Bermuda and the Bermuda Rise – A Poor Fit to the Classical Mantle Plume Model

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Introduction

The mid-plate Bermuda volcanoes and the swell on whose crest they reside (Figure 1), are often included in global studies of mid-plate oceanic swells, but they are among the most difficult for a deep mantle plume model to explain. In fact, Bermuda offers problems for every current model. A comprehensive synthesis, history and review is presented in Vogt & Jung (2007).

The "Bermuda Islands" comprise the small subaerial summit of a 15-100 m thick, 665 km^2 cap of reef and reef-derived carbonates, resting on the eroded stump – the Bermuda Pedestal – of a mid-to-late Eocene shield volcano. Three other submerged edifices, together with Bermuda, form a NE-trending, 100-km-long line, paralleling the plate-tectonic fabric of the ca. 123-124 Ma oceanic crust on which the volcanoes rose.

The volcanic line is located near the summit of the evidently related Bermuda Rise, a NE-trending oval swell (1500 km long and 500-1000 km wide) representing at its summit a 800-1000 m positive depth anomaly (*e.g., Sclater & Wixon*, 1986; *Detrick et al.*, 1986; *Sheehan & McNutt*, 1989), whose exact magnitude depends on the oceanic crust age-vs-depth model assumed. Associated with the depth anomaly is a geoid high of ca. 5-10 m (*Crough*, 1978; *Detrick et al.*, 1986; *Sheehan & McNutt*, 1989) over the rise summit. Taken in concert with its depth anomaly, this geoid high implies a compensation depth in the range 40-80 km; *Sheehan & McNutt* (1989) derived 55 ± 10 km.

A corresponding regional heat flow anomaly is at most 5 to 10 mW/m^2 (*Detrick et al.*,1986; *Louden et al.*, 1987), and recent demonstrations of the importance of low-temperature hydrothermal effects (*e.g., Harris et al.*, 2000; *McNutt*, 2002; *von Herzen*, 2004; *DeLaughter et al., 2005*) makes even this value suspect.

For a mid-plate setting, the Bermuda Rise is anomalously active sesimically, an observation *Zhu & Wiens* (1991) attributed to thermoelastic stress caused by hotspot reheating. Seismic tomography (*e.g., Zhao*, 2004; *Ritsema, 2005*) has so far failed to detect a significant wave-speed anomaly extending from below Bermuda into the middle or lower mantle.

