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CONSTRAINTS ON THE MANTLE PLUME MODEL FOR MESOZOIC ALKALINE INTRUSIONS IN NORTHEASTERN NORTH AMERICA

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ABSTRACT

Mesozoic alkaline intrusions occur with elongate patterns of distribution in southern Quebec and central New England, and similar magmas formed the chain-like New England seamounts in the adjacent North Atlantic Ocean basin. Both igneous groups have been linked by a "hotspot" model in which the North American plate overrode a stationary mantle plume between 125 and 70 million years ago. Evidence for a hotspot plume includes mantle enrichment followed by melting to produce alkaline magmas, a progression of radiometric ages for the New England seamounts, and an apparent orientation of intrusions with plate motion. In keeping with the popularity of a mantle plume origin for all seamount chains, the model of a New England hotspot plume is often described as a demonstrated fact rather than as one of several hypotheses. Closer study reveals that major problems exist with a hotspot link between the seamounts and continental alkaline rocks in northeastern North America. In particular, many alkaline igneous intrusions in northeastern North America do not fit any plume track in age or geographic distribution, despite petrological similarities that imply a common origin. A deep columnar plume cannot be the principal cause of magmatism; rather, the geological evidence calls for widespread, heterogeneous source-areas in the mantle that produce alkaline basalts in concert with the tectonic re-activation of lithospheric structures, allowing isolated alkaline intrusions as well as linear chains to form through space and time.

Keywords: hotspot, New England seamounts, Monteregian Hills, Cretaceous alkaline plutons, Quebec, New England.

SOMMAIRE

Les complexes alcalins d'âge mésozoïque définissent une distribution quasi-linéaire dans le sud du Québec et la partie centrale de la Nouvelle-Angleterre, et des suites magmatiques semblables ont été mises en place dans une série de guyots dans le bassin adjacent de l'océan Atlantique. Ces deux groupes de roches ignées seraient des manifestations d'un seul point chaud. Selon ce modèle, la plaque tectonique de l'Amérique du Nord se serait déplacée latéralement par dessus un panache asthénosphérique stationnaire entre 125 et 70 million d'années passées. Sont cités en évidence d'un tel panache un enrichissement géochimique du manteau, suivi d'une fusion partielle, pour expliquer la formation de magmas alcalins, une progression des âges radiométriques dans la chaîne de guyots de la Nouvelle-Angleterre, et un alignement des complexes intrusifs en concordance avec la direction du déplacement de la plaque. Comme l'hypothèse d'un panache asthénosphérique est celle qui est la plus couramment retenue pour expliquer toutes chaînes de guyots, on traite souvent ce modèle de fait établi, plutôt que d'hypothèse parmi d'autres. Une étude plus approfondie révèle une série de problèmes importants avec l'idée que les guyots et les complexes magmatiques alcalins du nord-est de l'Amérique du Nord résultent d'un point chaud dans le manteau. En particulier, plusieurs des complexes intrusifs alcalins de ce secteur ne concorde pas avec le tracé proposé d'un panache asthénosphérique, soit par leur âge ou leur distribution géographique, malgré leurs ressemblances pétrologiques qui supposent une origine commune. Un tel panache ne pourrait pas être la cause principale du magmatisme; les observations géologiques requierrent plutôt des régions du manteau hétérogènes et régionales, propices à la production de magmas basaltiques alcalins lors de la réactivation tectonique de structures lithosphériques. Ces circonstances permettraient la formation dans l'espace et dans le temps de massifs intrusifs alcalins, soit en isolation, soit en chaînes linéaires.

(Traduit par la Rédaction)

Mots-clés: point chaud, guyots de la Nouvelle-Angleterre, collines montérégiennes, plutons alcalins crétacés, Québec, Nouvelle-Angleterre.

INTRODUCTION

Oceanic volcanoes and seamounts occur both as members of linear chains and as non-oriented clusters within ocean plates (*e.g.*, Epp & Smoot 1989). Although early models related them to ocean transforms and fracture zones (Marsh 1973, Sykes 1978), chains of seamounts are now generally ascribed to rising mantle plumes beneath moving plates (Burke & Wilson 1976). In contrast with oceanic regions, continental volcanic chains that correlate with plate motions are uncommon or difficult to recognize, despite the abundance of continental alkaline basalts and plutons. Even more rare are chains of plutons that could mark hotspot tracks across continent–ocean boundaries. One region in which continental alkaline plutons are commonly linked with a chain of seamounts is in New England and adjacent Quebec (Coney 1971, Crough 1981, Morgan 1983, Sleep 1990). However, there has been a tendency to oversimplify the evidence for a hotspot track across the New England region by ignoring important features that should apply to the mantle plume model. This paper is a discussion of problems with the proposed link of Cretaceous igneous rocks of the New England – Quebec province and the New England chain of seamounts.

