Mesozoic igneous provinces of New England and the opening of the North Atlantic Ocean

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ABSTRACT

Mesozoic igneous rocks in New England and adjacent areas can be divided into four provinces, on the basis of their ages, distribution, physical aspects, and petrology. These provinces represent intraplate magmatism that is correlated with successive stages in the opening of the Atlantic Ocean. The Coastal New England province includes three alkalic complexes and possibly some olivine dolerite dikes, Late Permian to Early Triassic in age, that are located in southern Maine and coastal New Hampshire and that were formed during uplift and early rifting in the Gulf of Maine region. Early Jurassic dolerite dikes occur in most of New England and are part of the Eastern North America province that extends along the eastern Appalachians from Alabama to Newfoundland, correlated with maximum rift-basin formation and continental breakup. Plutons of the classic White Mountains Magma Series are mainly Early Jurassic syenitoids and granitoids in central and northern New Hampshire. This elongate north-south province may have formed along an ancient transform or rift fault in the New England basement crust. After a relatively nonmagmatic period during the Late Jurassic, the Early Cretaceous New England–Quebec province of alkalic syenite-gabbro plutons and lamprophyre dikes formed in a large area of northern New England and adjacent Quebec. Similar magmas created seamount chains southeast of the New England coast, possibly along an extension of transverse Appalachian fracture zones. The Mesozoic New England igneous intrusions and tectonic activity represent incipient rifting in the continental platform, related to mantle convection and plate motions in the North Atlantic basin.

INTRODUCTION

The eastern Appalachian region of North America contains a wide variety of igneous rocks in overlapping petrographic provinces ranging in age from Precambrian to Tertiary. In the New England region, Mesozoic intrusions are exceptionally abundant. The region has great potential for unveiling the mechanisms of magmatism and tectonism in a continental intraplate environment, as correlated with the breakup of an ancient landmass and progressive formation of a large ocean basin. Before these mechanisms can be properly studied, the igneous rocks must be organized into appropriate groups reflecting the geological changes through time and space.

This paper divides the Mesozoic igneous rocks in the New England region into four groups (Fig. 1), redefining some of the provinces used in previous discussions and proposing a new group. The goal is a more detailed and organized history of Mesozoic events in New England and the correlation of New England Mesozoic features with related tectonic-magmatic events in and around the North Atlantic Ocean.

Two independent sequences of events are developed and integrated into a geological history. First, the Mesozoic intrusions of New England are divided among the four provinces according to age, distribution, and petrologic character. Second, a history of sea-floor spreading in the adjacent North Atlantic is described from features of the oceanic crust. Finally, we evaluate the relationships between the two sequences, comparing the New England magmatic events with episodes in the North Atlantic region.

Petrologists have long attempted to integrate data on igneous rocks so as to form groups based upon several critical common features. These features include age, geographic distribution, physical characteristics, and petrologic factors such as mineralogy and chemistry. Although members of a group are sometimes defined as magmas that are genetically related to one another, as in "magma series," many factors such as mode of intrusion, size and shape, style of solidification, differentiation, contamination, and level of exposure may conspire to obscure the actual magmatic relationship of one igneous body to another. We therefore consider an *igneous province* to be defined best by a common age and by contiguous distribution, and only secondarily by membership in a *magma series*. Several magma series can exist within the same igneous province. Descriptions of four igneous provinces in New England (Fig. 1) are partially summarized in Table 1 and are discussed below. Their age distinctions are best shown by a histogram of radiometric dates, Figure 2. Certain chemical parameters are summarized by graphical plots (Figs. 3 and 4) and in the following descriptions.

COASTAL NEW ENGLAND PROVINCE

Three plutonic complexes in Coastal New England (CNE) share important characteristics: all are well east of the main groups of Mesozoic plutons (Fig. 1); they are chiefly syenite or alkali granite (Barker, 1965; Hussey, 1962); and their apparent ages are close to the Permian-Triassic time boundary (Foland and Faul, 1977). The few available chemical analyses for the CNE intrusive complexes show alkalic compositions, such as for the Litchfield complex of eastern Maine in accordance with its unusual feldspathoids and lithologies (Barker, 1965). Owing to its alkalic nature and postorogenic emplacement, the Litchfield complex was long considered to be a member of the White Mountains Magma Series (WMMS), even though it lies almost 100 km east of the New Hampshire plutons (Fig. 1). After Burke and others (1969) reported unusually old K-Ar mineral dates of 234 ± 5 Ma and 244 ± 5 Ma for the pluton, its status as a WMMS member came into question. Foland and Faul (1977) added two other "old" dates for plutons in southern Maine, 228 ± 5 Ma for Agamenticus and 221 ± 8 Ma for Abbott (Fig. 1), and they pointed out the separation in time and space of these three Maine plutons from other New England intrusions. The 228 ± 5 Ma K-Ar age receives strong support by a whole-rock Rb-Sr date of 222 ± 3 Ma reported by Hoefs (1967) for the Agamenticus complex.

There are numerous examples of older dolerite dikes cut by Cretaceous and Jurassic lamprophyre and dolerite dikes in coastal exposures of New Hampshire and Maine. At many localities along the New England coast from Boston

