dykes are traceable up to 100 km or more. By analogy with more southern areas (of the U.S.A.), additional and perhaps smaller dykes related to these large Canadian intrusions may be found with more detailed mapping. The Atlantic Provinces dykes show typical dolerite petrography: fine to coarse grained, with subophitic to ophitic textures. A quartzo-feldspathic groundmass in all of the dykes indicates that the last liquid to crystallize was very siliceous. Some samples show glomeroporphyritic aggregates of pyroxene, enclosing plagioclase laths. Augite is common as phenocrysts and also in the matrix of all dykes, whereas pigeonite and Fe-rich augite appear only in the groundmass.

Coastal New England (CNE) subprovince

Early Triassic ages for dolerites (Bellini *et al.*, 1982) and three syenitic plutons (Foland and Faul, 1977) outline an alkalic, post-orogenic igneous province in a belt less than 75 km from the coasts of eastern Massachusetts, New Hampshire, and Maine (Fig. 1; McHone and Butler, 1984). Mapping of the Seabrook nuclear power plant in southernmost coastal New Hampshire revealed numerous fine-grained olivine dolerite dykes as much as 4 m thick, trending around N45°E. Maps of the cooling tunnels for the plant show 38 dykes in a distance of 4.8 km. Nine whole-rock K-Ar dates on the dolerite dykes at Seabrook and on others nearby range from 212 to 237 Ma (Bellini *et al.*, 1982).

In many areas, crosscutting relationships show the presence of CNE dykes in excellent exposures along the seacoast. From Seabrook, New Hampshire northward at least to Kennebunkport in southern Maine, older fine-grained olivine dolerite dykes are crosscut by coarser, commonly porphyritic dolerites of probably Early Jurassic age (McHone and Trygstad, 1982). Rare crosscutting camptonite and monchiquite dykes are thinner and distinctive in texture and mineralogy, and belong to the Cretaceous igneous province described in a later section. We thus discern at least three groups of mafic dykes of differing ages along the coast of New England.

ENA dolerite dykes of the Boston Platform

At least five dyke swarms have been recognized among the estimated 1000 to 2000 mafic dykes intruded into Proterozoic to Silurian rocks of the northern portion of the Boston Platform in Massachusetts (Fig. 1). The swarms have general trends of NW (two swarms), NE, E-W, and N-S, in order of decreasing dyke frequency. Seven petrographic varieties of dolerites and altered dolerites and three varieties of lamprophyres have been identified (Ross, 1984; 1985). The Boston Platform dykes are of special interest because they record a longer, more complex history of mafic dyke intrusion than is generally true elsewhere in eastern North America, and they are located in a crustal block believed to have been exotic to North America prior to about the middle to late Paleozoic (Williams, 1978; Barosh, 1984).

Field evidence and eleven published K-Ar dates suggest the N-S and NE-trending dolerites, and the NE-trending lamprophyres are Triassic to Early Jurassic in age, and that the remaining swarms are Cambrian to Permian (Ross, 1985; unpublished dates by H. Krueger, personal communication, 1985). The relationship of the Mesozoic dykes of the Boston Platform to the Mesozoic dykes of eastern North America, and of New England in particular, remains problematic. Their similar NE trend suggests common tectonic controls, but their somewhat different compositions and petrographies suggest different magmatic histories. Additional chemical and radiometric analyses are needed before more definitive models and group comparisons can be made.

Whole-rock geochemistry

On the basis of roughly one hundred analyses of ENA dolerites, Weigand and Ragland (1970), followed by numerous others, grouped ENA dolerites and basalts as olivine-normative, high Fe quartz-normative, low Fe – high Ti quartz-normative, and low Fe – low Ti quartz-normative. Ragland and Whittington (1983) amended these categories to divide olivine-normative dolerites into a group rich in large-ion-lithophile (LIL) elements and another poorer in LIL elements, and adding a group, based on the CNE subprovince, of transitional to alkali-olivine basaltic chemistry. Ragland and Whittington (1983) further suggest that the high-iron group is actually a variably differentiated product of the other dolerite types, rather than a separate group. Although high-Ti quartz and alkali-olivine dolerites appear to dominate the Northern Appalachians, the groups apparently co-mingle in many areas of the ENA province. Additional chemical data are further obscuring the distinctions between such compositional groups.

Bertrand and Coffrant (1977) and de Boer and Snider (1979) used available ENA dolerite analyses to study regional variations in compositions. A major problem with their approach was the lack of comprehensive chemical data for large regions, which are only now becoming available. Bertrand and Coffrant (1977) succeeded in showing a statistically valid, compositional similarity between ENA dykes of the Northern Appalachians and Early Jurassic dolerite dykes of NW Africa. Much as in the model proposed by Bryan *et al.* (1977), de Boer and Snider (*op. cit.*) attempted to show regional chemical patterns suggestive of "mantle-plume" basalts along an Appalachian-parallel section of the ENA province.

We have compiled 649 whole-rock analyses for six regions of the ENA dolerite province, and for two groups of lamprophyres from one region discussed in a later section (Table I). Many volcanic basalt analyses are also available, but for this study, dyke analyses were specifically sought and only averages of basalt compositions are included. Studies underway or as yet unpublished will add several hundred analyses to future compilations.

