

Non-plume magmatism and rifting during the opening of the central Atlantic Ocean

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Abstract

Major Early Jurassic basaltic magmatism accompanied Pangaeon rifting during the formation of the central North Atlantic Ocean. Some geodynamic models attribute Early Mesozoic Atlantic rifting and magmatism to a large mantle plume. However, the central Atlantic basalts occur in overlapping provinces of distinct dike trends and compositional types, not as magmas generated from a single plume-style source. Continental rifting was active for 25 m.y. before and after the magmatic event, during which rifting and magmatism evolved into a spreading ocean crust. Rift basalts within the continents may be contemporaneous with a large basalt wedge that marks the eastern North American margin at the start of ocean-crust production, but there are no Jurassic hotspot tracks in the Atlantic Ocean crust, and the much younger alkalic ‘hotspots’ in the eastern Atlantic Ocean cannot be linked to the rift basalts. Thus, there is no physical evidence of a plume mechanism for Early Mesozoic Pangaeon rifting and magmatism. Several convection cells beneath the rift zone may be responsible for both tectonic basins and basaltic magmas, as influenced by pre-existing lithospheric structures. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The popularity of mantle plume modeling has led to the statement that it has become a ‘paradigm’ for understanding events of intraplate rifting and magmatism (Thompson, 1998). Once limited to selected chains of ocean islands and some triple junctions of plate rifts, mantle plumes are now pandemic. To account for magmatism during Pangaeon rifting between North America and western Africa, a plume mechanism has been developed by Morgan (1983), White and McKenzie (1989), Hill (1991), Wilson (1997), and others.

This plume model is especially related to the pattern of Early Mesozoic dikes around the initial rift, which May (1971) described as radial about the Blake Plateau, an area roughly east of Florida in the pre-drift configuration (Fig. 1). The apparent success of the plume model for explaining rifting and magmatism of the South Atlantic Ocean and northern North Atlantic Ocean has provided further encouragement (White and McKenzie, 1989).

However, Early Mesozoic features that are related to the Pangaeon continental rifting and magmatism of the central Atlantic differ from features to the south and north. Mafic dikes (and former flood basalts) of the central region are geographically very extensive, and their timing and compositions are problematic for the plume model.

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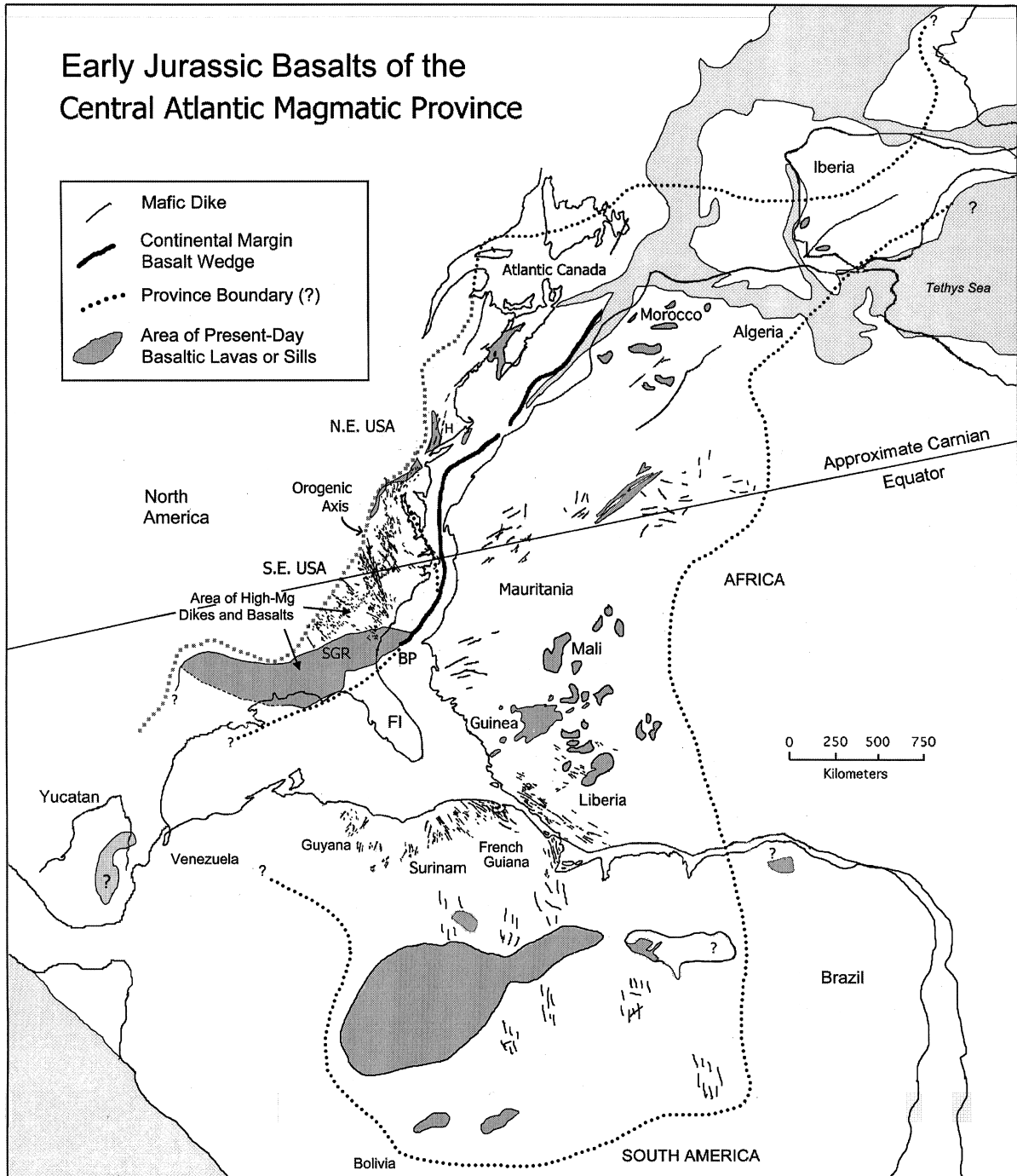