By original definition, a "hotspot" is a place where igneous features (especially volcanoes) have formed through some mechanism not related to plate-margin magmatism. The term "hotspot" is now also used in reference to the assumed location of a plume within the mantle as well as to the geographic surface-point above a plume, even where that surface shows no volcanic features (*e.g.*, Epp & Smoot 1989). The success of the plume model in explaining the origin of chains of seamounts has led to the proposal that mantle plumes are necessary mechanisms for the production of alkaline basalts, both continental and oceanic (Burke & Wilson 1976). By their nature, mantle plumes are evidenced by a series of volcanoes or plutons as an age-progressive linear chain in the direction of plate motion. However, alkaline volcanic and intrusive rocks, particularly in continental areas but also in oceans, commonly occur in isolated structures or individual plutons that are not links of an age-progressive chain; these fit only the original (non-genetic) and not the more recent (mantle plume) usage of the term "hotspot". Also, many alkaline magmas are associated with continental rifts that are not caused by plumes (Moreau *et al.* 1987, Bradshaw *et al.* 1993, Anderson 1994, Pederson & van der Beek 1994), and so some authors confine plume-generated magmas to demonstrable volcanic–plutonic age-progressive chains, or "hotspot tracks" (Morgan 1983). A distinction is then made among "types" of hotspots (Sleep 1984, Marzocchi & Mulargia 1993), which implies different mechanisms for the origins of very similar alkaline basalts.

Critical arguments concerning a hotspot track in northeastern North America should center upon the ages and geographic patterns of its Mesozoic alkaline igneous rocks. A model of an independent mantle plume, as proposed for only some of the alkaline magmas in New England, must be reconciled with petrological similarities among many other intrusions widely distributed in space and time, but which are not part of a hotspot track. Whatever mechanism was actually in force should work anywhere, in continents as well as in oceans, and it should suffice for any occurrence of alkaline intraplate magmas.

Mesozoic Igneous Provinces

Mesozoic igneous rocks of eastern North America have been described elsewhere (McHone & Butler 1984, de Boer *et al.* 1988, Jansa & Pe-Piper 1988). Although intrusions such as kimberlites and some seamounts appear to be relatively isolated, most plutons are members of geographic and temporal groups that occur within bounded provinces (McHone & Butler 1984). Figure 1 includes Jurassic and Cretaceous plutonic intrusions and provinces, but it omits the more wide-ranging Early Jurassic Eastern North American tholeiitic dikes and flood basalts that occur along the entire seaboard (de Boer *et al.* 1988). Such tholeiitic basalts were produced during Jurassic ocean-opening events that preceded most of the alkaline hotspot magmas, and they possibly include a thick basaltic wedge that is responsible for the East Coast magnetic anomaly (ECMA on Fig. 1; Holbrook & Keleman 1993). Although opinions vary concerning their origin (*e.g.*, de Boer *et al.* 1988), the Early Jurassic tholeiites do not have characteristics of plume-related magmas.

Intrusive complexes of the White Mountain magma series (WMMS), mainly of Early Jurassic age, are located in central and northern New Hampshire, where they form a roughly NNW-trending belt of large syenite – monzonite – alkali granite plutons (Fig. 1; McHone & Butler 1984). Most radiometric dates are between 190 and 160 Ma, but several smaller plutons in the province are considered to be older by 10 to 30 Ma (Foland & Faul 1977). Crustal structures (faults and folds) are not correlated with the pluton trend of the Jurassic WMMS rocks (McHone & Shake 1992). Many hundreds of tholeiitic to mildly alkaline basaltic dikes, most of which appear to be Early Jurassic, maintain a northeasterly trend across and among the WMMS plutons (McHone 1984). The Conway granite is a late member of both the Early Jurassic WMMS and the more strongly alkaline Early Cretaceous plutons in New Hampshire, indicating a common origin from partial melting of the same crust.

