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Earth and Planetary Science Letters 241 (2006) 372–380
EPSL
www.elsevier.com/locate/epsl

The single largest oceanic plateau: Ontong Java–Manihiki–Hikurangi

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Received 9 August 2005; received in revised form 29 November 2005; accepted 29 November 2005
Available online 4 January 2006
Editor: R.D. van der Hilst

Abstract

Oceanic plateaus are mafic igneous provinces commonly thought to derive from ascending mantle plumes. By far the largest, the Ontong Java Plateau (OJP) was emplaced ca. 120 Ma, with a much smaller magmatic pulse of ca. 90 Ma. Of similar age and composition, the Manihiki and Hikurangi Plateaus (MP and HP) are separated from the OJP by ocean basins formed during the Cretaceous long normal magnetic period. I present new seafloor fabric data that indicate the three plateaus formed as one (OJMHP). The data support previous interpretations that the Osbourn Trough is the relict of the spreading center that separated the MP and HP but they require a different interpretation than prevailing tectonic models for the Ellice Basin. Closely spaced, large offset, fracture zones in the Ellice Basin bound former right-stepping spreading segments that separated the OJP and MP. The MP was emplaced near the axis of the Pacific–Phoenix ridge and additional plateau fragments formerly bordered its eastern margins. Following OJMHP break-up, seafloor spreading removed these fragments to the east and SSE, together with the symmetric conjugates to the extant Phoenix magnetic lineations.

Keywords: oceanic plateau; Ontong Java; Manihiki; Hikurangi; Ellice Basin; Cretaceous spreading

1. Introduction

There are several enigmas in current models for the Cretaceous evolution of the southwest Pacific. First, the Phoenix M-series magnetic lineations have no symmetric conjugates [1–3]. Instead, the Ellice Basin, Robbie Ridge and Manihiki Plateau occupy the area where the symmetric lineations are expected (Fig. 1). Various models involving ridge jumps, rifting, and/or volcanic overprinting have been proposed to explain this situation but none resolve all the issues [3–5]. Second, the Ontong Java and Manihiki oceanic plateaus have nearly identical volcanic histories and compositions, including formative volcanism at 119–125 Ma and secondary phases some 20–40 My later, despite being separated by ~2500 km [4,6–8]. Thus models for their formation require an amazing coincidence of events over thousands of kilometers and tens of millions of years. Third, mantle plume models for these plateaus do not fit several of their first order features, including submarine emplacement, minor subsidence with age of the OJP, the similar geochemistry of eruptions separated by so much space and time, and the lack of an obvious plume-tail trace [8,9].

Deciphering the evolution of the Pacific Plate west of 150°W between the equator and 40°S (Fig. 1) has been made difficult by the lack of lineated magnetic anomalies during the Cretaceous long normal period (Chron 34, 124.6–84 Ma, [10]) and by younger volcanic seamounts, and sediments which shed from them that obscure the original oceanic crustal fabric. Map-

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doi:10.1016/j.epsl.2005.11.049

