Igneous Features and Geodynamic Models of Rifting and Magmatism Around the Central Atlantic Ocean

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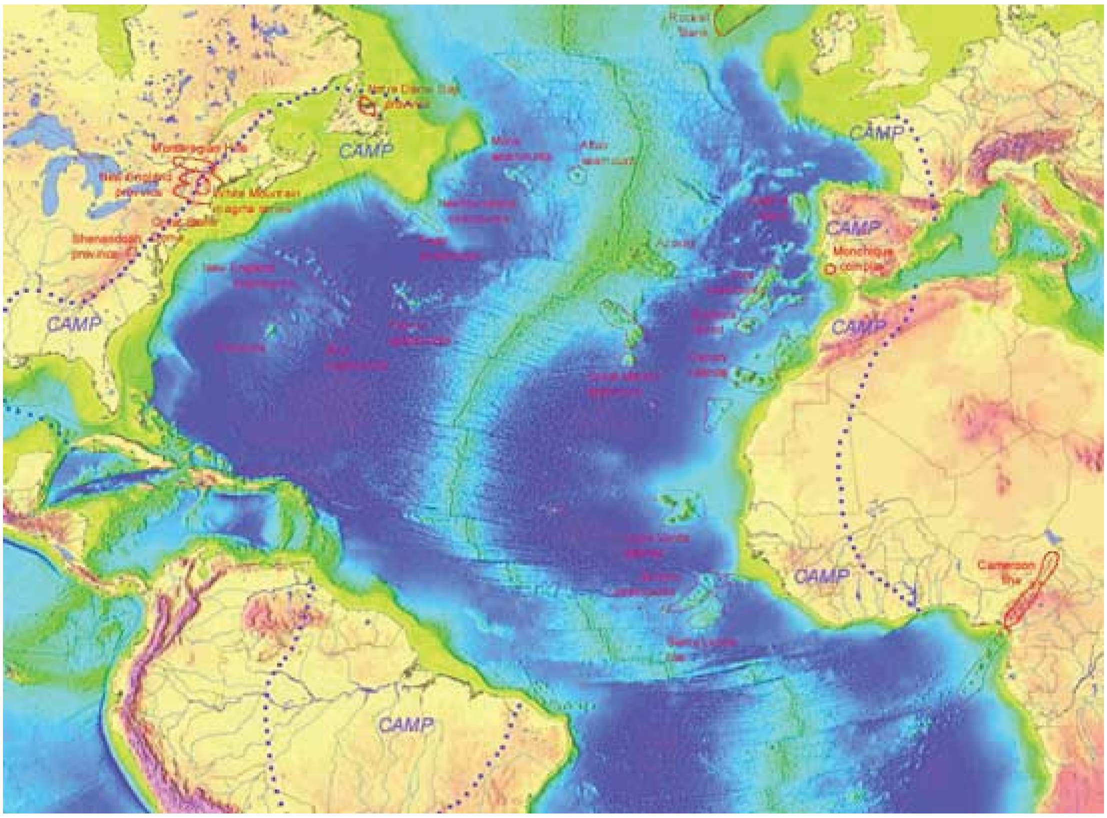
Introduction

The early history of the central Atlantic Ocean basin is receiving new interest from studies of a vast tholeiitic flood basalt province that was active over 10 million km^2 of central Pangaea, starting about at 201 Ma during continental rifting, and before the initiation of new ocean crust (*Hames et al.*, 2002). This newly-recognized LIP is known as the Central Atlantic Magmatic Province, or CAMP (*Marzoli et al.*, 1999), and it apparently evolved into the mid-ocean rift production of Atlantic Ocean crust, starting in the Early Jurassic and continuing into the present.

After the initial split of Pangaea, little igneous activity occurred within the central Atlantic Ocean during the next 70 Ma, outside of ocean ridge volcanism. In the Early Cretaceous, numerous alkaline igneous plutonic/volcanic complexes developed in widely separated continental margin regions of eastern North America, Iberia, and western Africa. Subsequently throughout the Cretaceous and Cenozoic Periods, similar alkaline igneous events have marked many regions of the Atlantic seafloor with more than a hundred seamounts and volcanic islands.

