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FLOOD BASALT PROVINCES OF THE PANGAEAN ATLANTIC RIFT: REGIONAL EXTENT AND ENVIRONMENTAL SIGNIFICANCE

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Abstract

The original extent of Hettangian Pangaean rift basalts is estimated from maps of feeder dikes and Mesozoic basins that contain remnants of the basalts. Dikes and basalts across the initial Pangaean rift zone are correlated by radiometric dates near 200 Ma, stratigraphy of associated basin sediments, and chemical characteristics. Intermediate-Ti quartz-normative tholeiites in northeastern North America and Morocco were derived from large NE-trending dikes that define a northern subprovince over much of modern northeastern North America, northwestern Africa, and the Iberian Peninsula, with an area around 2.8 x 10^6 km^2. Other quartz and olivine tholeiites comprise 2 x 10^5 km^2 of flood basalts that remain beneath the southern U.S. coastal plain and continental shelf, as derived from large N-S and NW-SE trending dike swarms. The southern subprovince originally extended more than 3.2 x 10^6 km^2 across the present southeastern USA, western Africa, and northern South America. Gaps in the lava sheets were likely, and the relationship of these continental basalts with subsequent ocean-crust magmatism remains unclear. The environmental impact from such enormous volumes of basalt includes cooling and/or greenhouse effects from the potential liberation in the order of 10^{12} metric tons each of CO_2 and SO_2 aerosols, and proportionally large amounts of water vapor, halides and ash, all produced in a brief volcanic event.

Introduction

Recent work has demonstrated the presence of large volcanic provinces and wedge-shaped basalt bodies that may exceed 10^6 km^3 along portions of the eastern continental margin of North America (Austin et al. 1990; Oh et al. 1995). Such basalts appear to be associated with the initial production of ocean crust during the Jurassic opening of the central Atlantic Ocean, and they explain geophysical features such as the East Coast Magnetic Anomaly (Holbrook and Keleman 1993). Although the Atlantic margin basaltic wedge is a major igneous feature, it has been difficult to discern beneath thick covers of sediment and ocean water. Possible landward counterparts to the Pangaean final-rift magmas are mainly exposed as diabase dikes within the circum-Atlantic continental regions (Fig. 1), and as tholeiitic lavas preserved within sections of some Early Mesozoic basins (Manspeizer 1988).

Because diabase dikes and sills are locally prominent in Triassic strata that underlie the basin basalts, stratigraphic and tectonic models have commonly assumed that the basaltic lavas originated from vents within each basin. Localized sources for basalts are also implied by popular "closed basin" models for their interstratified sediments (Klein 1969; Smoot 1985). Before the fundamental work of Philpotts and Martello (1986), little connection was made between the large regional diabase dike swarms and basalts within the Mesozoic basins.

Continuing field and petrologic studies in eastern North America have shown that Mesozoic diabase dikes are individually extensive (some more than 60 m wide and 250 km long), have ages and magma types similar to basalt flows, and can be physically connected to the basin lavas (Philpotts and Martello 1986; Sutter 1988; McHone 1992). Because of these observations, the original extent of surface flood basalts across the Mesozoic Pangaean rift terranes should be tied to the distribution of dikes rather than to the present geography of sedimentary basins. Former locations of Early Jurassic flood basalts can be estimated from maps of the dikes and modern basalts, from analyses of Late Triassic to Early Jurassic tectonism and topography, and from analogies with other flood basalt provinces. This model is mainly limited by our poor knowledge of the regional Early Jurassic topography that affected the locations, directions, and thickness of flows, and by the timing and nature of both syn-rift and post-rift erosion that reduced the basins and lavas to their present geographic pattern. In addition, it is likely that some or many of the smaller dikes did not reach the surface, or else made only minor contributions to the surface lavas.

Even allowing for a large error in estimating their actual sizes and geographic extent, significant volumes of CO_2, SO_2, and particulates must have been added to the air during fissure eruptions of the Pangaean rift basalts, with commensurate effects on animal and plant populations. An estimate of such atmospheric aerosols should be proportional to the effects calculated for other, better-known flood basalt eventssuch as the Laki eruption of 1783 and the Columbia River lavas (Sigurdsson 1990).

Mesozoic Basins and Basalts

Early Mesozoic rift basins are exposed in eastern North America, Iberia, and western Africa, while more basins thought to be of this group are covered by water and/or post-Jurassic sediments of the continental shelves on both sides of the North Atlantic Ocean (Hutchinson et al. 1988). Many of the basins display a half-graben geometry, in some places as pairs of basins that are symmetrically opposed, such as the Hartford and Newark basins (Manspeizer 1988). Sub-basins within the Durham basin of North Carolina, partly buried by Cretaceous sediments, would be split into similar symmetrically opposed basins if another 500 m of erosion had occurred (Manspeizer and Gates 1995). The truncated nature of basin strata beneath the onlap of the Coastal Plain indicates that most of the tilting, uplift and erosion of the rifted terrane was finished before the deposition of Cretaceous sediments.