The transitional to alkalic character of the CNE subprovince dykes is recorded by their low Si and high Ti as well as high alkalis (Table I; Fig. 3). Dolerites of Virginia and North Carolina appear to have especially "primitive" values of high Mg and low Si, Ti, and K (Table I). As indicated by large standard deviations in SiO_2 and MgO, the chemical variations of the ENA dykes allow for both quartz and olivine-normative types, but the means of the southern regional groups are clearly olivine tholeiites while quartz tholeiite dominates in the north (outside of coastal New England).

The three major dykes of the Canadian Atlantic Provinces represent quartz-normative tholeiite magmas, with SiO_2 and alkali contents characteristic of the ENA province (Fig. 3), but there are significant differences in TiO_2, MgO, CaO, and the alkalies between ENA dykes from Canada and those from New England (Table I). Except for SiO_2 values, the Canadian dykes resemble the ENA dolerites of

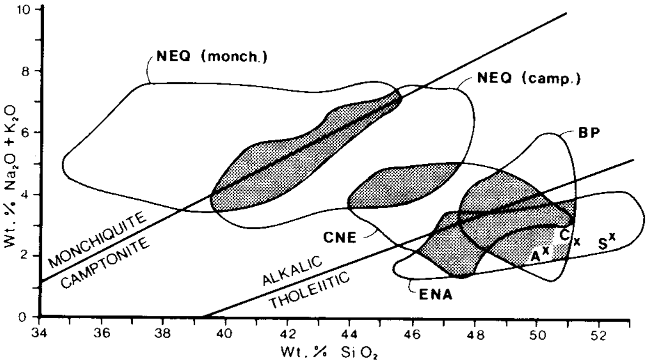

Figure 3. *Alkali vs. silica diagram showing fields of Mesozoic dolerite and lamprophyre dyke analyses from eastern North America. Discriminant lines are discussed in the text. Abbreviations of igneous provinces are as in Figure 1.*

Table I

Compositions of Mesozoic Mafic Dykes by Regional Groups

Group	1		2		3		4		5		6		7		8	
N	37		54		25		84		186		93		133		37	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Oxide (Wt %)																
SiO_2	39.76	1.58	43.49	1.19	47.73	1.53	51.41	1.24	51.20	1.89	47.79	2.11	48.81	1.21	48.38	1.64
TiO_2	2.95	0.26	3.02	0.14	1.97	0.33	0.92	0.16	1.63	0.72	0.55	0.24	0.74	0.18	0.69	0.10
Al_2O_3	11.83	0.87	13.62	0.63	15.33	1.10	14.80	0.74	14.82	0.43	15.36	0.50	16.17	1.28	15.98	0.98
FeO*	11.01	0.63	11.16	0.68	11.56	1.41	10.14	0.98	10.38	2.30	9.96	0.37	10.90	1.06	10.53	0.88
MnO	0.23	0.02	0.24	0.02	0.21	0.05	0.19	0.02	0.19	0.03	0.17	0.01	0.26	0.03	0.18	0.02
MgO	7.33	0.87	6.81	0.64	7.41	1.57	7.53	1.03	6.49	0.99	11.67	2.53	9.77	2.52	8.83	1.89
CaO	12.61	1.54	10.20	1.09	9.33	1.31	10.30	0.99	9.60	1.24	10.59	0.60	10.34	0.69	11.06	0.49
Na_2O	3.51	0.44	3.08	0.35	2.53	0.49	2.16	0.55	2.59	0.45	1.69	0.22	2.12	0.42	2.07	0.23
K_2O	2.17	0.30	1.73	0.24	0.94	0.38	0.57	0.23	0.80	0.35	0.40	0.20	0.28	0.15	0.40	0.30
P_2O_5	1.28	0.18	0.74	0.13	0.33	0.15	0.14	0.05	0.20	0.06	0.08	0.02	n.a.		n.a.	
H_2O	2.47	0.39	2.24	0.33	n.a.		0.85	0.42	1.22	0.56	1.02	0.31	n.a.		n.a.	
M (mol %)																
Qtz	0.00		0.00		0.00		3.12		3.60		0.00		0.00		0.00	
Hyp	0.00		4.36		15.97		21.80		17.29		16.54		17.31		14.28	
Ol	10.76		11.34		4.20		0.00		0.00		13.00		10.04		8.88	
Ne	8.09		0.00		0.00		0.00		0.00		0.00		0.00		0.00	
Di	17.06		7.97		13.33		17.25		16.14		14.81		14.23		17.69	
Age (Ma)	96-136		101-130		212-236		189-201		175-200		175-200		185-200		175-200	
Rock Type	Monchiquite		Camptonite		Transitional Tholeiite		Quartz Tholeiite		Quartz and Olivine Tholeiite (mixed within regions)							

M = CIPW normative mineral; N = number of analyses (single + multiple)

