Tectonic setting of Eocene boninite magmatism in the Izu-Bonin-Mariana forearc

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Abstract

Middle Eocene boninites were simultaneously generated over a large region during the early history of the Izu-Bonin-Mariana (IBM) arc. However, widespread boninite magmatism is not recognised in younger subduction zones of similar dimensions. This suggests that an additional tectonic or thermal factor influenced the generation of the IBM boninite suite. Regional uplift, ocean island basalt-style magmatism and high heat-flow also characterised the northern Philippine Sea plate at the start of the Middle Eocene. These features are similar to those observed in large volume basaltic volcanic provinces such as the early Tertiary North Atlantic and suggest that the IBM boninite suite may have been produced because a thermal anomaly already existed in the mantle beneath the Philippine Sea Plate. The reconstructed Middle Eocene location of the IBM arc and West Philippine Basin lies close to the present-day Manus Basin where petrological and geochemical evidence indicate the presence of a mantle hotspot. A calculated hotspot-track linking these locations through time also passes close to the Eauripik Rise, an aseismic ridge on the Caroline Plate, during the Oligocene and Miocene. Therefore, we propose that a thermal anomaly or mantle plume influenced the magmatic and tectonic development of the western Pacific from the Middle Eocene until the present day.

Keywords: Boninite, Izu – Bonin - Mariana, Philippine Sea Plate, subduction, plume, Manus Basin.

Introduction

Boninites are a magnesium- and silica-rich form of volcanic rock believed to form through melting of residual mantle in supra-subduction zone settings [Crawford et al., 1989]. There is a consensus amongst petrologists that several conditions must be met to generate boninitic magma. First, the magnesium- and silica-rich nature of the melts and very low absolute concentrations of some trace elements (e.g. Nb, Ta, Ti) and heavy rare earth elements requires low pressure melting of residual (harzburgitic) peridotite, such as may be found in oceanic mantle lithosphere overriding a subducted slab. Second, because this residual source had previously lost a basaltic melt fraction an abnormally high heat flux is required to promote melting [Falloon and Danyushevsky, 2000]. Third, boninite series lavas display enrichment of the large ion lithophile elements (LILEs) and light rare earth elements (LREEs) relative to high field strength elements (HFSEs). High LILE/HFSE ratios are widely regarded as indicating a (hydrous) fluid flux from subducted oceanic lithosphere into the depleted peridotite [Crawford et al., 1989; Hickey-Vargas, 1989; Stern et al., 1991; Pearce et al., 1992]. The presence of such a fluid in the source will also contribute to lowering the solidus temperature of the residual peridotite. Finally, a mechanism is required to explain the elevation of Zr/Sm, Hf/Sm and Zr/Ti ratios in boninites compared to other types of lavas. The most common explanations of this feature have involved sources related to ocean island basalt (OIB) magmatism [Hickey-Vargas, 1989; Stern et al., 1991; Hickey-Vargas and Reagan, 1987], or partial melting of the subducted oceanic crust in the amphibolite field [Pearce et al., 1992; Taylor et al., 1994]. New Hf isotope evidence appears to rule out the slab-melting hypothesis in boninites from the western Pacific and favours melting of mafic components stored in the shallow mantle or lower crust of the overriding plate [Pearce et al., 1999].

Boninitic rocks are found in two main settings. Several convergent margins contain boninitic lavas and these have been used to provide the primary evidence for the tectonic setting in which this style of magmatism occurs. The best studied locations of Cenozoic boninite lavas are the Izu-Bonin-Mariana forearc, Cape Vogel in Papua New Guinea, the Northern Tonga arc and the Setouchi Volcanic belt of Japan [Crawford et al., 1989 and references therein; Falloon and Danyushevsky, 2000]. A number of Phanerozoic ophiolite sequences also contain boninitic rocks, most notably the Cretaceous Troodos ophiolite in Cyprus [Cameron, 1985] and the Cenozoic Zambales ophiolite of the Philippines [Encarnación et al., 1999]. Boninites are absent in many arcs and where they do occur a notable feature is their limited volume compared to contemporaneous magmatism, principally in the form of island arc tholeiites [Crawford et al., 1989]. Boninites are volumetrically subordinate to tholeiitic lavas in Papua New Guinea [Jenner, 1981] and in both the Troodos and Zambales ophiolites [Cameron, 1985, Encarnación et al., 1999]. Where volume estimates have not been made boninites still apparently form rare or spatially restricted amounts of the total igneous assemblage *e.g.* Setouchi belt [Tatsumi and Maruyama, 1989], New Caledonia [Cameron, 1989] and the northern Tonga Trench [Falloon and Danyushevsky, 2000]. In stark contrast to this are the Middle Eocene boninitic lavas that comprise a significant fraction of basement throughout the Izu-Bonin and Mariana forearcs [Crawford et al., 1989; Pearce et al., 1992; Taylor et al., 1994; Bloomer et al., 1995]. This magmatic suite, which will be collectively referred to as the IBM boninite suite, requires that conditions conducive to boninite genesis occurred over a large area (2000km long by 300km wide) in a relatively short interval [Taylor, 1992] in the Eocene. Indeed, recent ^{40}Ar-^{39}Ar dating suggests that the boninite magmatism was initiated almost simultaneously throughout this area in the early part of the Middle Eocene and was, for the most part, a very short-lived event [Cosca et al., 1998].