From Virginia to Nova Scotia, and in Morocco, the Mesozoic rift basins that preserve Jurassic strata also contain one or more horizons of quartz-normative tholeiitic basalts that correlate closely in age, stratigraphic position, chemistry, and petrography (Bertrand 1991; Olsen et al. 1996; Puffer and Philpotts 1988; Puffer 1992). One to three different magmatic types are recognized in these rift basins, with the "best" dates ranging between 201 Ma (Dunning and Hodych 1990) and 196 Ma (Sebai et al. 1991). Stratigraphic mapping shows that the flows are only slightly above the Triassic-Jurassic boundary, or earliest Hettangian, and so they provide an important marker for dating that boundary

(Olsen et al. 1990).

The earliest of the basin basalts (i.e. lowest basalt stratum) is of the same magma type that also comprises most of the sills common to the Culpeper, Gettysburg, Newark, and Hartford basins (Woodruff et al. 1995), and it is the only type known within the large Fundy basin (Dostal and Greenough 1992). Puffer (1994) has labeled this magma the "Initial Pangaean Rift" (IPR) basalt. Along the western margin of the Fundy basin, the North Mountain basalt is truncated by a major coast-parallel fault, but underlying Triassic sediments still remain in a few places west of the basin (Stringer and Burke 1985). In offshore basins, basalt is present in the Nantucket basin and is suspected for other basins of the Long Island platform (Hutchinson et al. 1986). In on-shore and off-shore basins in Morocco, IPR basalts like these earliest units in North America also lie at the base of the Jurassic stratigraphic section (Bertrand 1991; Fiechtner et al. 1992).

Basalt-Dike Correlations

Radiometric ages of Mesozoic diabase dikes and basalts have been problematic. The "best" K-Ar dates are typically scattered between 180 and 210 Ma, even for basalts and dikes that should be the same age, and many such dates have been repeated in the literature as the actual igneous cooling ages (de Boer et al. 1988). However, basin stratigraphy in eastern North America indicates that all known basaltic lavas formed within a 570,000-year period immediately after the beginning of the Jurassic period (Olsen et al. 1996). In addition, diabase dikes within the basins are not found to crosscut any strata above the basalts, but many dikes occur in the Triassic sediments in the basins as well as within basement rocks adjacent to the basins, including basins with no lava remnants. All exposed basins that preserve Triassic-Jurassic boundary sediments also preserve basalts.

Several U-Pb isotopic measurements of baddeleyite and zircon of the northeastern North American basin sills and basalts show ages between 200 and 202 Ma (Dunning and Hodych 1990; Hodych and Dunning 1992). The U/Pb dates agree withsubstantial circa-201 Ma dates obtained by the ^{40}Ar/^{39}Ar method on dikes in eastern North America, western Africa, and northern South America, although a few other Ar dates indicate a second group of ages close to 196 Ma (Sutter 1988; Sebai et al. 1991; Fiechtner et al. 1992; West and McHone 1997; Deckart et al. 1997). These newer works supersede the numerous older, more scattered, K/Ar dates of eastern North American diabase dikes and basalts, which were affected by loss or gain of Ar in unpredictable ways. An age of 200 ± 2 Ma appears likely for most, and possibly all, of the tholeiitic Pangaean rift dikes and basalts, but more radiometric work is still needed.

At the base of basaltic lavas within the basins, specific dike-to-flow locations are known in the southeastern Hartford basin (Philpotts and Martello 1986) and in the northern Culpeper basin (Woodruff et al. 1995). Basin lava vents are mapped in the Newark basin of New Jersey (Puffer and Student 1992) and in the Hartford basin in Massachusetts (Foose et al. 1968); in some cases sub-surface feeder dikes are not well exposed, but the vents can be related to dikes found on-trend in the region. In the Fundy basin, Papezik et al. (1988) hypothesized a major fissure eruption somewhere in its southern area to account for a massive northward basalt flow, which fits a source from the Christmas Cove dike in coastal Maine (McHone 1996). In Connecticut, elongate vesicles in basalts indicate flow from southern sources in the southern Hartford basin, but to the north, basin flows have eastern sources (Gray 1982; Ellefson and Reidel 1985). Likely feeder dikes are mapped across the source locations in both areas (Philpotts and Martello 1986).

After erosion, volcanic fissure sources for flood basalts are located by large diabase dikes, as has been demonstrated in the Columbia River basalt group (Reidel and Tolan 1992). In eastern North America, source dikes crosscut the Triassic strata of present-day basins beneath portions of their flood basalt products, and the same or similar (co-magmatic) dikes continue far outside the basins (Fig. 1; Smith et al. 1975; Philpotts and Martello 1986). Diabase dikes of the Mesozoic basins are also members of large dike swarms that are characterized by particular orientations and/or magma types, which are found across regions widely separated from the modern basins.