Groups:
1 = New England and Quebec (Hodgson, 1968; McHone, 1978)
2 = New England and Quebec (Hodgson, 1968; McHone, 1978)
3 = Coastal New England (McHone, 1978; Hermes *et al.*, 1984; J. Bedard, unpublished data)
4 = Canadian Atlantic Provinces (Bertrand and Coffrant, 1977; Papezik and Hodych, 1980; Papezik and Barr, 1981; Dostal and Dupuy, 1984; Papezik and Greenough, 1985)
5 = New Jersey through New England (Walker, 1969; Weigand and Ragland, 1970; Bertrand and Coffrant, 1977; Maxey, 1973; McHone, 1978; Puffer *et al.*, 1982; Husch *et al.*, 1984; Ross, 1985; Philpotts and Martello, 1986)
6 = Maryland and Pennsylvania (Weigand and Ragland, 1970; Smith *et al.*, 1975; Bertrand and Coffrant, 1977)
7 = North Carolina and Virginia (Justus *et al.*, 1969; Weigand and Ragland, 1970; Drez, 1977)
8 = Alabama, Georgia, and South Carolina (Weigand and Ragland, 1970; Bertrand and Coffrant, 1977; Bell *et al.*, 1979; Warner *et al.*, 1985; Warner *et al.*, 1986)

the central and southern Appalachians more than the ENA dykes of New England.

The N- to NE-trending Mesozoic dykes of the Boston Basin include quartz and olivine-normative tholeiitic dolerites, transitional-alkalic dolerite, true alkali-olivine dolerite, and alkalic lamprophyres. As shown in Figure 3, SiO_2 and alkali values are generally higher, but overlap those shown by olivine dolerites of the CNE dykes to the north and southwest of Boston (Fig. 1).

Of the tholeiitic dolerites (columns 5 to 8, Table I), the Northern Appalachian examples are clearly richer in Si, Ti, and K, especially in the New Jersey – New England segment, when compared with Southern Appalachian dolerites. Such chemical values have been taken to indicate contamination of the dolerite magma by continental crustal rocks, either by assimilation or by a selective leaching process (Smith *et al.*, 1975; Bryan *et al.*, 1977; Dostal and Dupuy, 1984; Campbell, 1985). However, Wiegand and Ragland (1970), Pegram (1983), and Gottfried and Arth (1985) presented chemical models and data, especially Sr, Nd, and Pb isotopic ratios, that argue against significant assimilation. The chemical variations of the ENA dolerites are best explained by heterogeneities of mantle sources, varying degrees of partial melting, magma mixing, and crystal fractionation at deep levels of the lithosphere.

NOTRE DAME BAY IGNEOUS PROVINCE

Two gabbroic stocks and more than a hundred lamprophyre dykes are found in a zone approximately 70 km by 100 km across the shorelines and islands of Notre Dame Bay (NDB), northern Newfoundland (Fig. 1). Despite Late Jurassic (139 to 155 Ma, K-Ar) dates on the associated Budgell Harbour stock, the dykes have Early Cretaceous radiometric and paleomagnetic ages (Lapointe, 1979). The dykes trend generally to the northeast except near the

Budgell Harbour stock, where they appear to be more radial in distribution (Strong and Harris, 1974).

The lamprophyre dykes are mainly nepheline-normative monchiquite, but many have ocelli of more leucocratic compositions (Strong and Harris, 1974). Although data are limited, the dykes appear similar in age, petrography, and chemistry to lamprophyres of New England and southern Quebec, discussed below.

NEW ENGLAND – QUEBEC IGNEOUS PROVINCE

Early Cretaceous magmas of southern Quebec and northern New England are generally bimodal (syenite-gabbro) and alkalic, and include the classic Monteregian Hills intrusions (Gold, 1967) in Canada as well as several plutonic complexes in Vermont, New Hampshire, and southern Maine (McHone and Butler, 1984). Early Cretaceous lamprophyre dykes in the region are mostly camptonite with scattered groups of monchiquite, spessartite, and ultramafic types, and form a continuous dyke province among and crosscutting all of the coeval plutons. Dykes 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 the dykes and plutons under the name "New England – Quebec (NEQ) igneous province". Hodgson (1968), McHone (1978; 1984), and McHone and Trygstad (1982) have described and mapped more than 1300 of the estimated 10,000 to 20,000 dykes that belong to the overlapping NEQ, CNE, and ENA provinces in northern New England and adjacent southern Quebec (Fig. 1). Radiometric ages (mostly K-Ar) range between 96 and 136 Ma (McHone, 1984; Eby, 1985).

The lamprophyre dykes are typically 40 to 140 cm wide and rarely can be followed for more than a kilometre. The NEQ dykes trend near N65°W in Quebec, nearly E-W in the Lake Champlain Valley between Vermont and New York, and between N45°E and N60°E in southern and eastern Vermont and elsewhere in New England (Fig. 1). Unlike some felsic and intermediate dykes in the region, the lamprophyre dykes do not form radial patterns around the NEQ plutons. Major topographic lineaments and local fracture systems parallel the dyke sets, suggesting lithospheric controls with orientations that follow both Appalachian-parallel and transverse structures (Shake and McHone, 1986).