Early Cretaceous magmatism in southern Quebec and northern New England produced the classic Monteregian Hills intrusions (Eby 1984) in Canada, as well as several complexes in Vermont, New Hampshire, and southern Maine (McHone & Butler 1984). Both Si-saturated and Si-undersaturated rock types are well represented, with gabbro and syenite most common. Several thousand Early Cretaceous lamprophyre dikes in the region form a continuous dike-swarm among and cross-cutting all of the coeval plutons, overlapping the older WMMS province as well (Fig. 1). McHone & Butler (1984) grouped all of

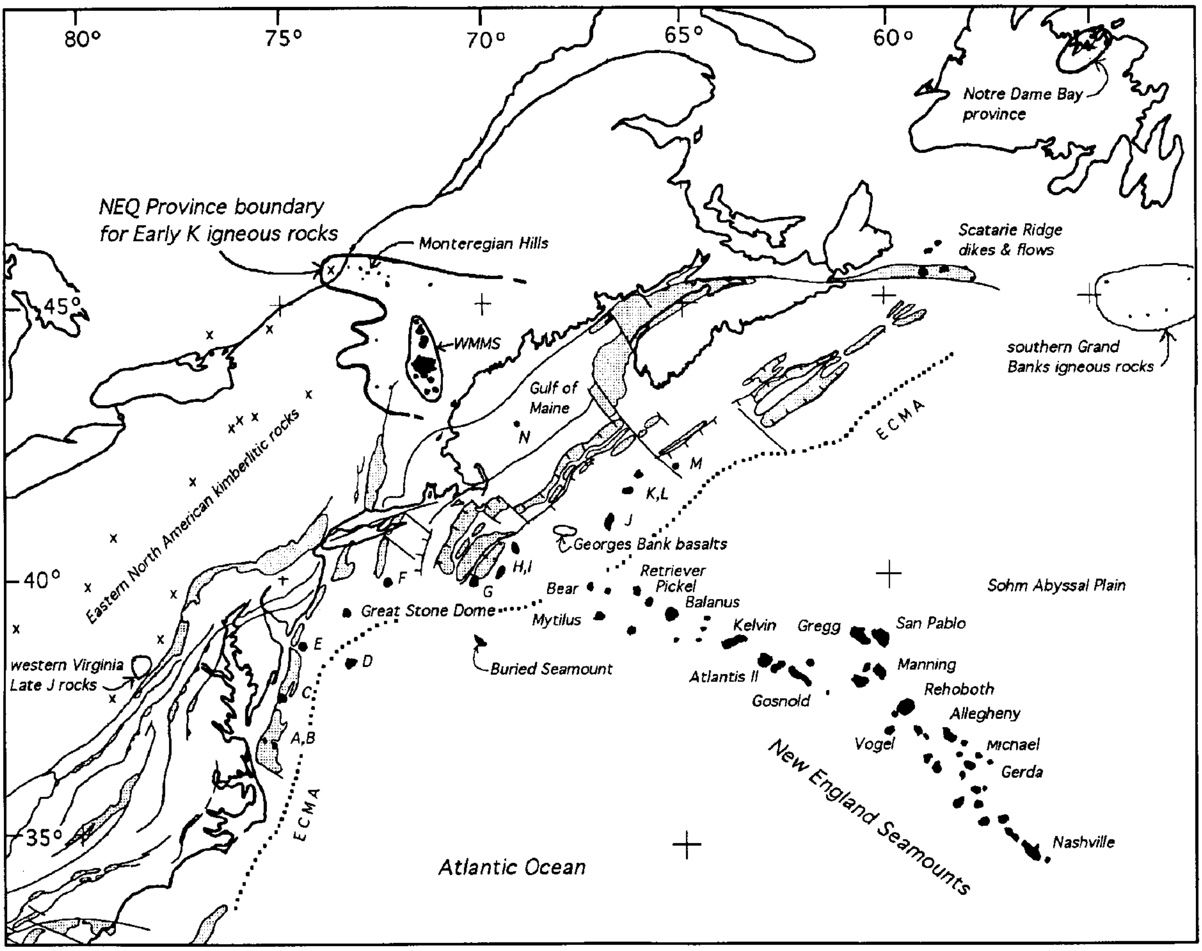

FIG. 1. Mesozoic continental and oceanic igneous features of northeastern North America. Plutons, volcanoes and seamounts are shown in solid black, with heavy lines showing province boundaries. Kimberlites and ultramafic intrusions are located by × symbols. Plutons A through N are inferred from geophysical anomalies (Klitgord *et al.* 1988). Late Triassic – Early Jurassic sedimentary basins are shown by shaded zones, and solid lines mark Mesozoic faults. NEQ is the New England – Quebec igneous province of McHone & Butler (1984), WMMS is the White Mountain magma series, and ECMA is the East Coast magnetic anomaly. Early Jurassic tholeiitic basalts and dikes are not shown. Most features are adapted from Figure 1 of Jansa & Pe-Piper (1988), Plate 2C of Klitgord *et al.* (1988), and Figure 1 of Swift *et al.* (1986).

the Early Cretaceous dikes and plutons under the name New England – Quebec (NEQ) igneous province.

