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Earth and Planetary Science Letters 234 (2005) 385–399

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Why did not the Ontong Java Plateau form subaerially?

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Received 6 December 2004; received in revised form 27 February 2005; accepted 8 March 2005
Available online 17 May 2005
Editor: K. Farley

Abstract

A recent drilling leg on the Ontong Java Plateau and subsequent studies have consolidated the following observation for this gigantic oceanic plateau: The bulk of the plateau was formed at ~120 Ma in a submarine environment. This rapid construction of a massive igneous body below sea level is impossible to explain with the popular plume head hypothesis. Though the bolide impact hypothesis for oceanic plateaus has recently been resurrected to offer an alternative, it is shown here that it fails to explain submarine eruption for exactly the same reason why the plume hypothesis fails. As a more dynamically promising model, the entrainment of dense fertile mantle by rapid seafloor spreading is proposed to account for voluminous magmatism in the submarine environment. It is also suggested that this chemically dense source mantle may naturally explain the anomalous subsidence history of this plateau as well as minor magmatism observed at ~90 Ma. Modeling the dynamics of compositionally heterogeneous mantle and its geochemical consequences remains as a challenging yet rewarding problem in mantle dynamics and igneous petrology.

Keywords: oceanic plateaus; plate tectonics; recycled oceanic crust; Stokes flow; isostasy

1. Introduction

The Ontong Java Plateau in the western Pacific (Fig. 1) is the largest igneous province in the oceanic environment, with a surface area exceeding 1.6×10^6 km^2 (roughly equivalent to the size of Alaska) and an estimated crustal volume of 4–5 $\times 10^7$ km^3 [1]. So far this is the best sampled oceanic plateau by drilling, whose results indicate that the bulk of this plateau was formed at ~120 Ma probably within a few million years, followed by relatively minor volcanism at ~90 Ma [2,3]. Though its relief from the surrounding seafloor is limited to ~2.5 km at most, seismic data suggest average crustal thickness greater than 30 km [4]. On the basis of the age and tectonics of the surrounding seafloor, the Ontong Java Plateau is believed to have formed on young (~15–30 Ma) seafloor created by a super-fast spreading center [5].

Perhaps the most puzzling feature of this gigantic plateau is that it formed below sea level [2,6]. If this plateau is formed by the upwelling of anomalously

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doi:10.1016/j.epsl.2005.03.011

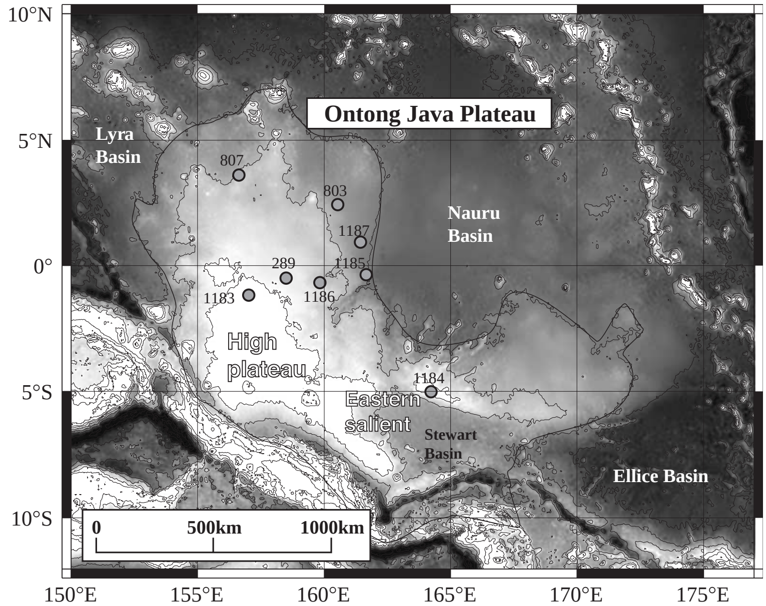

Fig. 1. Location of the Ontong Java Plateau with previous drilling sites. As in previous studies [2,8,25], 4000-m bathymetric contour is chosen to characterize the spatial extent of this plateau.

hot mantle and its melting, we would expect significant positive buoyancy from hot mantle as well as thick crust, which should be sufficient to raise the surface of the plateau well above sea level. Subaerial eruption is commonly observed for smaller-scale hotspots like Hawaii and Iceland. If viscous stress induced by upwelling is taken into account, predicted topography becomes even greater than a simple isostatic prediction. Another puzzling feature is its anomalous subsidence history; given its age of ~120 Ma, the plateau should have subsided by ~3 km or more, but it has not. The total subsidence is estimated to be only ~1–2 km [2,6]. Thus, the Ontong Java Plateau erupted anomalously low and now floats anomalously high.

These two geophysical conundrums remain as a challenge for those who wish to understand the origin and evolution of this plateau as a whole. Despite its success in satisfying various geochemical observations, a plume head hypothesis utterly fails to explain submarine eruption and low subsidence. Anderson's "perisphere" hypothesis [7] cannot even explain geochemical aspects [8]. Confronted with the failure of those endogenous models, an old exogenous hypothesis of impact melting for oceanic plateaus [9] has recently been revisited [8,10]. As I will demonstrate later, however, the impact melting model can explain neither submarine eruption nor anomalous subsidence.

The purpose of this research note is twofold. First, I would like to clarify the nature of geodynamical difficulty we need to resolve because it does not always seem to be understood in recent literature. Second, I will suggest an alternative working hypothesis for the formation of the Ontong Java Plateau, which may have a potential to explain both geochemical and geophysical observations in a dynamically consistent fashion. I begin with a simple isostatic model to show why a plume head hypothesis fails to explain the geodynamics of this plateau. Though similar demonstration has been attempted in the past [11,12], this warm-up exercise is necessary to better understand the following discussion.

2. Submarine eruption—why plume head does not work

The nonvesicular nature of lava flows as well as microfossil evidence suggest the minimum paleodepth of the main part of the Ontong Java Plateau (the High plateau; Fig. 1) must be greater than 800 m [2].

Geological evidence for shallower paleodepths on the High plateau is limited to thin vitric tuff sections found at Sites 289 and 1183, which probably reflect locally shallow features such as isolated summit volcanos [2]. Recently, on the basis of dissolved H_2O and CO_2 concentrations in glasses and their pressure-dependent solubilities, Roberge et al. [6] argue that the original eruption depth on the High plateau is ~1100 m below sea level on the central part of the plateau and 2200–3000 m below sea level on the northeastern edge.