The most abundant regional lamprophyres are camptonite and monchiquite, which are alkali lamprophyres chemically similar to alkali-olivine basalts (especially, basanite and nephelinite). Table I shows averages for camptonites and monchiquites of the NEQ province. Camptonite dykes tend to be widely distributed and abundant across the province, while monchiquite dykes are mainly concentrated in the western Monteregians, western Vermont, and smaller areas of eastern Vermont and New Hampshire (Fig. 1; McHone, 1984).

The lamprophyres are easily distinguished from ENA dolerites by their lower silica and higher alkali contents (Table I; Fig. 3). In Figure 3, the alkaline basalt — tholeiitic basalt discriminant line is defined by MacDonald and Katsura (1964) as $D_m = 0.374\,SiO_2 - K_2O - Na_2O - 14.63$, where alkaline basalts have $D_m < 0$ and tholeiitic basalts have $D_m > 0$. An analogous line for alkalic lamprophyres separates at least 95 per cent of regional monchiquite ($D_1 < 0$) from camptonite ($D_1 > 0$), where $D_1 = 0.526\,SiO_2 - K_2O - Na_2O - 16.83$.

TECTONIC MODEL: DISCUSSION AND SUGGESTIONS

Early Jurassic rifting

As noted by King (1961), the extensive ENA dyke swarm is generally confined to the eastern Appalachian Mountains, and it is now clear that the province extends from the major anticlinoria axes of the Appalachian highlands eastward to the continental margin. Only a few dykes in the Carolinas and Pennsylvania cross westward into the Valley and Ridge province of the Appalachian orogen. The structure responsible for this boundary is not known, but a logical feature could be a relict basement boundary that functioned as a Mesozoic strain limit. By Early Jurassic time, the dolerite dykes surrounded the incipient central Atlantic basin. Possible structural controls on the eastern boundary to the intrusions in present-day Africa and Iberia, and the western one in South America (Fig. 2) are not yet apparent.

The pattern, ages, and chemistry of the dykes are prime evidence that the dolerites are related to the Jurassic break-up of Gondwanaland. As discussed by Weigand and Ragland (1970), Bryan *et al.* (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 (Fig. 2). Chemical comparisons between the ENA dykes and the oldest Atlantic crust are obscured by a lack of good samples of the ocean crust near the continent, but Bryan *et al.* (1977) point out that the ENA dyke compositions have higher K_2O values and $^{87}Sr/^{86}Sr$ ratios than do typical mid-ocean ridge basalts. The large amount of partial melting involved in seafloor spreading could have depleted incompatible elements that were initially present in the mantle.

The NE orientation of the Atlantic Provinces dykes appears to be caused by rift-related stresses during the opening of the North Atlantic Ocean. The locations of emplacement may have been in part structurally controlled, crudely following the lithotectonic Humber Zone of Williams (1978). In other areas associated with rifting (Basaltic Volcanism Study Project, 1981), rift volcanic rocks display a decrease in alkalinity in a direction towards the rift axis and with increasing time after the inception of stretching (Neumann and Ramberg, 1978). The Atlantic Province dykes, separated by 300 km perpendicular to the rift axis, show no such compositional changes in reference to the regional Mesozoic rift basins and continental margin, unlike the suggestion made by Hermes *et al.* (1984) for just such a relationship in southern New England.

The pattern of Early Jurassic dykes reflects extensional stress regimes that varied along the initial Atlantic basin. Some of this variation may be caused by domal uplift, as suggested by May (1971) and others, but the dimensions of the province segments — roughly 500 by 3000 km in North America alone — make one uplifted area an unlikely source for all the dykes. The three ENA dyke trends, and trends of Early Jurassic dykes in Africa and South America, closely parallel three major rift directions that formed the new ocean basin (Fig. 2). The upper mantle may have had several flow patterns during the rifting stage, and extensional stresses from such movements pulled apart the

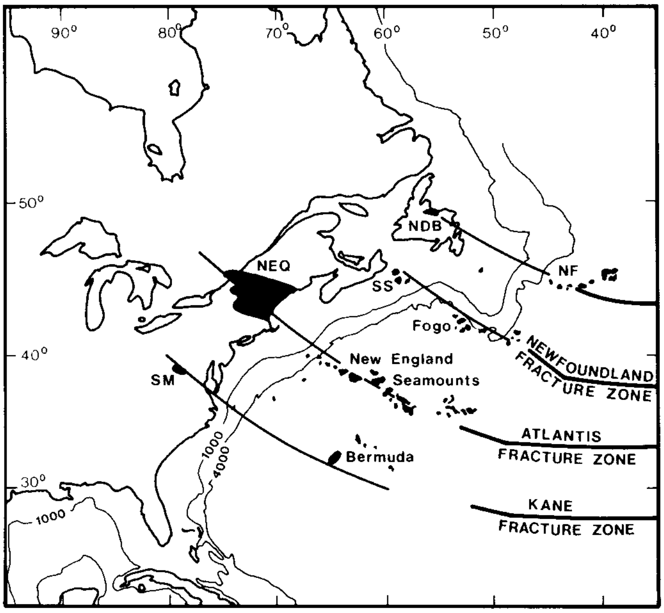

Figure 4. Locations of Cretaceous and younger igneous provinces relative to the edge of the North American continent, and major oceanic fracture zones extrapolated into the continent, modified from Sykes (1978). Abbreviations are as in Figure 1, except: SM = Eocene intrusions of the Shenandoah Mountains region (Johnson et al., *1971); SS = Early Cretaceous volcanic rocks of the Scotian Shelf (Jansa and Pe-Piper, 1985); Fogo = Fogo Seamounts; NF = Newfoundland Seamounts.*

lithosphere along three pre-existing structural zones. The ENA dykes have permanently recorded the zones and trends of extensional stresses and strains operating in Early Jurassic time.