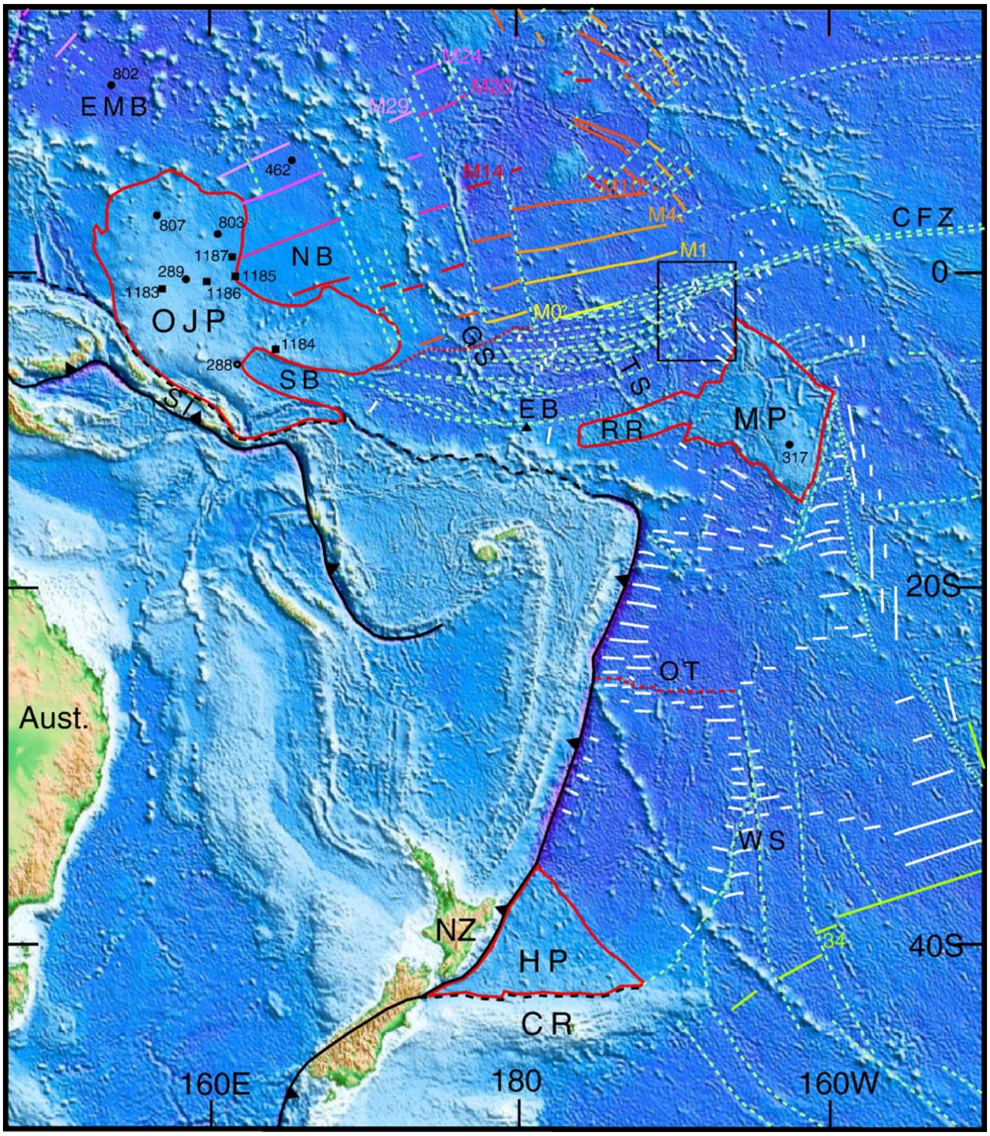

Fig. 1. Bathymetric map [44] showing the location (outlined in red) of the Ontong Java Plateau (OJP), Manihiki Plateau (MP), Hikurangi Plateau (HP), and Robbie Ridge (RR). Abyssal hill seafloor fabric interpreted from swath bathymetry data (white lines), fracture zones (coarse dashed green lines), triple junction traces (fine dashed green lines), zigzag rift boundary (fine dashed red line), trenches (black lines with barbs on the upper plate), and sutures (dashed black lines) are shown. Small black numbers label seafloor drill sites (DSDP, circles; ODP, squares). Select magnetic lineations are color-coded and labeled 34 and M0 through M29 [2,4,16]. Australia (Aust.), Chatham Rise (CR), Clipperton Fracture Zone (CFZ), Ellice Basin (EB), East Mariana Basin (EMB), Gilbert seamounts (GS), Nauru Basin (NB), New Zealand (NZ), Osbourn Trough (OT), Solomon Islands (SI), Stewart Basin (SB), Tokelau seamounts (TS), Wishbone Scarp (WS). Black triangle in EB shows dredge of ≥ 83 Ma MORB [43]. Black box locates Fig. 2.

ping the seafloor fabric has been helped by the advent of wide-swath multibeam systems, but the region is so large that it will be decades before even a sizeable fraction has been fully surveyed. In the interim, the combination of satellite altimetry predicted bathymetry, ground truthed with multibeam swath bathymetry, has provided insights to the origin of several key tectonic elements.