Recent hypotheses for generation of the IBM boninite suite have favoured models in which a high geothermal gradient was achieved through the combination of two effects. These are that (1) very young, and hence hot, oceanic lithosphere, or even a spreading centre, was subducted beneath (2) young, hot lithosphere of the Philippine Sea Plate [Crawford et al., 1989; Pearce et al., 1992, Taylor et al., 1994]. The combination would generate an abnormally high heat flux in the subduction zone thus permitting melting of both the residual harzburgitic lithosphere in the overriding plate and the subducted slab. However, there are geodynamic problems with such a tectonic arrangement. First, the Izu-Bonin-Mariana forearc basement is composed largely of the IBM boninite suite and associated tholeiites with only localised evidence for pre-Eocene magmatic activity (e.g. DSDP Site 458 [Hickey-Vargas, 1989]). This implies that subduction was initiated close to, and almost parallel to, a spreading centre over a distance of approximately 2000km and that very young, buoyant crust was the first crust to enter the trench over its entire length. Comparison with other sites of known ridge-subduction zone collision suggests this is extremely unlikely. Attempted ridge subduction west of the Antarctic Peninsula led to a cessation of subduction [Hole et al., 1995] and widespread boninitic magmatism is not recognised either here or in locations such as northern Cascadia where subduction of very young oceanic lithosphere has been successful [Green and Harry, 1999]. Second, new Hf isotope evidence indicates that slab melting played a negligible role in the genesis of the IBM boninites [Pearce et al., 1999]. This finding removes one of the principal geochemical requirements for subduction of a young slab. Third, although a young, hot overriding plate can be reconciled with models for the early Cenozoic tectonics of the region this cannot explain the evolution of geochemistry in lavas from the backarc region of the overriding plate. Pre-Eocene magmatism produced trace element-depleted I-MORB but this was succeeded by trace element-enriched and isotopically distinct magmatism during the Middle Eocene, followed by a reversion to I-MORB geochemistry (see below).

While their association with the onset of widespread subduction in the Izu-Bonin-Mariana arc is well established [Bloomer et al., 1995], boninites have not been identified in more recently initiated subduction zones of similar dimensions such as the Bicol arc in the eastern Philippines [Divis, 1980] or the Sunda and Banda arcs in eastern Indonesia [Wheller et al., 1987]. There are probably several tectonic scenarios that can achieve the combination of heating and hydrous fluxing of harzburgite that are required for boninite magmatism as is reflected in the presence of boninitic rocks in a number of subduction zones and supra-subduction zone ophiolites. However, the exceptional volume of boninitic lavas erupted in the Middle Eocene IBM, compared to other Cenozoic arcs and Phanerozoic supra-subduction zone ophiolites, suggests that unusual thermal, chemical and/or tectonic conditions may have prevailed at that time. In order to identify the conditions that generated the IBM suite it is necessary to understand the Middle Eocene tectonics of the western Pacific.

Middle Eocene tectonics of the equatorial western Pacific

Boninites of the IBM suite were erupted at the present eastern margin of the Philippine Sea Plate during the Middle Eocene [Bloomer et al., 1995; Taylor, 1992; Cosca et al., 1998; DeBari et al., 1999]. The geographic locations of relevant tectonic elements are highlighted in Figure 1, and Figure 2 shows a reconstruction of the area at 50 Ma after Hall [Hall, 1996].

Pre-Middle Eocene Philippine Sea Plate

Fragments of oceanic crust dredged from the inner trench wall of the Izu-Bonin Trench bear a distinctive Indian Ocean (I-)MORB isotopic signature [DeBari et al., 1999]. The age of these crustal fragments is unknown but is probably similar to or greater than Late Cretaceous ages determined radiometrically for rocks dredged from the Amami-Oki Daito Province, which forms the northern part of the Philippine Sea Plate ([Shiki et al., 1985]; Fig. 1). This suggests that prior to the Middle Eocene the Philippine Sea Plate was comprised of the Amami-Oki Daito Province, which is probably of arc origin [Taylor, 1992; Shiki et al., 1985; Mills, 1980], and some oceanic crust generated in the I-MORB domain.