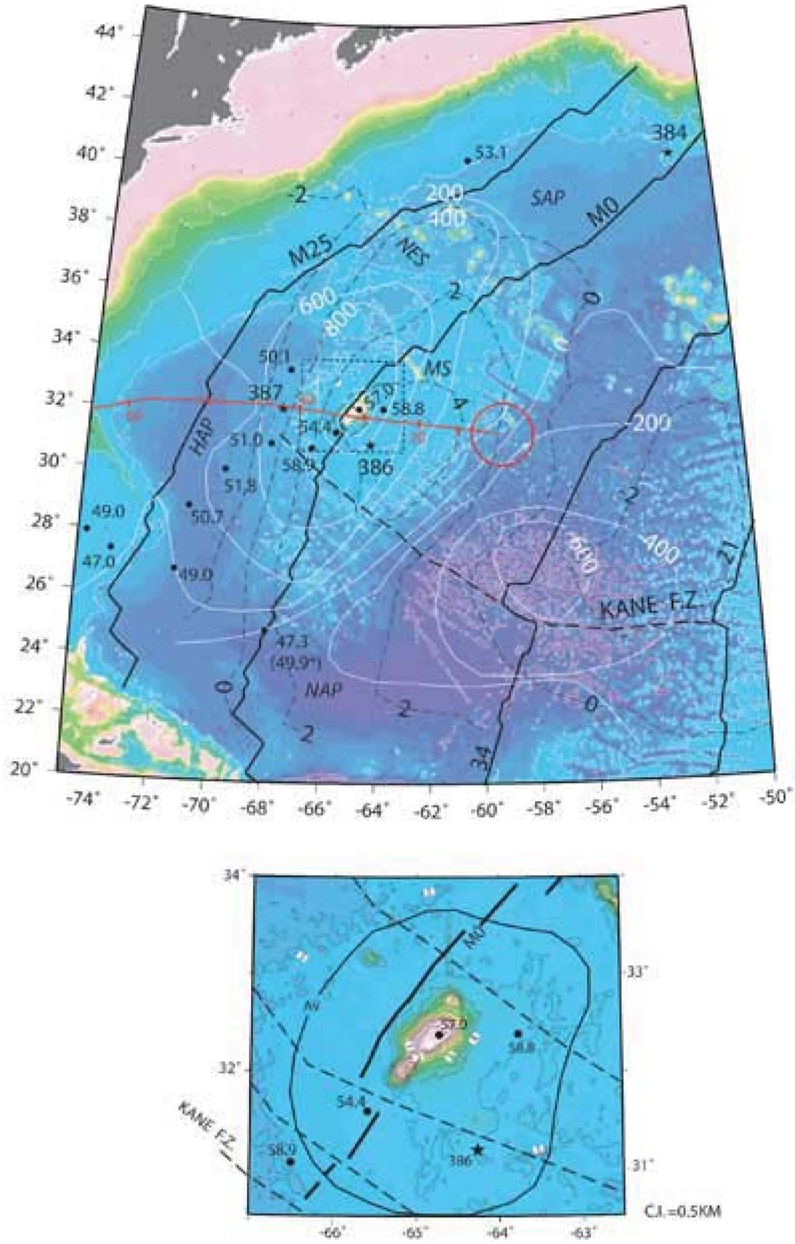

Figure 1. Top: Greater Bermuda Rise region: Bathymetry (Smith & Sandwell, 1997), key magnetic lineations (Mueller et al., 1993), DSDP Leg 43 drill site locations (stars); heat flow values (Detrick et al., 1986; Louden et al., 1987); residual depth anomaly (white contours at 200 m interval; Sclater & Wixon, 1986); residual geoid anomaly (meters; dashed black lines); trace of Kane Fracture Zone (dashed line, after Jaroslaw & Tucholke, 1994); and predicted track (red) of North America plate over a fixed Bermuda hotspot (Duncan et al., 1984), with predicted present hotspot location shown by large red circle. Heat flow station on southern BR shows the value 47.3 mW/m^2 calculated by Detrick et al. (1986), recalculated to 49.9 mW/m^2 by Louden et al. (1987) using the same data. NES, New England Seamounts; SAP, Sohm Abyssal Plain; HAP, Hatteras Abyssal Plain; NAP, Nares Abyssal Plain; MS, Muir Seamount. Bottom: Bathymetry (Smith & Sandwell, 1997) of Bermuda and vicinity, with heat flow stations (W/m^2) from Detrick et al. (1986) and Hyndman et al. (1974), location of DSDP site 386 (The Shipboard Party, 1979), and sea-floor spreading magnetic anomaly M-0 from Klitgord & Schouten (1986). Solid line shows outer limit of seismic reflector Av – caused by volcanogenic sediments of Bermudan origin (Tucholke & Mountain, 1979). Dashed lines indicate major fracture zones as interpreted from geophysical data.