One insight was the recognition that the 8-km-deep Nova-Canton Trough is a fracture zone at the western end of the Clipperton Fracture Zone [11]. The curvature of the Clipperton and related fracture zones allowed Joseph et al. [12] to calculate the pole of Pacific–Farallon spreading during Chron 34. Another was the proposal that the MP and HP were formerly one and that the Osbourn Trough (at ~26°S, Fig. 1) is the relict of the spreading center that separated them with motion parallel to the SW arm of the Wishbone Scarp and the SE margin of the Manihiki Plateau [13,14]. Yet another, the trace of the Pacific–Farallon–Aluk triple junction has been located extending SSE from the eastern corner of MP, and the rapid spreading of the associated Pacific spreading centers has been estimated as 18–20 cm/yr during Chron 34 [5,13,15]. The multiple trends of fracture zones and abyssal hills south of MP to Chatham Rise and magnetic anomaly 34 (Fig. 1) require at least two distinct plates (Hikurangi and Aluk) spreading to the south away from the Pacific Plate (e.g., [14]).

The continued collection of swath bathymetry data has provided further evidence of seafloor fabrics of Chron 34 oceanic crust (summarized in Fig. 1) that support the interpretations above. Here I report additional data that require a different interpretation than prevailing tectonic models for the Ellice Basin, namely that it formed by ~east–west seafloor spreading between the OJP and MP. Accepting the former unity of MP and HP, I propose that the three plateaus originated as one (OJMHP). This hypothesis resolves several enigmas in current models for the Cretaceous evolution of the SW Pacific and highlights the uniquely voluminous emplacement of the OJMHP.

2. Ellice Basin evolution

The Phoenix magnetic lineations east of the OJP define a southward-younging history of spreading between the Pacific and Phoenix Plates from M29 (157 Ma) to M1 (127 Ma) [1,2,10], and possibly M0 (125 Ma) [3,10,16]. West of longitude 180°, Nakanishi et al. [2] identified the conjugate (northward-younging) sequence M1 to M3. Larson [3], however, argued that these anomalies were misidentified, being related instead to a region of lineated gravity anomalies and bathymetric features that he termed the Nova-Canton rift system. He noted that the fracture zone offsets of the Phoenix lineations were also terminated along the northern border of this system that, in the west, has a zigzag trace extending to the eastern edge of the OJP (Fig. 1). He concluded that the Pacific–Phoenix spreading center was disrupted synchronously some time after the formation of the youngest magnetic anomaly (M0). I concur with these suggestions, although the M0 anomaly identification remains in question as it coincides with the boundary of the terrane to the south. Larson [3] then proposed a model of distributed rifting (fed by magmas from separate OJP and MP plumes) that disrupted Pacific–Phoenix spreading and formed a wide divergent plate boundary zone.

New multibeam bathymetry data, however, support the orthogonal interpretation that the lineated gravity anomalies and bathymetric features of the Ellice Basin are formed by long fracture zones that offset former short spreading segments. Seafloor fabric revealed by satellite altimetry predicted bathymetry (fracture zones) and the few available bathymetry swaths (fracture zones and abyssal hills) across the Ellice Basin are summarized in Fig. 1. In this interpretation, the dominant fabric is from closely spaced fracture zones and the intervening abyssal hills have azimuths that swing from NE in the west to NW in the east. Where mapped, such as at 180° and just north of the Nova-Canton Trough (senso stricto, Fig. 2), lazy-S-shaped abyssal hill fabric indicates that the spreading segments were dominantly right stepping (i.e., the transform faults were left-lateral). The presence of northerly trending abyssal hills in these areas immediately south of the boundary to the Phoenix lineations is not compatible with an origin of the Ellice Basin by north–south rifting.