Middle Eocene spreading in the West Philippine Basin

The West Philippine Basin forms the largest tract of the Philippine Sea Plate and is bounded by the Philippine Trench to the west, the Ryukyu Trough to the northwest, and the Palau-Kyushu Ridge to the east (Fig. 1). It comprises three main sections; a northwestern sub-basin, the main or northern sub-basin and a southern sub-basin [Mrozowski et al., 1982]. The northern sub-basin can be further divided into the Amami-Oki Daito province in the north and the deeper central portion containing the NW-SE striking Central Basin Fault. The Central Basin Fault represents an extinct ocean ridge system that facilitated separation of the Amami-Oki Daito province and the undated southern sub-basin by seafloor spreading [Mrozowski et al., 1982; Lewis et al., 1982; Hilde and Lee, 1984].

Mrozowski [Mrozowski et al., 1982] identified paired magnetic anomalies 20-17 trending NW-SE in the central part of the basin giving a minimum age of 46 Ma for the initiation of spreading at the Central Basin Fault. Hilde and Lee [Hilde and Lee, 1984] interpreted magnetic anomalies extending through the Amami-Oki Daito province as indicating spreading from about 60 Ma. However, Okino [Okino et al., 1999] have suggested that the seafloor immediately south of the Amami-Oki Daito Province may preserve a different, N-S spreading fabric. Radiometric ages of 49 Ma and 19 Ma have been obtained by ^{40}Ar-^{39}Ar dating of magmatic rocks from DSDP Site 294, which sampled basement immediately south of the Oki Daito Ridge (Fig. 1; [Ozima et al., 1977; Hickey-Vargas, 1998]). Excess argon may have confounded the latter determinations [Hickey-Vargas, 1998] since the older age is similar to that of nearby magnetic anomalies and the age inferred for the sedimentary cover drilled at Site 294. Furthermore, the older age is in closer accord with Middle Eocene ages (c. 45 Ma) determined for basement at DSDP Site 291 on the opposite margin of the basin ([Hickey-Vargas, 1998]; Fig. 1). The radiometric ages and their overlying sediments indicate that the onset of spreading in the central West Philippine Basin began in the latest part of the Early Eocene or the earliest Middle Eocene.

The oceanic crust of the southern sub-basin is distinct from the central part of the West Philippine Basin. Acoustic basement in the southern sub-basin is smoother and is at shallower depth below sea-level than the crust closer to the Central Basin Fault, suggesting greater crustal thickness [Mrozowski et al., 1982; Okino et al., 1999]. Thicker, smoother crust devoid of fracture zones is a characteristic found in many parts of the North Atlantic close to Iceland, which White [White, 1997] attributed to higher melt fluxes and slower cooling rates as a result of higher mantle potential temperature. The differences in crustal structure suggest the initial, Middle Eocene, phase of opening in the West Philippine Basin involved more voluminous melt generation than during subsequent spreading, possibly as a result of hotter mantle and higher heat-flow. The initial oceanic crust may also have formed with a higher spreading rate [Mrozowski et al., 1982; Okino et al., 1999].

Non-boninitic Middle Eocene magmatism

The IBM boninite suite was not the only magmatic event to affect the Philippine Sea Plate during the Middle Eocene. Magmatism also occurred in the newly forming West Philippine Basin and in the Amami-Oki Daito province on the northern margin of the rift (Fig. 1 and 2). Rifting was responsible for the opening of the West Philippine Basin but the range of trace element and isotopic compositions characterising magmatism in these two areas can not be reconciled solely with decompression melting of depleted upper mantle.

Pre-Middle Eocene lavas from the West Philippine Basin that are depleted in the most incompatible elements have Sr, Nd and Pb isotopic ratios that resemble I-MORB [DeBari et al., 1999] while Middle Eocene lavas tend to be incompatible element-enriched and show isotopic evidence for the presence of an additional component similar to EM-2 [Hickey-Vargas, 1998]. This latter signal is strong in the igneous basement of DSDP Sites 291, 292 and 294 on the southern- and northern-most edges of the West Philippine Basin (Fig. 1). These sites represent the first crust that formed during Middle Eocene spreading. Incompatible element-enriched sills with EM-2 isotopic ratios were also emplaced into early Middle Eocene sediments in the Daito Basin (at DSDP Site 446; [Hickey-Vargas, 1998]) and have yielded early-Middle Eocene radiometric ages [Hickey-Vargas, 1998; McKee and Klock, 1980] suggesting this source was available throughout the newly forming rift. Further north, Middle Eocene conglomerates from DSDP Site 445 (Fig. 1) commonly contain fragments of alkali basalt with titanaugite phenocrysts [Mills, 1980; Tokuyama et al., 1980] and potassic trachyandesite dated as 48.5 ± 2 Ma has been dredged from the Amami Plateau [Matsuda et al., 1975]. Hickey-Vargas [Hickey-Vargas, 1998] refers to lavas displaying trace element enrichment and EM-2 isotopic affinity collectively as Philippine Sea Plate OIB (PSP-OIB). Drilling and dredging throughout the northern part of the West Philippine Basin suggest that alkaline magmatic activity was relatively widespread during the Middle Eocene. Furthermore, all analyses conducted thus far for alkaline and tholeiitic lavas with reliable radiometric or stratigraphic age controls indicate that this part of the basin was characterised by magmatism with EM-2 ocean island basalt geochemistry [Hickey-Vargas, 1998].