In contrast to the brief but enormous pulse of Early Jurassic CAMP magmatism, the Cretaceous and younger continent margin/ocean basin volcanoes were mainly local and independent events, with individual histories of activity. Despite the time gap of 70 Ma and the compositional gulf between quartz tholeiites and alkali olivine basalts, some geologists have attempted to connect and explain these different igneous features through a model of a deep mantle plume. However, such models do not explain the geographic patterns and petrologic histories of numerous volcanic features in and around the central Atlantic Ocean, which must therefore be products of upper-mantle tectonics and lithospheric rifting. This paper is a brief discussion of these features and models.

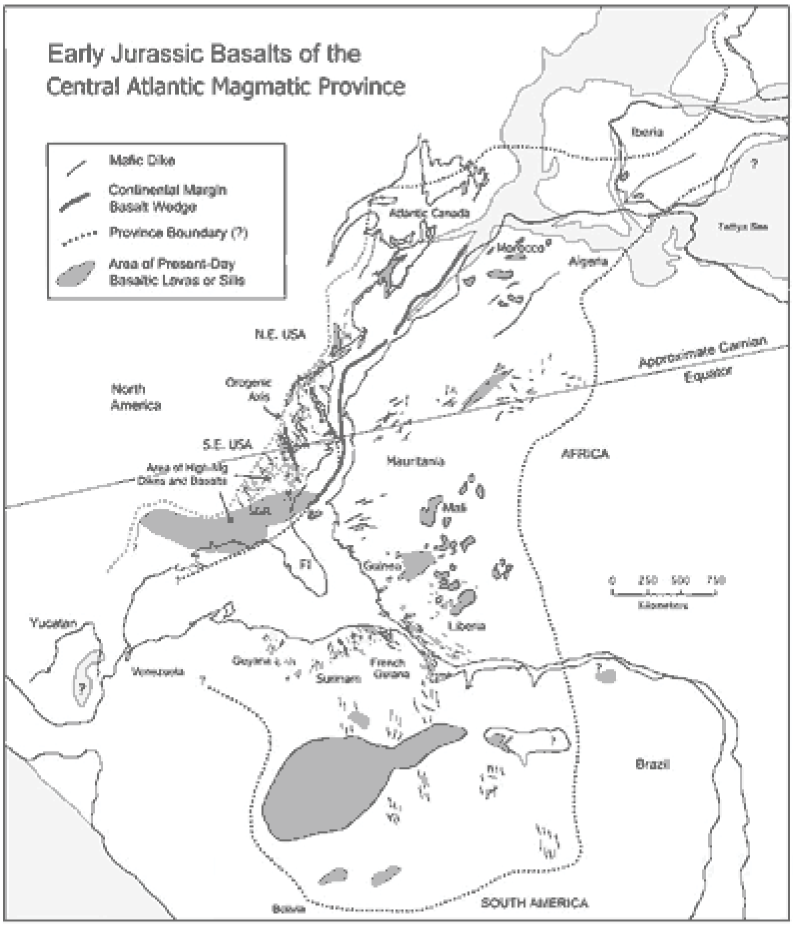


Map of the central Atlantic Ocean and adjacent land areas. Late Mesozoic seamounts and continental alkaline igneous provinces are circled in red, and the Early Mesozoic Central Atlantic Magmatic Province (CAMP) is outlined by a blue dotted line. The base map source is http://www.ngdc.noaa.gov/mgg/image/global_topo_large.gif .

Early Mesozoic Features

Starting in the Middle Triassic, a rift zone about 5,000 km long was actively developing through central Pangaea along the eastern side of the ancient Caledonian-Hercynian orogenic belt. Continental rifting progressed slowly over 30 Ma until the beginning of the Early Jurassic (now considered to about 201 Ma), when a vast volcanic event overwhelmed the entire rift zone (and beyond) with tholeiitic basalts. Sometime afterward, the initiation of sea-floor spreading split Pangaea into northern and southern super-continents. This Jurassic ocean became the central Atlantic, which along with the Gulf of Mexico, spread Laurasia away from Gondwana for at least 60 Ma before the northern and southern Atlantic Oceans opened (along with other large igneous events). In concert with those oceans, the central Atlantic has continued to widen between northwestern Africa and eastern North America.