Fig. 2 shows a map of bathymetry data where there is a clustering of wide-swath multibeam tracks northwest of the MP (Fig. 1). As Joseph et al. [11,12] showed, abyssal hills trend at a high angle to the Nova-Canton Trough and the western end of the Clipperton Fracture Zone. The new data reveal that this pattern extends significantly to the south and southwest, i.e., beyond the presumed limit of Pacific–Farallon spreading marked by the northeast rifted margin of the MP (Fig. 1). Furthermore, there are multiple fracture zone azimuths in the range 057°–075°, with two dominant sets trending 060° ± 3° and 072° ± 3° that form V-shaped intersections (Fig. 2). These fracture zone characteristics indicate that there were changes in the pole of Ellice Basin opening and that there were long offsets along the transform faults between the spreading segments, similar to the upper Cretaceous fracture zones of the central Pacific [17]. This configuration is also attested by the satellite predicted bathymetry data that show a series of trapezoid-shaped seafloor regions offset en echelon to the southwest across the Ellice Basin (Fig. 1). Each of these trapezoids is bounded to the north and south by easterly fracture zones (the early opening set) which are connected by multiple fracture zones rotated 10°–15° clockwise in between (the late opening set, Fig. 1). In some areas the original seafloor fabric is overprinted by volcanic eruptions, such as near 2°S, 170°W (Fig. 2). The largest eruptions formed the Gilbert and Tokelau seamount chains (Fig. 1) and the Phoenix Islands (Fig. 2). These seamount chains have been ^{40}Ar/^{39}Ar dated at 58–72 Ma in the Ellice Basin [18]. The limited narrow-