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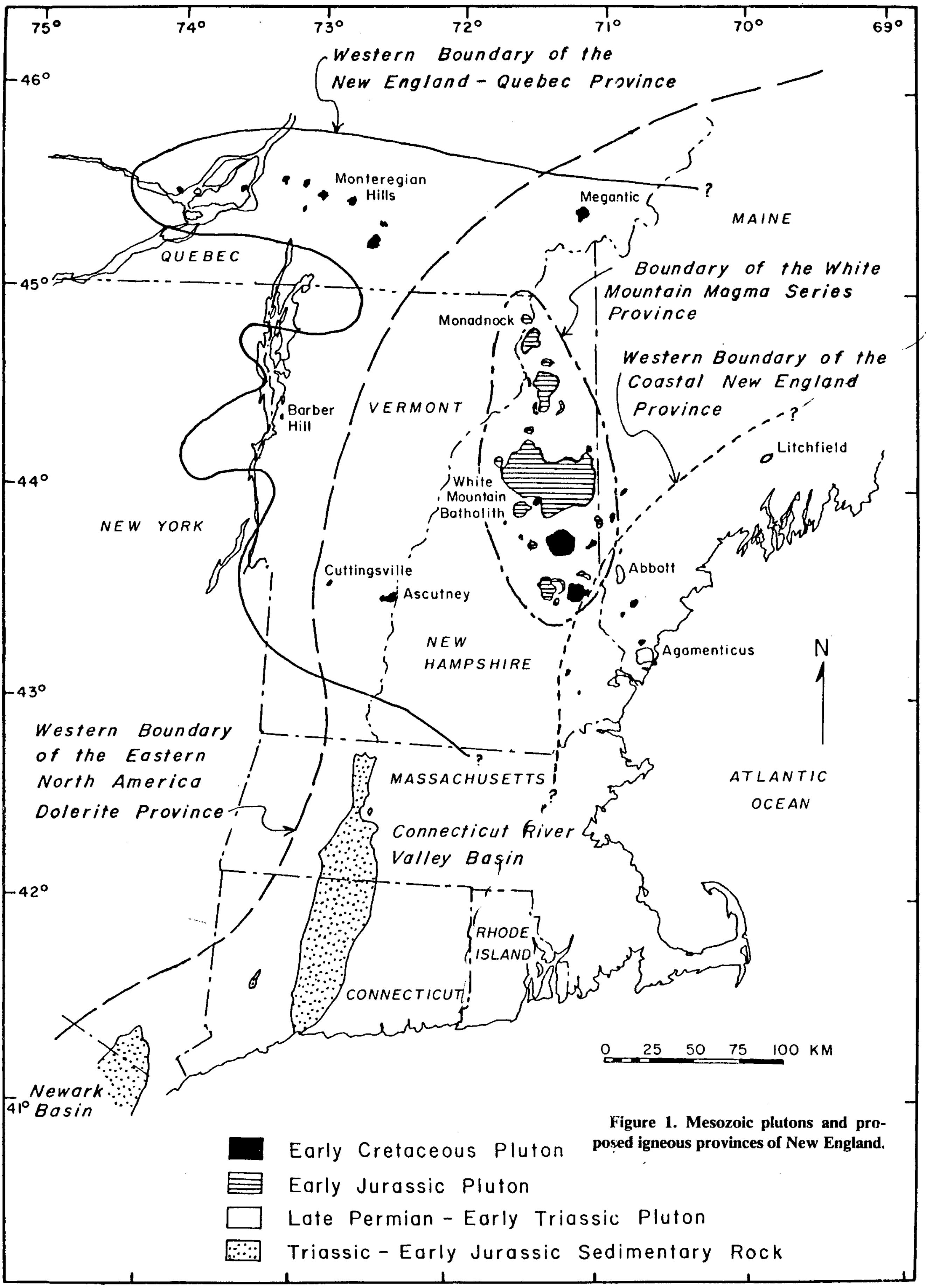

Figure 1. Mesozoic plutons and proposed igneous provinces of New England.

TABLE 1. CHARACTERISTICS OF MESOZOIC IGNEOUS PROVINCES OF NEW ENGLAND

Attribute	CNE	WMMS	ENA	NEQ
Location	Within 60 km of eastern coast	75 × 100-km zone in northern New Hampshire	East side of Appalachian anticlinorium	Most of northern New England and adjacent Quebec
Age range	210–240 m.y.	160–200 m.y.	165–200 m.y.	95–135 m.y.
Major rock types	Alkali syenite, alkali dolerite	Syenite, granite, monzonite	Alkali dolerite, tholeiite basalt	Gabbro, syenite, lamprophyre
Orientations	NE plutons and dikes(?)	N-NW chain of plutons	N30°E dikes	E-W and NE dikes, W-NW chains of plutons(?)
Geophysical anomalies	Little gravity, magnetics not known	Mainly negative gravity, variable magnetism	Not usually detected (too small)	Positive gravity and magnetism
Surface areas of intrusions (km^2)*	Plutons, 170; dikes, 280(?)	Plutons, 1,555	Basalts, 800; dikes, 1,125	Plutons, 506; dikes, 500

*Plutons measured by planimeter, estimated error ± 2%; dikes and basalts estimated.

to the Castine region of Maine, older, fine-grained dolerites are cut by coarser, commonly porphyritic dolerite dikes of probable Jurassic age (McHone and Trygstad, 1982). The lamprophyre dikes and porphyritic dolerites also crosscut the Agamenticus complex. We thus discern at least three groups of mafic dikes of differing ages along the coast of New England, where they are more abundant than inland.

Mapping of the Seabrook nuclear power plant site in southernmost coastal New Hampshire revealed numerous fine-grained olivine dolerite dikes as much as 4 m thick trending N40°E to N45°E; the site foundations exposed 28 dikes and many more were seen in cores (Bellini and others, 1982). Maps of the cooling tunnels for the plant show 38 dikes within a distance of 4.8 km. Of 9 whole-rock K-Ar dates on the dolerite dikes on site or nearby, 7 range from 212 to 236 Ma (Bellini and others, 1982), close to the ages of the CNE plutons. Farther to the south, at Gloucester, Massachusetts, another mafic dike was dated (whole-rock K-Ar) as 226 ± 10 Ma by Weston Geophysical (1977). Other dikes in the area of the Boston basin are thought to be either Early Jurassic or Paleozoic (Ross, 1981). No geochemical analyses are available for dikes of the CNE province.

EASTERN NORTH AMERICA DOLERITE PROVINCE

King (1971) called attention to the vast system of basaltic dikes in eastern North America, pointing out their geographic patterns and systematic changes in trends along the eastern Appalachians. It is evident that the basalt flows and sills of the Mesozoic sedimentary basins in the same region are products of some of the dikes of this province. Weigand and Ragland (1970) provided the commonly used name of Eastern North America (ENA) dolerite (here used as a synonym for diabase) for the dikes of the province, and they grouped the rocks into one olivine-normative and three quartz-normative chemical types. In addition to those four tholeiitic groups, Pierce and Hermes (1978) and McHone and Trygstad (1982) found many eastern New England ENA dikes to be distinctly alkalic (Fig. 3), in many cases with normative nepheline and/or K_2O values greater than 1 wt %. May (1971) correlated dolerite dikes on the western coast of Africa and northern coast of South America with the ENA dikes in a prerift configuration and related the dike pattern to a radial stress system centered at the present south-central Atlantic Ocean. Manspeizer (1981) also correlated ENA basalt flows with some western African basalts. McHone (1978) and de Boer and Snider (1979) made additional interpretations of the dike patterns and tectonic stresses.

Despite King's (1971) observation that New Hampshire dolerites appear to be similar to other ENA dikes, many workers have ignored the dolerite dikes of northern New England in their discussions of the swarms. On the basis of their age, petrology, and orientation (McHone, 1978), the dolerite dikes of northern New England are a mixture of quartz, olivine, and alkali-olivine basaltic intrusions that are surely members of the ENA province. We have drawn a western boundary of the ENA province in New England (Fig. 1) that encloses all known dolerite dikes. The eastern boundary of the ENA province is the continental margin.