Age dating

Age-dating the Bermuda volcanism and rise development plays a crucial role in testing any model, especially the stationary deep mantle plume model. Boreholes on Bermuda, as well as DSDP Site 386 located in a fracture valley 140 km SE of Bermuda (*Tucholke & Vogt*, 1979) indicate that submarine eruption building up the shield began no later than the late Middle or early Late Eocene, when erosional debris from the emergent edifice first arrived at Site 386. While K-Ar whole-rock dates of 52 Ma (1958 borehole; *Gees*, 1969) and 47 and 91 ± 5 Ma (1972 borehole; *Reynolds & Aumento*, 1974) were reported for these pillow lavas, their alteration makes these dates very unreliable. In a later igneous episode, highly titaniferous dikes (sheets) were intruded into the edifice. However, the sheets have yielded consistent and credible dates of 33-34 Ma, confirmed by recent Ar-Ar dating reported by *Williamson et al.* (2006). Phlogopite weathered out of the eroding sheets first arrived at Site 386 (*The Shipboard Scientific Party*, 1979) in the middle to upper Oligocene (ca 30-25 Ma), consistent with the radiometric dates. The initiation of Bermuda Rise uplift has been stratigraphically dated (early to middle part of the Middle Eocene, i.e., ca 48-45 Ma; *The Shipboard Scientific Party*, 1979; *Tucholke & Vogt*, 1979) by the cessation of biogenic turbidites that had covered the central and western parts of the present rise area. The initiation of igneous activity and uplift may therefore have been coeval. However, while evidence to date suggests Eocene shield formation was succeeded by 33-34 Ma intrusions, analysis of seismic reflection returns from successively tilted turbidites in the Kane Fracture Zone valley suggests that Bermuda Rise uplift continued into Miocene, with 400-500 m of uplift occurring after the sheet intrusion phase.

A Bermuda Plume?

Bermuda ranks very low when observational data are compared to predictions of the mantle plume model (*Courtillot et al.*, 2003; *Anderson*, 2005). Both the 100-km-long volcanic lineament and the 1500-km-long Bermuda Rise trend northeast, nearly at right angles to the trace predicted from North America "absolute" motion models (Figures 1 and 2; *Morgan*, 1983; *Duncan*, 1984; *Mueller et al.*, 1993). Bathymetry shows no evidence for any geologically young igneous activity along the predicted trace, which extends east 650 km from Eocene Bermuda to the predicted present site of a putative Bermuda hotspot (*Vogt & Jung*, 2007). Moreover, *Jaroslaw & Tucholke* (1994) found no evidence for migratory uplift associated with the Bermuda Rise. The shallow depth of volcanic basement under Bermuda shows that little or no subsidence has occurred. *Morgan & Crough* (1979), who were aware of the lack of a hotspot trace, proposed a causal relation between uplift of the Cape Fear Arch on the North American margin, and the passage of the plate over a Bermuda plume; however, more recent studies of this arch are inconsistent with this idea. Those authors also related Cretaceous kimberlites and other igneous rocks in Eastern North America to the passage of the plate over a Bermuda plume.

Some authors (*e.g.*, *Cox & Van Arsdale*, 2002) have held on to the Morgan-Crough Bermuda plume model, which would require a a pulsating ("lava lamp") plume and/or severe control by lithospheric structure on melts rising into or erupting onto the crust. In support, *Cox & Van Arsdale* (2002) note that predicted Bermuda hotspot tracks cross the ca. 65 Ma igneous activity in Mississippi, and also the ca 115 Ma activity in Kansas (Figure 2). However, there is no "LIP" (large igneous plateau) in Kansas or elsewhere that might represent the effects of a "plume head" at the beginning of the putative Bermuda plume track. Moreover, Cretaceous and Cenozoic igneous rocks elsewhere in North America (some are noted in simplified form in Figure 2) would necessarily require other plumes (*McHone*, 1996) [Ed: See also CAMP page].