In contrast to PSP-OIB, Philippine Sea Plate crust created prior to the opening of the West Philippine Basin resembles I-MORB [DeBari et al., 1999]. Similarly, the youngest drilled and dredged sections of the West Philippine Basin at DSPD Site 447 and the Central Basin Fault possess I-MORB trace element and isotopic signatures [Pearce et al., 1999, Hickey-Vargas, 1991]. Furthermore, the spreading rate in the main part of the basin may have decreased in the latter part of the Middle Eocene [Mrozowski et al., 1982; Hilde and Lee, 1984; Okino et al., 1999]. Therefore, an isotopically distinct source that yielded lavas with large enrichments of incompatible trace elements and an EM-2 isotopic signature appears to have been introduced into the mantle beneath the West Philippine Basin at, or immediately before, the time that seafloor spreading began. Towards the end of the Middle Eocene magmatism forming the central portion of the West Philippine Basin closely resembled I-MORB again [Pearce et al., 1999; Hickey-Vargas, 1991]. Suitable samples are not available to test for the presence of similar magmatism in the southern sub-basin of the West Philippine Basin but its morphological similarities suggests that it may be a complementary margin to the Amami-Oki-Daito province (see above).

Middle Eocene uplift in the West Philippine Basin

Several authors have suggested that the Early Eocene or earliest Middle Eocene saw a period of uplift affecting the Amami-Oki Daito Province. A lack of *in situ* shallow water fossils in Upper Cretaceous to Lower Eocene sediments of the Amami-Oki Daito province correlates with a transgression of Pacific reefs [Mills, 1980]. However, *Nummulites boninensis* is a common constituent of the Middle Eocene sections of DSDP/ODP holes and dredge hauls throughout the Amami-Oki Daito province suggesting proximity to a shallow sea environment at this time [Shiki et al., 1985; Mills, 1980; Tokuyama et al., 1980; Tokuyama et al., 1985]. An increased abundance of chlorite, serpentine and quartz in Middle Eocene sediments, relative to smectite-dominated Lower Eocene beds, led Chamley [Chamley, 1980] to propose either a decrease in volcanic activity or regional uplift of this area at the beginning of the Middle Eocene. The presence of Middle Eocene conglomerates and coarse grains and clasts in other contemporaneous deposits of DSDP Site 445, along with the exposure of Cretaceous rocks throughout the Amami-Oki Daito province, are more consistent with significant uplift [Chamley, 1980; Misawa et al., 1985]. Furthermore, schist clasts in the Daito Ridge conglomerates preserve evidence of two metamorphic events. Radiometric dating identified an intermediate- to high-pressure regional event during the Late Cretaceous while low-pressure contact metamorphism occurred at 49 ± 4 Ma [Tokuyama et al., 1980]. The inclusion of clasts of the younger event in Middle Eocene conglomerates indicates significant erosion, probably as a result of rapid uplift, at this time. Finally, Misawa et al. [Misawa et al., 1985] suggested that an unconformity observed between the (Cretaceous) basement and the overlying *Nummulites*-bearing strata on seismic lines throughout the Amami-Oki Daito province resulted from uplift of the region at some time during the Early Eocene or the earliest part of the Middle Eocene.

Subaerial exposure that affected parts of the Amami-Oki Daito province was relatively short-lived and was succeeded by the regional development of shallow marine, *Nummulites*-bearing beds [Mills, 1980, Tokuyama et al., 1980, Misawa et al., 1985]. Conglomerates are coarsest at the base of the Middle Eocene section but are replaced up-section by sandstones and mudstones [Tokuyama et al., 1980] and the provenance of Upper Eocene sediments in this area is wholly marine [Chamley, 1980]. These observations suggest relatively rapid elevation occurred in the Amami-Oki Daito province, bringing localised areas above sea level, between the end of the Cretaceous and the Middle Eocene which was quickly succeeded by subsidence to shallow marine depths [Mills, 1980; Tokuyama et al., 1980; Chamley, 1980; Misawa et al., 1985].

