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Impact origin for the greater Ontong Java Plateau?

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Abstract

The ~120 Ma Ontong Java Plateau and neighboring, contemporaneous Nauru, East Mariana, and (probably) Pigafetta basin flood basalts in the western equatorial Pacific Ocean comprise the Earth's largest flood basalt province. Geophysical, geochemical, and geodynamic evidence from the province are difficult to reconcile with mantle plume models; absence of an obvious hotspot source or track, minor crustal uplift associated with emplacement, minor total subsidence compared with normal oceanic crust or other oceanic plateaus and submarine ridges, high degrees of melting at shallow, upper mantle depths, low water contents of basalts, enrichment of platinum group elements in basalts, and a ~300 km deep, seismically slow mantle root are more consistent with the consequences of an impacting bolide. An object ~20 km in diameter impacting relatively young (~20 Myr) Pacific lithosphere and penetrating into the uppermost asthenosphere would have initiated massive decompression melting in the upper mantle, and may have resulted in emplacement of the greater Ontong Java Plateau.

Keywords: Ontong Java Plateau; large igneous provinces; bolide impact; mantle plumes; mantle melting; Ocean Drilling Program; Pacific Ocean

1. Introduction

Large igneous provinces (LIPs), commonly believed to result from ascending mantle plumes, represent the dominant form of volcanism in our solar system [1]. On Earth, the largest known flood basalt province is the Ontong Java Plateau (OJP), which together with neighboring ocean basin flood basalts comprise the 'greater OJP', encompassing 4.27×10^6 km^2, or ~0.8%, of the Earth's surface (Fig. 1). Emplaced in Early Cretaceous time at ~120 Ma [2,3], the greater OJP's crustal volume is estimated to be 5.8×10^7 km^3 [4,5], with a maximum crustal thickness of ~35 km [5,6]. Extending beneath the OJP ~300 km into the mantle is a low-velocity root [6]. Basalts of the greater OJP, sampled from nine Deep Sea Drilling Project (DSDP) and Ocean Drilling Pro-

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gram (ODP) sites as well as from obducted sections in the Solomon Islands of Malaita and Santa Isabel (Fig. 1a, 1b), are tholeiitic with strikingly uniform petrologic and geochemical characteristics [7–11]. They result from large degrees (> 30%) of partial melting at shallow upper mantle depths [2,12,13].

Experimental and quantitative modeling of the OJP's emplacement and evolution has focused on one or more ascending mantle plume heads as the underlying mechanism [14–18]. Alternatively, speculation that the OJP formed because of a bolide impact [19,20], or because of a mantle avalanche resulting from a bolide impact [21], has persisted for more than two decades. Here, we evaluate whether mantle plume or impact models are more appropriate for the origin of the greater OJP in light of relevant geophysical, geochemical, and geodynamic evidence.

2. Evaluation of mantle plume models and the OJP

Plate tectonic theory does not satisfactorily explain the origin of LIPs, areas of prodigious magmatism recognized by extensive basaltic volcanism [4]. This has led to the proposal that LIPs originate from the heads of mantle plumes arising from deep within the Earth to erupt on the surface by decompression melting [22,23]. Plumes may have a 'tail' that remains 'fixed' to a mantle boundary layer and that feeds the surface, allowing for the plume to erupt continually or sporadically to create long-lived expressions on the surface referred to as hotspots [24]. Although the Louisville hotspot has been suggested as an original source [23,25], the OJP cannot be linked convincingly to it or any other hotspot track or cur-