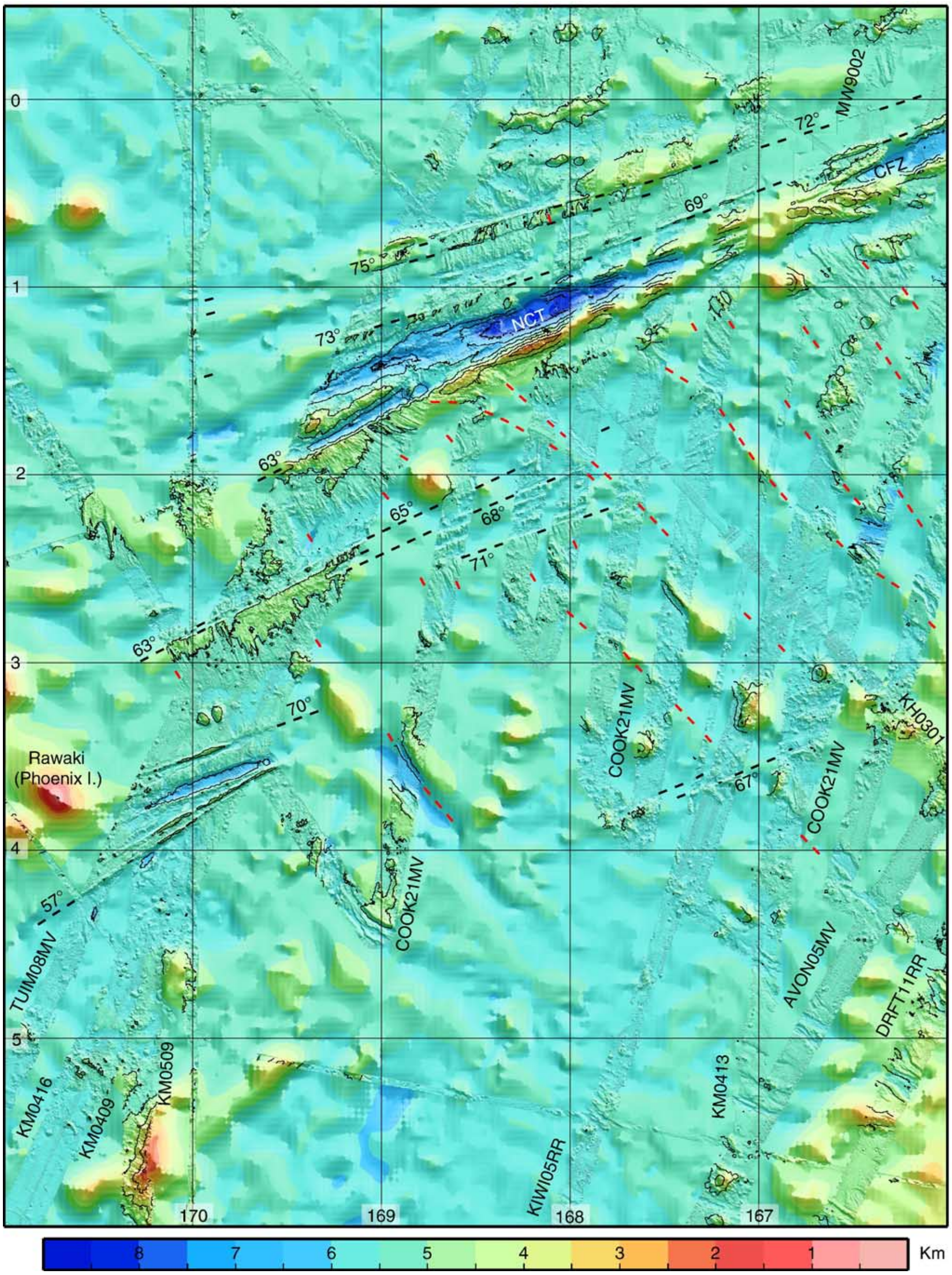

Fig. 2. Illuminated bathymetry: multibeam swaths (with black contours every kilometer) overlain on bathymetry of [44]. Wide swath data, labeled with cruise name, reveal abyssal hill fabrics (interpolated in red dashes) at sub-orthogonal angles to the fracture zones, several of whose azimuths are shown with black dashes. The two dominant fracture zone sets (060° ± 3° and 072 ° ± 3°) form V-shaped intersections in the Nova-Canton Trough (NCT) and east of Rawaki. Clipperton Fracture Zone (CFZ).

swath data that cover the older crust in the northwest corner of Fig. 2, which formed by Pacific–Phoenix spreading, do not evidence a clear abyssal hill fabric.

From the available swath bathymetry and satellite altimetry data, I infer that the Ellice Basin formed by ~east–west spreading that separated the previously emplaced OJP and MP. Also, it appears that Robbie Ridge (RR), a western salient of the MP, may reconstruct into Stewart Basin, an eastern re-entrant of the OJP (Figs. 1 and 3). Although this seems a natural fit, it is not an essential feature of the model. The Ellice Basin fracture zones north of RR are poorly defined,

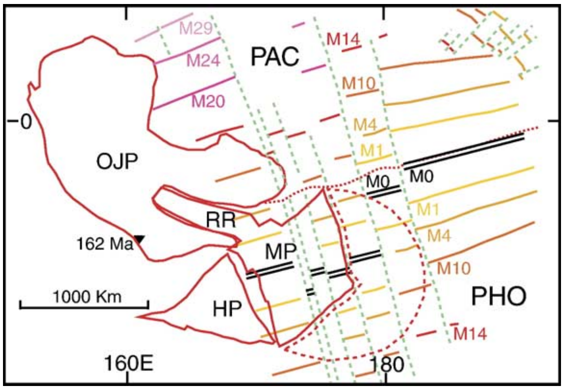

Fig. 3. Reconstruction of the Ontong Java–Manihiki–Hikurangi Plateau at M0 time (~125 Ma, [10]), just before its break-up and the end of Pacific (PAC)–Phoenix (PHO) spreading. Coarse dashed red line depicts possible former plateau east of MP. Inverted triangle locates 162 Ma lower crust beneath Malaita [28]. Other symbols are as in Fig. 1.

being partially overprinted with seamount volcanism, and there are no basement samples from RR to compare with OJP and MP. The reconstruction (Fig. 3) can only be approximated until the fracture zone locations are better resolved to constrain it. Indeed, the fracture zones as drawn are not perfectly co-polar (Fig. 1), but they conform to the best information currently available.