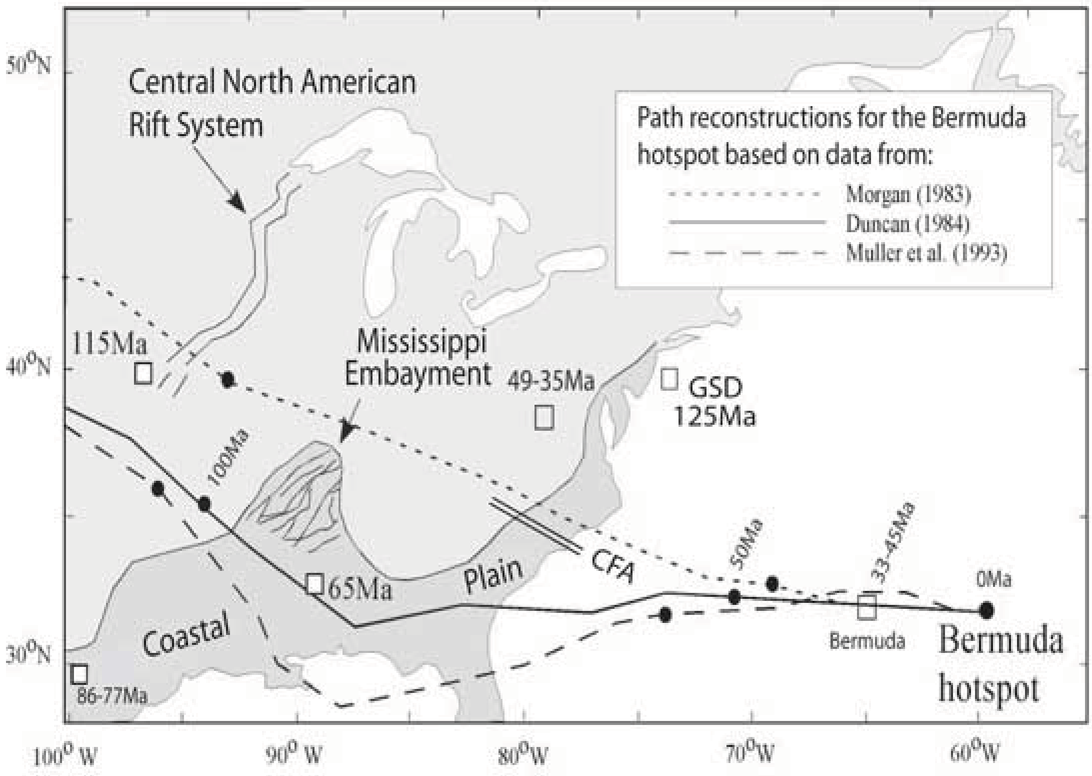

Figure 2. Alternative traces of the Bermuda "hotspot" relative to the North America plate, as predicted by the plate/mantle motion models of Morgan (1983), Duncan (1984) and Mueller et al. (1993), with filled circles indicating the predicted hotspot location at 0, 50 and 100 Ma for each trace. Thin lines within the Mississippi Embayment are the Mississippi Valley graben faults, and open squares show the average location of the earliest (ca. 115 Ma) and latest (ca. 65 Ma) eruptions along a migratory path of igneous activity. CFA and GSD denote Cape Fear Arch and Great Stone Dome. Modified from Figure 1 of Cox & van Arsdale (2002).

Models

A number of attempts have been made – mostly in the late 1970s-1980s – to model the formation and present state of the Bermuda Rise, in many cases along with some other, similar mid-plate swells (*e.g., Crough*, 1978; *Sclater & Wixon*, 1986; *Detrick et al.*, 1986; *Louden et al.*, 1987; *Liu & Chase*, 1989; *Sheehan & McNutt*, 1989). In any case, the geoid and depth anomalies require the Bermuda Rise to be supported by a low density root at depth within the lithosphere or/and upper asthenosphere – it is not thickened oceanic crust. If anything, the crust under the Bermuda Rise (except at the Bermuda volcanoes) is anomalously thin (*Lizzaralde et al*., 2004). Little or no low-seismic-wave-speed anomaly has been detected by tomography in the mantle below Bermuda (*Zhao*, 2004). The lack of current subsidence and the low or nonexistent heat flow anomaly have been problematic for most models. However, published models suggest that certain combinations of thermal expansion, dynamic uplift, and perhaps residual lower-density melt accumulation below the rise, may account for observations. (The latter was proposed by *Phipps Morgan et al*., 1995, for the Hawaii and Cape Verde "hotspots"). Thermal expansion by itself cannot explain the rise except in combination with convection – purely conductive models require too high a temperature anomaly. Some of the models have to be rejected or at least refined to account for continuous but non-migratory Eocene-Miocene uplift (*Jaroslaw & Tucholke*, 1994) and possible lack of a mantle-related heatflow anomaly.