Fig. 1. Early Jurassic basalt provinces of the central Atlantic Pangaeian rift. The pre-drift configuration of present-day continents is adapted from Klitgord and Schouten (1986). The location of the North American margin volcanic wedge is from Kelemen and Holbrook (1995). Other features are from Olsen (1997). Dike locations (generalized) are compiled mainly from May (1971), Philpotts and Martello (1986), McHone et al. (1987), Ragland (1991), Oliveira et al. (1990), Deckart et al. (1997), Marzoli et al. (1999), and unpublished work by the author. Abbreviations: BP = Blake Plateau; FL = Florida; SGR = South Georgia Rift; S.E. = Southeast; N.E. = Northeast.

The same is true for tectonic rifting, for which a ‘zipper effect’ of extensional progression was formerly described. Several expected plume features are lacking, and even the past and present locations of the plume remain in doubt.

This paper is a brief outline of several problems for the plume mechanism in the central Atlantic Pangaeon rift. In particular, the origins and emplacement of circum-Atlantic Early Mesozoic magmas, although still not completely studied, are crucial to understanding how mantle convection is related to continental rifting in this region. And, if Occam’s Razor is still a viable concept, we might expect that the mechanism for such events in the central Atlantic also had a role in rifting to the north and south, regardless of present concepts for plume mechanisms.

2. Rift tectonics

Pangaeon tectonic events during the Early Mesozoic are reflected by a series of continental faults and fault-bound rift basins around the central Atlantic (Olsen, 1997). Although some earlier work suggested a ‘zipper effect’ in which rifting progressed from south to north (Manspeizer, 1988), detailed compilations by Olsen (1997) and others show a pattern of tectonic activity and sediment deposition as old as Middle Triassic in both the northern areas (Fundy and Argana basins) and southern areas (Deep River basin) of the rift zone. Post-rift erosion has removed several kilometers of strata in the exposed basins, so that the youngest possible ages for sediment deposition, and thus synrift tectonism, are unknown. However, strata within the Hartford basin of the northeastern USA may be as young as Middle Jurassic (Olsen, 1997).