Magnetic lineations on the surrounding seafloor and other geophysical data indicate that the plateau was formed off ridge, on relatively young, rapidly spreading seafloor [5,13]. The cooling of oceanic lithosphere is rapid when it is young [14], and as a result it subsides rather quickly (Fig. 2); the seafloor depth increases from ~2.5 km at the ridge axis to ~4 km in the first 15–30 Myr. Consider the emplacement of the Ontong Java Plateau with a topographic relief of 2.5 km on such seafloor. Just by putting this much relief, the top of the plateau reaches 1.5 km below sea level. This means that, even if we could emplace the plateau crust *without disturbing the preexisting geotherm* (Fig. 3, geotherm A), the top of the plateau could reach 1.5 km below sea level, which is only ~400 m below the minimum paleodepth for the High plateau [6]. (Note: When isostatic compensation is assumed, thick crustal root is already balanced by topographic relief, and we only have to consider subsurface thermal structure to predict uplift or subsidence).

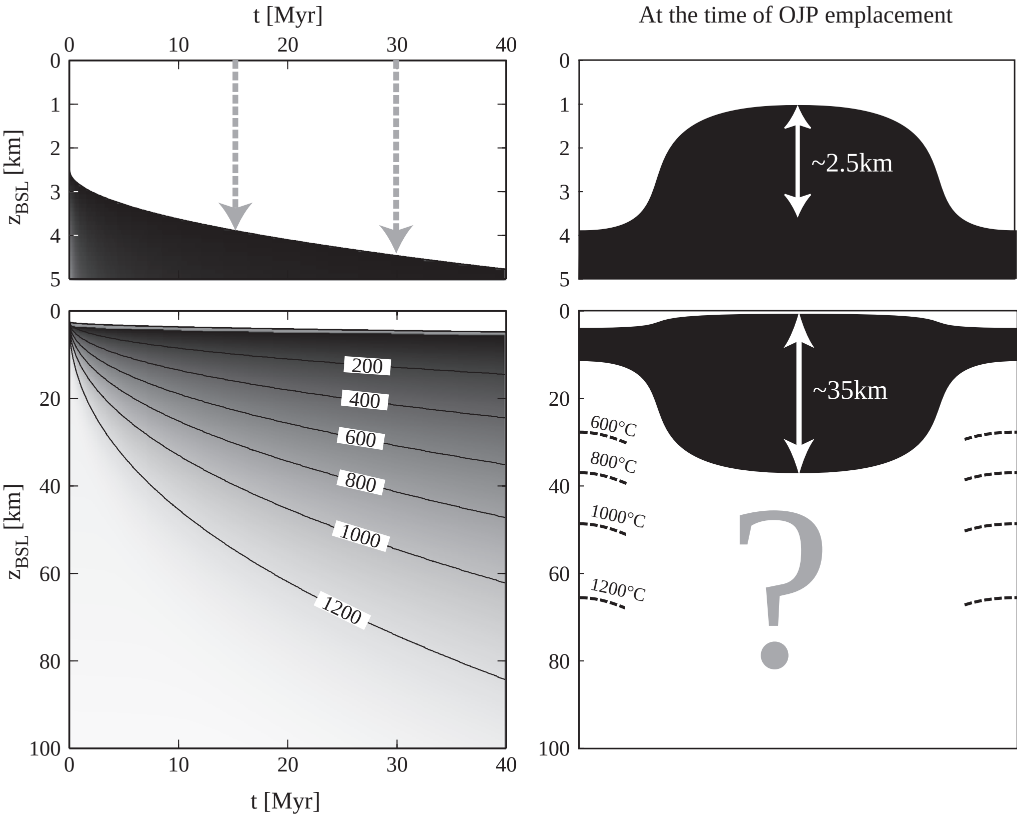

Fig. 2. Pre- and post-emplacement bathymetry and thermal structure. (Top-left) Normal seafloor subsidence according to half-space cooling. z_{BSL} denotes depth below sea level. (Bottom-left) Corresponding thermal structure. (Top-right) The Ontong Java Plateau has ~2.5 km relief with respect to the surrounding seafloor and its top surface was ~1 km below sea level at the time of emplacement. (Bottom-right) The average thickness of plateau crust is ~30 km and the thickest part is probably 35–40 km thick. The thermal structure at the time of emplacement is unknown.

The exact thermal structure when the plateau was emplaced is of course unknown, but maintaining the pre-emplacement geotherm is impossible for a large plateau characterized by thick crust (note: it may be plausible for the formation of a much smaller-scale seamount). At least ~30-km-thick plateau crust must have been initially hot, because it is the product of mantle melting. Thus, the coldest possible geotherm would be geotherm B in Fig. 3, in which the liquidus temperature of ~1200 °C is assigned to the top 35-km crustal section. Lithospheric mantle is assumed to maintain its pre-emplacement temperature, which is highly unrealistic, but this geotherm predicts the plateau depth of ~500 m below sea level (Fig. 3), which is already inconsistent with the geological constraints.

Probably a more realistic lower bound for geotherm would be geotherm C, which is a mantle adiabat with potential temperature of 1300 °C. This corresponds to the situation beneath mid-ocean ridge axis, which is typically found at ~2.5 km below sea level, but in our case with excess 2.5 km topographic relief (owing to thick crust), this geotherm would put the plateau surface right on sea level. Note that, because of latent heat of fusion consumed by partial melting, actual geotherm expected for adiabatically upwelling mantle is slightly lower than geotherm C. However, latent heat of solidification is in turn released by freezing crustal layer, so in term of total heat content relevant to the growth of thermal boundary layer, such details do not matter. In fact, isostatic topography is sensitive only to the *integrated* heat content up to the depth of compensation (~200 km) [15]. The prediction of isostatic topography here is based on temperature difference from the reference geotherm (geotherm C in Fig. 3) averaged over the top 200 km, and this differential approach minimizes the influence of vertical redistribution of latent heat.