Dike and pluton trends vary across the NEQ province. Major trends are near N65°W in southern Quebec, almost E–W in west-central Vermont, and between N45°E and N60°E throughout southern Vermont and the rest of New England (McHone 1984). The northeasterly trends of the Cretaceous dikes mimic trends of earlier Jurassic and Triassic dikes in the same region. Dike trends of the NEQ province correlate also with some major topographic and geophysical lineaments, and there are strong correlations of the topographic lineaments with regional fracture-zones (McHone & Shake 1992). West–northwest-trending lineaments through the area are parallel to the New England chain of seamounts of the adjacent Atlantic basin (McHone & Butler 1984).

Late Jurassic to Early Cretaceous plutonic provinces (Fig. 1) also are found in Newfoundland (Strong & Harris 1974) and western Virginia (Rader *et al.* 1986). The rock types are remarkably similar to those of dikes and plutons in the NEQ province. Kimberlites and related ultramafic dikes are scattered in a linear belt in the Allegheny plateau and western Appalachians from Tennessee northeastward to the western edge of the Monteregian Hills of Quebec (Fig. 1). The only well-established dates are for Late Jurassic kimberlites in central New York State (de Boer *et al.* 1988).

The New England seamounts comprise an irregular chain of many small and large volcanic suboceanic mountains that extends at least 1000 km southeastward from the continental rise (Fig. 1). In common with many other mid-plate volcanoes, dredged and drilled samples of the New England seamounts display mainly alkaline hypabyssal basalts and volcanic rocks (Duncan 1984, Taras & Hart 1987). Initial models related the New England seamounts to fractures either propagating from the continent or continuous with ocean-ridge transforms (Uchupi *et al.* 1970, LePichon & Fox 1971, Sykes 1978). The interpretation of the New England seamounts in terms of a trace of a mantle plume was proposed by Coney (1971) and developed by Morgan (1971), Crough (1981), Sleep (1990) and others. This model received a strong endorsement from Duncan (1984), who found evidence for an age progression along the chain that appears to be consistent with plate motions. Most of these authors also link the track of seamounts with the belts of Monteregian and New England Mesozoic plutons. Although commonly described as a "well-established" hotspot or plume track (de Boer *et al.* 1988, Sleep 1990), other petrologists consider the plume model for these ocean and continental rocks to be problematic (McHone 1981, Lameyre *et al.* 1984, Swift *et al.* 1986, Jansa & Pe-Piper 1988, Hale & Friberg 1995).

Although attractive in its simplicity and generality for explaining intraplate magmas, the hotspot–plume model fails for some important igneous features of the New England region. The following observations are intended to provide counterpoints to specific aspects of the model for a mantle plume and hotspot track of alkaline magmas through New England, across the continent–ocean border, and into the western Atlantic Ocean basin.

Problems with the Hotspot Model

Many WMMS (Jurassic) magmas are petrologically similar to NEQ (Cretaceous) magmas

The original proposal for a New England hotspot track included all of the White Mountain magma series (WMMS) of New Hampshire (Morgan 1971), which are mainly Early Jurassic in age. The WMMS has since been described as a province separate from the larger region of Cretaceous intrusions (McHone & Butler 1984). Several Triassic plutons also are known, which may themselves form an independent igneous province. Although mainly granitic and syenitic rocks comprise the WMMS, many Early Jurassic alkaline dikes and several mafic to felsic plutons also in the province are petrographically and chemically similar to Early Cretaceous intrusions that overlap. Because the proposed trace of the New England hotspot commenced to the northwest of New Hampshire and continued far beyond it, the WMMS plutons and volcanic rocks cannot represent an early expression of the same mantle plume.