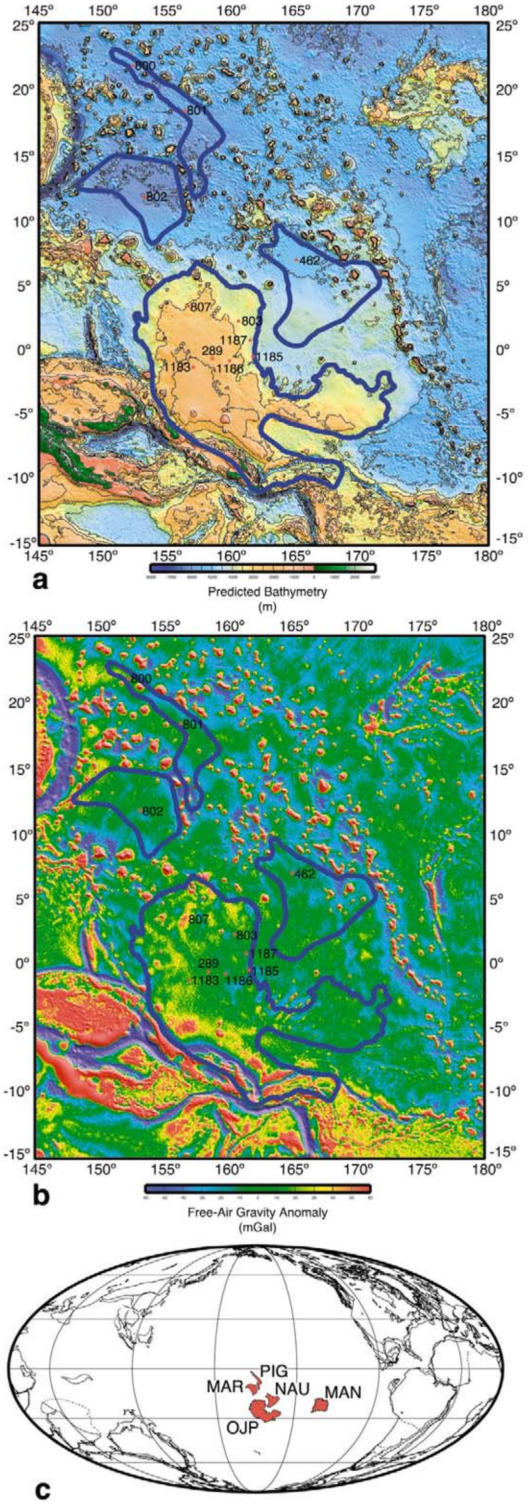

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Fig. 1. The OJP, and the Nauru (NAU), East Mariana (MAR), and Pigafetta (PIG) basin flood basalts in the Pacific Ocean. (a) Predicted bathymetry with drill sites that penetrated flood basalts superimposed [83]; DSDP: Deep Sea Drilling Project; ODP: Ocean Drilling Program. (b) Satellite-derived free-air gravity field with same drill sites as (a) superimposed [84]. (c) Plate tectonic reconstruction at 118.7 Ma (chron M0), also showing Manihiki Plateau (MP) (after [85]).

rently active hotspot on the basis of geochemistry [2], plate reconstructions [12], paleomagnetic data [26], or combined hotspot motion and true polar wander [27].

The a priori assumption that a deep mantle plume created the OJP [28] is based on its huge crustal volume and the unusual conditions required to generate such extensive magmatism. The arrival of hot, buoyant, ascending plume material at the base of oceanic lithosphere, accompanied by voluminous decompression melting, should result in a combination of thermal expansion, buoyant uplift, and crustal growth capable of maintaining the plateau above sea level [15,17,29]. Both general isostatic (e.g., [30]) and experimental dynamic plume models (e.g., [29,31]) predict that seafloor is uplifted by 1000–2000 m due to the arrival of a 1000–2000 km diameter plume at the base of the lithosphere, in agreement with observations of seafloor swells associated with major hotspots (e.g., Hawaii, Cape Verde). Specific OJP plume models, both dynamic [15] and isostatic [17], predict elevation of the seafloor by 3000–4000 m, and 1000–3000 m, respectively (Fig. 2a). The presence of Mesozoic marine magnetic anomalies in the OJP's neighboring Nauru Basin [32] (Fig. 1) suggests that the ~120 Ma OJP formed within ~130 to ~155 Ma [33] oceanic crust. Global age–depth curves [34,35] predict that 10–35 Myr old oceanic crust typically lies at depths of ~3600 to ~4700 m