It should be clear by now why submarine eruption is so difficult to explain. Mantle potential temperature estimated for the Ontong Java Plateau is >1500 °C [16,17], and such hot mantle (geotherm D in Fig. 3) would place the plateau surface at >1 km above sea level. If dynamic support by an impinging plume head is taken into account, it should rise further. Without calling for hot mantle and its dynamic upwelling, however, submarine eruption at ~1 km below sea level is already almost impossible to explain by our conventional wisdom; even geotherm B does not work. It appears that we need to have some kind of chemical anomaly in the mantle or a combination of thermal and chemical anomalies to generate extensive magmatism that led to plateau formation. If we invoke thermal anomaly only (i.e., the high-degree melting of

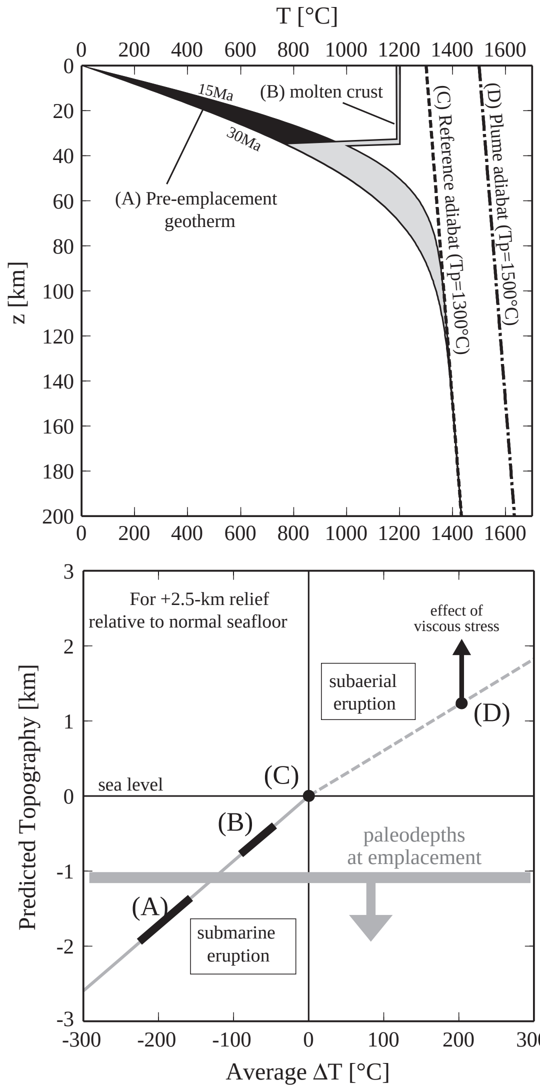

Fig. 3. (Top) (A) Pre-emplacement geotherm beneath 15–30 Ma seafloor, (B) the same as (A) except the top 35 km is replaced with 1200 °C, (C) mantle adiabat with potential temperature of 1300 °C, and (D) mantle adiabat with potential temperature of 1500 °C. (Bottom) Predicted isostatic topography corresponding to geotherms A–D. Assumed here are air density (0 kg m^{-3}), water density (1000 kg m^{-3}), mantle density (3300 kg m^{-3}), and compensation depth (200 km). Paleodepth constraints are from [6].

hot mantle), we are doomed to fail to explain submarine eruption.

In addition to this enigmatic topography at the time of eruption, the Ontong Java Plateau also has anomalous subsidence history afterwards, which is equally difficult to understand. Currently existing hypotheses for the formation of this plateau all fail to explain why this plateau has subsided only by 1–2 km in the last 120 Myr. Once it is formed, the plateau is subject to continuous surface cooling like any other place on the Earth because subsurface is hotter than surface. How exactly it should subside depends on the choice of cooling models such as half-space or plate models, but for the duration of as long as 120 Myr, it should subside by at least 3 km. Unless something other than cooling happened *after* the emplacement, such little subsidence cannot be explained. The prolonged construction hypothesis proposed by Ito and Clift [11] was attractive because such a model could provide heat from below over tens of millions of years, but the hypothesis is no longer supported by the geochronology of plateau basalts [2]. Anomalous subsidence is a separate issue from submarine eruption, but any successful model of the formation of the Ontong Java Plateau will have to provide satisfactory answers to both phenomena.

3. No free lunch—why bolide impact does not work

Recently, Ingle and Coffin [10] proposed that mantle melting caused by a bolide impact, an idea originally put forward by Rogers [9], could explain submarine eruption as well as anomalous subsidence. Contrary to their claim, however, the bolide impact model fails to explain them for exactly the same reason why the plume head model fails.

A meteorite impact can melt the mantle in three different ways [18,19]: (1) shock heating, (2) transient depressurization by shock wave propagation, and (3) permanent depressurization by crater excavation. Shock heating is significant only near the surface, so it does not concern us here. Transient depressurization, on the other hand, can lead to large degrees of partial melting down to the depth of several tens of kilometers, depending on preexisting geotherm. However, this melting is only transient because it is caused by propagating shock waves. After the shock waves passed through, this depressurization is restored and melt solidifies back to solid. Unless melt extraction is virtually instantaneous (which is unlikely given the viscosity of silicate melts), this transient depressurization would not lead to the construction of igneous crust. Therefore, only permanent depressurization by crater excavation is potentially relevant to the generation of large igneous provinces. How much of melting is expected from crater excavation is, however, a matter of debate. For example, Ivanov and Melosh [19] argue that, even though transient crater excavation is significant (e.g., ~70 km depth for 20-km-diameter impactor), final crater depth is much shallower because the crater rim slides and collapses inward.

For the sake of discussion, however, let us assume that such crater collapse is trivial. My point is that, even with this ideal situation that is assumed by Ingle and Coffin [10], permanent depressurization cannot explain the formation of the Ontong Java Plateau. Fig. 4 shows a depressurized geotherm in case of crater excavation of top 60 km (geotherm B). A considerable fraction of lithosphere is removed by an impact and the mantle below is uplifted by viscous relaxation, which would take place on the order of thousand years. It should be apparent that this depressurized geotherm is almost identical to the mantle adiabat with potential temperature slightly higher than normal (DT ~40 K). The corresponding isostatic topography is thus above sea level (Fig. 4).