The earliest (IPR) basalt flows are especially noted as having a very similar initial major and trace element chemistry in every northern basin (Bertrand, 1991; Pegram 1990; Puffer 1994). IPR basalts (and some subsequent basalts) can be correlated with specific co-magmatic dikes (Table 1 and

Fig. 2). In major-element chemistry, the TiO_2-MgO ratios of IPR magmas define a crystal fractionation line in which the feeder dikes are centered on a basalt fractionation trend (Fig. 2), which is especially well illustrated by the North Mountain basalt of the Fundy basin. Dikes and lavas that formed soon after the IPR magmas have slightly lower TiO_2-MgO ratio trends as well as some lower large-ion lithophilic elements (Pegram 1990; Puffer and Philpotts 1988). IPR basalt and diabase average somewhat higher in Ti (at about 1.2 %) than the other northern basalts, thus their label of "High-Ti Quartz normative" or HTQ basalt (Weigand and Ragland 1970). However, some dikes in west Africa and Brazil actually have much higher Ti contents (Puffer, 1994).

In the southern and central areas of eastern North America, several hundred dikes of moderate to large sizes occur in two discrete swarms with generally northwest-southeast and north-south trends (Fig. 1; Smith et al. 1975; de Boer et al. 1988). In comparison, the northeast-southwest trending diabase dikes of New England and Atlantic Canada are fewer, but they tend to be very large, up to 20 to 60 m wide and 75 to 400 km long (Fig. 1; McHone 1992; Pe-Piper et al. 1992; McHone et al. 1995). Likewise, the northeast-trending IPR-type Foum-Zguid and Messejana dikes in Morocco and Spain each extend more than 400 km, while the Ksi-Ksou dike in southwestern Algeria may exceed 800 km (Fig. 1; Bertrand 1991). Portions of major lava flows from these very large dikes remain in exposed and subsurface basins of Morocco and Portugal (Fiechtner et al. 1992).

The petrologic correlation among dikes and between dikes and basalts is strong in the northern circum-Atlantic basalt province, but the extrapolation of flood basalts over feeder dikes is more conjectural in the southern region. Limited chemical analyses from drill cores into the sub-coastal plain flood basalt near Charleston, South Carolina indicate a magmatic source from the large quartz tholeiite dikes that extend northward through the Carolinas and Virginia (Ragland 1991), while the western sections of the buried flood basalt are physically close to, and probably overlie, NW-SE olivine diabase dikes in Georgia. Recent work indicates a similar circa-201 Ma age for the SE USA dikes (W. Hames, personal comm. 2000).

Dike swarms and very large sills in western Africa and northern South America are need additional correlation work with southeastern U.S. dikes, especially between swarms with similar trends (see Ragland at al., this volume). Nevertheless, radiometric and petrologic studies (Deckart et al. 1997) show that the southern province magmatic history is analogous to the northern province, where dikes are feeders to flood basalts. Recently, Marzoli et al. (1999) have shown by new radiometric and chemical analyses that sills and dikes in northern and central Brazil are also mainly quartz tholeiites of circa-200 Ma age. Their major expansion beyond Figure 1 of this paper adds at least 2 million km^2 to the province, which Marzoli et al. (1999) have named the Central Atlantic Magmatic Province, or CAMP. McHone (2000) provides additional description of CAMP and its geodynamic problems.

Mesozoic Basaltic Landforms

Massive basalt eruptions occurred along the incipient central North Atlantic Ocean rift, during or soon after the creation of the first ocean crust between 185 Ma and 175 Ma, or perhaps earlier (Holbrook and Keleman 1993). Around 200,000 km^2 of basalt (or possibly much more) presently underlies Cretaceous sediments across sections of the southeastern U.S. and continental shelf, where it merges with a portion of the thick basalt wedge that settled into the new continental margin (Austin et al. 1990; Oh et al. 1995). The final rift basalt occurs as a wedge along most of the eastern margin of the continent, as indicated by the East Coast Magnetic Anomaly (Holbrook and Keleman 1993). Just inland from the hinge zone, Middle (?) Jurassic flood basalts presently cover portions of the Georges Bank basin (Hurtubise et al. 1987; Hutchinson et al. 1988). The petrology of these final rift basalts is poorly known relative to the older (?) inland basin tholeiites, but if new work can link them by chemistry and stratigraphy, their age and the age of the initial ocean crust may be closer to 201 Ma than to 175 Ma.

Inland from the Cretaceous Coastal Plain of eastern North America, no examples of Early Jurassic basalts or sills are known to be preserved in surface exposures outside of the Early Mesozoic basins, probably due to uplift and erosion into the surrounding metamorphic basement. However, there are other areas of western Africa and northern South America in which sills and surface flows intrude and cover older basement rocks (Bertrand 1991; Deckart et al. 1997). Figure 1 includes an estimate of the potential area covered by the Early Jurassic Pangaean flood basalts, based on several assumptions of low to moderate relief, and flow lengths in proportion to dike sizes, as follows (illustrated mainly by northeastern North America):

(1) Early Mesozoic basins were originally completely covered by basalts derived from dikes in the same regions, including basins now covered by younger sediments and offshore basins.