Non-plume alternatives

If Bermuda was not formed by a pulsating lava-lamp-type plume, what can account for the observations? Whatever is happening under Bermuda is evidently traveling with the North America plate. *Sclater & Wixon* (1986), *Vogt* (1991), *King & Anderson* (1998) and *King* (2007) [Ed: See also EDGE page] have examined an "edge-driven" convection that models predict should be generated where thick, cold continental lithosphere abuts an oceanic plate, once the ocean has widened sufficiently. The models predict rising convection currents ca. 1000 km seawards of the boundary. The persistent Eocene to Miocene uplift of the Bermuda Rise, as well as the rise location and orientation, are qualitatively consistent with edge-driven convection.

Vogt & Jung (2007) note that Bermuda Rise formation and volcano formation were coeval, within error bounds, with the Hawaii-Emperor Bend (long dated at ca 43 Ma, but recently redated to ca. 50 Ma; *Sharp & Clague*, 2006). This and other coeval events might represent an abrupt rearrangement of mantle convection, plate motions, and intra-plate stresses triggered by the closing of the Tethys at about that time. Such a global rearrangement has been suggested by Rona & Richardson (1978), among others. Alternatively or relatedly, slabs accumulating near the 660-km discontinuity may have sunk into the lower mantle at that time (*Fukao et al.*, 2001), triggering rearrangements of mantle flow.

While such a global change might have triggered the "Bermuda event", what can explain its geographic location and rise orientation? Edge-driven convection (*e.g., King*, 2007) can explain this, as noted. "Lithosphere pre-conditioning" is another (*Vogt & Jung*, 2007). Both the rise and the volcanic lineament parallel the structure of the underlying oceanic crust, i.e. the isochrons. The rise was developed in crust and mantle lithosphere known to have been formed at very low spreading rates, and exhibiting the rough basement typical of slow spreading. *Lizzaralde et al.* (2004) found this crust to be anomalously thin, with the underlying mantle atypical. This led *Vogt & Jung* (2007) to speculate that the nature of the mantle lithosphere may have made it more vulnerable to partial melting at depth. Alternatively, the mantle below the North American plate that happened to underlie the Bermuda rise region during the Eocene might have been anomalous in composition and/or temperature.

Future research opportunities

How can future research discriminate among the wealth of models so far presented in the literature, and perhaps others still to be developed? First, earthquake-source seismic tomography with even better resolution than *e.g.,* that presented in Fig. 19 of *Zhao* (2004) may delineate a "slow" region in the upper 400 km of the mantle below the Bermuda Rise. Below some such depth, the mantle must be decoupled from the motion of the North America plate. Explosion-source seismic experiments with OBS arrays on the rise, expensive and perhaps not feasible due to concerns for marine mammals, would probably be needed to test for a buoyant refractory root (*e.g., Phipps Morgan et al.*, 1995; *Holm*, 2006) which might extend from ca. 50 km (the depth of swell compensation deduced from geoid data) to 200 km below the rise. (The depth of origin of the Bermuda sheets is ≥ 150 km; *Olsen*, 2005). Airgun-source multichannel profiling of the type conducted by *Lizarralde et al.* (2004) across the southern Bermuda Rise might detect cooled intrusions which reached the upper mantle lithosphere. However, any reduced wave-speed anomalies would have to allow for melt retention under the slow spreading rates forming most of the crust under the Bermuda Rise (*Lizarralde et al.*, 2004). Spreading-rate-dependent mantle velocities should change only gradually northwards along isochrons, whereas any anomalies associated with the Bermuda Rise should reach extrema under the rise summit. Future deep seismic experiments in the ocean surrounding Bermuda are influenced by concerns – whether scientifically justified or not – that the airgun sources will adversely impact marine mammals, particularly whales.