Significantly, Early Jurassic (?) basalts buried in the South Georgia rift basin (Fig. 1) apparently truncate underlying Triassic strata that are tilted and eroded within tectonic blocks, whereas the basalt flows remain subhorizontal and nearly concordant with Cretaceous and younger strata of the overlying post-rift coastal plain (McBride, 1991). In the Deep River basin of North Carolina (SE USA), dike groups that trend north–south and northwest–southeast crosscut border faults and

tilted basin strata without being offset or tilted themselves (Ragland, 1991). Jurassic sediments and possible surface lavas from these Piedmont dikes are missing, presumably from erosion of the basalts and non-deposition of the sediments. Because these SE USA dikes and buried basalts are probably all nearly 201 Ma in age (Ragland, 1991; Olsen, 1997), tectonic rift basin activity in the SE USA portion of the rift zone must have ended before the start of Jurassic time. Later uplift with erosion created a major hiatus and unconformity between early and late Mesozoic sediments of the Atlantic coastal plain, but this event is relatively uniform across eastern North America and it postdates the initial ocean rifting.

In contrast to the southern rift basins, tectonic activity in the north continued through the Early Jurassic (Olsen, 1997). All basaltic and sedimentary strata in the Mesozoic basins of the NE USA are tilted and truncated by major border faults. As discussed by McHone (1996b) and McHone and Puffer (1999), border faulting may be as young as 170 Ma — activity that may postdate formation of the initial central Atlantic Ocean crust. The continuation of northern tectonism was not accompanied by significant additional continental magmatism, however. Several kilometers of erosion of the northern rift zone is evident before the continental margins were overlapped by Cretaceous and younger coastal sediments. Widespread Early Cretaceous alkaline magmatism in the NE USA may have been accompanied by faulting, but not by new sedimentary basins (McHone, 1996a).

3. Magmatism and opening of the central Atlantic

The widespread dikes fed fissure eruptions and flood basalts that appear to be immediate precedents to the initial ocean crust, which implies that the central Atlantic started to open in the Early Jurassic. Evidence for the close link between continental magmatism and ocean crust formation along the new margin of North America is described by Austin et al. (1990) and Holbrook and Kelemen (1993), who determined that subaerial volcanic flows comprise at least the upper section of seaward-dipping seismic reflect-

tors, or a basalt wedge, along most of the central Atlantic continental margin. In the SE USA, strong sub-horizontal seismic reflectors of continental flood basalts of the South Georgia basin intersect or overlap the seaward-dipping reflectors (Oh et al., 1995). This very thick (to 25 km) basalt and plutonic cumulate wedge is uniformly large along most of the eastern North American margin (Fig. 1), as shown by the east coast magnetic anomaly and seismic reflections, and by itself constitutes a major large igneous province (Kelemen and Holbrook, 1995).

Originally, a genetic link was proposed between the Kelvin or New England Seamount hotspot plume and the opening of the central North Atlantic Ocean (Morgan, 1971; Burke et al. 1973). This model was soon refuted by Vogt (1973), who pointed out that volcanism along this seamount chain (as with other volcanic islands of the Atlantic Ocean) is probably not older than Early Cretaceous, whereas the initial ocean crust is at least Middle Jurassic in age and apparently evolved from the Early Jurassic rift basalts. Hotspot plume proposals for the origin of the seamounts shifted to the Cretaceous and later (Crough, 1981), although problems with the plume models are still apparent (McHone, 1996a).

Despite a gap of 80 m.y. or more, intraplate 'hotspots' that show only Cretaceous or Cenozoic alkaline igneous activity are often also proposed to cause Early Jurassic tholeiitic magmatism and Atlantic Ocean rifting (Burke et al., 1973; de Boer and Snider, 1979; Morgan, 1983; White and McKenzie, 1989; Oliveira et al., 1990; Hill, 1991; Oyarzun et al., 1997; Thompson, 1998). A common location given for the present expression of the plume is Cape Verde Island, offshore from Senegal (Fig. 1), mainly because this volcano is also close to the Blake Plateau in the pre-drift configuration. Other former and present plume locations have been suggested in the SE USA (de Boer and Snider, 1979), the interior of west Africa (Wilson, 1997), or migrating northward along the eastern Atlantic into Europe (Oyarzun et al., 1997).

Extrusive basalts of the central Atlantic are presently found around the ocean margins in fault-bound basins that preserve Early Mesozoic sediments (Manspeizer, 1988). The basin basalts

appear to be relatively minor remnants of a much larger flood basalt province that has been mostly removed by erosion (Rampino and Stothers, 1988; McHone, 1996b; McHone and Puffer, 1999). Sources of the flood basalts are represented by diabase dikes in enormous swarms along eastern North America, northern South America, West Africa, and Iberia, along and well beyond the central Atlantic rift zone (Fig. 1). Studies now suggest that dikes or basalts of these circum-rift provinces extend northward through northwestern France (Caroff et al., 1995), westward into Texas (Baksi, 1997), and southward into central Brazil (Marzoli et al., 1999). Dikes and sills also occur far to the east into Mali, West Africa (Bertrand, 1991). Although the entire igneous province stretches beyond 5000 km by 2000 km in extent, its actual limits are not yet known. Marzoli et al. (1999) suggest a province name of central Atlantic magmatic province, or CAMP.