Discussion

The evidence outlined in the previous section suggests that several notable tectonic events accompanied the generation of the IBM boninite suite. The reconstruction in Figure 2 places these events in a palaeogeographic context. During the Middle Eocene a curvi-linear array over 2000km long on the northern margin of the Amami-Oki Daito province was subject to IBM boninite magmatism, which locally succeeded and was regionally interspersed with arc tholeiites. To the south, seafloor spreading was initiating between the Amami-Oki Daito province and the southern sub-basin of the West Philippine Basin. The initial crust formed by spreading, and contemporaneous magmatism in the Amami-Oki Daito province, had trace element and isotopic characteristics of ocean island basalt [Hickey-Vargas, 1998] and was slightly thicker than I-MORB crust formed subsequently at the same spreading centre [Mrozowski et al., 1982; Okino et al., 1999; Hickey-Vargas, 1991]. In addition, the Amami-Oki Daito province was temporarily uplifted and experienced high temperature, low-pressure metamorphism. Any geodynamic model for genesis of the voluminous Middle Eocene boninite magmatism in the Izu-Bonin-Mariana forearc must explain these events. In addition a source of excess heat, relative to most convergent margins, must have been available in the mantle to produce the distinctive features of the boninites themselves.

A thermal anomaly in the western Pacific mantle

There are a number of similarities between the Middle Eocene western Pacific and the large volume basaltic provinces generated during continental rifting (e.g. [White, 1997; Ebinger and Sleep, 1998]).

1. There was a short-lived, voluminous mafic igneous event inferred to result from unusually high mantle temperatures. In volcanic rifted margins a combination of hot mantle and decompression causes genesis of large volumes of basaltic magma [White, 1997; Ebinger and Sleep, 1998]. At convergent margins, the combination of a hot mantle source and dehydration of downgoing oceanic lithosphere would also generate large volumes of basic magma but with distinctive, subduction zone, characteristics. These are the characteristics displayed by the IBM boninite suite. Relative to average arc growth rates the *excess* volume of crust generated in the IBM during the Eocene is comparable to excess crustal generation in hotspot settings. Bloomer et al. ([Bloomer et al., 1995] calculated that crustal production along 2000km of the IBM forearc during a 10Ma period in the Eocene exceeded mean rates of arc growth by 50 to 150 km^3/km-Ma. Such rates are comparable with estimates for the amount of excess crust

generated in the North Atlantic for 1000km to the north and south of Iceland (125 km^3/km-Ma [Ito et al., 1996]) relative to normal oceanic crust. The inferred *excess* forearc crust produced along the length of the IBM (1 to 3 x 10^5 km^3/Ma) is also comparable with estimated excess crustal production rates for the North Atlantic (2.5 x 10^5 km^3/Ma [Ito et al., 1996]), Hawaii (1.6 x 10^5 km^3/Ma [Watson and McKenzie, 1991]) and for the Columbia River basalts (1 to 9 x 10^5 km^3/Ma [Coffin and Eldholm, 1994]) but is a factor of 2-10 lower than estimates for some large igneous provinces in oceanic settings, such as Ontong Java and Kerguelen [Coffin and Eldholm, 1994]. However, subsequent ^{40}Ar-^{39}Ar age data indicate that much of the IBM forearc magmatism occurred in a very short period [Cosca et al., 1998], therefore, the existing calculations [Bloomer et al., 1995] may underestimate the actual excess growth rate by as much as a factor of two.

2. The Amami-Oki Daito province experienced a transitory phase of uplift of similar magnitude to that affecting large igneous provinces (≤ 1km [Coffin and Eldholm, 1994]). Due to the complexity of the inferred tectonic setting of the Amami-Oki Daito province it is impossible to unequivocally identify the mechanism(s) responsible for this uplift. Uplift can occur on the margins of rifts, and rifted arcs in particular can experience complex histories of uplift and subsidence in the absence of thermal anomalies in the mantle [Bloomer et al., 1995; Clift et al., 1995]. However, subsidence of the Amami-Oki Daito province from the Middle Eocene to Quaternary is in excess of that expected through isostatic subsidence alone [Mizuno et al., 1979] suggesting some component of dynamic uplift was associated with the original uplift.

3. Magmatism in and around the nascent West Philippine Basin possesses trace element and isotopic characteristics atypical of subduction zone environments and

more akin to magmatism associated with aseismic ridges and volcanic ocean island chains that are interpreted to represent focussed upwelling, or plumes, of anomalously hot mantle [Coffin and Eldholm, 1994]. In some cases aseismic ridges are linked to flood basalt provinces associated with continental break-up suggesting the initial stages of hotspot activity may affect very substantial area of lithosphere [Ebinger and Sleep, 1998]. There is some evidence (outlined above) that the initial oceanic crust at the northern and southern margins of the West Philippine Basin is thicker and morphologically distinct from the crust generated later. Although the thickness does not match that generated at present day hotspots the decrease in thickness and change in morphology are consistent with a drop in mantle potential temperature following the initial opening of the basin [c.f. White, 1997]. Since the exact location of the basin relative to any thermal anomaly cannot be pinpointed it is the changes in the crust that are the tectonically revealing properties, rather than the actual crustal thickness.