(2) Basalts within the basins flowed from fissure dike sources that also fed basalts flowing outside of the basins, as controlled by local topography.

(3) Basalts flowed from 50 to 400 km or more from dike fissures across regions that are far from modern Mesozoic basins. Such distances are demonstrated by single flows mapped from source dike vents of the eastern Columbia River Plateau basalt (Reidel and Tolan 1992).

(4) Late Triassic topographic relief may have been moderate to low across large sections of the early rift zone, punctuated by particular differential uplift zones known from tectonic studies, fission-track studies, and argon isotopic studies. Low relief is indicated by large regions of meandering fluvial Triassic sediment (Hubert et al. 1992). In addition, remnants of similar basal Triassic sediments are found in eastern Massachusetts (Kay 1983) and in eastern New Brunswick (Stringer and Burke 1985). Wintsch et al. (1996) report young mineral dates that require sediments of the Hartford basin to have been transported from source terranes that are well east of the Bronson Hill margin of the basin.

(5) Major fault activity, related to the development of higher relief within the Pangaean rift belt, occurred mainly after the Hettangian Age. Evidence is as follows:

(5a) Basin activity, shown by sedimentation rates and heat flow, accelerated during the Early Jurassic, starting with the onset of magmatism in the basins (Schlische and Olsen 1990; Roden and Miller 1991)

(5b) Direct K-Ar measurements (with tests for Ar corruption) of syntectonic minerals along extensions of the Mesozoic border fault in New Hampshire range around the Middle Jurassic (Lyons and Snellenburg 1971).

(5c) Mineral dates in the basins indicate a major thermal event around 175 Ma, perhaps linked to hydrothermal activity that accompanied mid-Jurassic faulting (Roden and Miller 1991).

(5d) Elevated zones include the Bronson Hills terrane, which was uplifted as much as 8 km along the Hartford basin's eastern border fault by 170 Ma (Harrison et al. 1989). Jurassic uplift of the Bronson Hills is also consistent with the production of fanglomerates along the Hartford eastern border fault, and with thinning and absence of strata around the Pelham dome of the Deerfield basin (Stevens and Hubert 1980).

(5e) Large phaneritic plutons of the White Mountain magma series in central New Hampshire were mostly emplaced during post-Hettangian Early to Middle Jurassic times, and as a thermal zone the WMMS are consistent with uplift adjacent to or connected with the Bronson Hills terrane high (Fig. 1).

(5f) As shown from organic maturation temperatures and fission track analyses, from 1.5 to 4 km of basin strata were eroded after Early Jurassic sedimentation ceased, but before the onlap of Cretaceous Coastal Plain sediments (Pratt et al. 1988; Roden and Miller 1991).

(5g) Pressure-enhanced stability of minerals indicates a much greater depth of crystallization of the Higganum dike, east of the Hartford basin, relative to the adjacent but co-magmatic Fairhaven dike within the basin, so that as much as 8 km of post-dike differential offset is indicated (Philpotts and Martello 1986).

(5h) Highway construction temporarily exposed a faulted contact of basin basalt against basement metamorphic rocks on the southeastern border of the Hartford basin (Mikami and Digman 1957). Many other northeast-trending high-angle faults offset the basalts within the basin (Rodgers 1985).

In southern Maine, Ar mineral data are interpreted to show differential vertical faulting of several km before and into Triassic time (West et al. 1993), but this tectonism apparently does not coincide with the dike intrusions. Northwest-trending faults crosscut some of the offshore basins (Hutchinson et al. 1988) as well as the Minister Island dike (Stringer and Burke 1985). A small NW-fault offsets the Caraquet dike in Maine (McHone unpub. data).

The feeder dikes cross all terranes east of the present highlands of the Appalachian Mountains, and the flood basalts would have flowed over all varieties of bedrock surfaces where allowed by topography. As shown by the timing of tectonic activity, inter-basin uplift was active during and after magmatism, and basalts would have been quickly eroded from uplifted areas. Basalts and accompanying sediments outside of the present basins must have been removed during the c. 80 Ma interval before Cretaceous sediments spread unconformably over basins within the coastal plain and continental shelf (Klitgord and Hutchinson 1985).

Although present in the Jurassic border conglomerates of the basins, basalt clasts are sparse. Basalt erodes rapidly when uplifted, and basalt clasts are not well preserved during stream transportation, as can be observed today in and around basin lavas. Sediments deposited above the basalts within the basins were mainly derived from exposed basement hills and highland source areas that were inland from the flood basalts, and their metamorphic minerals and grain fragments survived fluvial transport better than most basalt clasts.