Vogt (1973) developed a model previously suggested by de Boer (1967) and Weigand and Ragland (1970), in which Late Triassic or Early Jurassic dikes and basalts associated with the Mesozoic continental basins were precedents to sea floor spreading. Using trend patterns of eastern North American dikes as compiled by de Boer (1967), Vogt (1973) pointed out their parallelism with the major new ocean rift transforms and plate margins, an observation reiterated by McHone et al. (1987). Other links between lithospheric structures and Atlantic rifting were described by Le Pichon and Fox (1971).

The petrologic transition of the continental basalts to initial ocean crust was explored by Bryan et al. (1977). Although Bryan and Frey (1986) suggested that chemical variations in ocean ridge basalts reflect components of one or more mantle plumes, Sleep (1984) and Dosso et al. (1999) showed that mantle sources for mid-Atlantic rift basalt may be expected to be heterogeneous, with compositional zoning perhaps related to earlier subduction and magmatic events. As described above, the origin of the Early Jurassic basalts can be intimately linked with the creation of new ocean crust.

The age precision for the main pulse of magmatism associated with central Atlantic rifting has improved dramatically from studies by Sutter

(1988), Dunning and Hodych (1990), Sebai et al. (1991), Hodych and Dunning (1992), Fiechtner et al. (1992), Deckart et al. (1997), Marzoli et al. (1999), and others. Most dates fit between 196 and 202 Ma, and there is a possibility, also supported by stratigraphic studies of basin basalts (Olsen, 1997), that most or all of the magmatism occurred close to 201 ± 2 Ma (beginning Jurassic).

4. Dike compositions and trends

The total lengths of some dikes or single dike sets exceed 700 km (Fig. 1), and, remarkably, each maintains essentially the same distinct composition along its great length. In the region of the NE USA and Atlantic Canada, at least three distinct compositional subtypes comprise basin basalts that flowed within a 580 000 year period throughout the region (Philpotts and Martello, 1986; Olsen, 1997). Each of the three basalt subtypes also occurs in single great dikes that are from 250 to 700 km long. The internal uniformity of individual

dikes along such great distances implies one of two possibilities for magma sources. (1) There is a single, local mantle source for each large dike or dike swarm, and the magma in each large dike flowed away from this source in a sub-horizontal direction for 700 km, or more (or 350 km, or more, in opposite directions). Different magma subtypes could tap an evolving magma chamber or separate portions of that source. Or, (2) the mantle source regions consist of compositionally different sub-horizontal layers that are homogeneous across large regions, and mainly vertically moving magmas tapped the same layer for each dike and magma type. These alternatives are important to plume versus non-plume models of large igneous provinces.

In a very general way, chemical characteristics of the dikes and basalts can be used to divide them into three groups that also have geographic implications (Fig. 1). In northeastern North America, Iberia, and across much of West Africa, three or more quartz-normative tholeiite types comprise dikes and basalts with moderate TiO_2 (0.9–