Early Cretaceous rifting

By Early Cretaceous times, ocean-opening events had shifted to areas north and south of most of the Early Jurassic magmatism (Bryan *et al.*, 1977; Lapointe, 1979). However, rifting in several areas of eastern North America recurred as distinct zones of trans-lithospheric fracturing and magmatism, rather than as the creation of major grabens or new oceans.

Distributions of the Cretaceous and younger dykes of eastern North America are essentially transverse to Appalachian surface structures and the continental margin. Le Pichon and Fox (1971), Marsh (1973), Sykes (1978), and Black *et al.* (1985) have suggested that major fracture zones can affect both sides of continent-ocean boundaries around the Atlantic with magmatic and seismic activity. The post-Jurassic intrusions are located along extensions of several major oceanic fracture zones that are also followed by chains of alkalic seamounts in the western Atlantic Ocean basin (Fig. 4). The New England seamount chain has radiometric evidence of a progression of ages between 103 and 82 Ma from west to east (Duncan, 1984), but many other Cretaceous or younger alkali-volcanic seamounts in the North Atlantic Ocean are scattered in distribution and show no such age progression (Keen *et al.*, 1977; Jansa and Pe-Piper, 1985).

Although the fracture zones and alkalic-dyke provinces may together be aligned with plate-motion directions (as a tectonic consequence of such motions), the continental provinces do not show linear chains of age-progressive intrusion and volcanism. The large number of provinces, their distribution, similar ages, and distinct boundaries, all argue against an origin by a small number of long-lasting mantle plumes (the "hotspot" model of Crough, 1981; and Morgan, 1983). The transverse dyke swarms represent alkalic basaltic magmas that rose from relatively deep sources along tectonically active "weak zones" in the lithosphere. The dyke trends record the late Mesozoic extensional stresses in the uppermost crust of eastern North America along these zones.

ACKNOWLEDGEMENTS

The late V.S. Papezik performed much of our cited work on the dykes of the Canadian Atlantic Provinces. His enthusiasm and scholarship in our subject area will be long remembered. Valuable contributions of data and advice concerning various portions of our work have been given by J.Z. de Boer, P.C. Ragland, J.R. Butler, and J. Bedard. The study of the dykes of the Boston Platform was funded in part by awards to M.E. Ross from the Northwest College and University Association for Science and the Basalt Waste Isolation Project (Analogue Studies) under contract DE-AM06-76-RL02225 to Rockwell International, Hanford Operations. Part of McHone's work was funded by National Science Foundation Grants EAR76-14271 and EAR82-12496. Many improvements to the manuscript were suggested by H.C. Halls and H. Bertrand.

REFERENCES

Armstrong, R.L., and Besancon, J., 1970, A Triassic Time-scale Dilemma: K-Ar Dating of Upper Triassic Mafic Igneous Rocks, Eastern U.S.A. and Canada and Post-Upper Triassic Plutons, Western Idaho, U.S.A.: Eclogae Geologica Helvetica, v. 63/1, p. 15-28.

Barosh, P.J., 1984, Regional Geology and Tectonic History of Southeastern New England: *in*, Hanson, L.S., ed., Geology of the Coastal Lowlands — Boston, Massachusetts to Kennebunkport, Maine: New England Intercollegiate Conference Guidebook, p. 1-35.

Basaltic Volcanism Study Project, 1981, Basaltic Volcanism on the Terrestrial Planets: New York, Pergamon Press, 1286 p.

Bell, H., III, Books, K.G., Daniels, D.L., Huff, W.E., Jr., and Popenoe, P., 1979, Diabase Dikes in the Haile-Brewer Area, South Carolina, and their Magnetic Properties: U.S. Geological Survey Professional Paper 1123-C, 18 p.

Bellini, F.X., Corkum, D.H., and Stewart, A.J., 1982, Geology of Foundation Excavations at Seabrook Station, Seabrook, New Hampshire: *in*, Farquhar, O.C., ed., Geotechnology in Massachusetts: University of Massachusetts, Amherst, Mass., U.S.A., p. 107-117.

Bertrand, H., and Coffrant, D., 1977, Geochemistry of Tholeiites from North-east American Margin: Correlation with Morocco: Contributions to Mineralogy and Petrology, v. 63, p. 65-74.

Black, R., Lameyre, J., and Bonin, B., 1985, The Structural Setting of Alkaline Complexes: Journal of African Earth Sciences, v. 3, p. 5-16.

