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Oceanic plateaus: Problematic plumes, potential paradigms

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Abstract

Oceanic plateaus are vast areas ($>2\times10^5$ km^2) of thicker than average oceanic crust (up to 38 km) that typically are elevated 2–3 km above the surrounding seafloor. Because of their thick, relatively high-standing crust, portions of oceanic plateaus can accrete to convergent continental margins and thus have contributed to continental growth over time. Through studies of accreted oceanic plateau sections and from drilling of in-situ plateaus, knowledge of plateau structure, composition and age has increased considerably over the last 20 years. However, models for the origin of oceanic plateaus are still not without significant problems. Mantle plume models can explain many of the observed chemical and physical features, but other characteristics are not readily explicable by conventional thermal plume models. This is particularly true of the largest plateau, the Cretaceous Ontong Java Plateau in the western Pacific. If formed by a plume head, much of the surface of this plateau should have become subaerial, but instead largely appears to have erupted at water depths >1000 m; furthermore, post-eruption subsidence was much less than predicted by thermal plume models. Other models, such as meteorite impact-induced melting and spreading-induced upwelling of eclogite, are also fraught with problems. A solution to the anomalous uplift and subsidence of the Ontong Java Plateau may lie in its derivation from a thermochemical mantle plume. Modelling suggests such plumes can consist of large amounts of compositionally dense material, thereby reducing net plume buoyancy. Future work should explore in detail the capabilities of thermochemical plumes, the role of oceanic plateaus in continental growth, and links between the formation of plateaus and major environmental crises such as oceanic anoxic events.

Keywords: Ontong Java Plateau; Kerguelen Plateau; Caribbean Plateau; Thermochemical plume; Oceanic plateau

1. Introduction

Oceanic plateaus represent one of the least understood types of magmatic province on Earth. However, our rapidly increasing knowledge of the structure, composition and formation of plateaus is shedding new light on, and raising some new questions about, plateau origins and the nature of their mantle source regions. Oceanic plateaus are potentially more useful than their continental flood–basalt counterparts for deciphering mantle processes and sources involved in large igneous province formation, for two fundamental reasons. i) Most oceanic plateaus erupt through relatively young, thin (~6–7 km) mafic and ultramafic crust and so are unlikely to be chemically modified by crustal contamination as much as continental flood basalts. They therefore provide 'cleaner' samples of their mantle sources. ii) Because of their greater crustal thickness, and so buoyancy (compared to normal oceanic crust), oceanic plateaus are relatively unsubductable, particularly the thicker plateaus and those that reached subduction zones relatively soon after formation

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(e.g., Cloos, 1993; Abbott and Mooney, 1995). This means that they can 'dock' to the upper-plate margins of subduction zones and be at least partially preserved in the geological record as accreted terranes. Accreted plateau fragments are likely to have a greater preservation potential than the extrusive portions of continental flood basalts, which are constantly denudated by subaerial erosion even during formation. Thus, accreted plateau sections provide a potentially more-complete temporal record of volcanism than continental flood basalts (see Kerr, 2003).

In this paper we review the physical and chemical characteristics of oceanic plateaus, along with their potential environmental impact, before discussing some of the more problematic aspects of plateau formation for conventional mantle plume models and for other proposed origins.

2. Characteristics of oceanic plateaus

2.1. Physical characteristics and mantle source temperatures

It is interesting and perhaps significant that extant oceanic plateaus occur mostly in the Pacific and, to a lesser extent, Indian Ocean (Fig. 1). Even the Caribbean Plateau is generally regarded to have originated in the Pacific (e.g., Duncan and Hargraves, 1984). Oceanic plateaus are, as their name implies, vast areas (ranging to as much as 2×10^6 km^2) of elevated topography, generally 2–3 km above the abyssal ocean floor. The principal reason for the elevated nature of oceanic plateaus is their crustal thickness, which is generally much greater than the 6–7 km thickness of normal oceanic crust generated at spreading centres. For instance, the Ontong Java Plateau has a crustal thickness of at least 30 km over much of its area (e.g., Gladczenko et al., 1997; Richardson et al., 2000; Miura et al., 2004) whereas the Caribbean Plateau varies from 8–15 km thick (Case et al., 1990; Mauffret and Leroy, 1997).

The ability of an oceanic plateau to resist subduction and to increase its likelihood of being preserved in the geological record depends on both crustal thickness and plateau age. The older a plateau, the cooler and thus less buoyant it will be. Plateaus that collide with a subduction zone only a few million years after they form will be more likely to resist subduction than a plateau of similar thickness that encounters a subduction zone many millions of years later (Cloos, 1993). For example, the Caribbean Plateau largely resisted subduction because it

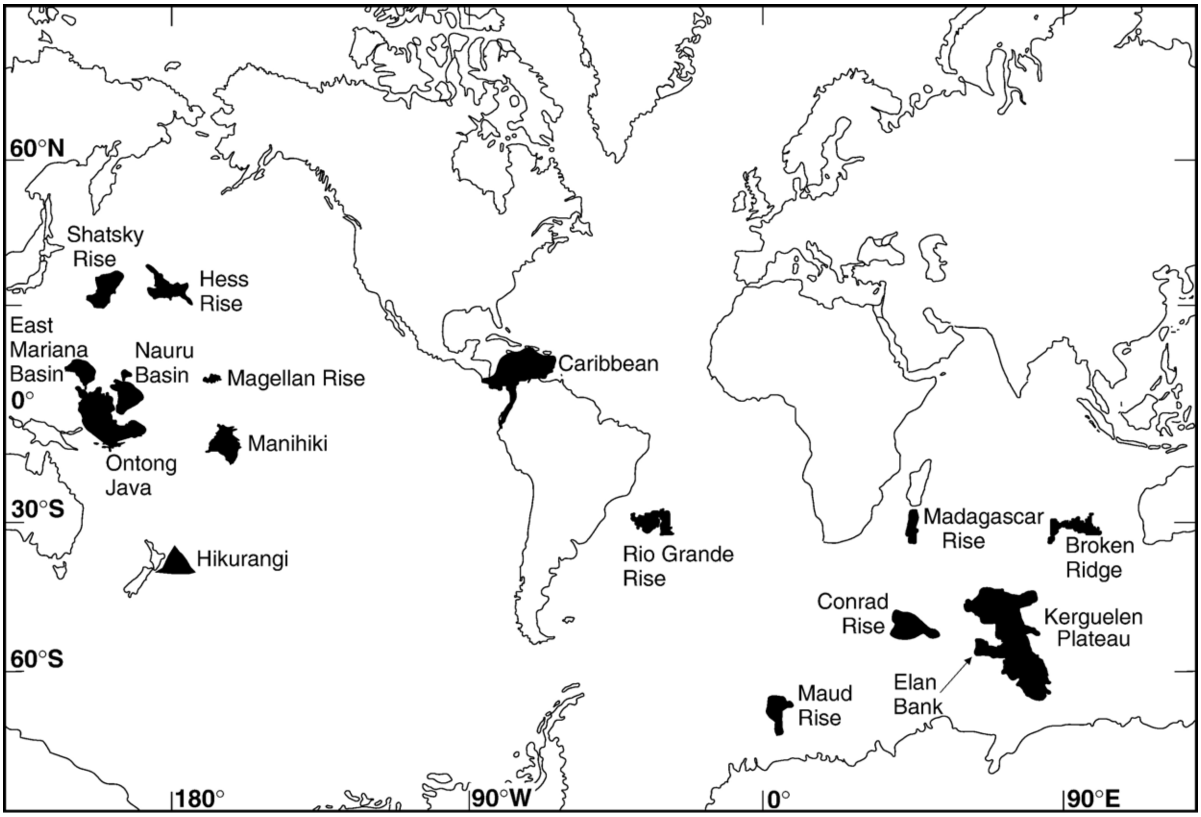

Fig. 1. Map showing the locations of Cretaceous oceanic plateaus (after Kerr, 2003).

collided with an arc at the entrance to the proto-Caribbean Basin only a few million years after the plateau formed at ~90 Ma (Burke, 1988; Kerr et al., 1999). The Ontong Java Plateau, most of which formed ~120 Ma, collided with the Solomon subduction zone ~100 my later (e.g., Petterson et al., 1997). The lower crust at the edge of the plateau has been subducted (Mann and Taira, 2004), but the plateau overall has resisted subduction because of a combination of very thick crust (Cloos, 1993; Abbott and Mooney, 1995), an anomalously small amount of post-emplacement subsidence (see Section 3.1), and a >300-km-thick mantle "root" (Richardson et al., 2000) that has helped to lock or choke subduction (Wessel and Kroenke, 2000).

When an oceanic plateau clogs a subduction zone various things can happen (Fig. 2). 1) At an ocean–ocean convergent margin, the subduction direction can reverse (so-called 'subduction flip'). This happened in the Solomon Islands subduction zone following the collision with the Ontong Java Plateau. In this specific case, the front of the newly subducting slab also appears to have collided with the plateau's thick root, blocking further subduction; presently, it is unclear how common such roots are below other plateaus. 2) In addition to subduction flip, the collision of a plateau with an island arc can occasionally result in subduction 'back-stepping' behind the accreting plateau, if the lithosphere behind the plateau is not too old and thick (Fig. 2). This situation appears to have occurred as the Caribbean Plateau moved into the oceanic gap between North and South America over the last 90 my; it has resulted in the present-day Central American arc and the isolation of the Caribbean as a separate plate (Burke, 1988). 3) Subduction back-stepping also occurs, but without subduction flip, when an oceanic plateau collides with an active continental margin (Fig. 2). This happened in the Late Cretaceous when part of the Caribbean Plateau collided with the northwestern margin of South America, leading to the preservation of oceanic plateau crust in accreted blocks (Kerr et al., 2003; Fig. 3). Indeed, this type of event appears to have happened more than once along this margin; portions of at least two plateaus appear to comprise accreted terranes that are commonly grouped with the Caribbean Plateau (see Section 3.2).