Most of the ENA magmatism in the New England region apparently occurred about 190 Ma ago, including the major basalt flows and sills of the Mesozoic basins of southern New England (Armstrong and Besancon, 1970; Sutter and Smith, 1979) and dikes of northern New England and Maritime Canada (McHone, 1978; Hayatsu, 1979; Papezik and Barr, 1981; Hodych and Hayatsu, 1980). Older dates of 220 to 230 Ma reported by Armstrong and Besancon (1970) for a few intrusions in southern New England and the southern Appalachians could be accounted for by excess argon (Sutter and Smith, 1979). Dolerite intrusions with ages near 175 Ma are found crosscutting the Mesozoic basins from Maryland through Connecticut (Sutter and Smith, 1979), and Deininger and others (1975) noted an age near 170 Ma for a

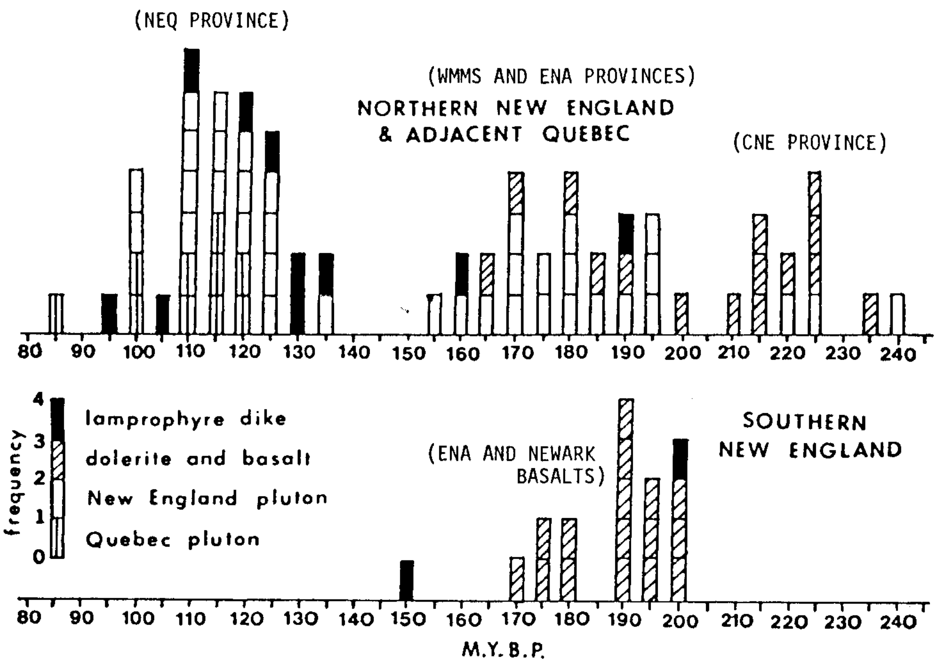

Figure 2. Histogram of radiometric ages of plutons and dikes in New England and adjacent Quebec. Modified after Foland and Faul (1977), with additional dates from Weston Geophysical (1977), McHone (1978, and unpub. data), Sutter and Smith (1979), Ross (1981), and Bellini and others (1982). Dates are rounded off to the nearest 5-Ma interval.

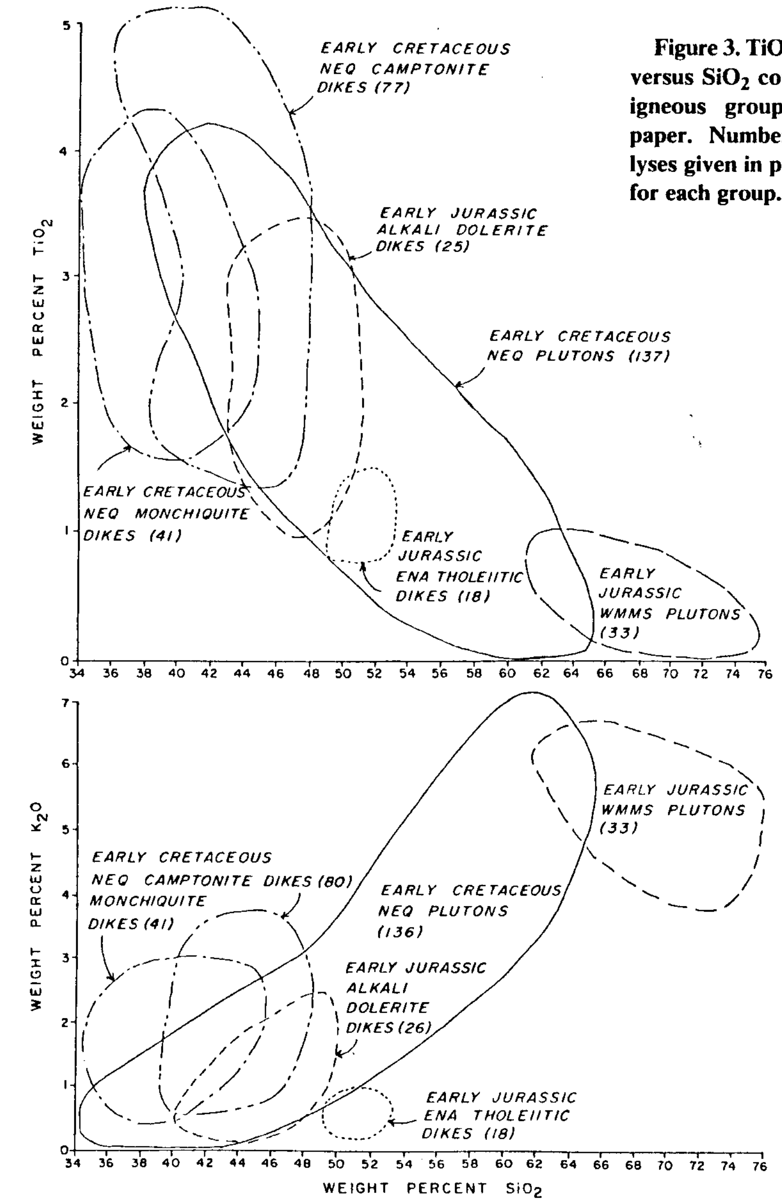

Figure 3. TiO_2 and K_2O versus SiO_2 compiled for igneous groups of this paper. Number of analyses given in parentheses for each group.

dike group in Alabama. Recently, Ragland and others (1983) suggested that the older and younger groups are olivine and quartz-normative, respectively, in the southern Appalachians. Such a chemical difference is not observed in the Mesozoic basins of southern New England, but it has not yet been sought for in dikes elsewhere in the region.