If we require a similar origin for similar rocks, an earlier plume could be proposed that was coincidentally within the track of a later Cretaceous plume. Alternatively, a long-lived lithospheric tectonic zone might control the geographic overlap of similar magmas of different ages, as discussed in a later section. The generation of basanitic and nephelinitic magmas requires the generation of enriched melts from mantle within or below the base of the lithosphere, but whether or not the same mantle must maintain a connection or move with the continental plate is unclear.

There is little evidence of age progression along 400 km of the NEQ province

Paleomagnetic poles measured for the Monteregian Hills and selected plutons through southeastern New Hampshire are statistically similar (Van Fossen & Kent 1992), in agreement with the short 122–124 Ma Ar–Ar age range reported by Foland *et al.* (1986) and Hubacher & Foland (1991) for some of the same intrusions. The cluster of magnetic poles measured by Van Fossen & Kent (1992) is also broad enough to match other North American paleomagnetic poles as young as 88 Ma, or about the age of seamounts measured by Duncan (1984) in the central part of the New England chain of seamounts (Fig. 2).

An important observation is that the 122–124 Ma magmatism was apparently concurrent over a large area of the continent. Other Rb–Sr, K–Ar, and fission-track measurements of Monteregian rocks range between 118 and 136 Ma (Eby 1984), and NEQ intrusions across central New England have been assigned dates from 101 to 136 Ma (see the compilation by McHone 1984). There is no consistent trend for published ages of Cretaceous alkaline intrusions in any direction across the region (Fig. 1 of McHone 1981). K–Ar and Rb–Sr whole-rock and mineral dates appear to cluster around 115, 125, and 135 Ma within the Champlain Valley lobe across the Vermont – New York border (McHone & Corneille 1980). In the northern Taconics region approximately 100 km farther south, the Cuttingsville complex and associated dikes consistently give an age between 100 and 110 Ma (McHone & McHone 1993), whereas 50 km to the east of Cuttingsville, the Ascutney pluton and associated dikes give an age near 122 Ma (Hubacher & Foland 1991).

Seamount volcanism is not limited to hotspot-progression ages

Duncan (1984) compiled and measured both K–Ar and Ar–Ar whole-rock and mineral dates for dredged and drilled samples from tops and flanks of New England seamounts. Most dates range between 80 and 95 Ma along various seamount positions of the chain, except for a cluster of $^{40}Ar/^{39}Ar$ whole-rock dates around 101 Ma for the westernmost (Bear) seamount