Plateaus that collide with intra-oceanic island arcs can also eventually be accreted onto and incorporated into continental crust. Consequently, it has been suggested that the accretion of oceanic plateaus may have contributed to continental crustal growth throughout much of geological time (e.g., Kroenke, 1974; Abouchami et al., 1990; Abbott and Mooney, 1995; Tejada et al., 1996; Puchtel et al., 1998). Although not without controversy (e.g., Bédard et al., 2005), sequences interpreted to be of plateau origin (e.g. Puchtel et al., 1997, 1998; Kerrich et al., 1999; Polat and Kerrich, 2001) recently have been argued to be an important component in several Precambrian greenstone belts; such sequences are often associated with rocks interpreted to be subduction-related. Condie (1997) argued that a significant proportion of the Archean and Proterozoic lower continental crust, in particular, may have originated from accreted plateaus. The overall contribution of plateau accretion to continental growth, however, is probably much less than that of subduction-zone magmatism (e.g., Davidson and Arculus, 2006).

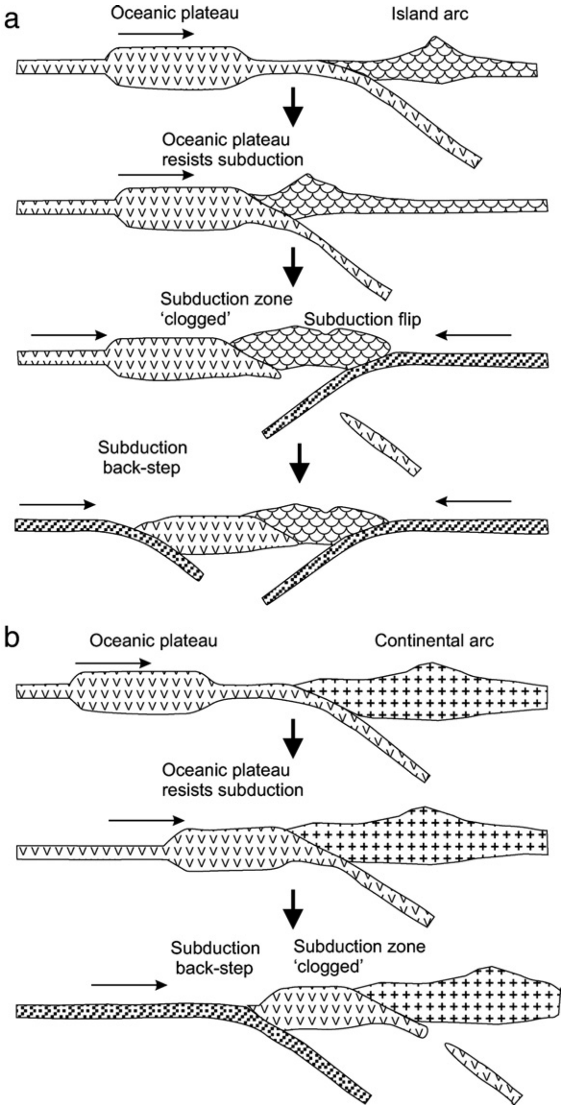

Fig. 2. Schematic cross sections showing the possible effects of oceanic plateau collision with a) an island arc and b) a subduction zone at a continental margin. See text for a detailed description.

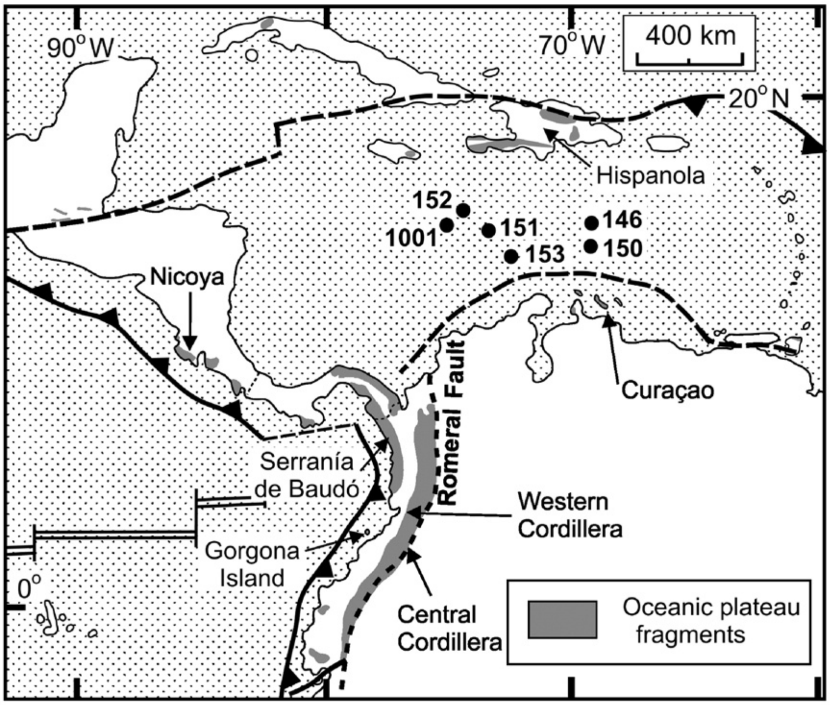

Fig. 3. Map showing the locations of accreted oceanic plateau fragments around the Caribbean and in northwestern South America. Locations of high-MgO lavas are indicated by arrowed labels. Also shown are the locations of DSDP Leg 15 holes (146, 150–153) and ODP Leg 165 Hole 1001. (After Kerr et al., 1997).

From accreted plateau fragments (e.g. Petterson et al., 1997; Kerr et al., 1997) and from seismic and gravity surveys on extant plateaus (e.g. Farnetani and Richards, 1994; Miura et al., 2004) we can build up a picture of the crustal structure of oceanic plateaus. Briefly, a lowermost layer of predominantly olivine cumulates tends to be overlain by isotropic gabbros. The base of the extrusive sequence appears to be dominated by chemically heterogeneous high-MgO lavas that are in turn succeeded upwards by comparatively homogeneous basaltic lavas (similar models have been proposed for continental flood basalt provinces, e.g. Cox, 1980).

The most peculiar feature that emerges from studies of several obducted and accreted oceanic plateau remnants is the absence of a sheeted feeder-dyke complex, in marked contrast to many ocean-ridge-type and supra-subduction-zone ophiolites but similar to continental flood basalts. Instead the lava succession of oceanic plateaus is intruded by a significant number of thick sills (Kerr et al., 1997; Petterson et al., 1997). In the exposures of Ontong Java Plateau crust in the Solomon Islands, the general scarcity of dykes of any kind has been interpreted as evidence that most lavas are rather far-travelled (e.g., Neal et al., 1997). Alternatively, Kerr et al. (1997) suggested that the volume of magma being emplaced in many oceanic plateaus was too great to be accommodated by extension alone and that most magma was emplaced laterally in sills. This proposal is supported by recent 3D seismic work on North Atlantic volcanic rifted continental margins that provides evidence of a sill-dominated feeder system (Hansen et al., 2004).

Both the Ontong Java and Caribbean plateaus had more than one phase of eruption, but geochronological data suggest the vast bulk of the volcanism occurred in one main initial episode, with the succeeding activity in both cases being volumetrically minor. The main phase of Ontong Java eruption appears to have occurred within a few million years around 120 Ma (e.g., Mahoney et al., 1993; Tejada et al., 1996, 2002; Parkinson et al., 2001; Chambers et al., 2004), whereas the bulk of the Caribbean Plateau formed from 93–89 Ma (reviewed by Kerr et al., 2003). Although recent ^{40}Ar–^{39}Ar dates have widened the apparent age span of Kerguelen Plateau formation, very large volumes of magma nevertheless were generated over geologically short times (<5 my) (Duncan, 2002; Coffin et al., 2002). The high rate and large volume of magma production in these plateaus, and in several large continental flood basalt provinces, implies a causal mechanism(s) that is not restricted to the shallow asthenosphere (e.g., Coffin and Eldholm, 1994). For example, assuming the Ontong Java Plateau formed by an average of 25% partial melting of peridotite (see Section 2.2.1), a source volume corresponding to a sphere more than 700 km in diameter (i.e., greater than the distance to the 660 km discontinuity) is required.

In order to generate the prodigious amounts of magmatic rocks found in oceanic plateaus, the source region must either be hotter, more fertile, or have a higher volatile content than ambient upper mantle, or undergo a large amount of decompression, or some combination of the above. The most common explanation for the high melt production rates is high mantle source temperatures. The evidence for elevated mantle source temperatures for oceanic plateaus includes the following.