The total thickness of Hettangian basalts varies widely among basins, but 200 meters is a conservative estimate for an average thickness over the rift terrane and adjacent continental dike swarms. For the province area estimate of 6 million km^2, one-half of the surface covered by 200 m of lava requires the extrusion of 0.6 million km^3 of basalt. An equal or greater amount is preserved in the numerous large dikes and sills now exposed within the province, and it remains possible that a million km3 of seaward-dipping reflector basalts are part of this same event.

Atmospheric Emissions

The only historically observed flood basalt of a large dimension was from the Laki fissure eruption in Iceland, which occurred mainly during the summer of 1783 (Table 2). During the peak of activity, lava flowed several km per day (Thorarinsson 1969). At this and other fissure eruptions, more than half of the gases that were dissolved in the magma escaped at the fissure's lava fountains, which may have risen to a km or more in height (Stothers et al. 1986). Such gases typically are dominated by H_2O, CO_2, and SO_2 in tholeiitic magmas, but halides such as Cl and F can be considerable components as well. During the summer of the Laki eruption, ash clouds reached across Iceland into northern Scotland, and for much of the summer, a strange "cold fog" was observed throughout Western Europe. The fog was probably due to sulfuric acid droplets formed by reaction of volcanic SO_2 in the atmosphere, and it reduced sunlight enough to cause mid-summer frosts and widespread crop failures that led to local famines (Bullard 1988, Sigurdsson 1982). In addition, local fluorine poisoning of Icelandic livestock has been recognized (Sigurdsson 1990).

[Table 2 about here]

Few published analyses of Pangaean rift basalts include CO_2, SO_2, or halides. In Table 2, we have assumed average emissions of CO_2 and SO_2 at fissure vents to be 0.3 and 0.15 weight percent of the tholeiitic magmas, respectively. Such amounts are roughly comparable to volatile measurements for lavas and feeder dikes at Laki and for the Miocene-age Roza flow, an important member of the Columbia River basalt group (Stothers at al. 1986). The Roza emissions are estimated to be about 100 times that of the Laki eruption, and most of the sulfur in its feeder dikes escaped at fissure eruption vents (Martin 1996). If the Higganum-Holden-Christmas Cove (HHC) dike system of New England had flow volumes and sulfur contents proportional to these younger flood basalts, its atmospheric emissions could have been triple those of the Roza flow, or between 10^9 and 10^{10} metric tons each of CO_2 and SO_2 from this 400 km-long vent system (Table 2). Sigurdsson (1990) has calculated that 10^9 metric tons of sulfuric acid aerosol could cause 3° to 4° C surface cooling, a major global climatic event.

Other preserved Initial Pangaean Rift basalts that probably were synchronous with the HHC-derived Talcott-North Mountain flood basalts include the Mt. Zion Church flows of Virginia, the Orange Mountain (First Watchung) flows of New Jersey, and several High Atlas flows of Morocco (Puffer 1994). McHone (1996) estimated a total area covered by IPR basalt of at least 500,000 km^2 across the northern Pangaean rift terrane, or roughly 25 times that of the HHC flow. These lavas are probably co-magmatic and coeval, and so their eruptive history may span only a few decades to centuries. Moreover, this lava-dike system comprises less than 10% of the total contemporaneous flood basalt province.

The total Pangaean rift volcanic dike vent systems (now exposed as groups of co-linear dikes around the entire Atlantic rift) can be estimated roughly as: 4 dikes about 500 km long; 10 dikes about 200 km long; 20 dikes about 100 km long; and perhaps 400 dikes averaging about 10 km long, for a conservative estimate of roughly 10,000 km of fissure eruption vents. In addition, the Pangaean dike-fissure system of Figure 1 is a minimal depiction of global Early Jurassic volcanism in that it excludes southern Karoo volcanism (South Africa), which has been dated around 193 ± 5 Ma by K-Ar and $^{40}Ar/^{39}Ar$ methods (Fitch and Miller 1984), and it also excludes contemporaneous Mesozoic volcanic events of the North American Cordilleran and Basin and Range provinces (Gilluly 1965). At discharges proportional to the younger flood basalt eruptions, gaseous aerosols from the Pangaean basalts must have totaled well above 10^{12} metric tons (Table 2). Although possibly spread over several eruptive events totaling 10^5 to 10^6 years, these enormous atmospheric emissions are likely to have caused major environmental problems.

Conclusions

The evidence points to a nearly synchronous event of co-genetic fissure eruptions, with rapid production of at least 10^6 km^3 of an initial rift magma along a pre-Atlantic zone from northern South America to the northern coasts of North America and Europe, as originally assembled within Pangaea. Very similar IPR dikes and basalts are found from Virginia to eastern Newfoundland, in northwest Africa, and in Iberia (Puffer 1994). As pointed out by McHone (1996), the distribution of these igneous features does not support an origin from a single plume or “hot-spot” source, but their magmatic uniformity requires a huge linear zone of eutectic-like mass melting, under conditions similar to some other major flood basalt events (Anderson 1994).