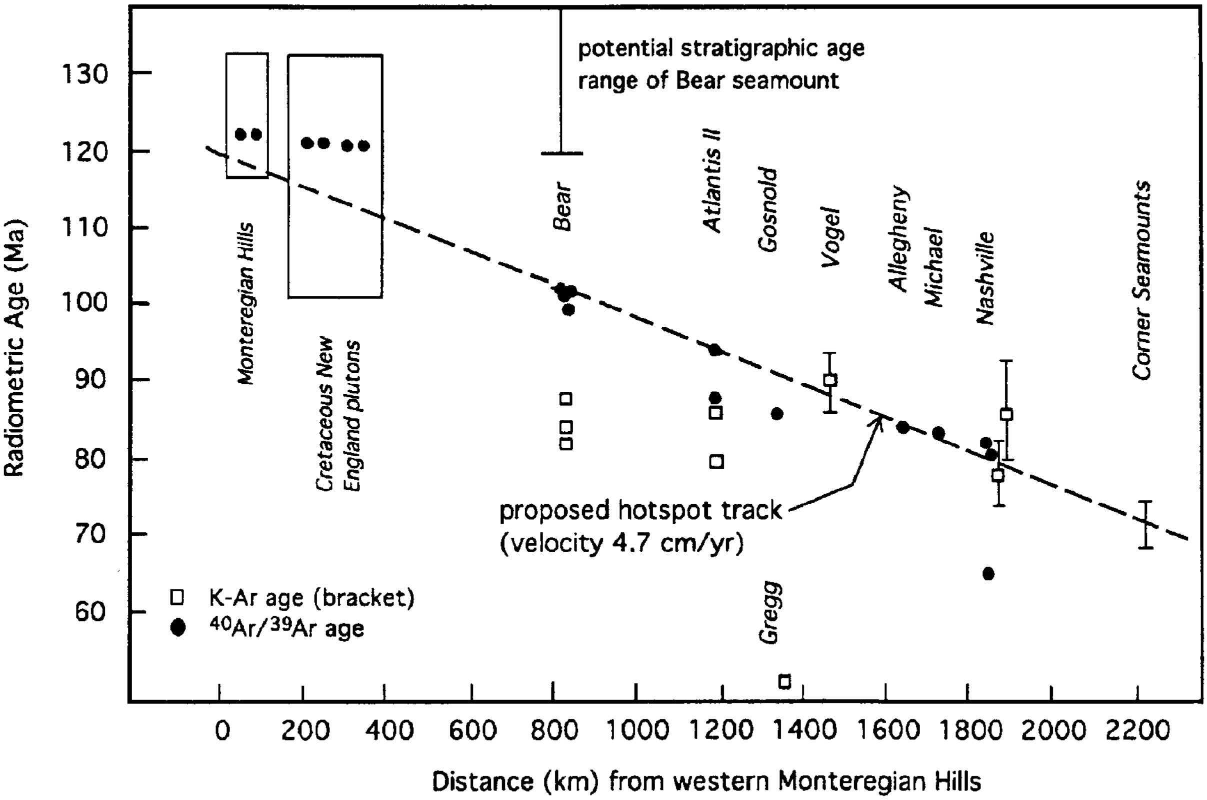

FIG. 2. Radiometric ages along the proposed New England continent–ocean hot-spot track. Modified from Figure 2 of Duncan (1984), with additional dates from Eby (1984), McHone (1984), Foland *et al.* (1986) and Hubacher & Foland (1991). The stratigraphically established minimum age for the Bear seamount is given in Swift *et al.* (1986). Older (Jurassic and Triassic) alkaline rock ages of the WMMS and New England are not part of this track and are omitted.

(Fig. 2). Using the Bear cluster and a tenuous connection to the 70–75 Ma Corner seamounts (a separate group about 400 km eastward of the Nashville seamount), Duncan (1984) proposed a linear progression that also fits most of the oldest $^{40}Ar/^{39}Ar$ seamount dates. This same line trends into the younger ages measured for the Monteregian Hills, as well as for some (but not all) of the New England intrusions (Fig. 2). Duncan (1984, p. 9982) suggested that the dates that do not fit this line, many of which were obtained by the K–Ar method, are unreliable or less important to the supporting evidence of an age progression through the continental province and seamount chain.

If one maintains an analogy with the continental intrusions, the radiometric and geological evidence for the seamounts also suggests that their volcanic activity was not limited to ages defined by the linear hotspot-track. Rock samples from the top or flanks of the seamounts may only date relatively minor volcano-capping phases of igneous activity. More importantly, stratigraphic evidence indicates that the Bear seamount was present before 120 Ma (Swift *et al.* 1986) and that the Mytilus seamount was sufficiently active to form an oceanic island in mid-Tertiary time.

New England provinces are not on line with the seamounts

The New England chain of seamounts is not very linear. As is shown in Figure 1, the eastern section (Nashville to Gregg) trends toward southernmost Nova Scotia, whereas the western section is on line with southernmost New England. Neither section trends toward the NEQ province of central New England and Quebec. The Georges Banks basalts (Hurtubise *et al.* 1987) could represent a nearby continuation of the seamounts, but an undated pluton in the Gulf of Maine ("N" in Fig. 1; Klitgord *et al.* 1988) is the only potential link in a conspicuous gap of Cretaceous rocks between the seamounts and southeastern New England.

The segmented pattern of seamounts is similar to patterns formed by smaller sections of the continental igneous rocks, such as the northwest–southeast elongate pattern of the Monteregian Hills, and westward-trending lobes of dikes and plutons in western New England (McHone 1984). The Jurassic White Mountain magma series forms its own roughly north–south group in New Hampshire (Fig. 1). Dike swarms within sections of the NEQ province also show distinctive linear groups and trends, which McHone & Shake (1992) ascribed to structural controls such as fracture zones within the upper crust. Both continental and ocean-island igneous complexes commonly show structural orientations of fractures and dikes that have been repeated through time. For example, the Canary Islands show distinct rifts and dike zones that have been active from the Late Cretaceous to the present (Carracedo 1994).