The dikes, sills, and surface basalts of the circa-201 Ma CAMP are spread over at least 10 million km^2 within four continents, centered upon but extending far outside of the initial Pangaean rift zone. Portions of formerly-extensive flood basalts that appear to have been co-magmatic over much of the CAMP are preserved in continental margin rift basins (*Olsen*, 1997; *McHone*, 1996a, 2000; *Hames et al.*, 2002). In addition, basalts of the East Coast Margin Igneous Province (ECMIP) of North America, which are now known to cause the East Coast Magnetic Anomaly, covered about 60,000 km^2 with perhaps 1.3 million km^3 of extrusive lavas (*Holbrook & Kelemen*, 1993). If only half of the continental CAMP area was originally covered by 200 m of lava, the total volume of CAMP and ECMIP basalt exceeded 2.4 million km^3 and may represent the largest known subaerial flood basalt event.



Map of dikes, sills, and lavas of the CAMP, as originally distributed on pre-rift (earliest Jurassic) Pangaea. Adapted from Fig. 1 of McHone (2002).

Compositional variations among older (western) Atlantic seafloor basalts were described by *Bryan et al*. (1977), who noted regional differences and some similarities with the continental CAMP basalts of eastern North America. More recently, *Janney & Castillo* (2001) studied radiogenic isotopes and trace elements of Atlantic seafloor basalts, and found that isotopic ratios of Pb, Sr, and Nd of older (120-160) Ma ocean crust are roughly intermediate between the 200 Ma CAMP basalts in eastern North America and younger (post-120 Ma) ocean crust. Citing the common assertion that a deep mantle source is indicated if isotope ratios are not similar to most mid-ocean ridge basalts, they proposed that a mantle plume was involved with the formation of the early ocean floor magmatism (and by association, with the CAMP basalts). However, *Janney & Castillo* (2001) also noted the absence of other features required by a deep-mantle plume, such as central domal uplift or a "plume tail" of Jurassic alkaline volcanic seamounts [Ed: See *The case for mantle plumes*, by I.H. Campbell, for summary of the predictions of the plume model], and they proposed that "mid-mantle" plume convection is indicated. Their interpretation presumes that reservoirs or mantle source regions for these isotopic characteristics cannot reside in the upper mantle. In contrast, *Anderson* (1995) and *Natland* (this website: *Samoa.html*) have presented convincing arguments to support upper mantle sources for similar components.

Observations of the CAMP include the following:

1. Tectonic activity along much of the Pangaean rift zone of the incipient central Atlantic Ocean started in the Middle Triassic at least 25 Ma before CAMP and

continued up to 10 Ma afterward (*Olsen*, 1997). This tectonism must reflect an increase and/or a new pattern of mantle convection.

2. The western border of the CAMP coincides with the cratonic terrane edge and orogenic axis of the Appalachian Mountains (Caledonides), along which the lithosphere had been thickened by terrane accretions during and before the Late Paleozoic. This orogenic lithospheric could have impeded or affected the new mantle flow patterns.

3. The best radiometric data indicate most (but possibly not all) magmatism occurred in a brief period of less than 1 to 2 Ma, near 200 Ma throughout the enormous CAMP area (*Baksi,* 2002). A wide area, or layer, of the upper mantle or lower lithosphere had achieved mass melting conditions about the same time, which released tholeiitic magmas in extensional dike swarms.

4. Intermediate Ti and Mg basalts are found over the entire 6,700-km length of the province. Low Ti-high Mg basalts are abundant only on the western side (southern USA), and high Ti-low Mg basalts are common only in the south-central zone around Liberia and northern Brazil.

5. Dike swarms occur in overlapping trend groups of distinct tholeiite varieties and sub-varieties that are not connected horizontally. The trend groups reflect extensional stresses derived from sub-lithospheric mantle movements.

6. The magmatic groups and sub-types indicate the presence of upper-mantle rocks related to Late Proterozoic subduction (*Pegram*, 1990) and other heterogeneous mantle source zones (*Puffer*, 2002), local differences in mantle melt depths and/or temperatures (*Salters et al.*, 2002), and modification by crystal-liquid fractionation processes (*McHone & Puffer*, 2003).