A mantle plume is a potential mechanism for generating all the unusual geological and geochemical features associated with the Philippine Sea Plate in the Middle Eocene; namely excess heat, high crustal production rates, uplift and an OIB-like reservoir. Mantle hotspots resulting from the presence of a plume are believed to be robust features on timescales of tens of millions of years. Therefore, it might be expected that a hotspot affecting the Philippine Sea Plate during the Middle Eocene would have left evidence in the subsequent geological record, although the rapid rotation of plates in the western Pacific during the Eocene and Oligocene [Hall et al., 1995; Hall, 1996] mean that such evidence would appear as temporary features. Hickey-Vargas [Hickey-Vargas, 1998] suggested that a mantle hotspot currently beneath the Caroline islands may have been responsible for an OIB signature in West Philippine Basin lavas but the present position of Kusaie, the youngest Caroline island, was significantly to the northeast of the Philippine Sea Plate during the Middle Eocene. The only other proposed location for a hotspot in the equatorial western Pacific is in the Manus Basin. Based on the petrology, geochemistry and $^3He/^4He$ of active magmatism in the eastern Bismarck Sea a mantle hotspot is postulated to exist in the vicinity of the Manus Spreading Centre and the St. Andrew Strait Islands [Macpherson et al., 1998 and references therein]. The position of the Manus Basin, adjusted such that it remains fixed with respect to the Hawaiian hotspot, is plotted on Fig 2 and lies within the area that experienced the tectonic phenomena outlined above. A small circle plotted around this projected location is of similar size to the hypothesised plume head associated with initiation of hotspot magmatism in Afar [Ebinger and Sleep, 1998]. There is a striking similarity between the scale of plume influence at Afar and the region of the western Pacific affected by uplift and magmatism in the Middle Eocene. Upwelling and magmatism in Greenland and northwest Europe during the early Tertiary also occurred in a zone of similar dimensions [White, 1997].

Figure 3 explores this coincidence further by comparing Nd and Pb isotopic compositions of western Pacific Middle Eocene lavas with those of lavas recently erupted in the Manus Basin. Although the data are limited, the Manus Basin lavas are transitional between those erupted in the Oligocene to Miocene backarc basins of the eastern Philippine Sea Plate and the Middle Eocene PSP-OIB lavas of the West Philippine Basin (Fig. 3). The Manus Basin specimen possessing the highest $^3He/^4He$ ratio lies very close to the field of trace element enriched Middle Eocene PSP-OIB. Also plotted in Figure 3 are isotopic data for Eocene IBM boninites (grey symbols). The majority of these describe a near vertical array between the field of Pacific MORB, with relatively high ε_{Nd}, and a low ε_{Nd} component. The low ε_{Nd} contaminant could be sediment like that thought to contaminate the source of the active Mariana arc ([Elliott et al., 1997], Fig. 3). The low ε_{Nd} of Chichijima lavas is consistent with an input from a very low ε_{Nd} component that could be subducted sediment (see also [Pearce et al., 1999]). However, for a given $^{206}Pb/^{204}Pb$ the remaining IBM boninites have lower $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ than active Mariana arc lavas with similar ε_{Nd}. This suggests either a different sediment contaminant or a different component altogether. An alternative low ε_{Nd} contaminant for the IBM boninite lavas (excluding Chichijima) is mantle similar to the source of PSP-OIB. A role for OIB-type mantle has previously been proposed to explain both the low ε_{Nd} and the high Zr/Sm and Hf/Sm ratios of IBM boninites [Hickey-Vargas, 1989; Hickey-Vargas and Reagan, 1987] but recent Hf isotope data suggest the excess Hf (and Zr) in IBM boninites may be acquired from basaltic lithologies at very shallow depths in the mantle lithosphere or lower crust [Pearce et al., 1999]. Therefore, use of Hf and Zr may lead to erroneous conclusions regarding the presence [Hickey-Vargas, 1989; Hickey-Vargas, 1987] or absence [Pearce et al., 1992; Taylor et al., 1994] of OIB-type mantle during genesis of IBM boninite. Previous models of OIB involvement proposed disparate veins or zones contained in the mantle lithosphere that were composed of frozen metasomatic melts derived from OIB “plums” in the asthenosphere [Hickey-Vargas, 1989; Hickey-Vargas, 1987]. If an OIB source was responsible for low ε_{Nd} in IBM boninites the geologic evidence summarised in this work suggests that it originated in a discrete thermal anomaly in the convecting mantle that was present throughout much of the nascent IBM arc/West Philippine Basin system during the early Middle Eocene. This is a specific, regionally recognised composition rather than a generic OIB reservoir.