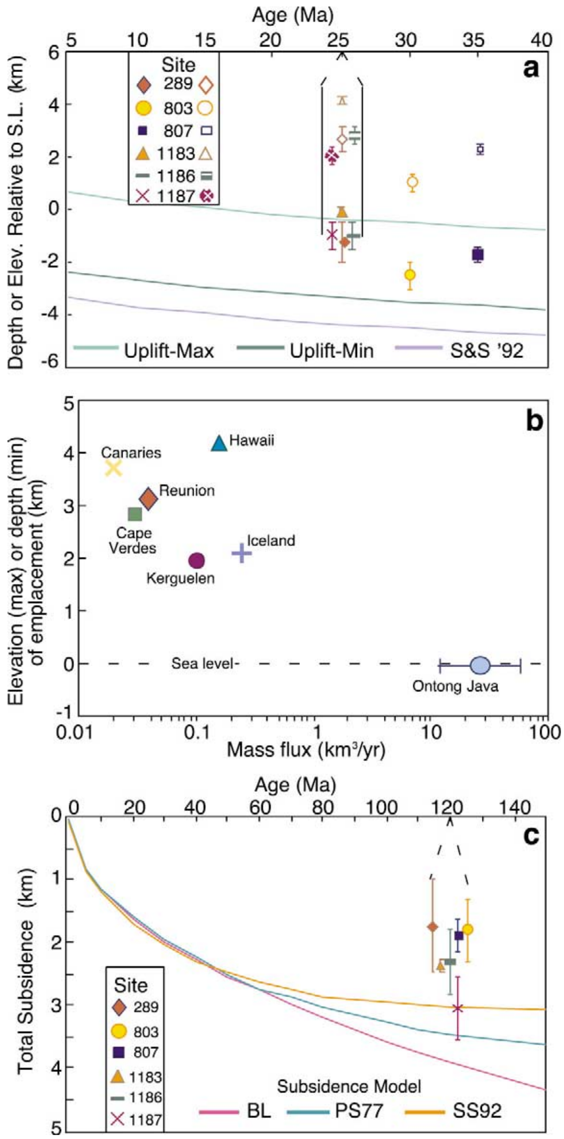

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Fig. 2. Geophysical and geodynamic characteristics of OJP. (a) Model-predicted paleodepths of preexisting oceanic crust (SS92) [35] at time of OJP formation at ~120 Ma [2,3], range of uplift of oceanic crust predicted by specific OJP dynamic (Uplift-Max) [15] and isostatic (Uplift-Min) [17] plume models. For individual DSDP and ODP sites, we compare model-predicted paleodepth ranges for the top of OJP crust (open symbols with bars) to paleodepth ranges of Aptian sediment directly overlying OJP basalts interpreted from paleoenvironmental data (filled symbols with bars) [13,39,40], with elevation of final flood basalt emplacement at ~120 Ma predicted by either water-corrected isostasy (for calculations below sea level) ($\Delta h = \Delta c(\rho_m - \rho_c)/(\rho_m - \rho_w)$), or by water- and air-corrected isostasy (for calculations below and above sea level, respectively) ($\Delta h = \Delta c(\rho_m - \rho_c)/(\rho_m - \rho_a)$) where Δh = deviation in height; Δc = crustal thickness in excess of normal oceanic crust (7 km [35]); ρ_m = mantle density (3300 kg/m^3); ρ_c = crustal density (2800 kg/m^3); ρ_w = water density (1030 kg/m^3) below sea level; ρ_a = air density (0 kg/m^3). Crustal thickness values from [5], and ages of preexisting crust estimated from extrapolating Mesozoic marine magnetic anomalies in the Nauru Basin (Fig. 1; [32]). (b) Mass fluxes and peak eruption levels of currently active hotspots and the OJP. Note that of all the hotspots, only Iceland coincides with a mid-ocean ridge. References: Mass flux, OJP (this paper), all others [86], OJP emplacement elevation relative to sea level [13]. For the OJP, the error bars represent the mass flux range assuming an emplacement rate from 1–5 Myr. (c) Total subsidence vs. age for OJP basalts (error bars on symbols denote range interpreted from [39,40,87]). Subsidence curves are from: BL and PS77 [34], and SS92 [35].

(Fig. 2a). Therefore, according to specific OJP plume models [15,17], oceanic crust should have been uplifted to between ~400 m above sea level to ~3700 m below sea level prior to constructional magmatism (Fig. 2a).

According to simple isostasy, emplacement of the OJP's up to ~35 km thick crust following uplift of preexisting ~7 km thick oceanic crust [36] should have resulted in major, widespread subaerial volcanism at minimum culminating elevations of ~700 to ~4200 m on the central OJP (Fig. 2a). Although no contemporary analogs on such a scale exist, the Earth's six most active hotspots in the ocean basins, characterized by mass fluxes orders of magnitude smaller than the OJP's, all feature large-scale subaerial volcanism (Fig. 2b). Similarly, most oceanic plateaus, submarine ridges, and seamount chains attributed to mantle plumes, and sampled by drilling, have experienced significant subaerial volcanism during construction (e.g., [37,38]). Yet all OJP basalts, either drilled or sampled from obducted Solomon Islands sections, erupted below sea level, and sediments deposited just above this basement are marine [11,13] (Fig. 2b).