As shown in Figures 3 and 4, the alkalic dolerites of New England generally contain more than 1.6 wt % TiO_2, whereas the basalts and dolerites of the Mesozoic Connecticut Valley basin are less than that value. Although the three groups of quartz-normative basalts in Figure 4 were made using some samples from Connecticut (Weigand and Ragland, 1970), Puffer and others (1981) showed that the Connecticut basalts form a somewhat different, but overlapping pattern (Fig. 4). The olivine dolerite dikes of the southern Appalachians have much lower TiO_2 and higher MgO contents than do the olivine dolerites of New England. More radiometric dates and chemical analyses are needed to study the magmatic relationships among the ENA basalts and dikes of New England, but it seems likely that there are major differences in magma sources and styles of differentiation across the region.

WHITE MOUNTAIN MAGMA SERIES AND PROVINCE

The White Mountain Magma Series (WMMS) achieved recognition largely through the work of Billings (1956 and earlier) and his associates, building on a few older classic studies. The WMMS has often been used as as the group name for all Mesozoic intrusions found in northern New England, although the original studies concerned the large plutons found in central and northern New Hampshire, southwesternmost Maine, and northeasternmost Vermont (Fig. 1). Armstrong and Stump (1971), Foland and Faul (1977), Weston Geophysical (1977), and Loiselle and Hart (1978) produced and compiled radiometric data that limit the large plutons of the New Hampshire region to ages of about Early Jurassic (Fig. 2). When only plutons of Early Jurassic ages, contiguous New Hampshire occurrence, and characteristic petrology are included, the classic WMMS has a much more cohesive nature as a distinct province.

Creasy and Eby (1983) divided the WMMS intrusions among four petrologic associations: (1) gabbro-diorite-monzonite; (2) syenite-nepheline syenite; (3) alkali syenite–quartz syenite–granite; and (4) subaluminous biotite granite. Syenite and granite predominate by far, a composition that is reflected by geophysical measurements showing mainly negative to inconspicuous gravity anomalies (King and Zietz, 1978) and low magnetic anomalies (Zietz and others, 1980). An exception is the Mount Monadnock pluton in northeastern Vermont (Fig. 1). Although primarily syenite in surface exposures (Chapman, 1954), the Mount Monadnock pluton exhibits a sharply positive anomaly similar to that of gabbro-rich plutons in the region (Zietz and others, 1980).

The WMMS plutons are comparatively large. The White Mountain batholith of central New Hampshire is actually a composite of several intrusions, some of which have outcrop areas of 50 to 100 km^2 or larger, giving the batholith a total area of 1,009 km^2. Several other WMMS plutons are also larger than 50 km^2. The large WMMS plutons appear to be derived from widespread zones of melting in the lower crust of New Hampshire, probably from a type of basement lithology different from the Grenvillian terranes of Vermont and Quebec. As suggested by Loiselle and Hart (1978), Creasy and Eby (1983), and others, some of the smaller-volume lithologies could be derived from upper-mantle melts of alkali-basaltic affinities, thereby producing an overlap of chemical parameters (Fig. 3).

Chapman (1968) related the WMMS plutons (as then defined) to a network of north-northwest– and east-west–trending lattice lines that could reflect fracture controls on their emplacement. Other workers, most recently Morgan (1981), related the WMMS and other Mesozoic intrusions in New England to movement of the North American plate over a "hot spot," or mantle plume. Our boundary for the WMMS province results in an elongated north-south pattern (Fig. 1) that McHone (1982) compared with the Connecticut Valley and Champlain Valley to the west, perhaps as a series of north-trending faults and rift valleys active

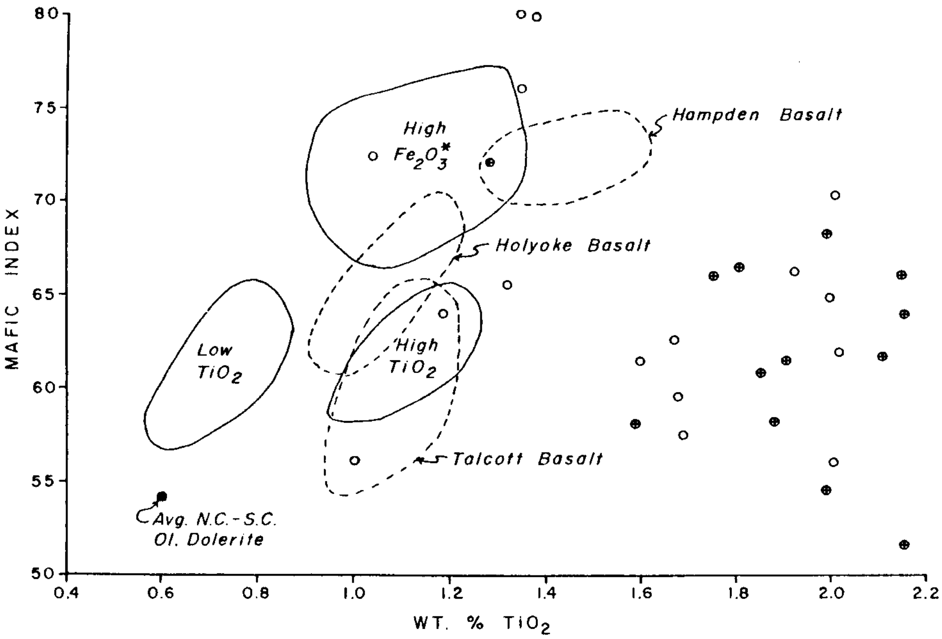

Figure 4. Mafic Index (Fe_2O_3*/Fe_2O_3*+MgO) versus TiO_2 compiled for ENA basalts and dolerites of New England. Fe_2O_3* is total iron calculated in the ferric state. Solid-line groups are quartz-normative basalts from Weigand and Ragland (1970), dashed-line groups are Connecticut basin basalts analyzed by Puffer and others (1981). Open circles and crossed circles represent quartz-normative and olivine-normative dolerites, respectively, from northern and southeastern New England (Pierce and Hermes, 1978; J. G. McHone, unpub. data).

during Jurassic time. There is little evidence for major faults along Chapman's (1968) lattice lines, and there is no significant progression of ages along the WMMS province (or within any of the New England igneous provinces), as suggested by the hot-spot model (McHone, 1981).