To assess the subsequent role of a thermal anomaly at the present location of the Manus Basin we have traced the movement of plates using a recent plate reconstruction that models the tectonic development of SE Asia and the western Pacific in one million year intervals [Hall, 1996]. The calculated "hotspot track" is illustrated in Figure 4. At the earliest point in the reconstruction the track runs through the Amami-Oki Daito province towards the Izu-Bonin-Mariana forearc at c. 50 Ma. At this stage the track can be modelled as part of either the northern (Amami-Oki Daito province) or southern (southern sub-basin) plate fragments that were spreading in the West Philippine Basin (Fig. 2). The change in crustal thickness in the northern and southern sections of the West Philippine Basin, compared with the central portion (see above), suggests that both plates may have been influenced by the anomaly at around 50 Ma, therefore, the track can been modelled as belonging to both fragments. The separation of the two tracks during this period (50Ma to 45Ma) is due to subsequent (N-S, present orientation) extension of the West Philippine Basin (and Palau-Kyushu Ridge) about the Central Basin Fault (Fig. 4). Both tracks for this period trend towards the east under the Palau-Kyushu Ridge suggesting the Izu-Bonin-Mariana forearc rotated over the thermal anomaly during the late Eocene. Data pertaining to the cessation of boninitic magmatism in the Izu-Bonin-Mariana forearc is equivocal. However, it is possible that boninites were generated in Guam and Palau, close to the parts of the track crossing the arc, for some time after the main phase of forearc magmatism had ended [Cosca et al., 1998]. Later opening of the Parece Vela Basin and the Mariana Trough has further disrupted the northern track (Fig. 4). After traversing the arc the anomaly would have lain beneath part of the Pacific Plate that was subsequently subducted under the east Philippine Sea plate margin and therefore the track disappears from c. 46 to 33 Ma.

The hotspot track reappears at the southern margin of the Caroline Plate in the early Oligocene (c. 33 Ma) and crosses the central part of the plate describing a northward path to 25 Ma, after which it reverses to trend south until 10 Ma (Fig. 4). This path lies close to the Eauripik Rise, a bathymetric high trending N-S across the Caroline Plate (Figs. 1). Unfortunately the nature of the Eauripik Rise is virtually unknown from direct sampling. However, bathymetric and seismic profiles suggest it formed through excess volcanism [Altis, 1999 and references therein]. The coincidence of the calculated hotspot track with this feature suggests that the Eauripik Rise may record the Late Oligocene to Miocene location of the hotspot postulated to presently exist in the Manus Basin. Calculation of the track during the Late Miocene to Quaternary is complicated by the large number of plate fragments required in the reconstruction of north New Guinea and the Bismarck Sea. The calculated position at 10 Ma lies slightly southwest of Manus Island, but this may be due to subsequent subduction of the southernmost Caroline Plate at the Manus Trench. This would result in the 10 Ma hotspot position appearing on the plate that has overridden the actual hotspot-stained lithosphere. Jaques [Jaques, 1981] used trace element characteristics to propose that Quaternary lavas from western Manus Island, the M'Buke and Johnstone Islands and St. Andrew Strait represent a hotspot trace trending southeast towards the Manus Basin. This trace could represent the youngest manifestation of a thermal anomaly currently located beneath the eastern Bismarck Sea.

In summary, the geological evidence suggests that the mantle currently lying beneath the Manus Basin has generated excess magmatism for substantial portions of the Cenozoic. At the start of the Middle Eocene crust formed in the nascent West Philippine Basin had an EM-2 isotopic signature [Hickey-Vargas, 1998] and was slightly thicker than the crust subsequently generated in the same basin. In addition, boninitic and basaltic magma were derived from a hot mantle source close to the Izu-Bonin-Mariana forearc [Taylor, 1992] in volumes that exceed normal arc production by amounts similar to those characterising active hotspots. From the Oligocene to the present day the central Caroline Plate, where the Eauripik Rise is now located, migrated south then north across the present position of the Manus Basin hotspot. The Quaternary part of the hotspot track may be preserved in the lavas on and around Manus Island.

Origin of the IBM boninite suite

Taken together these pieces of evidence suggest that a thermal anomaly has existed in the western Pacific mantle since at least the Middle Eocene and has influenced tectonics and magmatism on several plates. Middle Eocene magmatism was dispersed over an area comparable to that postulated for the initial phases of magmatism associated with Iceland and Afar [White 1997; Ebinger and Sleep, 1998]. We speculate, therefore, that the Middle Eocene magmatism of the western Pacific developed its particular character because subduction was initiated in a region in which there was already a “start-up plume head”, or in which hot mantle was very efficiently transported laterally from a more restricted anomaly in a short period. Such a scenario would provide the excess heat required to uplift the Amami-Oki Daito province and to generate IBM boninitic magmatism, and could also provide the distinctive reservoir sampled by lavas in the overriding plate during the Middle Eocene. A combination of the excess heat provided by a large thermal anomaly and fluid released from the slab would promote melting of mantle lithosphere in the overriding plate that is refractory in most subduction zones [Crawford et al., 1989]. Under these circumstances mafic veins or domains in the shallow lithosphere or lower crust would also be expected to melt providing the high Zr/Ti, Zr/Sm and Hf/Sm of the boninites [Pearce et al., 1999]. Where temperatures were not sufficient to cause melting of the overriding lithosphere fluid fluxing of anomalously hot mantle wedge would produce large volumes of relatively depleted island arc tholeiite [Bloomer et al., 1995].