The following two issues should be emphasized regarding the bolide impact hypothesis of Ingle and Coffin [10]. First, excavation-induced melting is essentially the same as the melting of hotter-than-normal mantle. Instantaneous depressurization by crater excavation is equivalent to raising the potential temperature of the underlying mantle. Thus, a bolide impact does not offer an alternative mechanism that may explain submarine eruption. Second, excavating top 60 km is not sufficient to generate the volume of melt needed to construct the Ontong Java Plateau. It can raise the potential temperature only by 40 K. Crustal production is almost the same as that of normal mantle, i.e., the thickness of newly formed crustal layer is expected to be less than 10 km [20]. I note that the mantle geotherm assumed by Glikson [21] (which also appears to be assumed in [10]) is

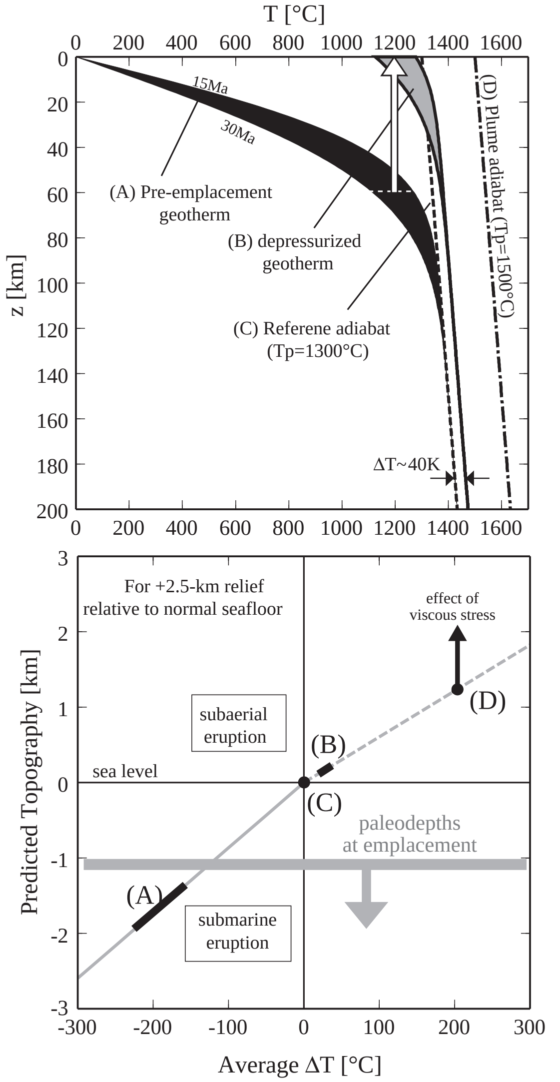

Fig. 4. Same as Fig. 3, except that geotherm B here is constructed by removing the top 60 km of the pre-emplacement geotherm and moving up by 60 km, corresponding to depressurization considered by [10].

characterized by an unrealistic mantle adiabat with >10 K/km; this may have let them to propose 100% melting of depressurized mantle (by the way, 100% melting of mantle produces peridotitic melt, not basaltic melt observed at the Ontong Java Plateau).

Moreover, since a bolide impact is a one-time event, it has no physical connection to the subsequent cooling of the plateau. Just as the plume hypothesis cannot explain anomalous subsidence, therefore, the bolide impact hypothesis does not offer any solution to this mysterious observation.

Here I focused only on geophysical flaws in the bolide impact hypothesis. Readers are referred to Tejada et al. [8] for an excellent summary on how this hypothesis fails to account for a number of geochemical aspects of this plateau. Given that we have no geological evidence that indicates a large meteorite impact in ocean basins at the time of ~120 Ma, it appears that we have no reason to consider the bolide impact hypothesis for the formation of the Ontong Java Plateau, as far as geophysics and geochemistry are concerned.

4. Discussion: need for a new paradigm

In addition to the plume head and bolide impact hypotheses we just considered, the perisphere model [7] is also sometimes brought up when discussing the origin of oceanic plateaus [8]. The perisphere is hypothesized to be a volatile-rich, near-solidus enriched mantle layer beneath lithosphere, which is usually located away from mid-ocean ridges but can be occasionally tapped when a spreading center suddenly jumps. The tectonic setting when the Ontong Java Plateau was formed is not very favorable for this hypothesis, because it was formed near mid-ocean ridges that were producing normal oceanic crust. Thus, it requires some special mechanism to account for why a perispheric material was not tapped by nearby spreading centers [8]. Besides this geological and other geochemical arguments against the perisphere hypothesis [8], the geophysical nature of the perispheric mantle has an opposite sense when it comes to explain submarine eruption. The perispheric mantle is assumed to be intrinsically more buoyant than normal mantle [7]; this is why it ponds beneath lithosphere. What is needed for submarine eruption is, however, *negative* buoyancy originating in some kind of chemical heterogeneities.

Thus, none of existing hypotheses seems to be able to explain submarine eruption, let alone anomalous subsidence. Then what else? This appears to be the point of stagnation in recent studies on the Ontong Java Plateau [3]. Whereas researchers are aware of this geophysical issue, some geochemists still favor the plume head hypothesis. Chazey and Neal [22], for example, note that “While there are still problems with a simple plume origin for the OJP, it appears that these are less severe than with the alternatives. Therefore, for this chapter we assume the origin of the OJP via a surfacing plume head.” Similarly, Fitton and Godard [16] state that “In the absence of a viable alternative, we have to conclude that a peridotite mantle plume with Tp > 1500 °C provides the only plausible explanation for the formation of the OJP”.

The isostatic topography is, however, a very robust prediction and there is not much we can do with the plume head hypothesis. There must have been something dense below the plateau to pull it down below sea level. Can the entrainment of dense core material result in sufficiently negative buoyancy? According to Chazey and Neal [22], mixing of up to 1 wt.% of core material in source mantle may explain the abundance of platinum-group elements in the plateau lavas. If the thermal buoyancy of a plume head is counter-balanced by the entrainment of core material, however, such a densified plume head would not be able to rise through the mantle column. In fluid mechanics literature, “plumes” refer to upwelling or downwelling driven by self-buoyancy. If a plume was made dense enough to explain submarine eruption, we must face a paradox why such a plume should rise in the first place.

There must be some mechanism other than self-buoyancy that can bring up denser-than-normal mantle. I suggest that plate tectonics may provide enough viscous stress that can entrain dense mantle. Denser-than-normal mantle should be sinking in a *static* environment, but it can be dragged up by a dynamic flow field associated with plate tectonics. Magnetic lineations M0–M7 east of the Ontong Java Plateau indicate a super-fast spreading rate (~150 km/Myr) for ~122–129 Ma [5]. Sager [23] recently noted that other oceanic plateaus in the Pacific seem to have formed near ridge–ridge–ridge triple junctions, and Neal et al. [12] speculated that the Ontong Java Plateau may have formed near the Pacific–Izanagi–Phoenix triple junction. Though available magnetic lineations provide no positive evidence for this triple junction, Ishikawa et al. [24] recently suggested such a triple junction could have existed near the plateau based on the age of mantle xenoliths from Solomon Islands. If in fact the Ontong Java Plateau was formed near a triple junction of fast spreading centers, then the tectonic situation might have been optimal for such entrainment. Fast spreading by itself is probably sufficient for entrainment, but its combination with a triple junction can further enhance such process. An important coincidence is that the Cretaceous Pacific had both tectonic elements.