The limited chemical fractionation observed within various segments of the initial basalt has been explained by ponding at the base of the crust (Pegram 1990) or within the crust (Philpotts and Martello 1986), and by fractional source melting and crystal-liquid segregation (Philpotts 1992). A model that explains some of the chemical variations between the northern and southern basalt was presented by Cummins at al. (1992), who proposed that the homogeneous northern basalts originated close to the axis of the mantle “keel” along the rift zone, and farther off the axis for heterogeneous southern magmas.

The slightly younger but also voluminous basalts that followed the IPR basalt have their own distinctive characteristics and widespread distribution, adding to what must have become very large plateau-like flood basalt provinces across the rift terranes around what would become the central North Atlantic Ocean. As indicated by sediments as well as by tectonic studies, the basalt plains were interspersed with basement highlands that were eroding into the basins and surrounding areas. Basalts must have flowed around basin fault scarps and basement hills, and where dikes crossed highlands, downhill from those regions. The model implies that stream-deposited Triassic sediments could also have been present over many areas between basins, so that at least into Hettangian time, we are reminded of the original Broad Terrane hypothesis of Russell (1880) in which some strata of modern basins were originally inter-connected. Post-basalt faulting and uplift then accelerated the isolation of the basins. Jurassic faulting and uplift are also responsible for the nearly complete erosion of the northern flood basalt province, as well as for the preservation of its remnants within today's basins.

Enormous flood basalt eruptions across what were then the equatorial and tropical belts of the earth could have had a catastrophic effect on terrestrial life forms. Sulfuric acid haze is known from the Laki eruption to significantly reduce sunlight, a problem that would have been many times more severe for the Pangaean fissure eruptions. Based on stratigraphic relationships of lavas that could be far from their fissure sources, Olsen et al. (1990) concluded that the IPR basalts are slightly too young to be related to the Triassic-Jurassic mass extinction event. Olsen et al. (1990) instead proposed an asteroid impact cause for the Tr-J extinction, but their suggested Quebec Manicouagan event is now known to be too old (Hodych and Dunning 1992). Although Rampino and Stothers (1988) proposed that flood basalts can be triggered by large impacts, the simpler assumption is that major basaltic eruptions cause extinctions by themselves (Stothers 1993).

More recently, fossil and stratigraphic data described by McElwain et al. (1999) and Palfy et al. (2000) support the proposal that CAMP eruptions could have caused or contributed to the Tr-J mass extinction. The model of Palfy et al. (2000) suggests that a terrestrial extinction preceded a marine extinction event, which might be related to different times of CAMP volcanism. Because volcanism in the northern portion of the pre-Atlantic rift terranes occurred so close to the terrestrial extinction event, slightly older flood basalt events in other portions of the CAMP remain a potential cause for the end-Triassic ecological catastrophe.

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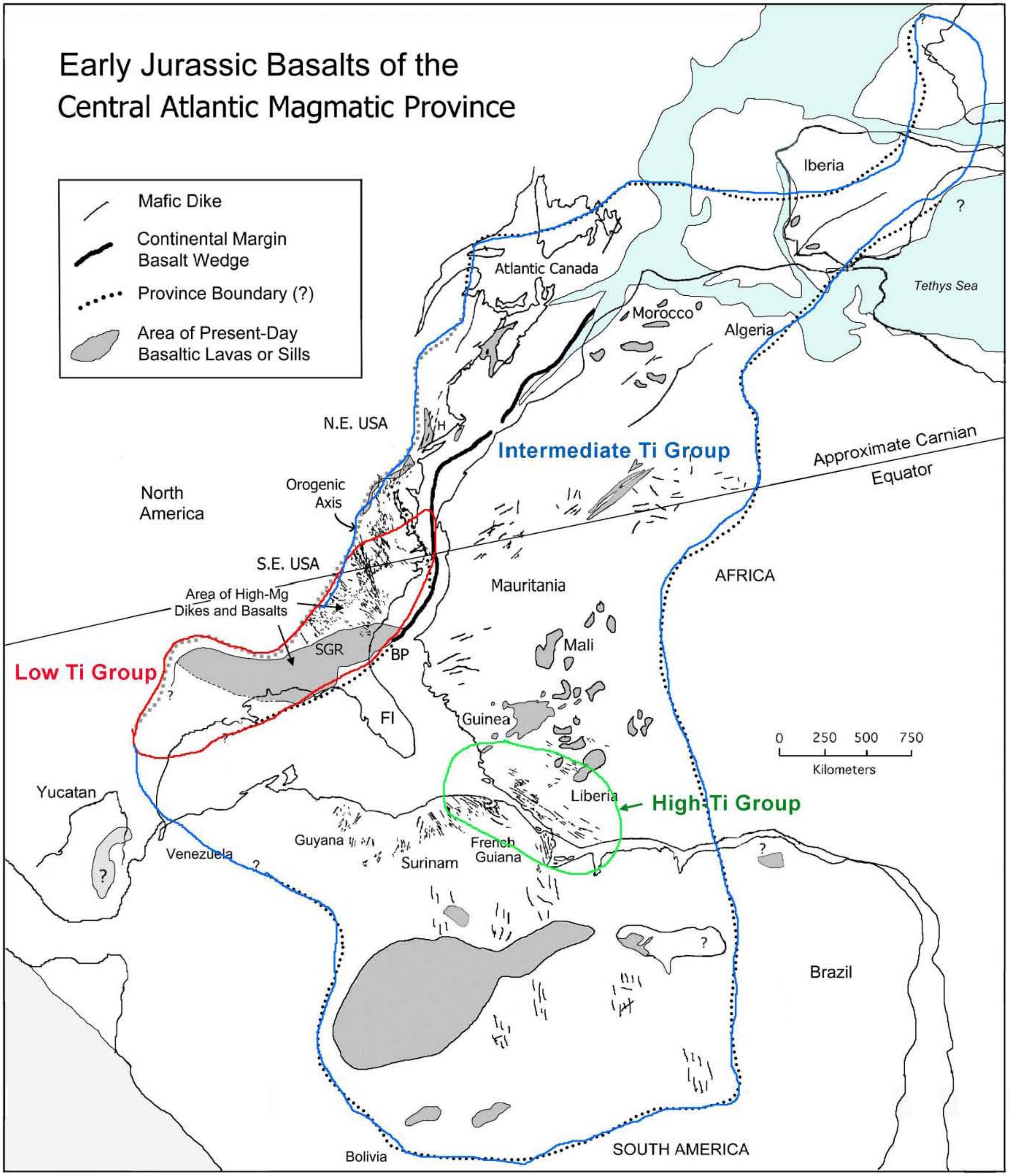
Figure Captions