Many other seamounts and continental plutons are not on a hotspot trace

It is also possible that the New England chain of seamounts actually trends westward near the continent–ocean boundary (marked by the ECMA, Fig. 1) so that it connects with the Great Stone Dome and other geophysical anomalies (A–I, Fig. 1) that probably represent Cretaceous plutons or volcanic plugs (Jansa & Pe-Piper 1988, Klitgord *et al.* 1988). However, the continental margin plutons and geophysical anomalies (A–M, Fig. 1) essentially form their own northeasterly line that trends toward the Early Cretaceous Scatarie Ridge dikes and flows off shore from Nova Scotia (Fig. 1, Jansa *et al.* 1993). Similar alkaline dikes and plutons occur farther to the northeast around Notre Dame Bay, Newfoundland (Fig. 1; Strong & Harris 1974) and to the east in the southern Grand Banks (Jansa & Pe-Piper 1988, Pe-Piper *et al.* 1994). To the southwest, Late Jurassic alkaline plugs and dikes are known in a limited area of western Virginia (Fig. 1; Rader *et al.* 1986).

The northeasterly trending continental margin plutonic line roughly parallels a linear group of kimberlites and kimberlitic intrusions in the interior of eastern North America (Fig. 1). Although radiometric ages for the kimberlites vary, they could all be late Jurassic in age, and Crough *et al.* (1980) and Crough (1981) proposed that these and other kimberlites also may mark Mesozoic mantle plumes. This and other northeast–southwest linear groups are difficult to reconcile with plate motions, however, and a lithospheric fracture – tectonic control is more widely accepted (Parrish & Lavin 1982, Jansa & Pe-Piper 1988).

There is little evidence for uplift from heating along a plume track

Crough (1978) noted that many volcanic regions are also topographic highs, or swells. This is especially evident on the ocean floor, which subsides as it ages and cools away from ocean ridges and seamount activity. Crough (1981) proposed the same effect for the New England area in Cretaceous time, citing especially the Adirondack dome to the west of the track as well as other basement highs to the northwest of the track in Canada. Sleep (1990) utilized this conclusion as evidence for changes in the "buoyancy flux" of the proposed mantle plume. Crough (1981, pers. comm.) expressed doubts that a mantle plume is capable of mechanically lifting the overhead lithosphere, nor could it significantly heat the lithosphere by conduction from below. Instead, hotspot swells could be expected to result from lithospheric expansion by heat from magmas injected within the lithosphere, thus an indirect result of any mechanism for magmatism.

Topographic highs of the southern and northern Appalachians, and the Bermuda Rise of the western Atlantic, contain Cenozoic alkaline igneous rocks (de Boer *et al.* 1988), but do not conform to traces of any known hotspot (Vogt 1991). Various estimates of Mesozoic and later uplift of central New England have been based upon fission-track studies (Doherty & Lyons 1980), stratigraphy (Zen 1991), and Ar–Ar isotopes (West *et al.* 1993). Estimates of 3 to 8 km of erosion are common, especially near major high-angle faults. However, as well discussed by Zen (1991), the presence of both Jurassic and Cretaceous volcanic rocks in New England constrains the amount of uplift and erosion to no more than 2 to 3 km for associated plutons on the hotspot track. Maps of formation boundaries and structures in central New England show no particular patterns of deformation that would indicate greater uplift than in other sections of the Appalachians, although small differences might be difficult to discern.

In support of an uplift zone, Triassic–Jurassic sedimentary basins are apparently small or absent within the Gulf of Maine along the hotspot track (Klitgord *et al.* 1988). It is conceivable that this conspicuous gap between the Bay of Fundy and the Hartford basin of southern New England (Fig. 1) is due to deeper erosion of early Mesozoic sediments. The general scarcity of Cretaceous plutons between New England and the New England seamounts provides no help to the model of uplift by magmatism in this area. Other Cretaceous plutons along the continental margin, such as the Great Stone Dome and Scatarie Ridge intrusions, are associated with small domal uplifts (Jansa & Pe-Piper 1988), but not large anomalous swells or anticlines that might affect patterns in nearby Mesozoic basins (Fig. 1).

There is no consistent chemical signature of a mantle plume

Geochemical characteristics that are proposed to mark plume-derived basalts include enrichment in volatiles, large-ion elements, light rare earths, and radiogenic Sr–Nd–Pb isotopes (Wilson 1993); many of these characteristics are considered to be derived from long-lasting mantle zones or reservoirs that underlie the depleted upper mantle. Chemical enrichment of mantle zones could also result from migration of fluids (Nielson & Wilshire 1993), older magmas frozen in the mantle (Sleep 1984), or sections of subducted crust (Pegram 1990). The depths of such zones are poorly constrained. A plume should contribute magmas or fluids that mix with shallow-mantle melts, because the plume itself must melt as it rises (Sleep 1984); its heat is also transferred better by injecting its melts than by much slower conduction through adjacent solid mantle (Crough 1978).