In my OJP–MP–HP reconstruction, the M-series Pacific–Phoenix fracture zones parallel the northeast margin of MP (Fig. 3). Abyssal hill fabric formed by MP-Farallon spreading (northeast MP), MP–HP spreading (southwest MP), and Ellice Basin spreading (Pacific-MP, northwest MP) are all sub-parallel and trend northwest (Fig. 1). Multibeam bathymetry data show that the conjugate margins of the southwest MP and northeast HP are multiply-step-faulted scarps [13,19] and that the trapezoidal MP has rifted margins on the northeast and southwest (Fig. 1). The southeast margin of the MP is obliquely sheared [15] and the northwest margin may be likewise. Some transform motion between RR and MP during the OJMHP break-up would allow a tighter fit between the eastern salient of the OJP and the northwest margin of the MP (Fig. 3).

3. Ontong Java–Manihiki–Hikurangi Plateau

Does the proposed reconstruction of a single OJMHP accord with the known geology and geophysics of each individual plateau? The known ages of all three are very similar. Plagioclase crystals in volcaniclastics at Site 1184 on the eastern OJP salient give a weighted average of ^{40}Ar/^{39}Ar total fusion ages of 123.5 ± 1.8 Ma [20]. Re–Os isotope measurements on basalt samples from ODP Sites 1183, 1185, 1186 and 1187 on the OJP define a single isochron age of 121.5 ± 1.7 Ma [21]. OJP basalts exposed on the Solomon Islands of Santa Isabel, Ramos and Malaita (Kwaimbaita and Singgalo Formations), at DSDP Site 289 and at ODP Site 807 have ^{40}Ar/^{39}Ar ages of 119–125 Ma, whereas later, less voluminous, eruptions at ODP Site 803, on the Solomon Islands of Santa Isabel and San Cristobal, and in ash layers at DSDP Site 288 yield ages of 86–94 Ma [6,8]. Basalts on the MP at DSDP Hole 317A have ^{40}Ar/^{39}Ar ages of 123 ± 1.5 Ma [6] but only minimum ages of 75–82 Ma for the secondary MP volcanism are available [22]. In contrast to the geochronologic and stratigraphic evidence for bimodal ages of the OJP, new feldspar ^{40}Ar/^{39}Ar dates of HP basement samples (93–118 Ma) may indicate a more continuous magmatic evolution [23]. These dates overlap with ^{40}Ar/^{39}Ar ages (111–115 Ma) of flood basalts of Kwaimbaita type found in the Nauru Basin at Site 462 and in the East Mariana Basin at Site 802 (Fig. 1) [24,25]. Large alkalic guyots on the HP have ^{40}Ar/^{39}Ar ages (86–99 Ma) similar to the alkalic dykes (90 Ma) on the OJP [7,23]. Thus the basement of the three plateaus, flood basalts in the East Mariana and Nauru Basins, and late stage alkalic rocks of the OJP and HP, each have comparable ages. With some allowance for portions likely lost to subduction, this submarine volcanism covered ~1% of the Earth's surface. Also remarkable is the lack of a significant spatial age progression for all dated basement samples between Site 807 on the OJP and Site 317 on the MP (a distance of ~2500 km within the reconstructed OJMHP, Figs. 1 and 3). This rules out a plateau origin at a single spreading center such as is occurring today at Iceland.

Lava suites from the three plateaus also have very similar geochemistry. OJP basement exposed in a >3.5 km thick section in the Solomon Islands and recovered at eight deep ocean drill sites includes three geochemically distinct units [8,25]. The voluminous Kwaimbaita Formation is fractionated, but isotopically indistinguishable, from the higher MgO (9–10.5%) Kroenke-type basalts found at ODP Sites 1185 and 1187, which may represent the parental magma for the bulk of the OJP [25,26]. Sr–Nd–Pb isotopic data and flat chondrite-normalized rare earth element (REE) signatures show that their OJP mantle source is less depleted than the source of normal mid-ocean ridge basalt (MORB) [25,26]. Late, lower degree, Singgalo melts were derived from an even less depleted mantle source [8]. Drill-hole (123 Ma) and dredged basalts from the MP also have flat REE, and bimodal isotopic signatures that overlap with, but extend to greater ranges than, those of the OJP [6–8]. The younger (~90 Ma) Sigana tholeiitic basalts of the OJP have a Kwaimbaita-type isotopic signature, but rare 90 Ma alkalic dykes that are light-REE-enriched and have high $^{238}U/^{204}Pb$ (HIMU) characteristics are also present [7]. The HP basement rocks (basalts, dolerites and gabbros) have flat REE patterns and Sr–Nd–Pb isotope compositions in the range of the OJP and MP basement [23,27]. Late-stage seamounts on the HP have light-REE-enriched lavas and incompatible element and isotopic compositions of HIMU type [23]. Thus the lavas from the three plateaus, in comparable age groups, have very similar geochemistry. There are also minor younger lavas on the OJP and HP including, on Malaita, Eocene (44 Ma) alkaline basalts and Oligocene (34 Ma) alnöites [7]. $^{40}Ar/^{39}Ar$ ages of 160–162 Ma on spinel lherzolite and gabbro xenoliths in the Malaita alnöites suggest a significant fracture zone offset between the Nauru Basin and this pre-existing upper mantle and lower crust beneath the OJP or possibly that the OJMHP formed near a spreading triple junction [28].