Figure 1. Areas of potential cover by Early Jurassic flood basalts around the central North Atlantic Pangaean rift zone. Base information is adapted from figures by de Boer et al. (1988), Bertrand (1991), and Deckart et al. (1997). Initials label large northern province dikes: H = Higganum dike; X = Christmas Cove dike; C = Caraquet dike; S = Shelburne dike; A = Avalon dike; M = Messejana dike; F-Z = Foum-Zguid dike; K-K = Ksi-Ksu dike.

Figure 2. TiO_2 - MgO plot for selected Early Jurassic diabase dikes and basalts in eastern North America. Solid triangles represent analyses of the Christmas Cove dike of Maine (McHone, unpub. data). Solid diamonds represent North Mountain basalt analyses from Dostal and Greenough (1992). Other sources: Smith et al. (1975); Papezik and Barr (1981); Greenough and Papezik (1986); Philpotts and Martello (1986); Puffer and Philpotts (1988); McEnroe (1989). Not shown: dikes and basalts of the third flow, which generally plot in positions of high TiO_2 and low MgO, and other basalts of the final rift margin.


Early Jurassic Basalts of the Central Atlantic Magmatic Province
Mafic Dike
Continental Margin Basalt Wedge
Province Boundary (?)
Area of Present-Day Basaltic Lavas or Sills
Iberia
?
Tethys Sea
Atlantic Canada
Morocco
Algeria
N.E. USA
H
Intermediate Ti Group
Approximate Carnian Equator
Orogenic Axis
North America
S.E. USA
AFRICA
Mauritania
Area of High-Mg Dikes and Basalts
SGR
BP
Mali
Low Ti Group
?
Fl
Guinea
0 250 500 750
Kilometers
Liberia
High Ti Group
Yucatan
Guyana
Surinam
French Guiana
Venezuela
?
?
?
Brazil
Bolivia
SOUTH AMERICA