7. CAMP basalts may be contemporaneous with the thick linear continental margin basalt wedge along 2,000 km of the eastern edge of North America (*Oh et al*., 1995 but disputed by *Benson,* 2002).

8. There is no evidence for any region of significant domal uplift associated with the CAMP (a requirement of the plume model).

9. There is no Jurassic hotspot track or ridge associated with the CAMP (also a requirement of the plume model).

10. Early Jurassic rift structures do not define a “triple junction” that could mark a plume head impact.

11. Proposed modern locations for CAMP plume hotspots show only Cretaceous or younger alkaline igneous features that are unrelated to CAMP tholeiitic magmatism (*Epp & Smoot,* 1989; *McHone,* 2000; *Janney & Castillo*, 2001).

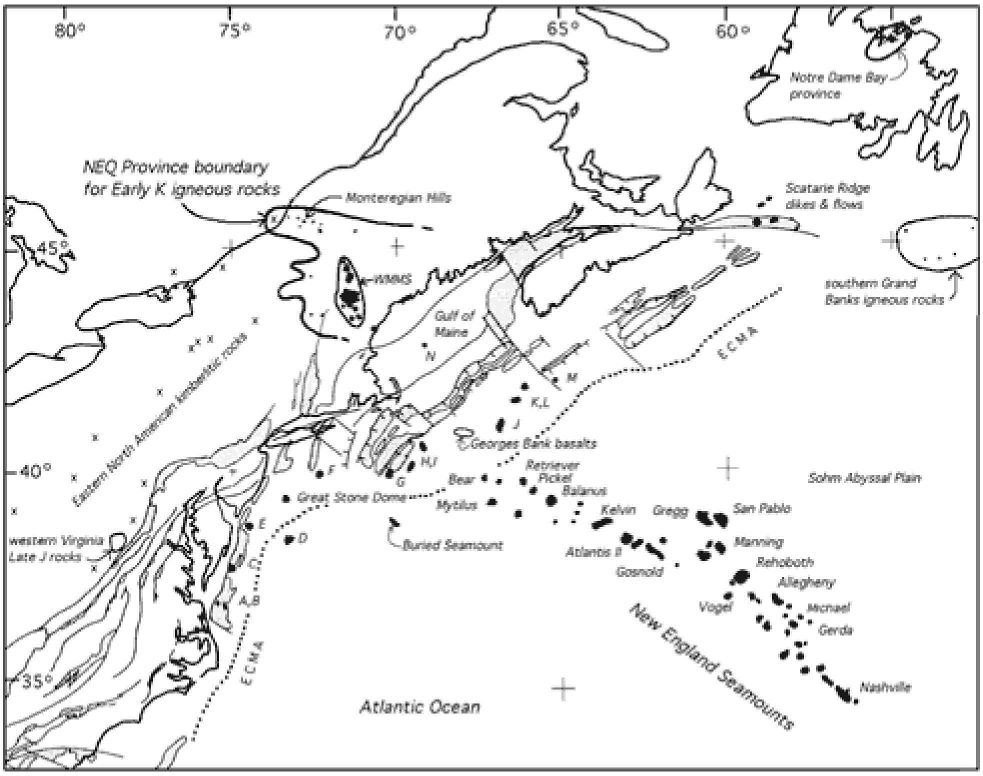
12. CAMP basalts (possibly through the ECMIP) evolved into ocean crust basalt, as produced by linear mid-ocean ridge processes.

Given these observations, a deep-mantle plume origin for the enormous CAMP event is neither indicated nor likely. Pangaean rifting and CAMP magmatism were essentially lithospheric plate events. CAMP-related geodynamic mantle activity is better modeled with regional convection cells and wide-ranging shallow thermal zones beneath the continental cover of Pangaea, with influence from lithospheric terrane structures. This is essentially the model of *King & Anderson* (1998). Given the aesthenospheric origin of modern mid-ocean ridge basalts, it is likely that the initial continental rift tholeiites were also melted from or near the base of the lithosphere. The Early Jurassic creation of the mid-Atlantic ridge and initiation of ocean crust production is a consequence of this upper-mantle convection and melting event, and not from a narrow stem or wide head of a deep-mantle plume that somehow spread over 10 million km^2 before producing surface magmas. Chemical/isotopic characteristics of the basalts must be related to variations in melting conditions and/or heterogeneity of upper-mantle sources.