Plateaus within oceanic lithosphere should subside via either thermal conduction [30] or continuous viscous spreading of the anomalous mantle material [29]. Many oceanic plateaus and submarine ridges have subsided similarly to oceanic crust of normal thickness [37,38]. Predicted total subsidence of ~120 Ma oceanic crust ranges from ~3000 to ~3800 m [34,35]. Paleoenvironments interpreted from sediment immediately overlying basalt at five out of six OJP drill sites [13,39,40] and basalt eruption depths calculated from H_2O and CO_2 concentrations in basaltic glasses [41] show that OJP crust, when reconstructed to account for sediment loading, subsided only 1000–2800 m, significantly less than either typical oceanic lithosphere [34,35] or other oceanic plateaus and submarine ridges [37,38,42] (Fig. 2c). Previous geodynamic inferences and models involving subsidence rates typical of most oceanic crust [43] and multiple stages of crustal growth [17,18], respectively, are inconsistent with subsidence determined from sedimentary paleoenvironments as outlined above, and a single major episode of constructional magmatism at ~120 Ma [2,3].

3. Petrogenesis of greater OJP basalts

Geochemical similarities among Early Cretaceous tholeiites from the OJP, and the East Mariana and Nauru basins, have led to proposals for a common genetic origin, possibly by an OJP mantle plume [7,9]. Mesozoic magnetic anomalies in the basins indicate that Late Jurassic and Early Cretaceous oceanic crust underlies the Lower Cretaceous East Mariana, Nauru, and Pigafetta flood basalts [32,44,45]. Castillo et al. [10] suggested that if one or more OJP plume head(s) had extended underneath these basins, high temperatures induced on preexisting lithosphere arguably could have raised the basalts above the Curie temperature, thus erasing the Mesozoic magnetic anomalies, and suggested that the basin basalts instead originated from isolated Cretaceous rifting events within preexisting Jurassic oceanic crust. However, the OJP, East Mariana, and Nauru basin basalts have similar ages, overlapping isotopic signatures, and generally comparable overall major and trace element compositions [7–10,46,47] and a common mantle origin for the OJP and these basin basalts seems reasonable.

To generate the major and trace element patterns of the greater OJP basalts requires partial batch melting of 30% or more, followed by extensive fractional crystallization [2,12,13,48]. Such large degrees of partial melting are known in seafloor spreading environments influenced by hot or wet mantle plumes [49,50]. Primitive mantle-normalized incompatible trace element patterns for greater OJP basalts suggest melting and fractional crystallization at shallow depths, comparable to magma chamber depths of normal mid-ocean ridge basalts (MORB; Fig. 3a). Eruption at ocean ridge crest depths is consistent with the absence of vesicles in greater OJP lavas (indicating minimum eruption depths of >800 m; [13]), vapor saturation pressures for the basalts indicating eruption depths [41,43], and overlying marine sediments. However, plume theory predicts that emplacement at a ridge would have elevated the OJP