NEW ENGLAND–QUEBEC PROVINCE

The Monteregian Hills (MH) petrographic province, as defined by Adams (1903), includes 10 Early Cretaceous alkalic stocks and plugs, along with numerous lamprophyre dikes and sills (Gold, 1967; Philpotts, 1974), in a linear chain extending east-southeast for 110 km across southern Quebec (Fig. 1). Eby (1983) recognized three magma series in the MH intrusions: (1) pyroxenite-gabbro-syenite; (2) carbonatite–essexite-nepheline monzodiorite–foyaite–tinquaite; and (3) quartz syenite–granite. Radiometric ages are mainly between 110 and 130 Ma (Foland and Faul, 1977; Eby, 1983). Mount Megantic, somewhat far to the east of the main group (Fig. 1), is now usually considered an MH pluton even though it has petrologic characteristics more like New England plutons.

Kemp and Marsters (1893), Gold (1967), and Laurent and Pierson (1973) included the Early Cretaceous dikes and plutons of western Vermont with the rocks of MH, because of their petrological similarity. On the other hand, Early Cretaceous plutons of eastern Vermont and the rest of northern New England have traditionally been grouped with the WMMS. Foland and Faul (1977) and McHone (1978, 1981) pointed out the synchroneity of magmatism in Quebec and northern New England and the problem of the large time gap among the plutons if they are members of the WMMS (as previously defined).

Early Cretaceous lamprophyre dikes (for the most part camptonite) are petrologically identical in both Quebec and New England, and they form a continuous dike province among all the Early Cretaceous plutons of the region (McHone, 1978). The Early Cretaceous plutons of Quebec and New England have their own similarities. All are relatively alkalic (rich in K_2O) and, like most alkalic suites, are bimodal (gabbro + syenite). In some of the New England stocks, an abundance of unexposed gabbro, underneath exposed syenite, is indicated by geophysical anomalies. Relatively steep walls and the interior gabbro tend to produce sharply positive gravity and magnetic expressions for the Early Cretaceous plutons in both New England and Quebec (Gold, 1967; Griscom and Bromery, 1968; Sharp and Simmons, 1978). Chemical parameters such as $^{87}Sr/^{86}Sr$ tend to be similar for most of the rock types and indicate an upper-mantle parentage followed by considerable fractionation, perhaps partially through liquid immiscibility (Philpotts, 1976).

A distinctive biotite perthite granite—the Conway granite—is most abundant in the Early Jurassic WMMS plutons but also occurs in some of the Early Cretaceous New England plutons in and near the WMMS province area. The Conway granite is not found in western Vermont or Quebec and thus may be restricted to a particular basement domain in the New Hampshire region. Significantly, Loiselle and Hart (1978) ascertained that the Conway granite of the Belknap complex in central New Hampshire is not part of the crystallization sequence of most of that pluton. Typically, Conway-type granite is one of the final members to have been formed in each of the New Hampshire region complexes, whether Early Jurassic or Early Cretaceous in age, and so may have an independent origin by partial melting along an otherwise unrelated magma chamber in the crust.

Philpotts (1974), Kumarapeli (1978), and others emphasized the structural control that high-angle fault intersections exerted upon the emplacement of MH plutons and smaller intrusions in Quebec. East-west faults extend from the Ottawa graben to the west and intersect north-northeast–trending faults that are also continuous with Champlain Valley and eastern Adirondack fault systems to the south. The close association of the graben-forming faults with the Early Cretaceous intrusions is key evidence for mid-Mesozoic (100 to 130 Ma B.P.) activity of the St. Lawrence Valley rift system (Kumarapeli, 1978). McHone (1982) extended this model of tectonic-magmatic activity to include New England.

We support Foland and Faul's (1977) proposal that all of the Early Cretaceous intrusions of the region be considered as a single magma group. The name of New England–Quebec (NEQ) indicates the continuous nature of the province from southern Quebec through northern New England, over an area approximately 300 km by 400 km (Fig. 1). The Monteregian Hills can be considered as a subprovince of the NEQ province, and the NEQ province overlaps, but is independent from, the earlier-formed CNE, ENA, and WMMS igneous provinces.

NEW ENGLAND SEAMOUNTS

The New England Seamounts have been genetically linked to New England magmas in discussions by many authors, such as Foland and Faul (1977) and Crough (1981), so that their occurrence and nature are pertinent to this discussion. The seamounts form a chain of about 30 major peaks and many smaller hills (Fig. 5) extending from the upper continental rise southeast of Cape Cod for about 1,350 km southeasterly across the Atlantic Ocean floor (Vogt and Tucholke, 1979). The rocks of the New England Seamounts and other seamounts common in the western North Atlantic have alkali-basaltic chemistries and mineralogies (Sullivan and Keen, 1977; Houghton, 1979) that are much like those of NEQ mafic dikes.

The East Coast Magnetic Anomaly (ECMA) shows right-lateral offset of 45 km where intersected by the seamount chain (Schouten and Klitgord, 1977), and Bear Seamount, at the western end of the chain, is situated within the gap in the ECMA (Fig. 5). The ECMA is believed to be at the rifted edge of the continental crust, marking the final break in Early Jurassic time that initiated ocean-crust production. Bear Seamount may, therefore, be constructed on continental or transitional crust, and all other seamounts of the chain may have intruded and piled onto oceanic crust at some post–Early Jurassic time.

Linear magnetic patterns of the ocean floor are interrupted at and near the New England Seamount chain. Some writers have agreed that the seamounts are generally along an inactive transform fault, but estimates of the offset along the zone vary from 30 km (Vogt and Einwich, 1979) to 400 km (Barrett and Keen, 1976). Ocean-floor magnetic anomalies, as well as the ECMA, change strike by about 20° at the seamount chain (Barrett and Keen, 1976; Vogt and Einwich, 1979). The offset along the zone apparently diminishes eastward, so that the transform fault ends somewhere between the easternmost New England Seamount (Nashville), on ocean crust about 85 Ma old (Vogt and Tucholke, 1979), and anomaly 32, with an age of 70 Ma (Barrett and Keen, 1976).

The age of earliest volcanism forming the seamounts is impossible to determine without drilling into their cores. The oldest estimate for the ocean floor, near the ECMA, is 190 Ma (Vogt and Einwich, 1979); the youngest is 165 Ma (Sclater and others, 1977). Seismic stratigraphy shows that acoustic horizons J_2 and J_3 are present as sediments on oceanic basement in the vicinity of the seamounts; J_2 has an age of about 165 Ma, and J_3 is older, possibly about 170 Ma (Klitgord and Grow, 1980). Reflection-seismic profiles across Bear and Mytilus Seamounts (Fig. 5) indicate that the sedimentary layers flanking them are not folded, faulted, or metamorphosed (Uchupi and others, 1970), suggesting that the seamounts could have been at least partially constructed before the sedimentation.