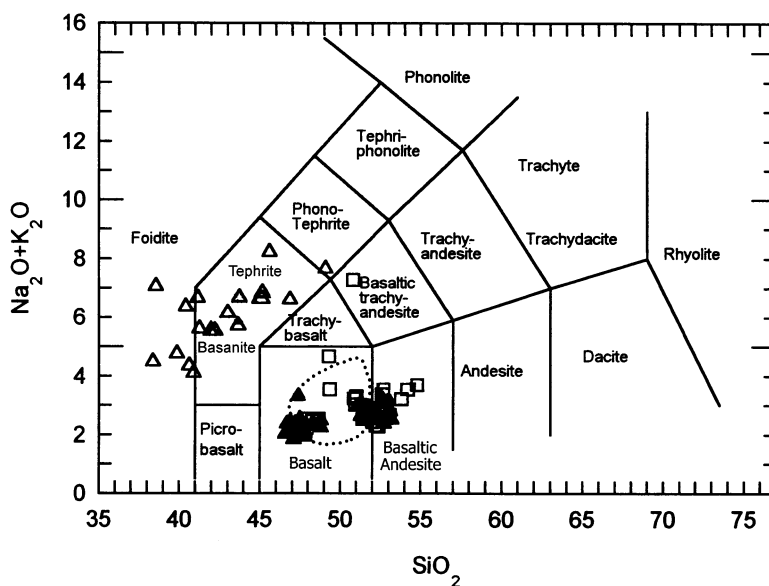


Fig. 2. Selected Pangaeian rift basalt analyses plotted on an SiO_2 -Total Alkalies classification diagram (LeBas et al., 1986). Symbols: open triangles, Cape Verde basalts (Gunn and Watkins, 1976); solid triangles, southeastern USA dikes, in two groups (Ragland, 1991); open squares, northeastern USA and Moroccan dikes and basalts (Philpotts and Martello, 1986; Bertrand, 1991; Dostal and Greenough, 1992; Puffer, 1992), here mostly coinciding with Si-rich dikes of the southeastern group. The dotted line encloses a mixed group of dike analyses from Liberia and South America (DuPuy et al., 1988; Oliveira et al., 1990).

1.4 wt%) and MgO (6–9 wt%), and fairly high SiO₂ (51–55 wt%), which class them as intermediate between basalt and basaltic andesite (Fig. 2). Bertrand and Villeneuve (1989) described similar types in Guinea, west Africa (Fig. 1), and they appear to be common in Brazil (Fodor et al., 1990; Marzoli et al., 1999). Caroff et al. (1995) described NW–SE-trending dikes in northwest France that are of this intermediate-Ti group. As shown in Fig. 1, from Iberia to West Africa, and in northeastern North America, dikes of this compositional group tend toward NE–SW orientations, but in South America and the southeastern USA there appears to be a mix of N–S and NE–SW trends [also see figures by Ragland et al. (1983), Deckart et al. (1997) and Marzoli et al. (1999)].

Subgroups of the northern group overlap in the southeastern USA with a separate dike group of olivine tholeiites, which have much higher MgO (7–14 wt%), lower TiO₂ (0.6–0.9 wt%), lower SiO₂ (46–49 wt%), and lower alkalis (Figs. 2 and 3). This Mg-rich basalt type (Fig. 2) appears to be limited to the southeastern and southern USA, although crystal cumulates elsewhere may mimic their compositions to some degree. Extensive basalt flows of this olivine type and also an intermediate-Ti quartz type are present beneath younger coastal sediments in the South Georgia

rift basin (SGR in Fig. 1) of the southeastern USA and Florida (McBride, 1991). Dikes of the Mg-rich group show a fairly consistent NW–SE trend throughout their range, without any convergence or radial tendency, and they define a west-central segment of the rift magma province (Fig. 1).

A third magma group occurs in Liberia and northeastern South America, and is represented by dikes and sills with compositions that range widely toward higher TiO₂ (1.6 to 3 wt% or more), somewhat higher iron oxides and alkalis, and SiO₂ values between 48 and 52 wt%. Such high Ti basalts are most abundant in Liberia and portions of northern Brazil and French Guiana, but they appear to be absent from North America, northwestern Africa, and Iberia. Dikes of this group display a strong NW–SE trend preference in Liberia but are mixed with more N–S trends in northern South America (Fig. 1). Baksi and Archibald (1997) presented evidence that at least some high-Ti basalts in northern Brazil are actually related to the Early Cretaceous Serra Geral flood basalt event.

Dike compositions of these regional groups are coherent enough to form some clusters on chemical diagrams. In Fig. 2, SiO₂ values for northern intermediate-Ti dikes (open squares) are similar to many of the quartz tholeiite dikes in the southeastern USA, but they are distinct from the lower SiO₂ values of the high-Mg dikes that overlap in the southern USA (closed triangles). Compositions of basalts from west Africa and northern South America (dotted line) overlap both fields, but with members that also have higher alkali contents. By way of comparison, the alkali basalts (foioidites and basanites) of Cape Verde Island are distinctly different (open triangles).