1) The eruption of high-MgO liquids (picrites and komatiites) in some oceanic plateaus, particularly in the Caribbean Plateau and in accreted Precambrian examples, provides evidence of source temperatures interpreted to be well in excess of the potential temperature (T_p) of ambient upper mantle (generally taken to be ~1280 °C; McKenzie and Bickle, 1988). Using parameterised experimental data on mantle melting phase relations, Herzberg and O'Hara (2002) estimated that the primary magmas of the Cretaceous plateau-derived Gorgona komatiites contained 18–20 wt.% MgO and issued from a source with a T_p of 1520–1570 °C at pressures ranging from 3.8–4.7 GPa (115–140 km depth). Furthermore, Herzberg and O'Hara (2002) calculated that Gorgona picrites originated from a primary magma containing 24 wt.% MgO and generated at 8 GPa (240 km depth) at T_p ~ 1700 °C. These results are in line with other estimates of primary magma MgO contents and temperatures based on the maximum forsterite (Fo) content of olivine in high-MgO rocks from Gorgona (Echeverría, 1980; Aitken and Echeverria, 1984; Révillon et al., 2000) and other locations throughout the Caribbean Plateau(s) (Kerr et al., 1996b, 2002; Herzberg, 2004). Some controversy exists as to the accuracy of temperatures estimated from the Fo content of olivine; in particular, unlike other studies, Green et al. (2001) found no evidence for significantly elevated temperatures for the largest modern hotspot, Hawaii. However, Putirka (2005) cautions that Green et al. (2001) may have used an Fe–Mg partition coefficient for olivine and an MgO content for Hawaiian primary magma that were too small.
2) Even when high-MgO lavas have not been sampled, mantle melting phase relations can, with some assumptions, be used to estimate the composition of the primary magma and the temperature and pressure of melting. Herzberg (2004) used hybrid forward and inverse models based on phase petrology to estimate that Ontong Java primary magmas contained 16.8–19.3 wt.% MgO and represent 27–30% partial melts of a peridotite source. His models further predict that melting initiated between 3.6 and 4.4 GPa (108–132 km depth) at T_p ranging from 1500–1560 °C.
3) Independent, trace-element-based estimates of the mean degree of melting in the source region of the Ontong Java Plateau range from 25–30% (Chazey and Neal, 2004; Fitton and Godard, 2004). Fitton and Godard (2004) noted that such a large extent of melting requires decompression of hot peridotite ($T_p > 1500$ °C) below relatively thin lithosphere. In a study of platinum-group elements in Ontong Java basalts, Chazey and Neal (2004) calculated that the basalts were derived from a mantle source with a *minimum* T_p of 1465–1515 °C.
4) Numerical modelling of the characteristics of oceanic plateaus and continental flood basalts (e.g., Farnetani and Richards, 1994) indicates that a high T_p is required in order to generate the large volumes of melt from peridotite.

Models like those outlined in numbers 2–4 above are all based on assumptions of an anhydrous, yet fertile or only slightly melt-depleted, peridotite mantle source. For the Ontong Java Plateau, the mantle source indeed appears to have been poor in water, on the basis of water contents measured in fresh glasses (Michael, 1999; Roberge et al., 2004). As discussed below, however, *a small proportion* of the Caribbean Plateau source region may have been more volatile-rich, and thus need not have been as hot as a near-anhydrous source to produce a given volume of melt.

In summary, lines of evidence ranging from phase petrology and major element composition, to trace element geochemistry and numerical modelling point towards the mantle source regions of oceanic plateaus having an elevated T_p, assuming the sources are composed predominantly of relatively volatile-poor peridotite. Assumption of an eclogite-rich source (e.g., Yasuda et al., 1997; Cordery et al., 1997; Korenaga, 2005) lowers the estimated T_p and generally increases the estimated amount of partial melting.

Several Cretaceous oceanic plateaus display significant evidence for subaerial or shallow marine eruption, consistent with sources hotter than ambient upper mantle: In the Western Cordillera of Colombia near the town of Belén de Umbria (5°14″56′N: 75°51″05′W — 45 km NW of Manizales), a sedimentary sequence overlies accreted, eroded Caribbean Plateau basalts (Moreno-Sanchez and Pardo-Trujillo, 2003). The sedimentary rocks consist of sandy shales, laminated sandstones, muddy sandstones, and bioclastic matrix-supported conglomerates with fragments of carbonized tree trunks, colonial corals, ammonites, fissurellid limpets, and gastropods of Campanian–Maastrichtian age (80–70 Ma). Coral remains have also been found in thin volcanic tuffs between oceanic plateau basalts in other locations in the Western Cordillera of Colombia, (Hall et al., 1972). These associations indicate that deposition occurred under relatively shallow-marine conditions and that some areas were even subaerial during the Late Cretaceous, whereas the absence of continental material suggests that the plateau was far from any continental margin.

Volcaniclastic deposits associated with the accreted Caribbean Plateau sequence on Aruba, in the southern Caribbean, contain no fossils. They do, however, display volcanological features such as accretionary lapilli tuffs and silicified coarse ignimbrite that are consistent with eruption in a shallow marine or subaerial environment (White et al., 1999). A 50-m-thick bed of volcanic breccia-conglomerate in the Aruba Lava Formation contains clasts of basalt, dolerite and volcaniclastic sandstone as large as 15 cm across; this bed is interpreted as representing a period of substantial erosion, most likely in a shallow marine environment (White et al., 1999).

All the holes drilled in Cretaceous portions of the Kerguelen Plateau (and on Broken Ridge, originally part of the Kerguelen Plateau) during Ocean Drilling Program (ODP) Leg 183 show evidence of subaerial eruption, particularly in the later stages of plateau formation. The evidence includes oxidised flow tops, aa and pahoehoe flow features, subaerial pyroclastic flows, fluvial conglomerates, a lack of pillow lavas and, at Site 1138, the presence above igneous basement of terrestrial and shallow marine sediments containing wood fragments, seeds, spores, and pollen (Coffin et al., 2000; Frey et al., 2003).

Portions of the Shatsky Rise also appear to have originally been near or above sea level (Sager et al., 1999). Shallow-water fossils were recovered by dredging on the flank of the rise's southern massif, and seismic reflection evidence suggests the surface of the middle portion of the rise was planed off by wave action.

In contrast, the Ontong Java Plateau shows very little evidence for shallow-water or subaerial eruption. As we discuss in Section 3.1, this represents a major paradox for the world's largest oceanic plateau. However, drilling at Site 1184 during ODP Leg 192 cored 338 m of (and bottomed in) basaltic pyroclastic deposits of phreatomagmatic origin comprising tuff and lapilli tuff that, in conjunction with oxidized horizons and wood fragments, indicate a substantial phase of subaerial eruption on the eastern lobe or salient of the plateau (Mahoney et al., 2001; Thordarson, 2004). The composition of basaltic clasts (Shafer et al., 2004) and the estimated age (123.5 ± 3.6 Ma (2σ); Chambers et al., 2004) of these deposits are consistent with the deposits being part of the main phase of Ontong Java magmatism.

2.2. Geochemical features of oceanic plateaus

Geochemically, the great majority of lavas and intrusions of oceanic plateaus can be subdivided into three main groups (Figs. 4–7):

1) Basalts and dolerites that display a restricted range of major element, trace element and radiogenic isotope composition, and have chondrite-normalised rare-

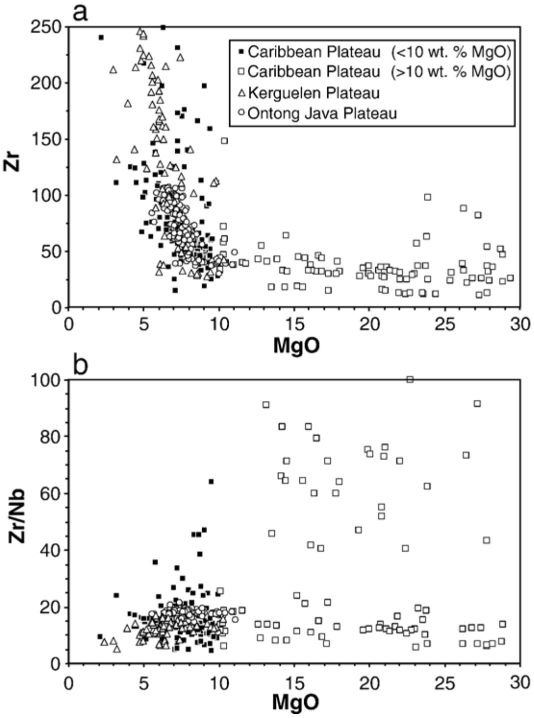

Fig. 4. Plots presenting data for the Ontong Java, Caribbean, and Kerguelen plateaus: a) MgO vs. Zr, showing that high MgO lavas are restricted to the Caribbean Plateau; b) MgO vs. Nb/Zr which shows that high-MgO Caribbean Plateau lavas can be grouped into those with MORB-like Zr/Nb and low Zr/Nb (more-enriched). Note that because of the significant heterogeneity in the Caribbean Plateau, lavas with >10 wt.% MgO have been given a different symbol. Data sources for this and subsequent diagrams are given in Electronic Appendix A.

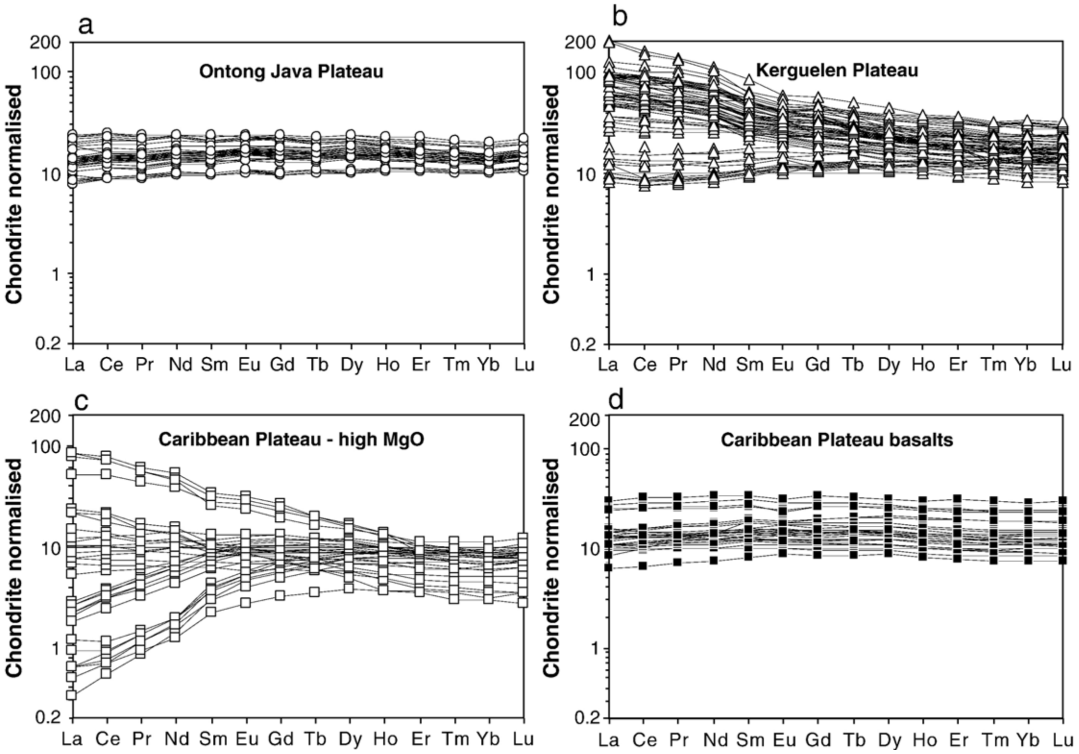

Fig. 5. Chondrite-normalised (Sun and McDonough, 1989) REE plots for a) Ontong Java Plateau basalts, b) Kerguelen Plateau basalts, c) Caribbean Plateau picrites and komatiites (>10 wt.% MgO), and d) Caribbean Plateau basalts (<10 wt.% MgO).