Additional drilling into the igneous basement of Bermuda and its three smaller satellites (Plantagenet/Argos and Challenger banks, and Bowditch seamount) is essential. Given the geologic complexity we know from volcanic islands (*e.g.,* the Cape Verde archipelago; *Holm et al.*, 2006), it seems highly unlikely that even the Bermuda edifice was formed by a simple two-stage process of an Eocene tholeiitic shield, followed after ca. 6-12 Ma of quiescence by the 33-34 Ma "Bermudite" (*Aumento & Gunn*, 2006) sheet intrusions.

Further, we have assumed – with no direct evidence! – that the three satellite edifices are of the same age as Bermuda. This remains pure speculation until they (and/or their flanking debris aprons) are cored, preferably to several km depth. A detailed magnetic and gravity survey of all four edifice summits and upper flanks should be conducted in advance of any drilling or further deep-tow, AUV, or manned submersible investigation, to help map the structural layout of intrusive sheets, lava accumulations, central conduits and flanking volcaniclastic debris aprons. We have proposed such work in cooperation with the Bedford Institute of Oceanography (Drs. Steve Blasco and Marie-Claude Williamson).

Several deep holes similar to those drilled at DSDP Site 386 (Figure 1) and 385 (New England Seamounts; *Tucholke & Vogt*, 1979) should also be placed around the bases of the four Bermuda edifices, as close as possible to the bases, but still practically penetrating the volcaniclastic debris and flows (i.e. the "inner" seismic reflector Av of *Tucholke & Mountain*, 1979), to recover and biostratigraphically date the youngest sediments overlain by the oldest Bermudan rocks. Recovery of larger, less altered rock fragments would also be more likely closer to the base of the volcanic edifices.

A transect of a few boreholes across and along the Bermuda Rise, just deep enough to sample the oldest hemipelagic sediment just above the Eocene biosiliceous turbidites, should be able to resolve the detailed spatial-temporal pattern of BR uplift initiation. Such boreholes might also recover the time when bottom currents were first steered by the BR (*e.g., Ayer & Laine*, 1982). Several boreholes should be placed along the Kane fracture zone to calibrate the uplift history deduced by *Jaroslaw & Tucholke* (1994) from seismic reflection mapping of more local turbidites. Abyssal plains, with gradients of 1:1000 or less (the present BR is surrounded on three sides by modern or at least late Pleistocene abyssal plains; *Pilkey & Cleary*, 1986), should be extremely sensitive to small elevation changes. The Mid-Eocene turbidite offlap pattern – in time and space – would depend on the uplift mechanism.

A plume model predicts rise uplift migrating radially outwards from a region above the upwelling plume head, whereas a "distributed source" model with simultaneous partial melting or/and temperature increase would predict simultaneous uplift over the entire area of the present Bermuda Rise. A plume-type model (*Griffiths & Campbell*, 1991; *Campbell*, 2006) predicts a possible lag of about 2 Ma between the first uplift above the center of the plume head, and uplift on the outer fringes of the expanding asthenosphere (I. Campbell, personal communication, 2005). Such a lag should be recorded by the offlapping turbidites, and is probably measurable from biostratigraphic dating of the first hemipelagics deposited on the last turbidites. The *Campbell* (2006) model also predicts a lag of ca 2-4 Ma between uplift initiation and onset of volcanism. Current dating (Middle Eocene for onset of uplift; late Middle to early Late Eocene or earlier for the volcanism) make such a lag possible, but not proven. The plume model also predicts a possibly testable early central uplift several hundred meters higher in the beginning, before spreading below the plate flattens the head and reduces swell height during the next ca. 2 Ma. The "swell root spreading" models of *Phipps Morgan et al.* (1995; their Fig.6) make even more specific and testable predictions about rise uplift and swell radius as a function of time.

Uplift resolution might be further refined by correlation of individual turbidites from one borehole to the next. Some of the thicker and compositionally distinctive Quaternary turbidites have been correlated from one core to another in modern abyssal plains surrounding Bermuda (*Pilkey & Cleary*, 1986). Readers interested in joining the authors in proposing the Bermuda Rise borehole transects discussed above are welcome. Please email us about your interest!

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