What, then, can be this denser-than-normal mantle? One possibility is fertile mantle with recycled oceanic crust (e.g., eclogite-bearing mantle). Unlike an eclogite-bearing plume, which has to be very hot to compensate its intrinsic density excess in order to rise up, dynamic entrainment by plate tectonic processes does not require high potential temperature for such fertile mantle. Dense, fertile mantle as the source mantle for the Ontong Java Plateau may be a logical deduction given the puzzling submarine eruption. In fact, Tejada et al. [25] have already considered the possibility of eclogite-bearing source mantle in their geochemical modeling and found that it could explain geochemical observations nearly equally well as the normal peridotite (pyrolite) source model. They noted that the fit to data is slightly better for the pyrolite model, but given the compositional variability expected for recycled oceanic crust, which was not fully explored in their modeling, such a minor difference in data fit should not be considered as a decisive factor. The notion of fertile mantle source appears to be out of trend in recent literature on this plateau, however. This may be partly because the one-component pyrolite model is much easier to deal with. Tejada et al. [8] also point out the lack of mixing trends in favor of a composite source model. Are there really no geochemical data in support of non-pyrolitic source mantle? We may benefit from a fresh look at geochemical data. In this section, I will first discuss the nature of source mantle for the Ontong Java Plateau on the basis of estimated primary melt composition, and then try to lay out several geodynamical issues relevant to the dynamical entrainment of eclogite-bearing mantle.

4.1. The nature of mantle source

One of the major achievements of the recent drilling leg on the Ontong Java Plateau is the discovery of the Kroenke-type basalt. An experimental study has shown that the Kroenke-type basalt is parental to the Kwaimbaita-type basalt [26], which is considered to represent a considerable fraction of this plateau [2]. The Kroenke-type basalt is isotopically indistinguishable from the Kwaimbaita-type and is characterized by high MgO contents. This more primitive nature of the Kroenke-type basalt has considerably facilitated the estimation of the primary melt composition for this plateau because it involves only fractionation correction for olivine [16].

This fractionation correction is, however, nonunique. It proceeds by adding incrementally a small amount of equilibrium olivine back to liquid, but when to stop this olivine addition is arbitrary as far as major element composition is concerned. If a large amount of olivine is added, the resultant melt would have very high MgO, characteristic of high-degree partial melting. If olivine addition is stopped prematurely, on the other hand, the melt would appear to result from low-degree melting. It is thus necessary to decide on some kind of termination criterion to this fractionation correction, and the most common choice is the forsterite content of equilibrium olivine. Since pyrolite mantle is usually assumed as source mantle, the fractionation correction is stopped when the forsterite content reaches Fo_{90} (or a higher value because melting increases the forsterite content of residual mantle olivine). Fitton and Godard [16], for example, tested two values of forsterite content, Fo_{90} and Fo_{92}. This type of criterion would be reasonable when we can safely assume that the source mantle is more or less pyrolitic. Unfortunately, this is clearly not the case for the Ontong Java Plateau. Pyrolite source mantle is something to be tested, not to be assumed.

An attractive alternative may be the Ni content of equilibrium olivine, as proposed by Korenaga and Kelemen [27]. Because Ni is compatible to olivine, its concentration in olivine is only weakly affected by previous depletion and fertilization processes. This is most clearly demonstrated by the distribution of Ni contents in mantle olivine, which clusters around 3000 ± 500 ppm for mantle xenoliths and around 2500 ± 500 ppm for abyssal peridotites (see Fig. 2 of [27]). Thus, the fractionation correction may be terminated when the Ni content of equilibrium olivine starts to exceed 3000–3500 ppm. Otherwise, the resulting melt would have too much Ni to be in chemical equilibrium with mantle olivine. It should be noted that the olivine-Ni criterion is not new; Allègre et al. [28] originally suggested its use in 1977. Compared to then, however, we now have far better controls on Ni-partitioning between olivine and basaltic melt owing to a large number of experimental data [29] and also on the distribution of Ni contents in mantle olivine thanks to global compilation studies [30]. The uncertainty in Ni-partitioning is not trivial [27,29], but this fractionation correction has also been successfully applied to normal MORB data as a benchmark, showing pyrolitic Mg# (defined as molar Mg/(Mg+Fe)) of ~0.90 for the MORB source mantle [27]. Thus, even though absolute Mg# is sensitive to how exactly one chooses the Ni partitioning coefficient, a relative change in Mg# with respect to MORB source mantle (i.e., more fertile or more depleted) can be inferred with reasonable confidence.

The fractionation–correction scheme of Korenaga and Kelemen [27] is applied to nearly aphyric (<5% phonecrysts), high-MgO (>9.0 wt.%) Kroenke-type samples, whose compositions have been reported by Fitton and Godard [16] (Fig. 5). All data are normalized on an anhydrous basis, and $Fe^{3+}/\sum Fe$ of 0.10 is assumed [16,17]. A constant $K_D^{Fe\text{–}Mg}$ of 0.30 is used to calculate equilibrium olivine, and the equation of Kinzler et al. [29] is used to calculate $D_{Ni}^{ol/liq}$ at each correction step. Estimated primary melt compositions are listed in Table 1, with olivine Ni contents of 3000 ppm and 3500 ppm. For comparison, the case with the Fo_{90} criterion is also shown in the table, together with the results of Herzberg [17]. Like Fitton and Godard [16], Herzberg [17] also assumed pyrolitic source mantle for his modeling of primary melt composition. Although Fitton and Godard [16] and Herzberg [17] employed different methods to estimate primary melt compositions and obtained similar results, this only means that their results are mutually consistent in the framework of pyrolite melting. Getting similar results does not justify their assumption of pyrolitic source mantle, nor disprove the existence of other solutions that may explain data equally well. Indeed, calculating the Ni content in equilibrium olivine for Herzberg's primary melts suggests that the assumption of pyrolite source mantle may not be valid. The Ni contents are too high, ranging from 4700 ppm to 5700 ppm.