Late Mesozoic Features

The central Atlantic Ocean (roughly latitude 10° to 50° N) contains more than a hundred volcanic seamounts grouped in chains, clusters, and individual features (*Epp & Smoot*, 1989). Although the Atlantic Ocean crust has been forming continuously from the Early Jurassic to the present with tholeiitic ocean ridge basalts, most of the seamounts were created during the Middle to Late Cretaceous as alkaline basaltic plutons and volcanoes, and some have continued to be active into recent times. In addition, several clusters and individual bodies of alkaline volcanic/plutonic magmas with Cretaceous and Tertiary ages are found in adjacent continental regions, mainly within a few hundred km of the ocean. One of the continental provinces (New England - Quebec) has been linked to one seamount chain (New England seamounts) by a model of a narrow fixed mantle plume (*Crough*, 1981; *Morgan*, 1983; *Duncan*, 1984; *Sleep*, 1990). Other seamounts are too geographically widespread to be caused by this plume, although they may be similar in age and composition.

The ocean lithosphere and adjacent continents experienced a major tectonic event in the Cretaceous, possibly related to a change in plate motions when mantle upwelling and convection, which led to lithospheric rifting, moved northward and southward into the Laurasia and Gondwana super-continents. Sub-lithospheric alkaline magmas collected during this event and moved rapidly to the surface along extensional fracture zones and fracture intersections, in the oceans and also in adjacent continents within the same plates.



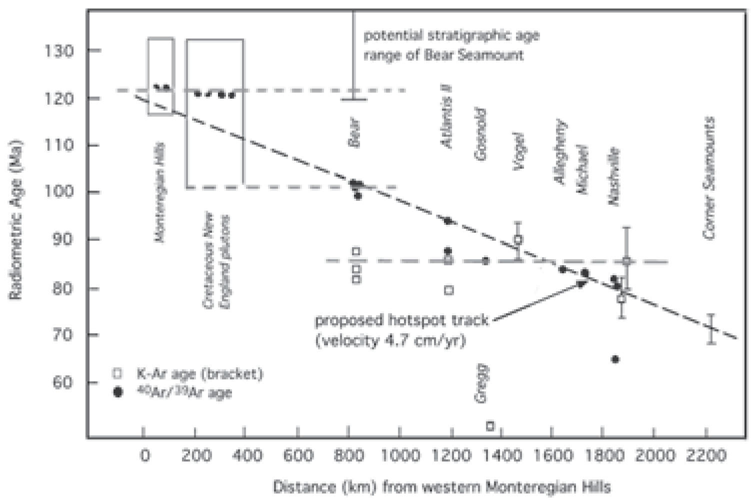
Late Mesozoic alkaline igneous features in eastern North America and the west-central Atlantic Ocean. Adapted from Figure 1 of McHone (1996b).

Similar to the CAMP, observations of geography and age distribution are pertinent to understanding how Atlantic volcanic seamounts were created. Most of the seamounts are clumped into elongate groups that are likely to have common origins and ages. Their ages tend to be significantly younger than the ocean crust they intrude, and the alkaline-enriched nature of their magmas indicates a different source and depth of mantle melting than the mid-ocean ridge tholeiites. The alkaline magmas are similar in both continent and ocean occurrences, thus indicating a source unrelated to the different lithospheres and probably aesthenospheres as well.

The groups of seamounts are generally not connected by ridges or rises, but appear as independent volcanic features. Some of the groups (e.g., New England seamounts, Fogo seamounts, Azores) have elongated patterns that may parallel the ocean spreading directions and fracture zones, but others (*e.g.*, Corner seamounts, Bermuda rise, Tora seamounts, Altair seamount, Cape Verde Islands) have patterns unrelated to spreading directions [Ed: See also Bermuda page]. It is clear that some were active at various times though the Cretaceous and Tertiary, which in the popular deep-mantle plume model would require many small, narrow plumes that existed simultaneously, could migrate in directions unrelated to plate motions, and/or could turn on and off at random intervals.