earth element (REE) patterns that are flat to slightly light-REE-enriched. Concentrations of the REE and other alteration-resistant incompatible elements tend to be similar to those in MORB (ocean-ridge basalts), whereas isotope ratios of Nd, Pb, Hf, and Sr are broadly ocean-island-like (Mahoney, 1987; and many later publications). Virtually all Ontong Java basement samples are of this type, as are many of the lavas of the Caribbean and Kerguelen plateaus.

2) Basalts that possess a signature consistent with contamination by continental crust (e.g. $La/Nb \gg 1$, initial $^{87}Sr/^{86}Sr > 0.705$, variably negative ε_{Nd}). A significant number of Kerguelen Plateau lavas belong in this category (e.g., Frey et al., 2002; Ingle et al., 2002; Neal et al., 2002). The overall range of isotopic variation can be considerable.
3) Picrites and komatiites with high MgO contents (>12 wt.%). As a group, such rocks have a wider range of isotope ratios and incompatible trace element concentrations and ratios (including both incompatible-element-depleted and -enriched types) than group 1. Such high-MgO rocks are found principally in the Caribbean Plateau (e.g., Sinton et al., 1998; Kerr et al., 2003).

2.2.1. Mantle sources

Most basement igneous rocks sampled from Cretaceous oceanic plateaus range in MgO content from ~6.0–11.0 wt.%, with the vast majority of lavas possessing a relatively restricted MgO range of 6.5–8.5 wt.%. (Fig. 4). A notable exception is the Caribbean Plateau, which has an abundance of lavas and intrusive rocks in the 6–11 wt.% MgO range but also contains a significant proportion of higher-MgO rocks. Such rocks were not sampled in the relatively shallow drill-holes in the Caribbean Basin but are relatively common in the stratigraphically deeper portions of accreted crustal sections from western Colombia to Gorgona Island, Costa Rica and Curaçao (Fig. 3; Kerr et al., 2003). The maximum observed Fo contents of olivine in these rocks suggest that their parental magmas contained between 15 and 24 wt.% MgO (Kerr et al., 1996b, 2002; Révillon et al., 2000; Herzberg and O'Hara, 2002). We have already noted the evidence from phase petrology and trace element geochemistry that Ontong Java basalts may have been derived from parental magmas with similarly high MgO contents. Why, then, are high-MgO rocks found in accreted sections of the Caribbean Plateau but not (thus far) in those of the Ontong Java

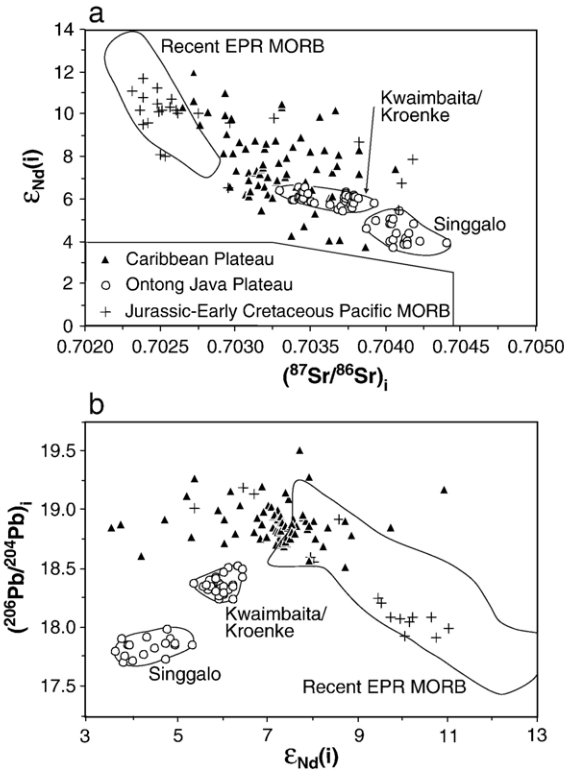

Fig. 6. a) Initial $^{87}Sr/^{86}Sr$ vs. ε_{Nd}; b) initial ε_{Nd} vs. $^{206}Pb/^{204}Pb$ for the Ontong Java and Caribbean. The Ontong Java data are divided into Kwaimbaita/Kroenke and Singgalo types (see text). Also shown are age-corrected data for Jurassic and Early Cretaceous Pacific MORB and a field for recent East Pacific Rise N- and E-MORB. Note that for the plateau and old MORB samples, the wide range of $^{87}Sr/^{86}Sr$ at a given ε_{Nd} is partly an effect of variable seawater-mediated alteration.

Plateau? Furthermore, why are the incompatible-element and isotopic compositions of high-MgO Caribbean Plateau lavas generally more heterogeneous than those of basalts from both the Caribbean and Ontong Java plateaus?

Kerr et al. (1998) proposed that the source regions of oceanic plateaus in general were heterogeneous and that the relative homogeneity of many plateau lavas and intrusions was a result of mixing and fractionation of magmas en route to the surface, in large magma chambers, as previously proposed for several continental flood basalt provinces (e.g., Wooden et al., 1993; Peng et al., 1994). For the Caribbean Plateau, Kerr et al. (2002) showed that the source region indeed was markedly heterogeneous over a wide area and on a relatively small scale. More generally, such heterogeneity is consistent with evidence from present-day MORB and oceanic islands (e.g., some individual islands display greater isotopic and elemental heterogeneity than yet found for the entire Ontong Java Plateau). Indeed, it is widely understood that the mantle sampled by melting is heterogeneous on a variety of scales (e.g., Davies, 1984; Allègre and Turcotte, 1986; Niu et al., 1996; Meibom and Anderson, 2003; Kogiso et al., 2004; Ito and Mahoney, 2005).

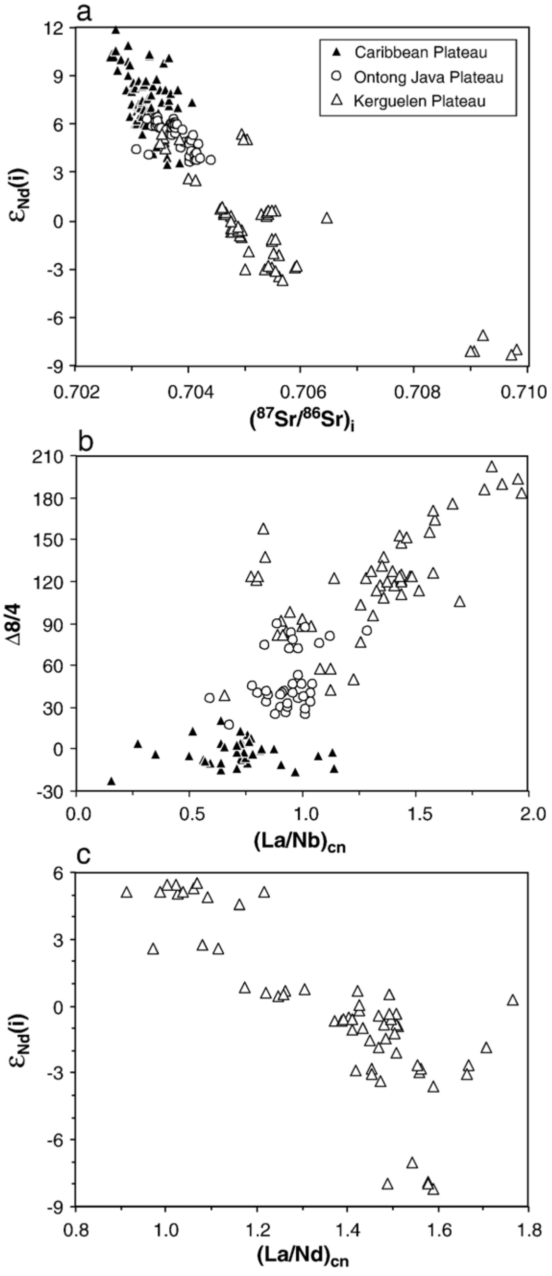

Fig. 7. Diagrams of a) initial $^{87}Sr/^{86}Sr$ vs. ε_{Nd}; b) $(La/Nb)_{cn}$ vs. Δ8/4 Pb; c) $(La/Nd)_{cn}$ vs. ε_{Nd} (cn — chondrite normalised) showing data for the Kerguelen, Ontong Java, and Caribbean plateaus. The Δ8/4 parameter represents the vertical distance of a data point above or below the average line defined by ocean-ridge and island basalts of the Northern Hemisphere in a diagram of $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ (Hart, 1984).