Volatile contents in glass rims of basaltic pillows indicate eruption depths ranging from 1 km on the crest to 2.6 km on the northeast edge of the OJP, and low water contents of the mantle source [29]. Likewise, the relief of guyots superimposed on the HP indicates that it was at a water depth of ~1500 m when the island volcanoes were eroded to sea level [19]. Volcaniclastic rocks with tholeiitic and alkali basaltic to trachybasaltic compositions recovered from the OJP, MP and HP were erupted from shallow-water late-stage volcanoes that in places formed wooded islands [19,20,22,30]. Based on their geochemistry, Castillo [31] proposed that the most likely origin for the Cretaceous volcaniclastic sediments at Site 802 in the East Mariana Basin was from the alkalic seamounts on the Manihiki Plateau. He could not reconcile the great distances and physiographic barriers between the two, but my new reconstruction substantially reduces those problems and is consistent with the volcaniclastics originating on the OJMHP.

Although the bulk of the three plateaus formed below sea level, the OJP has subsequently subsided only ~1–2 km, instead of the ≥3 km predicted for 120 Ma lithosphere [32]. The subsidence of the MP is not well constrained. That of the HP is complicated by its collision with the continental Chatham Rise of New Zealand. The southwest interior of the HP, closest to the suture, has subsided ~1600 m, but across the 500 km to the northeast rifted margin the plateau has been tilted down an additional ~1700 m [19].

All three plateaus have a layered velocity structure similar to oceanic crust, but the thicknesses vary from ~5 times that of typical oceanic crust on the high OJP to ~3 times on the MP and ~2 times on the HP [33–38]. The MP probably had a thicker crust before it was multiply rifted. The HP thicknesses are like those on the edges of the OJP. Calculations of OJP maximum crustal thickness based on Airy isostasy [39] or the ratio of geoid to topography [40] significantly underestimate the values measured by seismic refraction and tomography (33–38 km) [33,36,38]. Together with the uplift and subsidence patterns, this is further evidence that the mantle density structure beneath the OJP differs from normal oceanic mantle. Indeed, seismic tomography reveals a slow-velocity mantle root extending to ~300 km depth beneath the OJP [36] and its low shear-wave attenuation implies a compositional rather than thermal anomaly [41]. This root cannot represent the residue of the partial melting process that produced the OJP basalts, which should be less dense but seismically fast refractory harzburgite with Fe-depleted olivine about 85 km thick [26].

4. Discussion

As summarized above, the OJP, MP and HP have similar age, composition, velocity structure and submarine emplacement. Available seafloor fabric data are consistent with their having been separated by subsequent seafloor spreading. I therefore suggest that the three plateaus originally formed as one (OJMHP). This model for the Cretaceous evolution of the southwest Pacific readily explains the similarity of the three plateaus despite their current large separations. It also explains the lack of symmetric conjugates to the Phoenix M-series magnetic lineations as being the result of ~east–west spreading in the Ellice Basin between the OJP and MP. By reconstructing the original extent of the single oceanic plateau, the model highlights but does not address the enigmatic mantle characteristics that may have produced such a uniquely voluminous magmatic event.