Proposals for a deep-mantle plume origin for central Atlantic volcanoes mainly ignore most of the seamounts by focusing on the New England chain, which is the largest and (apparently) longest lived, but including one selected seamount in the eastern Atlantic such as Great Meteor Seamount, which is supposed to be on the current leading edge of the chain. The eastern members of the New England seamount chain are younger than those farther west (*Duncan*, 1984), and several tectonophysicists have proposed that this chain originated on land in southern Quebec (the Monteregian Hills) before migrating southeast through New England (the White Mountain magma series) and into the ocean crust (*Crough*, 1981; *Morgan*, 1983; *Sleep*, 1990). However, the pattern is not very regular, and in the continent the alkaline igneous intrusions range in age between 199 Ma and 105 Ma (*McHone*, 1984; *McHone & Butler*, 1984). Most of the larger White Mountain magma series plutons and volcanics in New Hampshire are Early Jurassic in age and are overlapped in space by similar but much younger Cretaceous intrusions. Linear igneous features such as the Monteregian Hills appear to be controlled by larger fault zones, and are about the same age within each group (*Foland et al.*, 1986; *Faure*, 1996). The time-distance plot for the New England seamounts could indicate discrete episodes of volcanism along segments of the igneous province, at least as well as it shows a regular progression of ages (McHone, 1996b).

Time-distance plot of New England alkaline igneous continental and seamount features, adapted from Figure. 2 of McHone (1996b), after Duncan (1984).



The following points related to the New England provinces and seamounts were discussed by McHone (1996b):

1. Many Jurassic plutons in New England are petrologically similar to much younger Cretaceous intrusions in the same region, which may all be linked to Paleozoic or older lithospheric structures (*McHone & Butler*, 1984).

2. There was no basaltic flood basalt "plume head" volcanism that marked the initiation of the Cretaceous "plume tail" volcanic chain.

3. There is little evidence of age progression along 400 km of the New England-Quebec igneous province.

4. Kimberlites that supposedly indicate an earlier expression of the New England plume (*Crough*, 1980; *Heamon & Kjarsgaard*, 2000) are selected from numerous, widely-scattered kimberlites in North America that are not on any plume trace (*McHone*, 1981; *Parrish & Lavin,* 1982).

5. New England seamount volcanism is not limited to hotspot progression ages (*Swift et al.*, 1986).

6. New England igneous features and the seamounts formed during several discrete episodes along different lines or lineament segments within the overall structural trend.

7. Most of the numerous Atlantic seamounts and Eastern North American continental plutons are not on hotspot tracks.

8. There is little evidence for uplift from heating along any plume track (*Vogt*, 1991).

9. There is no consistent chemical signature in the igneous rocks that requires a deep mantle source.

10. The Cameroon line of west-central Africa has a similar long history of igneous activity in the continent followed by much younger volcanism along the structural trend in the ocean crust (*Moreau et al.*, 1987).

The crustal-tectonic control mechanism so evident for the North American plutons is similar to proposals for African igneous plutons and volcanoes of the Cameroon line (*Moreau et al.*, 1987) and for several seamounts and volcanic islands offshore of Africa, such as the Guinea seamounts (*Bertrand et al.*, 1988) and the Canary Islands (*Carracedo*, 1994)

The Cameroon line of west-central Africa presents the most likely analogy with the New England plutonic – volcanic – seamount line. The Cameroon line extends nearly 2,000 km from central Africa southwestward toward the Gulf of Guinea. 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). Three oceanic islands appear to be co-linear offshore into the Gulf of Guinea 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) [Ed: See also Africa page]. Although *Lee et al.* (1994) proposed that the three oceanic islands mark a mantle plume track, they described the presence of a "hot zone" of enriched sub-lithospheric 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 for western Africa, New England, and eastern Canada alkaline igneous rocks, and probably for the ocean crust as well. In fact, a linear distribution for igneous features is a useful indication of tectonic stress patterns both on land (*Faure et al.*, 1996) and sea (*Nakamura*, 1977). Variations in basalt chemistry in continental rifts are related to lithospheric thinning along pre-existing crustal structures, which produced mantle upwelling in the rift zone and decompressive melting of the lower lithosphere and upper mantle. A similar mechanism must exist in the ocean lithosphere, but rather than along-rift zones as in thick continental crust, fractures in the ocean can promote and control deep-sourced alkaline magmatism when and where the mantle changes its convective flow.

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