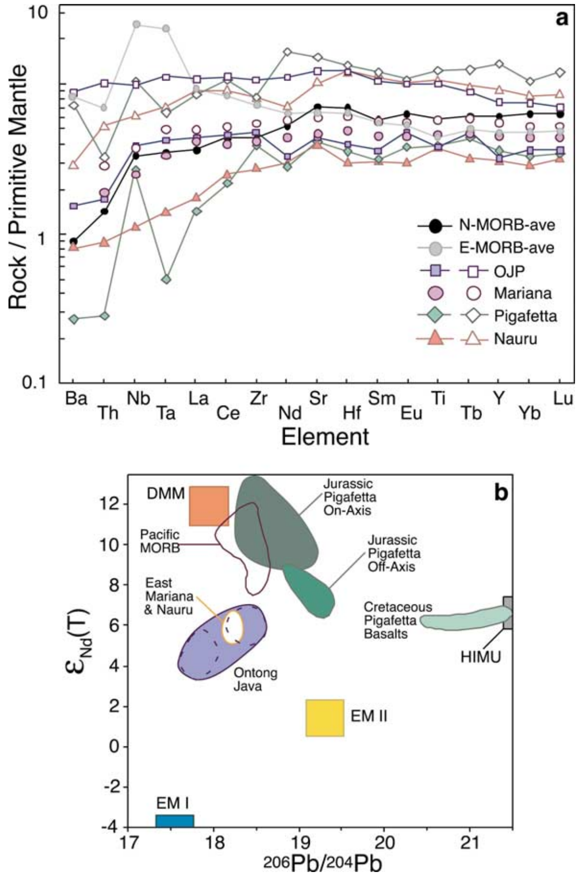

Fig. 3. Geochemical characteristics of the greater OJP basalts. (a) Primitive mantle-normalized [88] incompatible element diagrams for the Lower Cretaceous OJP and East Mariana and Nauru basin basalts [8]. Also shown for comparison are the Jurassic tholeiites from the Pigafetta basin [89], averaged 'normal' N-MORB and 'enriched' E-MORB [88]. Solid symbols represent the lower boundary for each sample suite and open symbols the upper boundary. (b) Age-corrected ε_{Nd} versus measured $^{206}Pb/^{204}Pb$ for the greater OJP and Pigafetta basalts [7–11] and Pacific MORB [90]. Also shown are the values for the mantle end-members [91].

well above sea level [15,17], and this is inconsistent with the absence of vesicles in the basalts and eruption depths determined from vapor saturation pressures, as well as the lack of significant uplift of the OJP. Away from a ridge, extensive melting could be aided if a plume were hydrous [50,51], but concentrations of H_2O in OJP basalts require a relatively dry mantle source [43].

Radiogenic isotopic compositions (Sr, Nd and Pb) of the Early Cretaceous OJP, East Mariana basin, and Nauru basin basalts are unlike present-day Pacific MORB (Fig. 3b). Isotopic values of nearby Jurassic and pre-120 Ma Cretaceous MORB-type Pacific tholeiites (e.g., Jurassic tholeiites in the Pigafetta Basin [9]; Fig. 1a) closely resemble those of modern Pacific MORB. Dissimilar Sr–Nd–Pb isotopic values between greater OJP basalts and pre-120 Ma Pacific tholeiites have been interpreted as precluding MORB-type upper mantle and favoring a plume originating from the lower mantle as the source of the OJP (e.g., [2,9–11,52]). However, isotopic signatures of off-axis Jurassic alkalic basalts from the Pigafetta Basin more closely resemble, although they do not overlap with, those of the OJP, East Mariana basin, and Nauru basin basalts [9]. Cretaceous Pigafetta basin basalts differ from the OJP, East Mariana and Nauru basin basalts, having isotopic compositions that trend between those of the Jurassic alkalic basalts and those of nearby seamounts [9]. The presence of geochemically dissimilar mantle domains in the vicinity of the greater OJP both before and after its emplacement suggests that the off-axis Pacific Ocean upper mantle was quite heterogeneous at local scales during Late Jurassic and Early Cretaceous time.

Platinum group elements (PGEs) are believed to be possible tracers for core input into large mantle plumes ascending from the core–mantle boundary (e.g., [53]). When the Earth formed, these elements were largely stripped from the silicate part of the Earth and incorporated into Earth's core. Therefore, any significant contribution to a plume from the core should be apparent in higher than normal concentrations and distinctive Os isotopic characteristics of the PGEs. PGEs in OJP basalts are high relative to values predicted assuming a primitive mantle source, and a possible, minor core component (0.5–1%) has been advocated to account for these elevated concentrations [54,55]. No evidence was found, however, for core input in the Os isotopic compositions of the OJP basalts [56]. Alternatively, to explain the PGE-enriched signatures in OJP basalts, the mantle source could have contained PGE-rich sulfide veins generated by metasomatic fluids derived from ancient continental recycling [57]. However, these fluids would likely leave an obvious imprint of the continental signature, as is left in the subcontinental lithospheric mantle [58], and the resulting Os isotopic values should not be primitive mantle like, as the OJP basalts are [56].