The reason why compositionally variable, high-MgO lavas have not been found on the Ontong Java Plateau but are relatively common in the Caribbean Plateau is probably related to differences in crustal thickness and in the maximum depth to which the crust has been exhumed in accreted sections (Kerr et al., 1998). High-MgO, heterogeneous lavas are most likely to be erupted where the crust is relatively free of magma chambers and the magmatic plumbing system is poorly developed; in such areas, discrete magma batches are more likely to travel relatively quickly from source to surface with minimal mixing in magma chambers. Therefore, in oceanic plateaus (and continental flood basalt provinces; e.g., Cox, 1980), the most likely place to find high-MgO lavas is at the base of the succession. Later magmas are more likely to become trapped and so mix and fractionate.

Accreted sections, when present, provide the best way of studying the internal anatomy of a plateau, because they tend to expose deeper levels of the crust than reached by drilling. However, only the top-most 3–4 km of Ontong Java Plateau basement crop out in accreted sections in the Solomon Islands, in the form of large thrust slices (Petterson, 2004). The lack of deeper exposures appears to be related to at least three factors. 1) As noted earlier, the plateau was ~100 my old at the time it docked with the Solomons block (~20–25 Ma). This factor (reduced buoyancy) may be less important than in some other cases, however, because all available evidence indicates that the main part of the plateau originally sat only 1000–1500 m higher than it does now (Michael, 1999; Roberge et al., 2005). 2) Docking was initially oblique, and the collision only very recently (~4 Ma) became more head-on; thus significant uplift in the collision zone began only recently (e.g., Petterson, 2004; Kroenke et al., 2004). 3) The crust of the plateau attains a thickness of as much as 38 km (e.g., Richardson et al., 2000; Miura et al., 2004); therefore, the base of the volcanic succession, where high-MgO lavas are more likely to exist, is much deeper than in the Caribbean case. Caribbean Plateau crust is 8–15 km thick (Case et al., 1990; Mauffret and Leroy, 1997), so less uplift was required to expose its lower levels in accreted sections. Also, as noted above, the Caribbean Plateau collided with a subduction zone <10 my after the plateau formed, and the crust stood at a comparatively high level at the time of collision (White et al., 1999).

Tejada et al. (2004) suggested that the predominant type of basalt sampled on the Ontong Java Plateau, the Kwaimbaita type, reflects a mantle source that was rather homogeneous at the very large scale and extent of melting. Kwaimbaita-type basalts are found across the plateau and in the adjacent Nauru and East Mariana basins. Samples from sites separated by distances as great as 2000 km, and within the ~3-km-thick pile of Kwaimbaita-type basalts exposed on the island of Malaita, exhibit a total Nd isotope range of only 1.1 ε_{Nd} units (+6.5 to +5.4). Long-distance compositional similarities observed within portions of some continental flood basalt provinces (e.g., Siberian Traps) have been attributed by some workers to mixing during differentiation in large magma reservoirs (e.g., Wooden et al., 1993). The Kwaimbaita-type basalts are indeed rather evolved (e.g., they have 5–8 wt.% MgO), and mixing of more heterogeneous magmas in large open-system magma chambers no doubt partly explains their isotopic and incompatible-element homogeneity. However, mixing would have to always yield essentially the same composition, and there is little evidence for magma mixing in the existing isotope and trace element data. Further, the highest-MgO lavas yet found on the Ontong Java Plateau, the Kroenke-type basalts (with 9–11 wt.% MgO), have identical isotope ratios to those of the Kwaimbaita-type basalts, and appear to be parental to them. In contrast to the Kwaimbaita-type lavas, the Kroenke-type basalts have lost only ~18–25% olivine, during fractional crystallisation, assuming a peridotite mantle source (Fitton and Godard, 2004; Herzberg, 2004), much less if the source was eclogite-rich (Korenaga, 2005). Given the great volume of melting and the large fractions of partial melting involved (estimated mean percentage of 25–30% if the source was peridotite and either fractional or equilibrium melting is assumed [Fitton and Godard, 2004; Herzberg, 2004]; minimum amount >50% if an eclogite-rich source is assumed [Korenaga, 2005]), it is probable that the melting process played a key role in averaging out smaller-scale source heterogeneity to produce the remarkable isotopic and incompatible-element homogeneity of the Kwaimbaita- and Kroenke-type basalts. Perhaps significantly, the estimated extents of melting for most of the Caribbean Plateau (14–26%, assuming a peridotite source and either fractional or equilibrium melting; e.g., Hauff et al., 1997; Révillon et al., 2000; Herzberg and O'Hara, 2002; Kerr et al., 2002) are lower than for the Ontong Java, a feature that would have resulted in less homogenisation of melts in the mantle.

2.2.2. Contamination of oceanic plateau magmas by continental lithosphere

Some lavas drilled on the Kerguelen Plateau, particularly some of those from the southern and central Kerguelen Plateau and the Elan Bank, possess initial $\varepsilon_{Nd} < -2$, $(La/Nb)_{cn} > 1.25$ (the subscript indicates normalization to the average chondritic value), and high $^{208}Pb/^{204}Pb$ relative to $^{206}Pb/^{204}Pb$ ($\Delta 8/4 > 100$) (Fig. 7). These features are consistent with contamination by continentally derived material, probably from continental fragments incorporated within the lithosphere of the Indian Ocean during break-up of Gondwana prior to formation of the plateau. During formation of the plateau, partial melts from these fragments appear to have been incorporated into some of the >90 Ma magmas (Weis et al., 2001; Frey et al., 2002; Neal et al., 2002). The light-REE-enriched signature of these Kerguelen Plateau basalts (Fig. 5d) also appears to at least partly be a result of contamination with continental crust, as a good negative correlation is present between initial ε_{Nd} and $(La/Nd)_{cn}$ (Fig. 7c).

Alternatively, it might be argued that the unusual geochemical signature shown by some of the early Kerguelen Plateau lavas was derived from a region of the shallow convecting mantle postulated by Anderson (1995) to lie just below the lithosphere, and termed the 'perisphere'. He argued that the perisphere is constantly enriched in incompatible elements and volatiles by subduction processes and by accumulation just beneath the lithosphere of small-degree partial melts. Given the ability of subduction zones to generate shallow mantle with high La/Nb, negative ε_{Nd}, high $^{87}Sr/^{86}Sr$, etc., perisphere with such characteristics theoretically could have been tapped at times during Kerguelen Plateau magmatism. However, the discovery at ODP Site 1137 of a conglomerate containing 534–2457 Ma garnet–biotite gneiss cobbles (Nicolaysen et al., 2001) demonstrated that at least one fragment of Gondwanan crust is present in the Kerguelen Plateau. Seismological evidence also indicates the presence of continental crust in parts of the plateau, although the overall amount is not well established (e.g., Charvis and Operto, 1999; Borissova et al., 2003). Contamination of ascending magmas by high-La/Nb continental material thus appears to be the most straightforward explanation for the anomalous geochemical signature of some Kerguelen Plateau basalts. It surely is no coincidence that the Kerguelen Plateau is as yet the only Cretaceous plateau to show a continental lithospheric signature *and* the only plateau known to contain fragments of continental crust.

2.2.3. A deep-mantle origin for plateau sources?

Platinum group elements and their isotopes, because of their siderophile nature, can provide valuable clues about the origin of oceanic plateaus. Brandon et al. (2003), in a study of the Gorgona komatiites, discovered coupled enrichments (relative to estimated primitive upper mantle values) in $^{186}Os/^{188}Os$ and $^{187}Os/^{188}Os$. Because ^{186}Os and ^{187}Os are the decay products of ^{190}Pt and ^{187}Re, respectively, rocks with high $^{186}Os/^{188}Os$ and $^{187}Os/^{188}Os$ reflect a long-term enrichment in ^{190}Pt and ^{187}Re. Earth's core is commonly postulated to have such enrichment, and Brandon et al. (2003) concluded that the $^{186}Os/^{188}Os$ and $^{187}Os/^{188}Os$ enrichments in Gorgona komatiites indicate a source originating near the base of the mantle, where at some time mass exchange with the outer core had occurred. This interpretation of Os isotope data has been challenged by Baker and Jensen (2004) and Schersten et al. (2004), although counter arguments have recently been made by Brandon and Walker (2005), and Lassiter (2006). In short, the jury still seems very much out on whether the Os isotope evidence indicates a contribution from the core to mantle plumes.

An input from the core to the source regions of the Ontong Java and Kerguelen plateaus also has been argued to be consistent with platinum-group element data. Ely and Neal (2003) and Chazey and Neal (2004, 2005) inferred that as much as 1% of core material may be incorporated in the mantle sources of these plateaus, although it should be noted that this figure is higher than may be allowed by ratios like Mo/Ce and Fe/Ni (see Sims et al., 1990; McDonough and Sun, 1995).

Révillon et al. (2002) proposed a deep-mantle origin for the source of the Gorgona komatiites based on high $^{3}He/^{4}He$ ratios (8–18 times the atmospheric ratio) measured in olivine and clinopyroxene. The high-$^{3}He/^{4}He$ signature could represent a contribution from relatively undegassed lower mantle (Révillon et al., 2002), or could be derived from degassing of the core (Kerr, 2005a). However, although a high-$^{3}He/^{4}He$ signature is generally regarded to indicate a lower mantle or core signature, recent experimental work suggests that He is more compatible than U and Th in olivine (Parman et al., 2005). Over time, this would result in a depleted (residual) upper mantle with much higher $^{3}He/^{4}He$ than allowed in previous models of He isotope evolution. The new results potentially help explain ocean island lavas with high $^{3}He/^{4}He$ that also record (in their Nd–Hf–Sr isotope ratios) a long-term history of source depletion. Conversely, Ellam and Stuart (2004) have proposed that high-ε_{Nd} oceanic basalts with high $^{3}He/^{4}He$ may be explained by mixing of depleted mantle with <10% of He-rich primordial mantle. It is not clear how either of these possibilities squares with the major-element and mineralogical evidence (see above) for a high-T_P source for the Gorgona komatiites.