Eby (1985) found that radiogenic Pb had been added to relatively depleted mantle before the generation of alkaline New England – Quebec continental magmas, possibly as a metasomatic event. Among the New England seamounts, Taras & Hart (1987) found essentially random variations of trace elements and isotopic characteristics, with no geographic trends except for higher levels of radiogenic Pb toward the southeast. The involvement of several different mantle sources is likely, including a less-radiogenic Pb source for the New England – Quebec igneous rocks (Eby 1985, Taras & Hart 1987). Cretaceous alkaline rocks from eastern Canada also have different trace-element and isotopic compositions (Pe-Piper *et al.* 1994), with no consistent compositional relationship to one or more mantle plumes.

Discussion

The Cameroon line of west-central Africa presents the most likely analogy with the New England pluton – seamount line. The Cameroon line extends nearly 2000 km from central Africa southwestward, crossing into the Gulf of Guinea (South Atlantic Ocean crust). The line contains at least 17 volcanoes and 60 continental plutonic complexes that show igneous activity over a 65 Ma time span (latest Cretaceous through Cenozoic), but with no age progression in the continental expressions of magmatic activity (Moreau *et al.* 1987). The line includes three oceanic islands that have all been active within the last 5 Ma, but with their oldest rocks decreasing in age from 31 Ma to 4.8 Ma oceanward (Lee *et al.* 1994). Moreau *et al.* (1987) demonstrated a strong correlation of the Cameroon line with a zone of lithospheric faults and other structures, consistent with other conclusions for structural controls of magmatism in Africa (Bailey 1992). Although Lee *et al.* (1994) proposed that the three oceanic islands mark the track of a mantle plume, they described the presence of a "hot zone" of enriched sublithospheric mantle that produced similar continental magmas over a long period, in response to tectonic controls in the lithosphere.

Crustal structures that extended in response to larger plate-tectonic events are therefore a common regional characteristic of alkaline igneous rocks in western Africa, New England – Quebec, and eastern Canada, although not to the degree of major rift-zones of eastern Africa and the western United States. Variations in basalt chemistry in continental rifts also have been related to lithospheric thinning along preexisting crustal structures, which produced mantle upwelling in the rift zone and decompressive melting of the lower lithosphere and upper mantle (Bailey 1992, Bradshaw *et al.* 1993, Pederson & van der Beek 1994).

The question continues as to exactly what constitutes a mantle plume, and of what characteristics a mantle plume must impart to alkaline and other basaltic magmas. Studies of mantle xenoliths provide support for ideas of lateral and vertical heterogeneity in the mantle, as well as for intramantle melts that change composition with migration (Nielson & Wilshire 1993). A heterogeneous suboceanic mantle (perhaps with zones of ancient plume-related material) can explain many of the variations found in ocean-basalt chemistry (Sleep 1984). Many alkaline and tholeiitic basalts show patterns of element enrichment that were apparently influenced by ancient subducted crust within the upper mantle (Wittke *et al.* 1989, Pegram 1990). The magmatic contributions of deep-mantle plumes, if any, must be masked by melts from these mantle heterogeneities. Finally, seismic tomography models of the upper mantle clearly show large domains of high temperatures that cannot be tied to hotspot plumes (Anderson *et al.* 1992). A very wide domain of high temperatures may be expected for magmatism that was nearly simultaneous in the separated igneous zones of northeastern North America (Fig. 1).

One or even several deep-mantle plumes do not provide a satisfactory mechanism for producing the Cretaceous alkaline rocks of northeastern North America and the adjacent western Atlantic. If altered compositions of mantle are reflected in alkaline basalts, perhaps additional samples of the ocean seamounts, continental plutons, and xenoliths in dikes will outline where and how mantle zones of the proper enrichment are formed. If an extended enriched zone within the upper mantle is a common link for magmas for New England and the seamount chain, there must also be other, smaller zones that have contributed magmas over much shorter time-spans into true non-track hotspots in the continent and ocean crusts. In both cases, lithospheric tectonic actions were necessary to start and stop the generation of magmas from the same sources in the mantle. New petrological studies should emphasize the local and regional tectonic features that could act in concert with larger-scale rifting events and movements of plates around and beyond the Atlantic Ocean basin, as controls of the generation and emplacement of alkaline magmas.

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