4. Origin of the OJP's mantle root

The OJP's 300 km deep low-velocity 'root' [6,59] is the first such observation from an oceanic intraplate setting. A shear wave splitting study concluded that ambient asthenosphere flows around the root, suggesting that it is rheologically strong and attached to the OJP's crust [59]. Centered beneath the OJP's thickest crust, but not extending to underneath the ocean basin flood basalts, the root is cylindrical with a diameter of ~1200 km, and is characterized by anomalously slow (~5%) shear wave velocities. If such velocities were entirely thermal in origin, then the root would be up to 700°K hotter than surrounding mantle, hot enough to cause continuing volcanism [59]. However, since the OJP shows no evidence of active volcanism, this keel was proposed to more likely represent a chemical heterogeneity [6,59]. The root has been interpreted as the frozen head of a plume that somehow failed to remain anchored in the deep mantle [59], but its volume is much larger than can be explained by the volume of mantle remaining from the melt extraction needed to form OJP basalts [12]. Mantle roots characterized by slow seismic velocities have also been detected beneath some continental LIPs, the Deccan Traps [60] and Paraná flood basalts [61], but these are characterized by smaller velocity anomalies (1.5 and 2.4% vs. 5%, respectively) than the root beneath the OJP [59].

5. Impact origin for the OJP?

Taken in total, many geophysical, geodynamic, and geochemical results from the OJP are at odds with various mantle plume models for its origin. The greater OJP cannot be tied convincingly to any hotspot or hotspot track. Anomalously minor uplift at emplacement and anomalously little subsidence since 120 Ma fit neither plume nor oceanic crustal models, making the OJP the only such anomalous feature identified so far in the ocean basins. High degrees of melting at shallow depths are difficult to reconcile with the likely intraplate emplacement environment and the low water contents in the mantle source. The basalts are geochemically homogeneous compared to other oceanic hotspots and are isotopically similar to some MORB from the Indian Ocean. PGEs are elevated relative to those predicted assuming a primitive mantle source. A low-velocity zone extending ~300 km into the mantle beneath the OJP has yet to be explained by plume models. As expanded upon below, we suggest that an extraterrestrial impact model is much more consistent with existing data and results.

A large bolide (>10 km in diameter) is required to instigate phenomena such as extensive mantle melting (e.g., [62]). Assuming a chondritic bolide ~20 km in diameter and vertical impact at a velocity of 20 km/s, the impact would vaporize the ~4 km thick water column, probably the entire ~50 km thick lithosphere, and perhaps part of the uppermost asthenosphere, with a total penetration depth of ~60 km [63] and a resulting crater diameter of ≥200 km [64] (Fig. 4a). The impact would generate tsunamis, but the confining ~4 km thick water barrier surrounding the impact site may have limited the radial distribution of both low- and high-energy impact ejecta (e.g., [65,66]). At the time of impact, shock waves imparting intense pressures would propagate hemispherically causing relatively minor shock melting of mantle rock in the wake of the waves [62] (Fig. 4b).

Massive decompression melting of the mantle left surrounding the crater would result from removal of 60 km of overburden [67], even if the depressurization effect was reduced to some extent by instantaneous lateral resurge partially filling the crater [68]. If 100% of the mantle melted, following roughly hemispherical patterns outward from the crater, melting to a depth of at least 300 km would be required (in the case of partial melting, melting to even deeper mantle depths would be required) to explain the greater OJP's crustal volume (5.8×10^7 km^3); such a depth corresponds to the depth of the OJP's tomographi-