Overall, then, a contribution from the core to the source regions of oceanic plateaus remains a rather controversial possibility with the evidence presently available.

2.3. Identifying ancient oceanic plateaus

Possible oceanic plateau fragments have been identified increasingly in the geological record on land, in large part as a direct result of our increased understanding of the petrology and structure of Cretaceous oceanic plateaus. Although not all workers agree (e.g., Bédard et al., 2005), crustal sequences preserved in several Archean and early Proterozoic areas, particularly greenstone belts, have been argued to be derived from oceanic plateaus: e.g., the Superior Province (Polat and Kerrich, 2001), Baltic Shield (Puchtel et al., 1998), Yilgarn Craton (Pirajno, 2004), Barberton greenstone belt (Chavagnac, 2004), and others (e.g., Abouchami et al., 1990; Storey et al., 1991; Arndt, 1994). If correct, portions of oceanic plateaus may be preserved within the stratigraphic record throughout a considerable proportion of Earth history and so can be used to track mantle sources, processes and temperatures through time.

Many different features can be used to identify oceanic plateau remnants. Kerr et al. (2000) and Ernst and Buchan (2003) have discussed them in some detail, and only several aspects will be mentioned here.

Igneous rocks formed in subduction zones are generally more evolved than oceanic plateau lavas; the great majority have high $(La/Nb)_{cn}$ (>1), and only very rarely are high-MgO lavas present. Where high-MgO lavas do occur in arcs they are relatively easily identified by their distinctive petrography and geochemistry. Additionally, although phreatomagmatic volcaniclastic layers have recently been discovered on the Ontong Java and Kerguelen plateaus (see above), oceanic plateaus do not possess the abundant, relatively evolved ash layers present in volcanic arc sequences. However, the fact that the Kerguelen Plateau has some high-$(La/Nb)_{cn}$ rocks highlights the importance of not relying on one geochemical discriminant of tectonic environment; other geological and geochemical evidence must be considered. As we have seen, most sequences of Cretaceous oceanic plateau lavas possess relatively flat REE patterns (Fig. 5); when coupled with moderate or low $(La/Nb)_{cn}$ (and/or $(La/Ta)_{cn}$), such patterns are useful in identifying ancient oceanic plateau sequences.

In the identification of ancient oceanic plateaus from geochemical criteria, the most problematic rocks are basalts formed in a back-arc basin (Kerr et al., 2000) and incompatible-element-enriched (E- or T-) MORB (Mahoney, 2005), because such basalts have many chemical and isotopic similarities to oceanic plateau lavas. However, few high-MgO lavas are erupted in back-arc basins and at mid-ocean ridges, probably because the mantle source temperature is lower than inferred for most plateau sources. Furthermore, because of their proximity to active subduction sites, back-arc basin sequences are more likely to contain abundant volcaniclastic horizons than oceanic plateaus. E-MORB are abundant along several sections of the present ocean-ridge system far from hotspots. They tend to differ from plateau basalts in their major element characteristics (e.g., Fe/Al, Ca/Al); however, alteration or low-grade metamorphism can make it difficult to discriminate plateau basalts from E-MORB on major-element grounds.

2.4. Potential environmental impact of oceanic plateaus

Oceanic plateau formation has been implicated as a cause of several periods of severe environmental crisis in the Cretaceous oceans, particularly around the Cenomanian–Turonian boundary (93.5 Ma) and in the early Aptian (~120 Ma) (e.g., Tarduno et al., 1991, 1998; Sinton and Duncan, 1997; Kerr, 1998, 2005b; Larson and Erba, 1999; Leckie et al., 2002; Snow et al., 2005). Increased oceanic volcanism at these times probably increased the flux of CO_2 to the environment, both directly from eruptions and by volcanically induced acidification of ocean waters, causing carbonate dissolution. A steadily warming atmosphere (note that plateau formation in the Cenomanian–Turonian appears to have occurred during a period when temperatures were already near peak greenhouse conditions [Huber et al., 2002]) and oceans, along with upwelling nutrients, stimulated primary organic productivity in the oceans. Some nutrients were of volcanic origin and some were derived from the deep ocean, which had been disturbed by changing circulation patterns. The increased productivity, along with warmer oceans, led to widespread anoxic/dysoxic conditions in the oceans and resulted in the demise of a significant number of marine species and the formation of extensive black shale deposits (Sinton and Duncan, 1997; Kerr, 1998, 2005b; Leckie et al., 2002; Snow et al., 2005). Interestingly, the main phase of Ontong Java Plateau formation (~120 Ma) appears to correlate with a massive release of methane hydrates (Jahren, 2002), whereas there is little evidence for a similar release during eruption of the Caribbean Plateau (Kerr, 2005b).

Other black shale deposits and anoxic/dysoxic events can also be correlated with periods of anomalous oceanic volcanism. For instance, although mostly a continental flood basalt province, the formation of the Karoo, Ferrar and Weddell Sea basalts (~183 Ma) is approximately coeval with the Toarcian anoxic event and associated black shales (Pálfy and Smith, 2000). Condie et al. (2001) have argued that the link between black shale deposition, paleoclimatic disturbance and large oceanic volcanic events extends into the Precambrian. Good correlations between environmental disturbance and inferred oceanic mantle plume activity occur at 1.9 and 2.7 Ga.

In other cases, unlike several large continental flood basalt episodes, the emplacement of oceanic plateaus did not result in any global-scale environmental disturbance. For example, eruption of the principal massif of the Shatsky Rise occurred at the Jurassic–Cretaceous boundary, yet the end of the Jurassic was not marked by a global environmental crisis, perhaps because the climate was rather cool at the time (Mahoney et al., 2005).

3. Problematic issues for oceanic plateau paradigms

From the evidence outlined above it is clear that oceanic plateaus are derived from hotter-than-ambient mantle assuming their source regions consist of anhydrous peridotite. Also, although much more controversial, there are indications that at least some source regions may have undergone mass exchange with the core. Taken together, the implication is that source regions may have been both deep and hot, consistent with the widely held view that many, perhaps most, continental flood basalts and oceanic plateaus are formed during the start-up phase of deep-rooted mantle plumes. However, as with all models for which the main causative mechanism cannot be directly observed, new data require testing of the model, and often lead to case-specific and sometimes to general refinements. Opponents of mantle plume models (e.g., Anderson, 1996; Smith and Lewis, 1999) tend to regard *ad hoc* adjustments as largely invalidating the models. We note simply that it is the testing, refining, modifying and, if justified by weight of evidence, rejection of proposed models that has typified most research in the geological sciences for many decades.

3.1. The largely submarine Ontong Java Plateau

The arrival and decompression melting of a hot, buoyant mantle plume head at the base of the oceanic lithosphere should result in eventual uplift of the ocean floor. Models predict that the formation of the Ontong Java Plateau by a hot plume head should have elevated much of the plateau's surface above sea level, resulting in a considerable amount of subaerial volcanism (e.g., Farnetani and Richards, 1994; Neal et al., 1997; Ito and Clift, 1998). However, although eight Deep Sea Drilling Project (DSDP) and ODP drill holes have penetrated into the volcanic crust of the plateau, only Site 1184 records any evidence of large amounts of subaerial eruption. Evidence at the other sites and in the Solomon Island exposures indicates the bulk of the plateau formed at considerable water depths (e.g., Mahoney et al., 2001). Michael (1999) and Roberge et al. (2005) used the CO_2 and H_2O contents of basaltic glasses to quantify eruption depth and post-eruptive subsidence of the drill sites. Their results reveal that (excepting Site 1184) not only did the basement lavas erupt in 1100–3000 m of water, but that post-eruption subsidence of the sampled sites was only 1500±400 m, much less than the 2700–4100 m predicted by plume-head models (e.g., Ito and Clift, 1998).

Rayleigh-wave tomography reveals the presence of a seismically slow upper-mantle "root" below much of the Ontong Java Plateau extending to depths of at least 300 km (Richardson et al., 2000). Interpretation of shear-wave splitting indicates the root moves along with the plateau as the plateau drifts with the Pacific plate (Klosko et al., 2001). If the anomaly were purely thermal, temperatures 350–700° above those of the surrounding mantle would be required; such temperatures should cause extensive present-day volcanism, yet no volcanism is occurring (Richardson et al., 2000; Gomer and Okal, 2003). Further, Gomer and Okal (2003) concluded that the combination of slow shear-wave speed and lower than average shear attenuation rules out a large residual temperature anomaly. Rather, their modelling suggests the velocity characteristics reflect a mineralogical and/or bulk chemical difference from the surrounding convecting mantle. Similar regions have not been found thus far below other oceanic plateaus. The origins of the root are by no means clear, but it seems likely that the uplift and subsidence history of the Ontong Java Plateau is closely linked to its presence. Regardless, the less-than-predicted initial relief and subsequent subsidence constitute a very serious problem for any plume-head model for the plateau.

Prolonged magmatism, with voluminous, widespread underplating and intrusion occurring for 30 my or more after a relatively small ~120 Ma phase of Ontong Java eruption, offers a possible solution (e.g., Ito and Clift, 1998; Ito and Taira, 2000). This hypothesis requires the long-term presence of a large, active mantle plume "tail" below the plateau long after a comparatively small plume-head stage. Despite the relative paucity of post-120 Ma volcanism, ~90 Ma ^{40}Ar–^{39}Ar ages for lavas and dykes in several areas around the margins of the plateau (and later magmatism at 44 and 34 Ma) appear to offer some support for the hypothesis. However, recent plate-motion modelling indicates the plateau drifted as much as 2000 km in the ~120–90 Ma period (Kroenke et al., 2004). If so, it is highly unlikely that an active plume-tail could have remained below the plateau for several tens of millions of years. On the other hand, some underplating and intrusion associated with passage of the plateau over other, perhaps multiple, plume tails remains possible and could help explain its anomalous subsidence history (e.g., Neal et al., 1997; Phinney et al., 1999; Kroenke et al., 2004).