Boucot, A.J., Griscom, A., and Allingham, J.W., 1964, Geologic and Aeromagnetic Map of Northern Maine: U.S. Geological Survey, Geophysical Investigations Map GP-312.

Bryan, W.B., Frey, F.A., and Thompson, G., 1977, Oldest Atlantic Seafloor: Mesozoic Basalts from Western North Atlantic Margin and Eastern North America: Contributions to Mineralogy and Petrology, v. 64, p. 223-242.

Burke, K.B.S., Hamilton, J.B., and Gupta, V.K., 1973, The Caraquet Dike: Its Tectonic Significance: Canadian Journal of Earth Sciences, v. 10, p. 1760-1768.

Burt, E.R., Carpenter, P.A., III, McDaniel, R.D., and Wilson, W.F., 1978, Diabase Dikes of the Eastern Piedmont of North Carolina: North Carolina Department of Natural Resources, Raleigh, N.C., U.S.A., Information Circular 23.

Campbell, I.H., 1985, Assimilation in Dykes: The Major Source of Crustal Contamination in Continental Tholeiites: *in*, Halls, H.C., ed., International Conference on Mafic Dyke Swarms — Abstracts: University of Toronto, Toronto, Ont., Canada, p. 27.

Crough, S.T., 1981, Mesozoic Hotspot Epeirogeny in Eastern North America: Geology, v. 9, p. 2-6.

Dallmeyer, R.D., 1975, The Palisades Sill: A Jurassic Intrusion?: Evidence from $^{40}Ar/^{39}Ar$ Incremental Release Ages: Geology, v. 3, p. 243-245.

Daniels, D.L., Zietz, I., and Popenoe, P., 1983, Distribution of Subsurface Lower Mesozoic Rocks in the Southeastern United States, as Interpreted from Regional Aeromagnetic and Gravity Maps: U.S. Geological Survey Professional Paper 1313, p. K1-K24,

de Boer, J., 1967, Paleomagnetic Study of Mesozoic Dike Swarms in the Appalachians: Journal of Geophysical Research, v. 72, p. 2237-2250.

de Boer, J., and Snider, F.G., 1979, Magnetic and Chemical Variations of Mesozoic Diabase Dikes from Eastern North America: Evidence for a Hot-spot in the Carolinas?: Geological Society of America Bulletin, v. 90, p. 185-198.

Deininger, R.W., Dallmeyer, R.D., and Neathery, T.L., 1975, Chemical Variations and K-Ar Ages of Diabase Dikes in East-central Alabama: Geological Society of America Abstracts with Programs, v. 7, p. 482.

Dooley, R.E., and Wampler, J.M., 1983, Potassium-argon Relations in Diabase Dikes of Georgia — the Influence of Excess ^{40}Ar on the Geochronology of Early Mesozoic Igneous and Tectonic Events: U.S. Geological Survey Professional Paper 1313, p. M1-M24.

Dostal, J., and Dupuy, C., 1984, Geochemistry of the North Mountain Basalts (Nova Scotia, Canada): Chemical geology, v. 45, p. 245-261.

Drez, P.E., 1977, Hydrothermal Alteration of Low-K Tholeiitic Dikes and Intruded Clastic Sediments: PhD Thesis, University of North Carolina, Chapel Hill, N.C., U.S.A., 324 p.

Duncan, R.A., 1984, Age-progressive Volcanism in the New England Seamounts and the Opening of the Central Atlantic Ocean: Journal of Geophysical Research (Crough Memorial), v. 89, no. B12, p. 9980-9990.

Dye, C.J., Sundeen, D.A., and Thoroman, M.C., 1985, Petrology, Age and Structure of the Onway Dike, a Tholeiitic Pluton in Rockingham County, Southeastern New Hampshire: Geological Society of America, Abstracts with Programs, v. 17, p. 17.

Eby, G.N., 1985, Age Relations, Chemistry, and Petrogenesis of Mafic Alkaline Dikes from the Monteregian Hills and Younger White Mountain Igneous Provinces: Canadian Journal of Earth Sciences, v. 22, p. 1103-1111.

Foland, K.A., and Faul, H., 1977, Ages of the White Mountain Intrusives — New Hampshire, Vermont, and Maine, U.S.A.: American Journal of Science, v. 277, p. 888-904.

Gibbs, A.K., 1987, Contrasting Styles of Continental Mafic Intrusions: *in*, Halls, H.C., and Fahrig, W.F., eds., Mafic Dyke Swarms: Geological Association of Canada Special paper 34.

Gold, D.P., 1967, Alkaline Ultrabasic Rocks in the Montreal Area, Quebec: *in*, Wyllie, P.J., ed., Ultramafic and Related Rocks: New York, John Wiley and Sons, p. 288-302.

Gottfried, D., and Arth, J.G., 1985, Sr and Nd Isotope Ratios and Geochemistry of Mesozoic Diabase Dikes from Georgia: EOS, v. 66, no. 18, p. 399.

Hermes, O.D., Rao, J.M., Dickenson, M.P., and Pierce, T.A., 1984, A Transitional Alkalic Dolerite Suite of Mesozoic Age in Southeastern New England: Contributions to Mineralogy and Petrology, v. 85, p. 386-402.