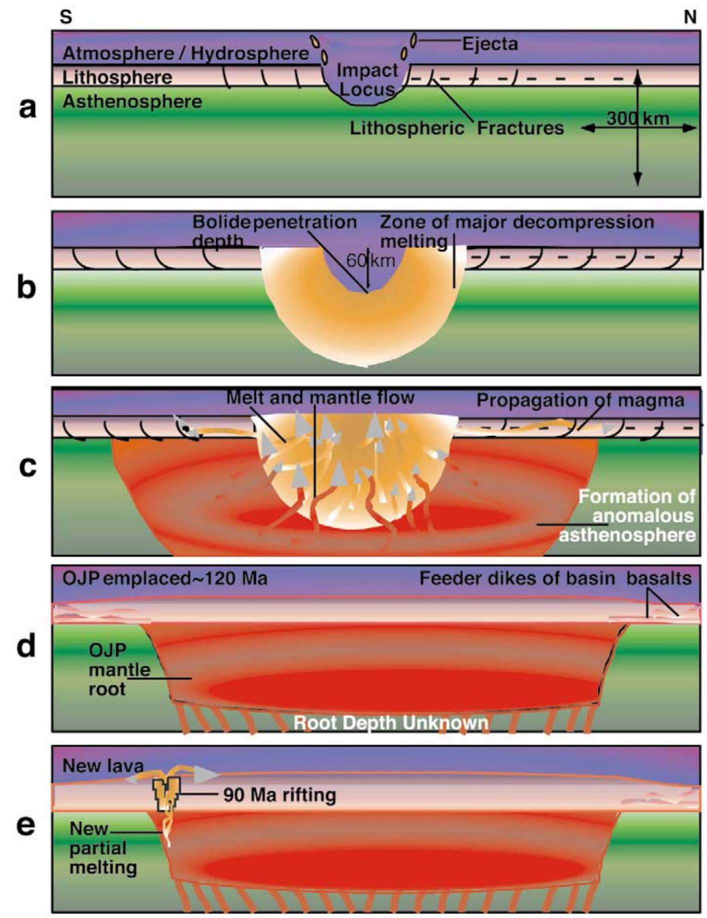

Fig. 4. Conceptual model showing possible sequence of events if an ~20 km diameter bolide instigated the creation of the OJP. (a) t_1 Moment of impact, water column is vaporized, 20 Myr old oceanic lithosphere (pink layer) at impact site is obliterated, uppermost asthenosphere is penetrated, and surrounding lithosphere fractures [62]. (b) t_2 Moment of maximum penetration, the crater is completely formed and melting region becomes focused. (c) t_3 Infill of void from bottom and sides, melt also migrates out along fractures in lithosphere, refractory surrounding mantle fills space vacated by outflowing magmas. (d) ~120 Ma, the OJP at end of emplacement (pink layer represents ~35 km thick crust). (e) ~90 Ma, tectonism causing new pressure release melting. Scale is maintained throughout the diagram.

cally imaged mantle root. Melt would overfill the crater due to thermal expansion, and it would also propagate radially from the crater along fractures created in the brittle, surrounding lithosphere to erupt in the proximal ocean basins (Fig. 4c). Solid mantle, not involved in the melting event, would then both rise buoyantly from beneath and flow from the sides to replace the volume vacated by the erupting, melted mantle (Fig. 4d). Because the melt and underlying solid mantle would ascend adiabatically, with buoyancy generated solely by thermal expansion of ambient mantle (as opposed to excess temperatures and resultant dynamic buoyancy characterizing plumes), relatively minor uplift and subsidence would be associated with emplacement of the greater OJP, and it would be in isostatic equilibrium with surrounding lithosphere [5,18,69] (Fig. 1b).

A large meteorite impact could result in the formation of a temporary magma lake. Such a process may have been common on Earth during heavy meteorite bombardment in Early Archean time [70], but has not been proposed for more recent times because of scarce, if any, evidence for large bolides impacting young, thin, and warm lithosphere and penetrating into the uppermost asthenosphere. Large degrees of mantle melting would be expected, creating high-MgO magmas that could undergo extensive differentiation resulting in relatively depleted, Fe-rich, low-pressure lavas. The slight PGE enrichment in some OJP basalts could be explained by minor amounts of condensed bolide material – chondritic meteorites (thought to represent the bulk Earth composition) are enriched, relative to Earth's primitive mantle, in PGEs [71], but have Os isotopic compositions comparable to Earth's primitive mantle [72]. Melting of the upper mantle should result in major and trace element compositions and radiogenic isotopic ratios that reflect those inherent to the melted region. Although greater OJP basalts are comparable in major and trace element compositions to some MORB [2], there is little isotopic similarity between Pacific-type MORB and the greater OJP basalts, which are instead similar to ocean island basalt (OIB). Therefore, the bolide impact might have struck a region of mantle fairly rich in geochemical heterogeneities (i.e. non-MORB-like components). Although the OIB-like isotopic values of the greater OJP basalts are a complication in the bolide impact scenario (see [52] for additional discussion), the average mantle composition, on the scale of the volume of mantle melted – a minimum of 300 km deep into the mantle – is not sufficiently known to exclude an upper mantle origin for the greater OJP basalts.