The common discriminant oxides of Ti, Fe, and Mg clearly separate northern dikes and basalts from dikes of the southern USA (Fig. 3), whereas the mixed West Africa–South America group overlaps their lower Mg examples and extends as a group toward much higher Ti. The Cape Verde alkali basalts have little relation even to the most Ti-rich tholeiites of Liberia. Although physically close to Cape Verde, analyses of dikes from Guinea are within the northern compositional group (Bertrand and Villeneuve, 1989) rather than the high-Ti type of southern dikes.

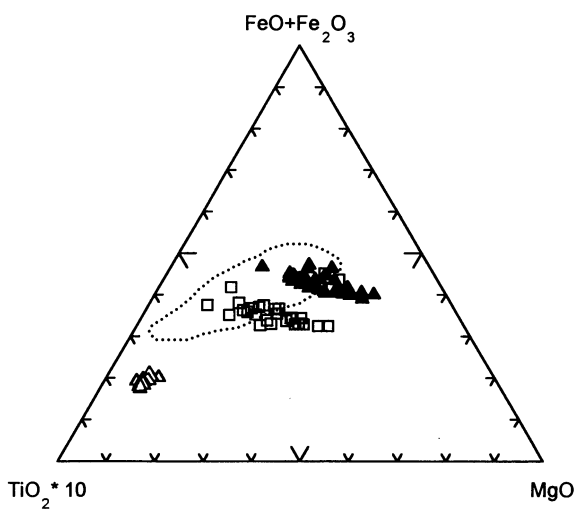


Fig. 3. Distribution of Ti, Fe and Mg oxides in Pangaea rift basalt groups. Symbols and analyses are as explained in Fig. 2.

5. Geodynamic models

Kelemen and Holbrook (1995) considered several possible origins for the volcanic wedge along the margin of the east coast of North America. Their preferred model calls for a relatively brief but intense linear upwelling beneath the incipient initial ocean rift zone, causing partial melting while still at some pressure under the overlying crust. The new ocean crust forms a sharp contact with the wedge, showing that along the break in the rift from wedge magmatism a rapid transition to normal seafloor spreading occurred. In their previous paper, Holbrook and Kelemen (1993) rejected a mantle plume mechanism because: (1) no plume track of appropriate age leads from a rift magma center; (2) the long duration of rifting and timing of magmatism are poorly matched; (3) no anomalous crustal thickness (igneous accretion) above a plume is known along the wedge; (4) the geometry of volcanism along the wedge is linear, not domal or radial. These same points apply to the entire rift province of dikes and basalts.

The lack of any particular domal uplift is especially well controlled near the Blake Plateau. As described above, the South Georgia rift basalts flowed over a surface of Triassic strata that had already been tilted and eroded nearly to a plain (McBride, 1991). Uplift of the nearby Blake Plateau (BP in Fig. 1) would certainly have caused erosion and removal of these relatively thin flows, but they remained little disturbed before eventual cover by Cretaceous sediments.

Oyarzun et al. (1997), Wilson (1997), and Thompson (1998) proposed models that call for massive horizontal translation of a mantle plume or plume material along the incipient Atlantic rift, which could also possibly account for the geometry of the margin volcanic wedge. Aside from discussing evidence that large, discrete portions of the mantle can move in this manner, Oyarzun et al. (1997) repeated the concept that Early Jurassic dikes form a radial pattern around a triple-junction-type plume near the present Blake Plateau or Florida peninsula [originally proposed by May (1971)]. Their model also requires that the dike magmas flowed in a sub-horizontal direction away from this mantle source as far as 3500 km to the northeast, a proposal developed by Greenough

and Hodych (1990). These ideas of dike geography and magma flow are appealing in their simplicity, but less attractive upon closer examination.

Many dikes around the Pangaeian central Atlantic rift do appear, at least in a general way, to converge on the proposed plume site of the Blake Plateau (Fig. 1). In detail, however, most dikes actually occur in sets that roughly parallel each other across swarm widths of 200 to 600 km or more. In some areas, several sets of dikes with different trends occur together. In addition, most large dikes tend to be discontinuous along strike, with en echelon patterns or segments that are offset by several kilometers. The magmas of such dikes must interconnect in a mainly vertical direction, overall. More commonly, swarms of many smaller dikes of the same magma type are also not mutually interconnected in any lateral sense. The compositional correlations among dikes within groups, the trend and compositional differences between groups, and the mainly vertical flow required by dike structures, indicate that each dike group is derived from its own mantle sources, and that each group has its own regional tectonic control.