Besides plume-head models, other origins also have been suggested. Here we briefly review two. Well before the appearance of the plume-head model, Rogers (1982) proposed the Ontong Java and other Pacific plateaus were formed by cataclysmic melting caused by meteorite impact. This idea was revisited by Ingle and Coffin (2004) and Tejada et al. (2004) for the Ontong Java Plateau, and more recently by Jones et al. (2005) and Korenaga (2005). Most important for the present discussion, Korenaga's (2005) analysis concludes that impact-induced melting cannot explain the Ontong Java Plateau's anomalously small amounts of uplift and subsidence. Instead, just as with plume-head models, large areas should initially have been above sea level and the plateau's surface should subsequently have subsided normally as the lithosphere cooled.

An additional difficulty with an impact origin is the ocean-island-like Nd–Pb–Hf–Sr isotopic signature of Ontong Java basalts (Tejada et al., 2004; Ingle and Coffin, 2004) which, as Fig. 6 shows, is distinct from that of both modern and pre-120 Ma Pacific N- and E-MORB. High-degree partial melting of the upper few hundred kilometres of the mantle caused by impacts in oceanic locations far from hotspots would normally be expected to produce MORB-type isotopic signatures.

An impact in the southern portion of the plateau appears to be ruled out by xenoliths of Jurassic-age spinel lherzolite and gabbro found in 34 Ma alnöite intrusions in the obducted Ontong Java section on the island of Malaita (Ishikawa et al., 2005). A large impact would have obliterated a vast area of oceanic lithosphere, yet the xenoliths appear to represent normal Pacific lower crust and uppermost lithospheric mantle, indicating that the southern part of the plateau is underlain by intact, pre-existing oceanic lithosphere. The alnöite intrusions are 500–600 km south-southeast of the thickest plateau crust, where the centre of an impact site might be inferred, and an impact in the northern half of the plateau remains possible; however, no sedimentary evidence of a large meteorite impact around the Barremian–Aptian boundary (~125–120 Ma) has been reported (Tejada et al., 2004). In short, presently it appears the impact hypothesis for the Ontong Java Plateau is fraught with as many problems as mantle plume models.

Another non-plume hypothesis for the Ontong Java Plateau was recently suggested by Korenaga (2005), who proposed that the abnormal uplift and subsidence can be explained by melting of dense, fertile eclogite dragged upward from a zone of neutral buoyancy near 660 km by rapid (but passive) upwelling of asthenosphere below a superfast-spreading ridge. The eclogite, postulated to correspond to subducted remnants of the basaltic portion of ancient oceanic crust, would melt to ≥50%, leaving a dense residuum below the crust. The lack of extensive subaerial volcanism is explained, because higher-than-normal mantle T_P is not involved. In addition, this hypothesis accounts for the plateau's anomalous subsidence and ~90 Ma volcanism by postulating later detachment and sinking of residual but still relatively fertile shallow mantle. Moreover, an eclogite-rich source can explain most of the chemical and isotopic characteristics of the Kwaimbaita- and Singgalo-type basalts nearly as well as a peridotite source (Tejada et al., 2002; Korenaga, 2005) (the Singgalo is a third Ontong Java magma type, together with the Kroenke and the predominant Kwaimbaita).

However, the plateau poses non-trivial difficulties for this model, too. For example, the Kroenke-type basalts appear parental to the predominant Kwaimbaita type, with higher MgO and lower incompatible-element concentrations than the Kwaimbaita but identical isotope ratios and nearly identical incompatible-element ratios, including flat REE patterns. Concentrations of incompatible elements that appear to be nearly immobile during dehydration of oceanic basalt in subduction zones (e.g., Kogiso et al., 1997) are significantly less in the Kroenke-type basalts than in N-MORB. Melting of eclogitised oceanic basalt cannot produce the observed combination of flat REE patterns and lower concentrations of middle and heavy REE, Zr, and Hf than in the original basaltic ocean crust. Melting of a mixture of eclogite and peridotite can, but only if the peridotite melts to a larger extent than it does in producing most MORB, which, however, would resurrect the T_P-uplift problem. Additionally, the very small (1.1 ε_{Nd} unit) range of isotopic variation in the dominant Kwaimbaita- (and Kroenke-) type basalts is rather difficult to explain with this model, even taking into account the averaging effect of large amounts of partial melting and large magma reservoirs. A huge amount of eclogite is required (see Section 3.2); if derived from subducted oceanic crust, it must have accumulated over a long period of time and from a large area of the oceans. (As an example, an area of seafloor as large as 2–2.5×10^7 km^2 could be required, which would take 308–385 my to subduct along a 1000-km-long trench at an average subduction rate of 65 km/my; of course, it is unlikely that the eclogite would be derived from a single subduction zone or single piece of seafloor) It thus would be expected to possess considerable Pb and Nd isotopic heterogeneity, because of (a) initial along-axis heterogeneity (MORB represent rather high extents of partial melting, yet the isotopic variation in Pacific MORB is much greater than seen for the Ontong Java Plateau; the difference is even greater if Indian and Atlantic MORB are included), (b) variable "aging" of seafloor prior to subduction (i.e., variable radiogenic ingrowth during variable amounts of time spent as variably altered seafloor between formation at a ridge axis and removal at a trench), and (c) variable periods of isotopic evolution in the mantle following subduction.

Another potential difficulty for the eclogite hypothesis is that spreading rates may have decreased from super-fast to intermediate values starting several million years before 120 Ma along the western part of the Phoenix spreading axis east of the plateau (Nakanishi and Winterer, 1998; M. Coffin, personal communication). If so, it is not clear that passive upward mantle flow would have been vigorous enough to entrain sufficient amounts of dense eclogite.

In summary, none of the models for the formation of the Ontong Java Plateau is without problems. If future sampling reveals pre-120 Ma, ~90 Ma, or later volcanism to be much more voluminous than presently indicated, difficulties for non-plume eclogite and meteorite-impact hypotheses could be compounded. Nor would plume models necessarily become any more viable, because evidence that the plateau drifted as much as 2000 km between ~120 and 90 Ma (Kroenke et al., 2004) would be difficult to reconcile with prolonged plume-fed crustal growth.

3.2. Volume of the Ontong Java Plateau

The sheer volume of the Ontong Java Plateau makes it an end-member for all models and severely strains some. For comparison with continental flood basalt provinces, for which only the erupted and shallow intrusive levels generally are accessible, we consider only the upper crust of the plateau. The area of the plateau proper is $\sim2\times10^6$ km^2, comparable to that of Western Europe (e.g., Fitton et al., 2004). Seismic refraction and reflection data for the southern part of the plateau indicate a two-layer upper crust consisting of 8–10 km of basalt (Miura et al., 2004), which appears even thicker in the central area of the plateau (Neal et al., 1997). Adding the 3.3×10^6 km^3 of Ontong–Java-related flows and sills that fill the Nauru Basin to the east and northeast of the plateau (Mochizuki et al., 2005), the volume of flows and sills can be estimated roughly at 19–23×10^6 km^3 (in addition, extensive Ontong–Java-related basalts cover the East Mariana Basin to the north of the plateau, but their total volume has not been established; Castillo et al., 1994). In contrast, estimates for the largest continental flood basalt provinces are substantially smaller (e.g., Courtillot and Renne, 2003).

The total crustal volume of the plateau proper is estimated to be between 57 and 44×10^6 km^3 (e.g., Gladczenko et al., 1997), depending on how much of the plateau is underlain by pre-existing oceanic crust; the 3.3×10^6 km^3 of plateau-related basalt in the Nauru Basin and the large but as yet poorly quantified volume in the East Mariana Basin should be added to these figures. However, the original volume of the plateau may have been still greater. Bathymetric data for the Ellice Basin between the Ontong Java Plateau and the Manihiki Plateau indicate that east–west seafloor spreading occurred there after the Ontong Java Plateau formed, and suggest the 8×10^5 km^2 Manihiki Plateau (now more than 2500 km east of the Ontong Java Plateau) may originally have been part of the Ontong Java (Taylor, 2006). Further, the 7×10^5 km^2 Hikurangi Plateau east of New Zealand appears to originally have been part of the Manihiki (Lonsdale, 1997; Billen and Stock, 2000; Larson et al., 2002; Worthington et al., 2006) and thus possibly the Ontong Java Plateau (Taylor, 2006). The volume of the Manihiki Plateau is estimated at 8.8–13.6×10^6 km^3, depending on the amount of pre-existing oceanic crust, and that of the Hikurangi Plateau at $>2.7\times10^6$ km^3 (Coffin and Eldholm, 1994). Therefore, the Ontong Java Plateau's total original volume may have been at least 59–77×10^6 km^3. Assuming the source region was peridotite and that crust was formed from magmas representing 25% of partial melting, on average, then at least 2.4–3.1×10^8 km^3 of mantle, corresponding to a sphere 770–840 km in diameter, would be required. If the crust instead was formed by an average of 50% partial melting of eclogite, then the source volume would be at least 1.2–1.5×10^8 km^3, corresponding to a sphere of eclogite at least 610–660 km in diameter.

The possibility that the Manihiki and Hikurangi Plateaus are rifted-off parts of the Ontong Java Plateau remains to be tested with further work on all three plateaus and in the intervening basins, but geochemical and geochronological data for DSDP Site 317, the only site drilled on the Manihiki Plateau, support a connection with the Ontong Java (e.g., Mahoney et al., 1993; Neal et al., 1997). The Site 317 lavas exhibit strong similarities with the Singgalo-type basalts, which lie above the Kwaimbaita-type lava pile in several areas of the Ontong Java Plateau; likewise, ^{40}Ar–^{39}Ar data for Site 317 yield an Ontong–Java-like age of 123.5 ± 3 Ma. Several dredged Manihiki basalts have ε_{Nd} values in the Kwaimbaita/Kroenke-basalt range, although they have somewhat lower ^{87}Sr/^{86}Sr and higher ^{206}Pb/^{204}Pb (Mahoney and Spencer, 1991; Ingle et al., in press). Basalts dredged from the Hikurangi Plateau have ^{40}Ar–^{39}Ar ages of 118–93 Ma, and may correspond to two phases of volcanism analogous to the ~120 and ~90 Ma episodes on the Ontong Java Plateau; also, they are geochemically similar to Ontong Java and Manihiki lavas (Hoernle et al., 2005).