$^{40}Ar/^{39}Ar$ ages of dredged volcanics from 6 of the seamounts range from 82 to 103 Ma (Duncan, 1982), whereas unpublished paleomagnetic data by M. A. Mayhew indicate formation ages of approximately 90 to 110 Ma. Recovery of Eocene and possibly Upper Cretaceous sediments from the tops of Bear and Mytilus Seamounts (Uchupi and others, 1970) also indicates that volcanism ceased before 55 to 38 Ma ago. Studies of drill cores from Vogel Seamount, near the center of the chain, and from Nashville Seamount farther east (Fig. 5) indicate that the last age of constructional activity was 94–88 and 94–80 Ma, respectively (Vogt and Tucholke, 1979).

There are two main theories regarding the origin of the New England Seamounts: (1) leaky transform fault (Uchupi and others, 1970), and (2) hot-spot trace (Morgan, 1981). The leaky-fracture model explains the positioning of the seamounts along the transform-fault zone and can be considered as an extension of continental fractures that controlled episodic magmatic events. However, if the volcanic activity along the seamount chain was progressional, as indicated by the data of Duncan (1982), some sort of propagation or gradational opening of the transform fracture must be hypothesized. In their studies of similar seamounts off the coast of Nova Scotia and Newfoundland, Barrett and Keen (1976) and C. E. Keen (1981, personal commun.) preferred a model for nearly simultaneous volcanism rather than any age progression.

With a maximum of 30 Ma separating magmatism in Quebec and the eastern New England Seamounts, ~2,000 km apart, a spreading rate of ~7 cm/yr is necessary over a fixed mantle plume in the hot-spot model. However, magnetic anomaly M4 (117 Ma old) and anomaly M34 (80 Ma old), both crossing the seamount zones, are only ~700 km apart and thus indicate a spreading rate of <2 cm/yr. Another problem with the hot-spot model is that it predicts uplift, or swelling, of the crust overlying the plume (Crough, 1981). Although this may be demonstrated in New England (Crough, 1981), Mesozoic sediments in the Georges Bank area and other zones along the proposed hot-spot trace in the Atlantic appear to be thick and unwarped (Klitgord and others, 1982).

Despite much discussion and analysis, well summarized by Foland and Faul (1977) and Vogt and Tucholke (1979), the problem of the origin of the New England Seamounts and their connection with the continental igneous prov-

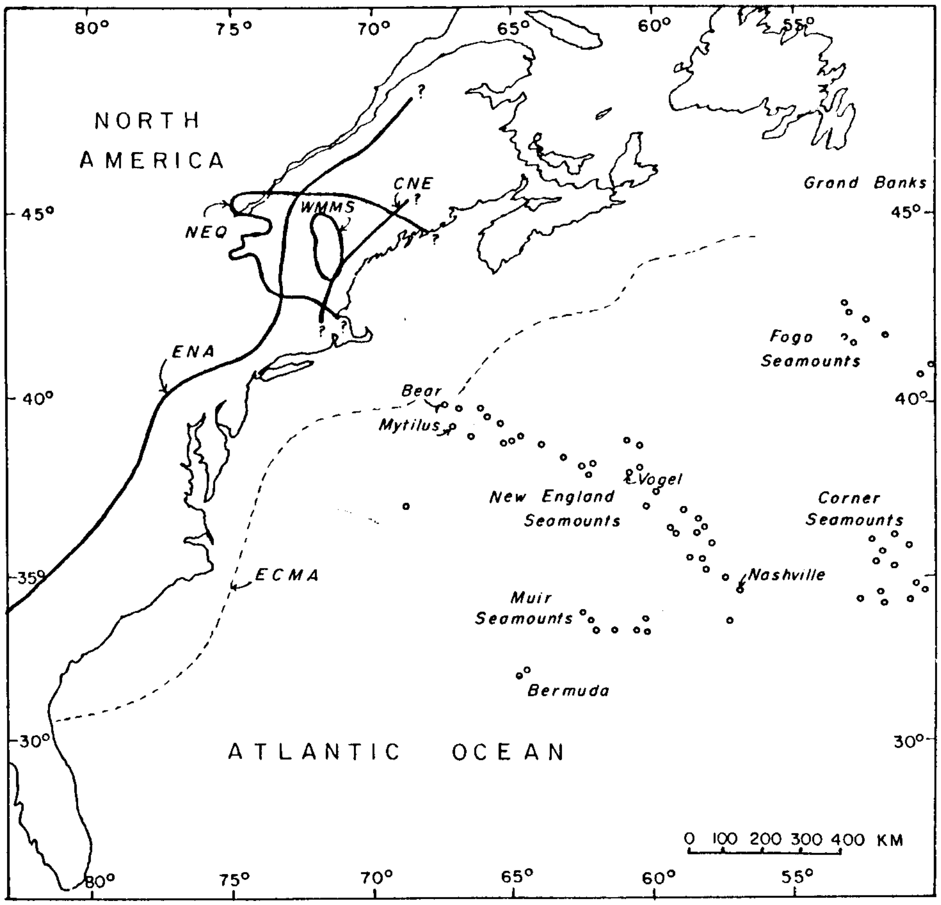

Figure 5. Locations of seamounts in the western North Atlantic Ocean relative to Mesozoic igneous provinces of this paper.

inces remains unresolved. The differences in mechanical and lithological properties between oceanic and continental lithospheres surely must have a role in complicating the models, but on the basis of our observations, we favor an extensional-fracture model that promoted similar Cretaceous NEQ and seamount magmatism.

EVENTS IN NEW ENGLAND RELATED TO THE OPENING OF THE NORTH ATLANTIC OCEAN

General

A summary of plate-tectonic events can be compiled entirely with data from the ocean basins, independently of assumptions about the oceanic influence on tectonic-magmatic events on the continents, and is shown in Figure 6. The timing of events depends heavily on recognition of linear magnetic anomalies in the oceanic crust and on dating of the anomalies at scattered localities by radiometric methods and fossils; published chronologies differ considerably but have tended to converge more recently, as new data accumulate. We use the chronology of Vogt and Einwich (1979) and Vogt and Tucholke (1979), who obtained an age of 190 Ma for initial formation of oceanic crust in the vicinity of the western New England Seamounts. As oceanic crust just east of the ECMA is a magnetic "quiet zone," correlation of magnetic stripes is difficult and the time of opening depends on spreading rates determined much farther offshore. Use of an estimate of faster spreading in the quiet zone thus gives an alternate initial opening age of 165 Ma (Sclater and others, 1977). Nearly all estimates are within the 190 to 165 Ma range.