Hodgson, C.J., 1968, Monteregian Dike Rocks: PhD Thesis, McGill University, Montreal Que., Canada, 168 p.

Husch, J.M., Sturgis, D.S., and Bambick, T.C., 1984, Mesozoic Diabases from West-central New Jersey: Major and Trace Element Geochemistry of Whole Rock Samples: Northeastern Geology, v. 6, no. 1, p. 51-63.

Hussey, A.M., III, 1971, Geologic Map and Cross Sections of the Orrs Island 7½′ Quadrangle and Adjacent Area, Maine: Maine Geological Survey, Augusta, Me., U.S.A., Geologic Map Series GM-2.

Jansa, L.F., and Pe-Piper, Georgia, 1985, Early Cretaceous Volcanism on the Northeastern American Margin and Implications for Plate Tectonics: Geological Society of America Bulletin, v. 96, p. 83-91.

Johnson, R.W., Milton, T.C., and Dennison, J.M., 1971, Field Trip to the Igneous Rocks of Augusta, Rockingham, Highland and Bath Counties, Virginia: Virginia Division of Mineral Resources, Information Circular No. 16, 68 p.

Justus, P.S., Thayer, P.A., and Weigand, P.W., 1970, Comparative Geochemistry and Petrology of Diabase Dikes in the North Carolina Triassic Basin: Geological Society of America, Abstr. v. 2, no. 3, p. 223.

Keen, C.E., Hall, B.R., and Sullivan, K.D., 1977, Mesozoic Evolution of the Newfoundland Basin: Earth and Planetary Science Letters, v. 37, p. 307-320.

King, P.B., 1961, Systematic Pattern of Diabase Dikes in the Appalachian Region: U.S. Geological Survey Professional Paper 424-B, p. 93-95.

King, P.B., 1971, Systematic Pattern of Triassic Dikes in the Appalachian Region: Second Report: U.S. Geological Survey Professional Paper 750-D, p. 84-88.

Lapointe, P.L., 1979, Paleomagnetism of the Notre Dame Bay Lamprophyre Dikes, Newfoundland, and the Opening of the North Atlantic Ocean: Canadian Journal of Earth Sciences, v. 16, p. 1823-1831.

Le Pichon, X., and Fox, P.J., 1971, Marginal Offsets, Fracture Zones, and the Early Opening of the North Atlantic: Journal of Geophysical Research, v. 76, p. 6294-6308.

MacDonald, G.A., and Katsura, T., 1964, Chemical Composition of Hawaiian Lavas: Journal of Petrology, v. 5, p. 82-133.

Marsh, J.S., 1973, Relationships Between Transform Directions and Alkaline Igneous Provinces in Africa and South America: Earth and Planetary Science Letters, v. 18, p. 317-323.

Maxey, L.R., 1973, Dolerite Dikes of the New Jersey Highlands: Probable Comagmatic Relation with the Mesozoic Palisades Sill and Dolerite Dikes of Eastern United States: Geological Society of America Bulletin, v. 84, p. 1081-1086.

Maxey, L.R., 1977, Petrology and Geochemistry of the Beemerville Carbonatite-alkalic Rock Complex, New Jersey: Geological Society of America Bulletin, v. 87, p. 1551-1559.

May, P.R., 1971, Pattern of Triassic-Jurassic Diabase Dikes around the North Atlantic in the Context of Predrift Positions of the Continents: Geological Society of America Bulletin, v. 82, p. 1285-1292.

McHone, J.G., 1978, Distribution, Orientations, and Ages of Mafic Dikes in Central New England: Geological Society of America Bulletin, v. 89, p. 1645-1655.

McHone, J.G., 1984, Mesozoic Igneous Rocks of Northern New England and Adjacent Quebec: Geological Society of America Map and Chart Series, MC-49, 1:690,000 Scale Map and 5 p. Text.

McHone, J.G., and Butler, J.R., 1984, Mesozoic Igneous Provinces of New England and the Opening of the North Atlantic Ocean: Geological Society of America Bulletin, v. 95, p. 757-765.