Geochemical modeling suggests that primary OJP magma requires ~30% melting of a peridotite primitive (not depleted MORB) mantle [26]. Melting occurred in both the garnet and spinel peridotite stability fields [6]. Given the absence of anomalous water contents [29], this extent of melting can be achieved by decompression of hot (potential temperature >1500 °C) peridotite beneath thin lithosphere [26]. However, the inferred high mantle potential temperatures and eruption rates, and the mantle plume models that predict same, are incompatible with the submarine emplacement and limited subsidence observed on the OJP [8,32]. Alternate origins have been proposed, including bolide impact (e.g., [42]) or entrainment of eclogite-bearing mantle by passive upwelling near a super-fast spreading ridge [9]. But to date, none of the models has found widespread acceptance as simultaneously explaining the geochemical, geophysical and marine geological features of the plateau [9,25].

In the absence of lineated magnetic anomalies, what constraints can be placed on the break-up of the OJMHP and the seafloor spreading between OJP–MP–HP? Note that the end of Pacific–Phoenix spreading is no longer precisely defined: it could have continued until east–west spreading in the Ellice Basin began to separate the MP and OJP. Obviously break-up occurred after the major formative phase of the OJMHP (Fig. 3). The MP has multiple summit (e.g., Danger Islands Troughs) and flank rift systems [4] so that it is possible, though not necessary, that break-up was nearly simultaneous on its four sides. Break-up much after 119 Ma would require even faster spreading rates (until the end of Chron 34 at 84 Ma) than the18–20 cm/yr calculated to the east of MP [3]. Similarly high rates and break-up times are required to the south if the spreading between the MP and HP ceased at the Osbourn Trough when the HP sutured to the Chatham Rise, estimated to be about 105 Ma [13], and to generate the Pacific–Aluk crust east of Wishbone Scarp between the MP and anomaly 34 [5] (Fig. 1). Even fewer constraints are available for the Ellice Basin. One MORB-type basalt dredged from the southern Ellice Basin near 10°S, 179.4°W (Fig. 1) has a ^{40}Ar–^{39}Ar total fusion age of 82.6 ± 1.2 Ma [43], which provides a minimum crystallization age near the end of Chron 34. More well-dated basement samples will be required to refine the spreading histories.

5. Conclusions

Accumulated seafloor fabric data are still consistent with the hypothesis that the MP and HP were formerly one, have conjugate rifted margins, and that the Osbourn Trough is the relict of the spreading center that separated them [13,14,19,23]. New seafloor fabric data, together with satellite altimetry predicted bathymetry, indicate that large offset, closely spaced, transform faults accommodated ~east–west spreading in the Ellice Basin. The OJP, MP and HP have similar age, composition, velocity structure and submarine emplacement because they originally formed as one and were separated later by Cretaceous seafloor spreading. My reconstruction shows the MP was emplaced near the axis of the Pacific–Phoenix ridge and additional plateau fragments formerly bordered its northeast and southeast margins. Subsequent seafloor spreading removed these fragments to the east and SSE, respectively, together with the symmetric conjugates to the extant Phoenix magnetic lineations. Cretaceous volcaniclastic sediments at Site 802 in the East Mariana Basin could have originated from alkalic seamounts on the OJMHP. No geodynamic model has found wide acceptance that can explain the voluminous, mostly submarine, eruption of magma from a dense fertile mantle source to form the OJMHP, the single largest oceanic plateau.

Acknowledgments

The collection of swath bathymetry data used in this paper was funded by the National Science Foundation, the University of Hawaii, MEXT of Japan, and Fugro Seafloor Surveys Inc. MW9002-SYS09, COOK21MV, KH0301 and TUIM08MV data are courtesy of Fugro Seafloor Surveys Inc., Dr. Roger Larson, Dr. Masao Nakanishi and Scripps Institution of Oceanography, respectively. Alyssa Aaby prepared Fig. 2 from data compiled by the author. Reviews by Mike Coffin, Robert Duncan, Stephanie Ingle, John Mahoney and Joann Stock are appreciated.

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