Extraction of lavas geochemically similar to greater OJP basalts would generate a highly depleted residuum [73], perhaps comparable to that generated during similar Archean melting events [74]. These depleted restites have relatively low densities but are characterized by *higher* seismic velocities than normal mantle peridotite [75]. Beneath Pitcairn hotspot, for example, such a high-velocity residue has been detected [76]. Additionally, as stated above, melt extraction (chemical origin) cannot account for the large volume of the OJP's root and a purely thermal origin for the root should result in continued volcanism. Therefore, we postulate a physical origin for the mantle root – solid mantle that replaced the extracted mantle should have experienced a catastrophic decrease in pressure during its emplacement beneath the OJP. Such 'replacement' mantle would likely have lower shear wave velocities (V_s = (shear modulus/density)$^{1/2}$) because lowering of ambient mantle pressures has a greater effect on reducing the shear modulus than on modifying the density of the replacement rock [77]. Alternatively, a large meteorite impact could have triggered a mantle avalanche that may have given rise to a large, deep mantle plume [21], but in this case the root should be thermal in origin and the lack of continuous volcanism since ~120 Ma would be problematic.

The main construction phase of the OJP had ended by ~120 Ma (Fig. 4d). Post-emplacement subsidence of the OJP has been minor, significantly less than normal oceanic lithosphere, because adiabatic (as opposed to dynamically upwelling, thermally anomalous) processes governed the formation of the OJP's crust and its coupled mantle root. We speculate that a regional tectonic event affected the southeastern portion of the OJP at ~90 Ma – contemporaneous with the proposed opening of the Ellice Basin to the east [12] – resulting in rifting, decompression melting in the mantle root formed as a result of the ~120 Ma impact, and lava emplacement as the relatively minor (by volume) ~90 Ma basalts (Fig. 4e). Tapping previously unmelted mantle, from a source similar to that which generated the ~120 Ma lavas, during the ~90 Ma rifting could also account for the near-identical geochemistry of the ~120 and ~90 Ma basalts.

6. Possibilities for testing an impact model

On the basis of current geophysical and geochemical data, an impact model for the origin of the greater OJP warrants further testing (see also [52]). Quantitative modeling of the impact event, including evolution of the crater morphology, of melt volumes and compositions induced by the impact, of emplacement of the melt, and of OJP uplift and subsidence is critically needed to assess the viability of the model. Samples from deeper in the OJP's crustal section are critical for further evaluating the geochemical homogeneity observed in the uppermost crustal basalts, and for determining the duration of the ~120 Ma event and the volume of the ~90 Ma event. Also needed are more primitive samples for PGE and other highly siderophile element analyses, with emphasis on isotopic systems sensitive to core and/or meteorite involvement (Cr, Os and W). Additional samples from the East Mariana, Nauru, and Pigafetta basin flood basalts, each currently penetrated at a single drill site, are needed to test age and geochemical relationships to OJP rocks. Distal, or even global evidence of an impact could include tsunami-related deposits on land, disturbed abyssal sediments of early Aptian age, and shocked minerals, tektites, spherules, and Ir anomalies in early Aptian terrigenous and marine sediments.

7. Implications of an impact model

Aptian time, coinciding with the emplacement of the greater OJP, is marked by major global events that include onset of the Cretaceous normal magnetic polarity superchron [28], the Selli oceanic anoxic event [78], significant marine faunal extinctions [79,80], and a worldwide radiogenic Sr isotopic excursion in marine sediments that suggests a rapid change from terrigenous-dominated values to mantle-dominated values [81]. Furthermore, we note that the approximately contemporaneous Manihiki Plateau (Fig. 1c) shares some geochemical characteristics with the greater OJP [7,46]. We suggest that a major bolide impact could have caused or contributed to such phenomena, although analyses thereof are beyond the scope of this study. The absence of recognized impact craters on Earth's deep ocean floor is remarkable considering that estimates based on the present-day terrestrial cratering rate predict that up to three ~10 km diameter bolides should have struck the deep ocean basins in post-Jurassic times [82]. The OJP and the neighboring ocean basin flood basalts show evidence of possibly resulting from one such impact.

8. Note added in proof

Shear velocity and attenuation characteristics of the OJP's anomalous mantle root determined from analyses of multiple ScS earthquake phases rule out a thermal anomaly as its cause [92], further supporting the idea that the keel represents a chemical heterogeneity [6,59].

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