The mainly vertical magma flow in chemically similar large dikes and dike groups in the Pangaeian rift system indicates wide regions of horizontally uniform mantle sources, because mainly horizontal flow from a localized mantle source cannot account for the geographic distribution of the variety of magma types. There are substantial amounts of basaltic magma involved: a dike that averages 30 m wide along 500 km, with a vertical dimension of perhaps 50 km, contains 750 km³ of basalt and may have fed surface lavas flows of 10,000 km² or more (McHone, 1996b). A local source would require a much higher percentage of mantle to melt than would a regional source spread over the lengths of the dikes and dike swarms.

Age differences among the magma groups, if any, are not well determined. Whether or not all Jurassic dikes around the central Atlantic rift are close to the same age (ca. 201 Ma), the swarms reflect separate extensional stress regimes that existed during the initial tectonic–magmatic events of the Pangaeian Atlantic rift. In addition, the western boundary for the central Atlantic magmatic province coincides with a major lithospheric

ric–orogenic structure. We must model the central Atlantic margin dike swarms as independent magmas linked by tectonic interaction, not as members of a radial swarm with horizontal magma flow from a single plume source.

Many Cretaceous and Cenozoic alkaline igneous volcanoes and plutons are present in eastern North America, the northern North Atlantic region, western Africa, South America, and especially, as seamounts and islands throughout the central North Atlantic Ocean (Epp and Smoot, 1989). If several of these ‘hotspot’ volcanoes are similar in age and petrology, as appears likely, there is little basis for selecting the Cape Verde Islands to be the modern representative of the mantle plume that rifted Pangaea and produced the largest of large igneous provinces. In addition, the northward drift of Pangaea during the Early Mesozoic (Olsen, 1997) prevents a simple ocean-spreading connection between the Blake Plateau and Cape Verde Islands.

Mesozoic to Cenozoic rifting of Pangaea progressed through a series of linear zones of mantle upwelling that gradually coalesced into the modern segments of the mid-ocean ridges. In the Early Mesozoic, the tectonic and magmatic events record major, widespread, and relatively deep convective mantle movements under the Appalachian–Hercynian orogens of central Pangaea. In the model discussed by Anderson et al. (1992), the lithosphere promoted an increase in upper mantle temperatures beneath the incipient rift zone, culminating in the great Early Jurassic magmatic event. With cooling from that event, the rift evolved into a zone of shallow linear upwelling and convection by which the mantle ejects ridge basalts and accretes new ocean crust.

More recently, King and Anderson (1995) observed that many flood basalt provinces have formed near the edges of continental cratons, where different lithospheric thicknesses are expected. As temperatures gradually increased by the insulation of Pangaeic continental masses, craton edge-driven convection in the upper mantle produced a linear upwelling cell that released large volumes of basaltic melt. Deeper convection and higher temperatures are responsible for higher-Mg (picritic) magmas, but most of the melts formed from a widespread sub-lithospheric layer that has

gradually become enriched with volatiles, alkalis, and other ‘incompatible’ elements. The different subtypes of basalt reflect the compositions of different sections of this upper mantle layer. King and Anderson’s (1995) model may explain why the western rift basalts appear to be bounded by the Appalachian orogenic axis (Fig. 1), which is close to the edge of the Grenville craton. It is not so clear whether flood basalts and dikes of the eastern side are also associated with craton boundaries in Africa and South America.

6. Conclusion

A mantle plume is not a likely mechanism for basaltic magmatism and rifting during the Early Jurassic opening of the central North Atlantic. Although there is better evidence for plume sources of some basalts formed during later rifting of the South Atlantic and northern North Atlantic Ocean, those magmas appear as overprints or anomalous sections of ocean crusts that are otherwise formed by mechanisms similar to the central region. Worldwide, it appears that mantle plumes are only rarely associated with mid-ocean rifts and the basic process of ocean crust generation and spreading. We may conclude that continental rifting and associated magmatism that precedes new oceans can also be independent of plume mechanisms.

Because magmatism and rifting were linked during the development of the central Atlantic, a successful geodynamic model must account for the long history of tectonic activity, the abrupt timing of magmatism across very large regions within and outside of the rift zone, the geochemical pattern of magmas, and the initiation and production of spreading ocean crust. Hotspot models have been stretched too far to be realistic, and the concept of deep mantle plumes does not explain the central Atlantic magmatic province and the rifting of Pangaea.

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