As also discussed by Macintyre (1977) and others, there is a close correlation of ocean-margin and mid-ocean igneous and tectonic events around the Atlantic Ocean. The following discussions are meant to show this connection in the New England and western North Atlantic region (see Fig. 6).

Uplift and Rifting Stages

The last major compressional events in New England probably occurred during the late Paleozoic Alleghenian orogeny. Sedimentary rocks at least as young as Stephanian A (about 285 Ma old) in southern Rhode Island are strongly folded, metamorphosed to sillimanite grade, and intruded by the post-tectonic Narragansett Pier Granite (Skehan and others, 1979). Monazite and zircon dates by U-Pb methods indicate an age of about 275 Ma for the Narragansett Pier granite (Hermes and others, 1981). The Westerly granite intrudes portions of the Narragansett Pier granite but is considered to be an aplitic facies rather than a separate magmatic phase. The post-tectonic granite near Milford, southern New Hampshire, also appears to be about 275 Ma old, according to Aleinikoff and others (1979).

The peak of Alleghenian regional metamorphism reached sillimanite grade at about 260 ± 13 Ma ago (Skehan and others, 1979). The rocks were then rapidly uplifted, with temperatures declining to about 500 °C at 255 Ma ago and 300 °C at 245 Ma ago, on the basis of $^{40}Ar/^{39}Ar$ dates (Dallmeyer, 1982). A Permian disturbance of K-Ar dates from 230 to 260 Ma ago occurs in a north-northeast–trending belt from Long Island Sound to western Maine (Zartman and others, 1970) and may extend into the eastern Gulf of Maine (Ballard and Uchupi, 1975). Rifting in Late Triassic time therefore was preceded by broad domal uplift of southern New England, with maximum uplift apparently taking place in the Alleghenian orogenic belt and beginning soon after granite intrusion and the peak of metamorphism. The uplift caused a regional erosion surface that truncated rocks ranging in age from Pennsylvanian to Precambrian.

The rifting stage began with widespread formation of Triassic fault-bounded sedimentary

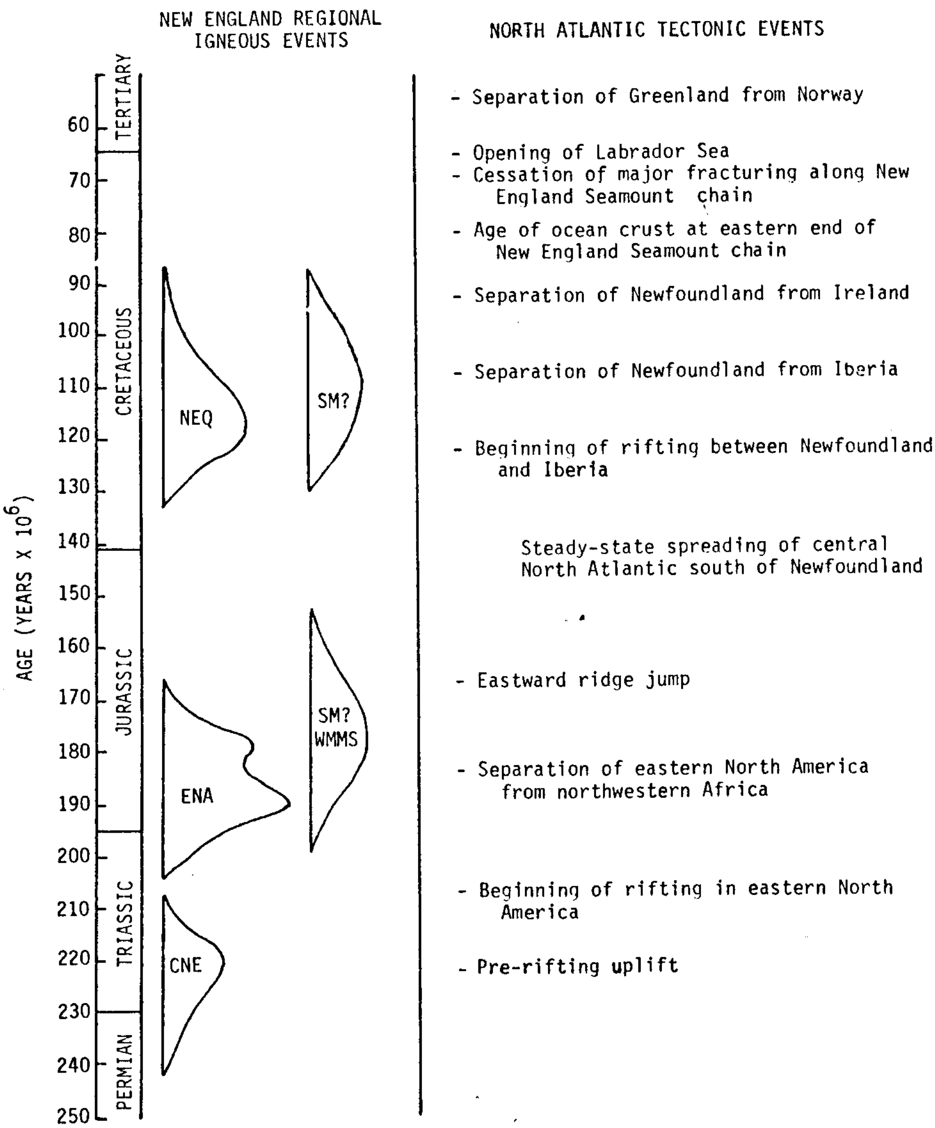

Figure 6. Correlation of igneous events (magmatic intensity) of New England with North Atlantic rifting and spreading events during the Mesozoic Era. Abbreviations as in text; SM = seamounts southeast of New England. North Atlantic events mainly after Macintyre (1977), Vogt and Tucholke (1979), Vogt and Einwich (1979), and Barrett and Keen (1976).

basins (Figs. 1 and 6), found in New England from southwestern Connecticut across to the ECMA on the east. These basins have a predominant north-south to northeast trend and are mainly bounded by similar-trending faults (Ballard and Uchupi, 1975; Wise, 1982). The north-south trend of the Connecticut Valley basin is unusual in eastern North America. Wise (1982) suggested that pre-Triassic structures controlled the basin orientation, as trends of master faults bounding the basin occur along westward-dipping flanks of the Bronson Hill anticlinorium. A family of normal faults striking N30°E contributes to the jagged nature of the basin margins and more accurately reflects the regional N60°W extension direction (Wise, 1982).