The olivine-Ni correction method results in a slightly lower forsterite content of equilibrium olivine (~0.885) than a typical pyrolitic value (~0.90). This

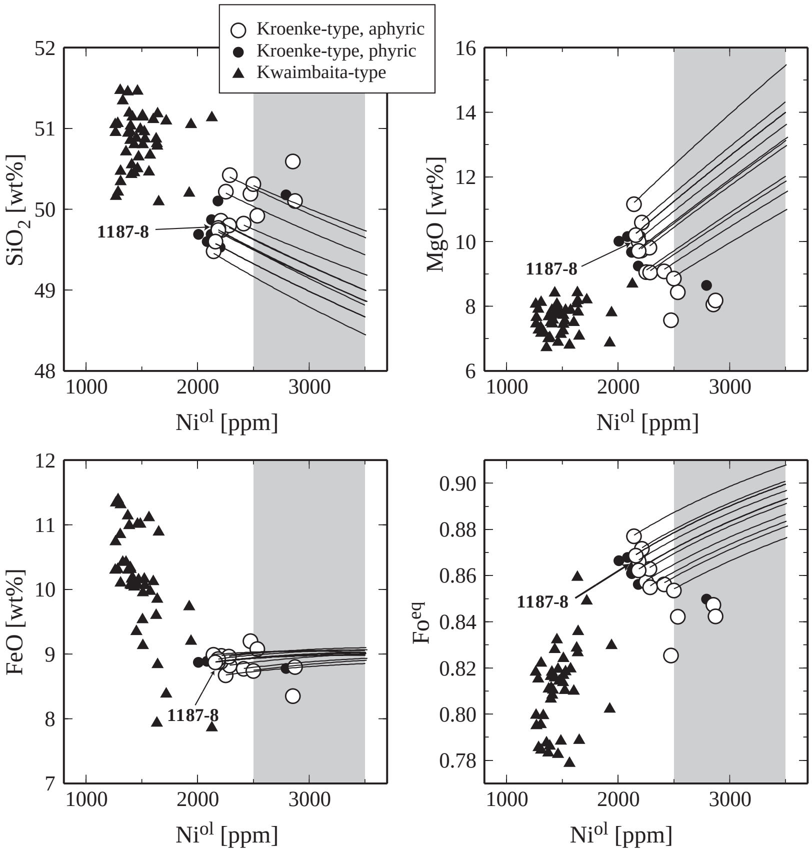

Fig. 5. Results of fractionation correction for lava samples from the Ontong Java Plateau. SiO_2, MgO, FeO, and equilibrium forsterite content are shown as a function of the corresponding Ni content in equilibrium olivine (Ni^{ol}). Gray shading denotes the likely range of Ni^{ol} in mantle olivine. Solid curves denote correction for olivine-only fractional crystallization. Original compositional data are from [16]. Sample 1187-8 is the one chosen by [17] for his estimate of primary melt composition.

may be surprising because the Ontong Java Plateau is usually considered to be a product of high-degree partial melting, which leads to a even higher forsterite content. This lower-than-pyrolitic forsterite content appears to call for a non-pyrolitic source mantle, and this is in favor of eclogite-bearing mantle, the melting of which is known to produce low Mg# melts [31,32].

As a working hypothesis, I would like to propose the following scenario for the formation of the Ontong Java Plateau (Fig. 6). First, I assume that subducted oceanic crust is somehow delaminated from a subducting mantle lithosphere, and because of its neutral buoyancy at the base of the mantle transition zone [33,34], a considerable amount of oceanic crust (transformed into eclogite) is pooled at ~660 km. Whether or not this can take place may be debatable [35], but for plate-tectonic processes to influence the entrainment of dense eclogite fragments, such fragments must be located close to the surface, not at the core–mantle boundary, which is another place this crustal segregation could potentially take place [36]. Any other mechanisms that can bring subducted crust to sufficiently shallow depths (e.g., within a few hundred km from the surface) would also be acceptable. I do not expect the spatial distribution of those eclogite fragments to be uniform. Because their existence depends on previous tectonic processes, some places could have highly concentrated fragments while other places could be almost free of them. Now suppose one of those high-concentration region happens to be in the proximity of a fast-spreading ridge, either by a sudden ridge jump or its gradual

Table 1
Estimated primary melt compositions for the Ontong Java Plateau

	This study			Herzberg [17]	
	Ni(ol) = 3000 ppm	Ni(ol) = 3500 ppm	Fo = 0.90	Fractional[a]	Equilibrium[a]
N^{b}	10	10	10	1	1
SiO_2	49.3	49.0	48.8	48.0	47.5
TiO_2	0.70	0.67	0.65	0.62	0.58
Al_2O_3	14.3	13.8	13.5	12.3	11.4
Fe_2O_3	1.11	1.11	1.11	0.90	0.83
FeO	9.0	9.0	9.0	9.2	9.2
MnO	0.17	0.16	0.16	0.17	0.16
MgO	12.0	13.2	14.2	16.8	19.3
CaO	11.8	11.4	11.1	10.3	9.5
Na_2O	1.57	1.51	1.48	1.36	1.26
K_2O	0.06	0.06	0.05	0.08	0.07
Fo[c]	0.884	0.894	0.900	0.915	0.925
Ni(ol)[d]	3000	3500	3944	4749	5648

Values for oxide concentration are in wt.%. Ni concentrations are in ppm.
[a] Accumulated fractional melting and equilibrium melting of Kettle River Peridotite assumed by Herzberg [17].
[b] Number of data.
[c] Fo content of equilibrium olivine based on $K_D = 0.30$ (Herzberg [17] reports Fo of 0.905 and 0.916 for fractional and equilibrium melting results).
[d] Ni content of equilibrium olivine based on olivine–liquid partitioning of Kinzler et al. [29].

migration, both of which took place frequently in the Pacific Ocean basin during the Cretaceous. Eclogite fragments then become entrained by passive upwelling, and since they have lower solidus than the surrounding peridotite matrix, they melt at off-axis (Fig. 6). By passive upwelling of 150 km/Myr, it may take only 4–5 Myr for eclogite fragments to travel from the base of the transition zone to the surface. (Note: if a ridge is located right above the concentrated region of eclogite fragments, a plateau would form on the ridge axis. The off-axis formation of the Ontong Java Plateau does not require such a coincidence).