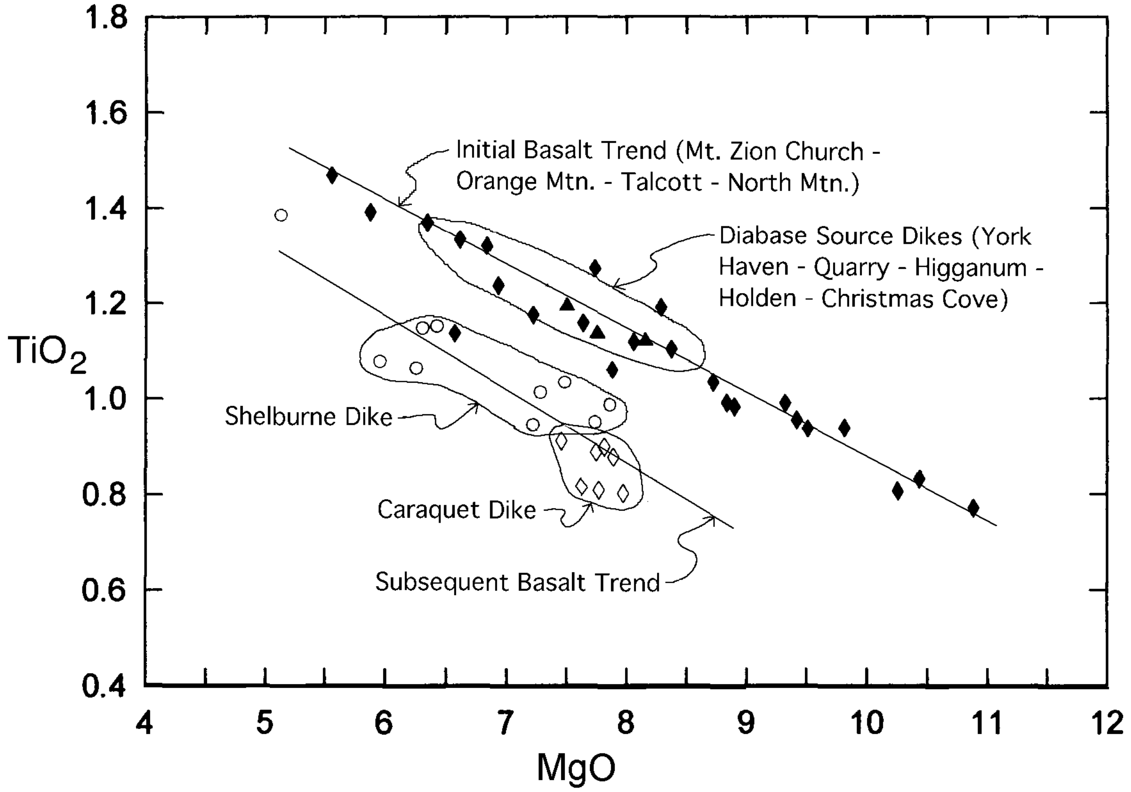

1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
TiO$_2$
4
5
6
7
8
9
10
11
12
MgO
Initial Basalt Trend (Mt. Zion Church - Orange Mtn. - Talcott - North Mtn.)
Diabase Source Dikes (York Haven - Quarry - Higganum - Holden - Christmas Cove)
Shelburne Dike
Caraquet Dike
Subsequent Basalt Trend

TABLE 1. COMPOSITIONS OF INITIAL PANGAEAN RIFT DIKES AND BASALTS

Source Dike	York Haven	Palisades Sill	Higganum	Christmas Cove	Minister Island	Foum-Zguid	Messejana
SiO_2	51.84	51.98	52.62	52.58	52.94	51.99	52.07
TiO_2	1.09	1.22	1.17	1.15	1.14	1.10	1.04
Al_2O_3	14.34	14.48	14.96	14.47	14.13	15.05	15.90
FeO*	9.93	10.19	10.20	10.53	10.05	9.52	9.28
MnO	0.20	0.18	0.17	0.18	0.20	0.18	0.16
MgO	7.72	7.59	7.59	7.81	7.92	7.69	7.16
CaO	10.73	10.33	10.94	10.57	10.94	11.75	11.51
Na_2O	1.96	2.04	2.33	1.98	1.97	1.97	2.16
K_2O	0.60	0.84	0.56	0.60	0.55	0.60	0.58
P_2O_5	0.12		0.20	0.13	0.14	0.15	0.14

Related Basalt	Mt. Zion Church	Orange Mountain	Talcott	North Mountain		High Atlas	
SiO_2	51.37	51.45	51.86	52.16		51.06	
TiO_2	1.18	1.02	1.07	1.06		1.06	
Al_2O_3	14.24	14.34	14.27	14.29		14.84	
FeO*	10.86	10.36	10.86	10.35		10.33	
MnO	0.17	0.15	0.16	0.16		0.19	
MgO	7.58	8.19	7.98	7.05		8.17	
CaO	10.78	10.86	11.24	10.35		12.25	
Na_2O	2.05	2.10	2.06	2.39		1.69	
K_2O	0.21	0.54	0.50	0.60		0.49	
P_2O_5	0.13	0.13		0.16		0.16	

Sources: Bertrand 1991; Dunn & Stringer 1990; McHone, unpub.; Philpotts & Martello 1986; Puffer 1992; Smith et al. 1975. Each of the above are averages of four to ten analyses.

TABLE 2. COMPARATIVE BASALT FLOWS AND ATMOSPHERIC EMISSIONS

Name	Fissures (km)	Age	Area (km^2)	Volume (km^3)	Rate (km^3/d)	CO_2 (m.t.)	SO_2 (m.t.)
Laki	25	1783 AD	565	12	0.2	$4x10^7$	$2x10^7$
Roza	100	17 Ma	3000	700	1	$4x10^9$	$2x10^9$
H-H-C	400	201 Ma	20,000	2000	2-4	$1x10^{10}$	$6x10^9$
Total est. Pangaean	10,000	201 Ma	$5x10^6$	$1.2x10^6$	10^2-10^3	$6x10^{12}$	$3x10^{12}$

Sources: Stothers et al. 1986; Bullard 1988; McHone 1996; Martin 1996
H-H-C = Higganum-Holden-Christmas Cove dike and estimated lavas; m.t. = metric tons