Sedimentation in the Connecticut Valley basin began in the Late Triassic, about 205 Ma ago, and the youngest beds are Early Jurassic, about 176 Ma old (Olsen and others, 1982). Exposed basins farther south in the Appalachians are somewhat older, with lowest units in North Carolina and southern Virginia being at least 210 Ma old. The Connecticut Valley basin is filled mainly with continental clastic rocks of fluvial and lacustrine origin (Hubert and others, 1978).

The age of the oldest sediments in the offshore rift basins is unknown, but they contain Upper Triassic beds and were at least locally filled by about 190 Ma ago, after which the sediments spread across broad areas of the continental shelf (Poag, 1982). The basins contain chiefly continental sediments, but thin evaporitic and carbonate units indicate brief marine incursions (Poag, 1982). Formation of marine evaporite basins on thinned continental crust occurred off Newfoundland in Late Triassic time (Jansa and others, 1980) and progressed southwestward, reaching the New England area by about the Early Jurassic (Klitgord and others, 1982).

The CNE intrusions (240 to 210 Ma old) were emplaced mainly or entirely before sedimentation began in the onshore basins, so that they represent intraplate magmatism correlated more with uplift than with rifting. The CNE intrusions are located in the northern part of the area, where K-Ar dates are disturbed by a Permian event (Zartman and others, 1970; Ballard and Uchupi, 1975) that may have continued into Triassic time in southern New England (Dallmeyer, 1982). We regard this Permian–Early Triassic uplift and magmatism as a distinct event precursing Atlantic rifting, perhaps in accord with Permian events near the British Isles and North Sea (Macintyre, 1977).

The ENA tholeiitic dolerites and basalts are part of a vast magmatic superprovince that surrounds most of the central and northern Atlantic (May, 1971). In the chronology of Figure 6, the most widespread magmatism at about 190 Ma ago is a brief episode very closely correlated with continental breakup. The occurrence of similar tholeiitic magmas over such a large area (Weigand and Ragland, 1970) and the systematic and continuous variation in dike orientations around the ocean basin (May, 1971; Ragland and others, 1983) also support the concept of a 190 Ma B.P. magmatic rifting event affecting much of central Gondwanaland. Several parental magmas are necessary to produce the varieties and distribution of ENA magmas, even within New England, and the ENA dikes may change character from quartz-tholeiitic through olivine-tholeiitic to alkalic basalts with increasing distance from the line of actual continental breakup (Pierce and Hermes, 1978; McHone and Trygstad, 1982). Smaller and more local ENA magmas (Sutter and Smith, 1979; Ragland and others, 1983) followed the main paroxysm.

Drifting Stage and Plate Reorientation

After the opening of the Atlantic, basaltic ENA magmatism ceased by 170 Ma ago. Overlapping ENA magmatism in time and space, but with completely independent characteristics, large quantities of granitic magma and variably undersaturated gabbro-diorite-syenite were generated in a relatively small region in New England as the WMMS province. One model of WMMS genesis (McHone and Butler, 1978) proposed a zone of melting in a thick crust by increased heat flow and/or volatile upwelling, partly mixed with upper-mantle melts and variably differentiated by crystal fractionation. The Conway granite was formed by partial melting of a distinct crustal type not found outside the New Hampshire area.

The elongate nature of the WMMS province could be caused by mantle upwelling along the continental remnant of an ancient transform fault or fracture zone with an extensional component, later reactivated and extended into the New England Seamount chain. More likely, the WMMS province reflects the location and orientation of a deep-basement north-south structure parallel to the Connecticut River Valley and Lake Champlain Valley to the west (Fig. 1). Partial melting of the lower crust took place where the continent was thickest, northwest of the domal Permian-Triassic uplift that had accelerated erosion and crustal thinning in southern New England. The WMMS therefore was localized where deep-basement structures became tectonically active in thick continental crust, under the influence of mantle convection during rifting to the east.

From 165 to 130 Ma ago, there was very little magmatic activity in New England. This span is within a period of steady-state spreading in the North Atlantic and coincides with a lapse in igneous events around the entire ocean basin (Macintyre, 1977).

Formation of the NEQ province required relatively small amounts of alkalic magmas to be generated over a large area (Fig. 1), emplaced as many hundreds of dikes, and as small plutons and stocks, unlike either the WMMS or the ENA provinces. The NEQ completely encloses the WMMS and most of the CNE provinces, as well as crossing part of the ENA province, and the conditions that caused the WMMS plutons to be large and felsic also had an influence on the NEQ plutons that occur within the WMMS province. Orientation of linear belts of NEQ plutons, such as the MH subprovince, apparently were localized by fractures in the lithosphere. Similar fracture and stress controls have been studied for dikes across northern New England (McHone, 1978). McHone and Butler (1978) proposed that camptonitic (basanitic) magmas, generated in the upper mantle, created both the abundant lamprophyre dikes by rapid movement into extensional fractures and the alkalic portions of the NEQ plutons by collection into slow-rising magma chambers that differentiated en route.

Formation of the NEQ province 100 to 130 Ma ago correlates with significant changes in the North Atlantic region, specifically, the rifting and separation of continental crust between Newfoundland and the Iberian Peninsula. Two intrusions that also may be correlative with the NEQ magmas occur southeast and northeast of the New England region, in the sedimentary wedge of the continental shelf. One, the Great Stone Dome, is a large Cretaceous mafic pluton that intruded into sedimentary rocks of the Baltimore Canyon trough, about 90 km southeast of the New Jersey coast (Grow, 1980). Extensive geophysical evidence indicates that probably there are no other similar intrusions anywhere in the continental shelf of the eastern U.S. (Grow, 1980). The second intrusion occurs in the continental shelf off Nova Scotia (L. F. Jansa and G. Pe-Piper, 1983, unpub. data), on line with the Fogo Seamount chain south of Newfoundland (Barrett and Keen, 1976), and it produced basanitic volcanics.

Magmatic activity in New England ended about 95 Ma ago, approximately the same time as did formation of ocean crust almost 1,700 km southeast of the region. Seamount volcanism continued after that time in many different areas of the Atlantic Ocean and nearby continental crust in other regions. Fission-track dates on apatite in New England indicate widespread uplift 130 to 80 Ma ago (Doherty and Lyons, 1980; Crough, 1981), but the data are not sufficient to clearly delineate the tectonic pattern. Future study of the Mesozoic geology of the New England region eventually will lead to improved understanding of the interaction of tectonism and magmatism, before, during, and after rifting.

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