The liquidus of anhydrous mid-ocean ridge basalt (MORB) is very similar to the solidus of dry pyrolite [37], so eclogite fragments entrained as hypothesized in Fig. 6a would experience 0–100% degree of melting, depending on the shallowest depth the fragments could reach. Thus, the average degree of melting is expected to be at least ~50%. Considering melt-retention buoyancy, it is probably unlikely that the melting of this eclogite-bearing mantle takes place in an entirely passive fashion. Small-scale active upwelling [38] may enable nearly 100% degree of melting of the eclogite component [39]. How this melt from ‘eclogite’ reacts with the surrounding matrix and overlying depleted lithosphere and whether the final melt volume would be reduced or increased depends on the exact composition of this recycled mafic lithology (though I am referring to it simply as ‘eclogite’, its expected compositional range is broad [40]). For an order-of-magnitude discussion here, I simply assume complete melting of the eclogite component. To produce ~24-km-thick igneous crust (excluding the preexisting 6-km-thick oceanic crust) by melting within a depth interval of 100 km or so [37], the fraction of the eclogite component in the heterogeneous mantle must be as much as 25%. Cooling due to the latent heat of fusion is expected to be somewhat buffered by heat influx from the surrounding peridotite matrix [41]. For a complete melting of 25% eclogite component, the temperature decrease is ~100 K for the latent heat of fusion of 400 kJ kg^{-1} and the heat capacity of 1 kJ kg^{-1} K^{-1}, in case of complete thermal equilibrium. This extent of temperature decrease does not significantly affect the melting of the mafic lithology, which usually has a much shorter melting interval compared to peridotites [40].

Thus, most of the plateau may have been constructed directly from below by the melting of eclogite-bearing mantle. Its horizontal dimension is

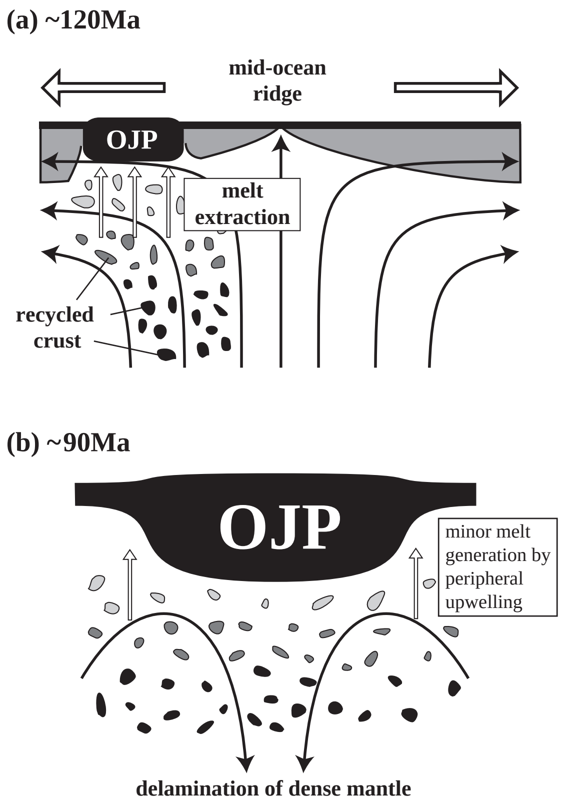

Fig. 6. A new working hypothesis for the emplacement and evolution of the Ontong Java Plateau. (a) Dense recycled oceanic crustal fragments are entrained by strong passive upwelling near a fast-spreading ridge. Corner-flow entrainment results in the melting of fertile components off-axis. At least 50% partial melting on average (up to nearly complete melting due to active upwelling induced by melt-retention buoyancy) may be achieved, and the residual mantle is located right beneath the plateau at least temporarily. Melting of dense fertile mantle may explain both voluminous magmatism and submarine eruption. (b) Chemical density excess associated with residual (but still fertile) mantle eventually leads to convective instability, when coupled with the growth of a thermal boundary layer by surface cooling. The delamination of dense residual mantle (and its circulation to shallower depths by secondary convection) may explain abnormal subsidence as well as minor magmatism at ~ 90 Ma (see text for details).

explained by fast spreading (~150 km/Myr), so this model predicts slight age-progression across the plateau (e.g., ~3 Myr for 500 km width), though this degree of age difference is within the uncertainty in currently available geochronological data. Excluding the preexisting normal oceanic crust, the total volume of the Ontong Java Plateau is probably $\sim 4 \times 10^7$ km^3, which is also the total volume of recycled crust needed assuming complete melting. With normal crustal thickness of 6–7 km, this is equivalent to an ocean floor of $\sim 2400 \times 2400$ km^2. The isotope geochemistry of this plateau is remarkably homogeneous [8,25]; for example, the Kwaimbaita/Kroenke-type signature is confined within a range of less than one εNd unit. Given the horizontal extent of the plateau, it would be difficult to reduce isotope heterogeneities in the source mantle by near-surface mixing such as in magma chambers. The observed isotope homogeneity probably requires the age distribution of recycled crust to be tightly clustered (one εNd unit corresponds to ~200 Myr difference in crustal age) and its original isotopic signature to be more or less uniform.

The trace element concentrations of Kroenke-type basalts are lower than those of normal MORB [16], which may argue against the involvement of recycled oceanic crust. The recycled crustal component, however, could be depleted in terms of trace element budget owing to likely depletion processes at subduction zones; in fact, eclogite xenoliths generally lack the quartz component and are depleted in trace elements with respect to MORB [42]. The complete melting of such slightly depleted eclogite can explain the picritic nature of the primary melt (Table 1). Moreover, adiabatically ascending melt can be ‘superheated’ and dissolve high-temperature olivine in depleted lithosphere, which also increases the MgO content of the melt [27]. Even with this likely melt–rock interaction, the trace element budget of the mafic lithology is still expected to dominate the overall isotope signature, except for osmium isotopes. The initial ^{187}Os/^{188}Os for the Ontong Java Plateau basalts is nearly chondritic [43], which may imply that the osmium isotope signature may have been reset by the interaction with oceanic lithosphere.