Finally, an unknown volume of crust appears to have rifted from the eastern Manihiki Plateau after it formed (Larson et al., 2002). We speculate that a remnant may be accreted to the western margin of northern South America. Kerr and Tarney (2005) proposed that the oceanic plateau fragment containing the island of Gorgona off the coast of Colombia, previously thought to be an accreted part of the Caribbean Plateau, is instead derived from a plateau that formed much farther south, at ~26–30°S. Too few Manihiki Plateau basalts are available to provide a precise estimate of paleolatitude; however, the calculated paleolatitude for the central Ontong Java Plateau at ~120 Ma is ~25°S (Riisager et al., 2004), close to that for Gorgona. ^{40}Ar–^{39}Ar data for Gorgona lavas indicate an age near 90 Ma (Sinton et al., 1998), but the latitude of the Ontong Java Plateau appears not to have changed greatly between 120 and 90 Ma as the plateau's motion during this period was largely east–west (Kroenke et al., 2004).

3.3. Oceanic plateaus with no succeeding hotspot track

Although the standard plume-head model predicts that a plateau should have a succeeding plume-tail trace in the form of a seamount chain or aseismic ridge, this is not always the case. For example, while the long Papanin Ridge, the northeast salient of the Shatsky Rise, may be a plume-tail trace (e.g., Sager et al., 1999), the Ontong Java Plateau lacks an associated post-plateau seamount chain. It is possible that such a chain existed but has been destroyed (e.g., Neal et al., 1997), because seafloor to the south and southwest of the plateau has been subducted down the old Solomon and Vitiaz Trenches. Likewise, seafloor spreading on the south-eastern side of the plateau (Taylor, 2006) may have placed a post-plateau seamount chain on oceanic crust that has since been subducted in the southern or eastern Pacific. The Kerguelen Plateau is illustrative in this regard, as the post-plateau seamount chain, the Ninetyeast Ridge, is preserved but lies on another plate across a spreading axis (the Southeast Indian Ridge).

It is also possible that some plume heads have little or no plume tail. If so, the lack of a post-plateau seamount chain would not rule out a plume-head origin. Seismology has long identified strong lateral heterogeneities in the region several hundred kilometres above the core-mantle boundary (e.g., Lay and Helmberger, 1983) and more recent work has resolved the structure of this part of the lower mantle in more detail (Fisher et al., 2003; Hung et al., 2005). The results indicate that this region is heterogeneous in both composition and density. Modelling suggests that the interaction between compositional heterogeneities and thermal convection near the core-mantle boundary can generate a range of plume types (Davaille et al., 2005; Farnetani and Samuel, 2005; Lin and van Keken, 2005a,b). The type of upwelling depends on the buoyancy ratio (B), the ratio of the stabilising chemical density anomaly to the destabilising thermal density anomaly (Davaille et al., 2005).

At higher values of B, chemical density anomalies are significant and plumes rising from the core-mantle boundary region can entrain some of the denser material lying at the base of the mantle (Jellinek and Manga, 2004). The entrainment of denser material anchors the plume, and experiments show that this anchor (and so the plume itself) can persist as long as there is a continuing supply of denser material in the plume source at the core-mantle boundary (Davaille et al., 2002). Thermochemical plumes of this nature clearly provide a potential mechanism to explain long-lived hotspots.

In contrast, at low values of B chemical density anomalies are small, and "domes" or "mega-plumes" can develop. Modelling suggests such domes are trailed by only a thin conduit or tail, which disappears relatively quickly as the dome rises through the asthenosphere, thus cutting off the dome from its source region (Davaille et al., 2005). The rising dome eventually spreads out at shallower mantle depths and may melt to produce a plateau or continental flood basalt province, but because of the weak plume tail no succeeding hotspot track is formed (Davaille et al., 2005). Although much research into the effects of thermochemical plumes still needs to be carried out, initial work has yielded fascinating results that may explain why the Ontong Java Plateau and some other large plateaus and continental flood basalts have no apparent plume-tail trace. Intriguingly, thermochemical mantle plumes can consist of large amounts of compositionally dense material, which would reduce the net buoyancy flux of such plumes, with a consequent reduction in the topographic uplift (Lin and van Keken, 2005b). We speculate that compositionally dense material in a thermochemical plume may provide a possible explanation for the anomalous uplift and subsidence of the Ontong Java Plateau.

3.4. Higher than 'normal' volatile contents in the Caribbean Plateau

The Caribbean Plateau, with its abundant accreted crustal sequences, is the best-sampled Cretaceous oceanic plateau (see Kerr et al., 2003). As we have seen, plateau crust in the Caribbean region presents a much greater degree of trace element and radiogenic isotope heterogeneity than the Ontong Java Plateau. Whether this difference is real or a function of the extent of uplift and the depth of exposure within the respective accreted sections is debatable. What is clear is that plateau-derived crust in the Caribbean region is derived from a markedly heterogeneous source. This heterogeneity also includes volatiles, the abundances of which vary considerably (Kamenetsky et al., 2003; Kerr et al., 2004). In marked contrast, the Ontong Java basalts appear to have been derived from a volatile-poor source (Roberge et al., 2004, 2005). The evidence for a more volatile-rich mantle source for plateau rocks in the Caribbean region is derived chiefly from two localities.

1) The Bolívar region in the Western Cordillera of Colombia hosts Mg-amphibole-bearing gabbros and pegmatites that intrude accreted basalts of the plateau (Kerr et al., 2004). The pegmatites and gabbros are essentially indistinguishable in age and radiogenic isotope composition from the basalts they intrude. These 'wet' intrusive rocks are an integral part of the plateau and were derived from a mantle source that contained >400 ppm of water.
2) Small melt inclusions (30–100 µm in width) trapped in cumulate olivines from a Gorgona komatiite flow contain elevated levels of volatiles (H_2O 0.4–0.8 wt.%, Cl 0.02–0.03 wt.%, B 0.8–1.4 ppm; Kamenetsky et al., 2003). Amygdales have also been observed in Gorgona komatiites (Kerr et al., 1996a).

Although such evidence for a relatively volatile-rich source might be used as an argument against a hot, deeply derived plume and in favour of a cooler and shallower non-plume source, it is not persuasive by itself because (a) evidence for wetter melting is seen only in a few localities, and (b) high-temperature, essentially anhydrous picrites and high-MgO rocks are present in other places in the plateau. Such rocks cannot be explained by 'wet' melting and require a high source temperature (Kerr et al., 1996b, 2002; Arndt et al., 1997; Révillon et al., 1999; Hauff et al., 2000).

We conclude that the mantle that produced plateau crust in the Caribbean region contained some relatively water-rich patches. This is not surprising if the source was a mantle plume, considering that one important source of plume material is generally regarded to be the remnants of subducted slabs. Upon descent into the lower mantle, slab remnants, although perhaps nearly wrung dry overall, may contain patches with up to 8% water and other volatiles (Dixon et al., 2002).

3.5. Conclusion

In this review we have tried to present a balanced picture of the current state of understanding of the origin and subsequent development of oceanic plateaus. Although both of us have advocated a mantle plume origin for plateaus in some of our previous papers, we emphasise that, particularly for the Ontong Java Plateau, thermal plume models fail to explain some key first-order observations. Nevertheless, in the absence of a viable general alternative mechanism, mantle plume models, although not without problems, still appear to provide a starting point for investigating the formation of oceanic plateaus. We note that most of the criticisms that have been levelled at mantle plume theory relate to purely thermal plumes. However, as we have outlined, research on thermochemical plumes, although still in its infancy, suggests such plumes may have the potential to explain at least some of the features of oceanic plateaus that cannot easily be accounted for by other models. If so, thermochemical plumes may offer one key to resolving the problematic origins of oceanic plateaus and may lead to the formulation of new paradigms.

4. Suggestions for future work

As this review has shown, knowledge of oceanic plateaus has increased dramatically in the last two decades, but many aspects of plateaus are still poorly understood. Future investigations into the formation, structure, consequences and fate of oceanic plateaus should seed seek to address the following research areas:

a) The Pacific plateaus should be sampled more extensively by an enhanced programme of drilling. This will not only help determine more precisely the age, mantle source composition(s), and paleoenvironmental consequences of these plateaus, but will also facilitate testing of the hypothesis that the Ontong Java, Manihiki, and Hikurangi plateaus were originally part of the same "super" plateau.

b) Geological and geochemical criteria for the identification of possible accreted oceanic plateaus or plateau fragments in the geological record will need to be continually refined to take account of new findings from studies of Cretaceous plateaus. An ultimate goal should be to arrive at a set of near-unequivocal criteria for the identification of ancient oceanic plateaus (although whether this is possible remains to be determined). An integral part of such work will be to evaluate the fate of plateaus at subduction zones, their subsequent reprocessing in the crust and mantle, and their importance to crustal growth through geological time.

c) The identification of oceanic plateau fragments older than ~150 Ma will enable a fuller assessment of potential links between plateaus and major environmental crises. Questions to be addressed include the following. Why does the formation of some oceanic plateaus not result in an environmental crisis, e.g. Shatsky Rise? Can geochemical signatures of plateaus be detected in sediments far from the site of eruption? Why does the formation of only some plateaus appear to correlate with the massive release of methane hydrates?

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.chemgeo.2007.01.019.

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