McHone, J.G., and Trygstad, J.C., 1982, Mesozoic Mafic Dikes of Southern Maine: Maine Geology, Bulletin 2, p. 16-32.
Merrill, L.H., and Perkins, E.H., 1930, First Annual Report of the Geology of the State of Maine: Bangor, Maine, U.S.A., p. 16.
Morgan, W.J., 1983, Hotspot Tracks and the Early Rifting of the Atlantic: Tectonophysics, v. 94, p. 123-139.
Neumann, E.R., and Ramberg, I.B., eds., 1978, Tectonics and Geophysics of Continental Rifts: Dodrech, Holland, Reidel Publishing Co., 278 p.
Papezik, V.S., and Barr, S.M., 1981, Shelburne Dike, an Early Mesozoic Diabase Dike in Nova Scotia: Mineralogy, Chemistry, and Regional Significance: Canadian Journal of Earth Sciences, v. 18, p. 1346-1355.
Papezik, V.S., and Greenough, J.D., 1985, Early Mesozoic Dikes of Atlantic Canada: *in*, Halls, H.C., ed., International Conference on Mafic Dyke Swarms — Abstracts: University of Toronto, Toronto, Ont., Canada, p. 119-123.
Papezik, V.S., and Hodych, J.P., 1980, Early Mesozoic Diabase Dikes of the Avalon Peninsula, Newfoundland: Petrochemistry, Mineralogy, and Origin: Canadian Journal of Earth Sciences, v. 17, p. 1417-1430.
Pegram, W.J., 1983, Isotopic Characteristics of the Mesozoic Appalachian Tholeiites: Geological Society of America, Abstracts with Programs, v. 15, no. 6, p. 661.
Philpotts, A.R., and Martello, A., 1986, Diabase Feeder Dikes for the Mesozoic Basalts in Southern New England: American Journal of Science, v. 286, p. 105-126.
Puffer, J.H., Hurtubise, D.O., Geiger, F.J., and Lechler, P., 1981, Chemical Composition and Stratigraphic Correlation of the Mesozoic Basalt Units of the Newark Basin, New Jersey, and the Hartford Basin, Connecticut: Geological Society of America Bulletin, v. 92, p. 515-553.
Puffer, J.H., Geiger, F.J., and Camanno, E.J., 1982, Mesozoic Igneous Rocks of Rockland County, New York: Northeastern Geology, v. 4, p. 121-130.
Ragland, P.C., and Whittington, D., 1983, Early Mesozoic Diabase Dikes of Eastern North America: Magma Types: Geological Society of America, Abstracts with Programs, v. 15, p. 666.
Ragland, P.C., Hatcher, R.D., Jr., and Whittington, D., 1983, Juxtaposed Mesozoic Diabase Dike Sets from the Carolinas: A Preliminary Assessment: Geology, v. 11, p. 394-399.
Ragland, P.C., Rogers, J.J.W., and Justus, P.S., 1968, Origin and Differentiation of Triassic Dolerite Magmas, North Carolina, U.S.A.: Contributions to Mineralogy and Petrology, v. 20, p. 57-80.
Ross, M.E., 1984, Mafic Dikes from Boston to Cape Ann: New England Intercollegiate Conference Guidebook, Boston, Mass., U.S.A., p. 81-108.
Ross, M.E., 1985, Mafic Dike Swarms of the Boston Platform, Eastern Massachusetts: *in*, Halls, H.C., ed., International Conference on Mafic Dyke Swarms — Abstracts: University of Toronto, Toronto, Ont., Canada, p. 142-147.
Shake, S.N., and McHone, J.G., 1986, Topographic Lineaments and their Geologic Significance in Central New England and Adjacent New York: Geological Society of America, Abstracts with Programs, v. 18, p. 65.
Smith, R.C., II, Rose, A.W., and Lanning, R.M., 1975, Geology and Geochemistry of Triassic Diabase in Pennsylvania: Geological Society of America Bulletin, v. 86, p. 943-955.
Stringer, P., and Burke, K.B.S., 1985, Structure in Southwest New Brunswick: Excursion 9, Annual Meeting Field Guide, Geologic Association of Canada, 34 p.
Strong, D.F., and Harris, A., 1974, The Petrology of Mesozoic Alkaline Intrusives of Central Newfoundland: Canadian Journal of Earth Sciences, v. 11, p. 1208-1219.
Sutter, J.F., and Smith, T.E., 1979, $^{40}Ar/^{39}Ar$ Ages of Diabase Intrusions from Newark-trend Basins in Connecticut and Maryland: Initiation of Central Atlantic Rifting: American Journal of Science, v. 279, p. 808-831.
Swanson, M.T., 1982, Preliminary Model for an Early Transform History in Central Atlantic Rifting: Geology, v. 10, p. 317-320.
Sykes, L.R., 1978, Intraplate Seismicity, Reactivation of Preexisting Zones of Weakness, Alkaline Magmatism, and other Tectonism Postdating Continental Fragmentation: Reviews of Geophysics and Space Physics, v. 16, p. 621-688.
Walker, K.R., 1969, The Palisades Sill, New Jersey: A Reinvestigation: Geological Society of America Special Paper 111, 178 p.
Warner, R.D., Snipes, D.S., Hughes, S.S., Steiner, J.C., Davis, M.W., Manoogian, P.R., and Schmitt, R.A., 1985, Olivine-normative Dolerite Dikes from South Carolina: Mineralogy, Chemical Composition, and Petrogenesis: Contributions to Mineralogy and Petrology, v. 90, p. 386-400.
Warner, R.D., Snipes, D.S., Burnett, L.L., Wylie, J.A., Sacks, L.A., and Steiner, J.C., 1986, Shoals Junction and Due West Dolerites, South Carolina: Southeastern Geology, v. 26, no. 3, p. 141-153.
Weigand, P.W., and Ragland, P.C., 1970, Geochemistry of Mesozoic Dolerite Dikes from Eastern North America: Contributions to Mineralogy and Petrology, v. 29, p. 195-214.
Williams, Harold, compiler, 1978, Tectonic Lithofacies Map of the Appalachian Orogen: Memorial University of Newfoundland, St. John's, Newfoundland, Canada, Map No. 1.