4.2. Order-of-magnitude geodynamics

The geodynamical plausibility of the proposed entrainment is probably best examined by a systematic employment of numerical modeling given its complex nature. Before attempting such a full endeavor, however, we may be able to get a rough idea from order-of-magnitude calculations. First of all, we must consider whether passive upwelling can entrain as much as 25% dense mafic components. At least two spatial scales are important for this issue. Each of eclogite fragments must be small enough so that their downwelling velocity is negligible with respect to the passive upwelling of the surrounding mantle. The velocity scale for such individual downwelling may be given by the Stokes flow formula for a rigid sphere [14]. For the upper mantle viscosity of 10^{20} Pa s [44] and for an eclogite fragment with a density excess of 100 kg m^{-3} [34] and with a radius of 6 km, downwelling velocity is on the order of a few mm/yr. In a tectonic setting characterized by super-fast spreading, therefore, individual downwelling is insignificant if fragments have dimensions of typical oceanic crust. Fragments also have to be similarly small to achieve a thermal equilibrium with the peridotite matrix during melting [41]. The other scale is the size of the mixture of peridotite and eclogite as a whole, which must be on the order of at least a few hundred kilometers, to account for the scale of the Ontong Java Plateau. For such a large-scale feature, the effect of the surface boundary becomes important. The classical Stokes flow formula is derived for a sphere moving in an infinite medium. The presence of a surface can slow down the movement of a sphere [45]; in an extreme case that a sphere is touching the surface, for example, the velocity of the sphere becomes zero. The actual shape and size of the eclogite-bearing mantle are definitely time-dependent, so a simple scaling argument does not apply. Nonetheless, the effect of the surface may always help to entrain a large-scale feature by passive upwelling. In fact, numerical modeling by Korenaga [46] shows that the dynamic entrainment of up to 30% eclogite component is possible for sublithospheric convection even without surface plate motion.

The latent heat of fusion would cool down the residual mantle by ~100 K as discussed above, which may result in sufficient negative buoyancy to explain submarine eruption (Fig. 3). A realistic estimate of dynamic topography, however, must wait for full convection modeling because the isostatic prediction must assume the depth of compensation, the validity of which depends on the viscosity structure as well as the spatial scale of the flow field.

The residual mantle characterized by negative buoyancy (which could have both chemical and thermal origins as discussed above) may be prone to delamination at a later stage when subsequent cooling brings it to convective instability. The time scale for this type of convective instability in a growing thermal boundary layer is on the order of a few tens of million years [47,48]. This delamination may have removed some fraction of lithospheric mantle, resulting in less-than-normal subsidence. Thus, the anomalous subsidence inferred for the Ontong Java Plateau may be a 'natural' consequence of dense fertile source mantle, which is required to explain simultaneously voluminous magmatism and submarine eruption. Furthermore, this delamination can generate the circulation of the residual mantle to shallower depths, which may have resulted in minor volcanic activities at ~90 Ma (Fig. 6b). The complete melting of all of entrained eclogite fragments is of course too ideal, and there could be some entrained but unmelted fragments beneath the depleted lithosphere. Mantle at the depth of ~100–150 km is likely to be still on the adiabatic geotherm at ~90 Ma (i.e., geotherm for 30 Ma seafloor in Fig. 3). Bringing this part of the (eclogite-bearing) mantle to shallower depths by delamination-induced secondary convection (Fig. 6b) could reproduce ~120 Ma eruption though at a much smaller scale inherent to sublithospheric convection.

The delamination of chemically dense mantle is different from so-called small-scale convection hypothesized beneath oceanic lithosphere, however, at least in one important aspect. Unlike thermal anomalies, chemical anomalies hardly diffuse, so once delaminated, the residual mantle can continue to sink to the base of the mantle transition zone where negative buoyancy due to the mafic lithology disappears. Though the delamination of thermally dense mantle may be regarded as enhanced cooling (i.e., more subsidence) [49], the delamination of chemically dense mantle reduces total subsidence unambiguously.

One may wonder why there could have been such fertile mantle in the Pacific upper mantle. There is no satisfactory answer to this question at this moment. But neither the plume head hypothesis nor the bolide impact hypothesis answers this type of question: Why did a plume head or a meteorite hit the particular place in the Pacific? The new working hypothesis proposed here may be more promising in this regard, however. If the fertility of the source mantle is indeed due to recycled oceanic crust, one may be able to better assess the geological likelihood of such recycling as our understanding of Precambrian plate tectonics improves.

5. Conclusion and outlook

On the basis of isostatic topography, the plume head and bolide impact hypotheses have been shown to fail to account for the submarine eruption of the Ontong Java Plateau. Furthermore, neither of them offers a plausible physical mechanism to explain the anomalous subsidence of the plateau because only simple cooling could take place after the plateau formation in those hypotheses.

As a dynamically promising alternative, I proposed the entrainment of dense fertile mantle by strong passive upwelling near a fast-spreading mid-ocean ridge. Rapid spreading may be able to bring dense mantle from the base of the transition zone within a few million years. This entrainment model does not require the breakdown of sublithospheric convection, which has been proposed to explain Iceland and the North Atlantic igneous province [46]; it is natural to expect such breakdown beneath a supercontinent [46,50] or an old seafloor [47,51], but not beneath a young seafloor near a ridge axis. The new model is thus complementary to the model of Korenaga [46] in terms of the type of tectonic setting involved.

Mantle dynamics with such fertile mantle may be able to explain submarine eruption, anomalous subsidence, and even minor volcanism at ~90 Ma. The feasibility of this new working hypothesis as well as the details of its geophysical and geochemical consequences must be tested by numerical modeling (preferably 3-D). Given the uncertainty in initial conditions (e.g., distribution of fertile mantle) and boundary conditions (e.g., surface plate motions and global mantle circulation), a systematic investigation will be essential. Such a numerical study will also be able to address why Iceland is subaerial and the Ontong Java Plateau is submarine because the former is also proposed to have originated in the melting of fertile mantle [46]. An order of magnitude difference in spreading rate may result in different entrainment and melting dynamics. Whether fertile mantle is entrained to on-axis (Iceland) or to off-axis (Ontong Java) should also be an important factor to consider.

Although the Ontong Java Plateau is so far the best sampled oceanic plateau, it is clear that we will benefit enormously from more geophysical and geochemical observations to validate and elaborate this new hypothesis (and of course any other possibilities with comparable potential). For example, the accurate characterization of crustal structure by seismic tomography may be able to better constrain the composition of primary mantle melt and thus the nature of mantle melting, when combined with geochemical constraints [20,27,52]. Moreover, the mantle beneath the Ontong Java Plateau is suggested to exhibit abnormal seismic characteristics [53–55]. If they are confirmed to be a robust feature by comparing with other high-resolution regional studies in the Pacific [56], the mineral-physics interpretation of such signatures will need to be carefully examined along with their implications for the new working hypothesis.

Acknowledgments

This paper has benefited considerably from discussion with John Mahoney. The author also thanks thoughtful reviews by Marc Hirschmann and Roger Larson.

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