Boninitic magmatism lasted only as long as hot material associated with the thermal anomaly was available to provide heat to the mantle lithosphere of the overriding plate. By the Late Eocene and Oligocene magmatism in the West Philippine Basin had reverted to an I-MORB affinity suggesting that the basin had been removed from the zone of influence of the thermal/chemical anomaly by clockwise rotation [Hall et al., 1995] and/or a diminution of the area influenced by the anomaly. In addition, mantle circulation through the mantle wedge would eventually replace anomalously hot material with upwelling asthenosphere from deeper levels resulting in more normal arc and backarc magmatism in the post-Middle Eocene IBM arc and West Philippine Basin, respectively. As noted above, localised boninite genesis in Guam and Palau may have post-dated the main phase of forearc magmatism [Cosca et al., 1998]. This would be consistent with conversion from a “start-up plume” during the Middle Eocene to a “plume tail” that subsequently generated a restricted Oligocene-Miocene aseismic rise on the Caroline Plate.

Initiation of the Izu-Bonin-Mariana arc

There is evidence for limited subduction zone magmatism in the Izu-Bonin and Mariana arcs prior to the Middle Eocene. Island arc tholeiites lie beneath boninite lavas at DSDP Site 458 [Hickey-Vargas, 1989] and arc magmatism was active at DSDP Site 296 at approximately 48 Ma [Ozima et al., 1977], but at other sites boninites and arc tholeiites are inter-bedded [Bloomer et al., 1995, Taylor, 1992]. The inception of subduction in the Izu-Bonin-Mariana arc may have been a localised phenomenon that was enhanced by the presence of large contrasts in mantle structure associated with a thermal anomaly. Warm, buoyant mantle associated with the anomaly would make the overlying lithosphere resistant to subduction while cooler asthenosphere underlay the lithosphere to the north and east (Fig. 2). Incipient or existing subduction close to the boundary between these domains could exploit this contrast to rapidly propagate along the boundary. Magmatism could commence nearly simultaneously along the margin of the thermal anomaly and would possess a boninitic character due to the unusual thermal structure of the mantle. From this it can be inferred that the *widespread* boninitic magmatism of the IBM forearc is a result of interaction between a subduction zone and a thermal anomaly, rather than a characteristic of infant subduction zones.

Since the excess heat required to promote melting of the oceanic mantle lithosphere is provided by the mantle, this model does not require, but does not preclude, subduction of an unusually hot (young) slab. Subduction of a young slab at the initiation of the north-facing Izu-Bonin-Mariana arc was first proposed to account for convergent motion between the arc and the Pacific Plate in tectonic reconstructions [Seno and Maruyama, 1984]. The Pacific Plate was moving northwards prior to the plate motion change at 43 Ma suggested by the bend in the Hawaiian-Emperor seamount chain. A young slab entering the Izu-Bonin-Mariana subduction zone was postulated as part of a (now fully subducted) North New Guinea Plate, which was spreading southwards from a WNW-ESE striking spreading centre in the western Pacific. As discussed above there are dynamic problems with subduction of young crust over such a large distance and this explanation also fails to satisfactorily answer the question as to how the arc was initiated. The absence of substantial amounts of IBM arc crust older than the Middle Eocene requires that subduction of the North New Guinea Plate must have been initiated parallel to the spreading ridge in relatively young lithosphere along a distance of some 2000km. Removal of the North New Guinea Plate from tectonic reconstructions reintroduces the problem of how to accommodate Middle Eocene convergence between the Philippine Sea and Pacific plates. One possibility is that there was no 43 Ma change in Pacific Plate motion [Norton, 1995]. Alternatively, clockwise rotation of the Philippine Sea Plate [Hall, 1996 and references therein], West Philippine Basin spreading [Hilde and Lee, 1984] and extension in the IBM forearc [Bloomer, 1995] are all mechanisms that could have operated at this time to provide suitable plate vectors. There may also have been other small plates in the western Pacific at this time.

Other examples of plume-subduction zone interaction

Interaction between hot mantle and subduction zones on a scale comparable with that suggested for the Middle Eocene Izu-Bonin-Mariana arc is not recognised in any active convergent margins. With the exception of the Izu-Bonin and Mariana forearcs, boninites are present in relatively small volumes compared to coeval magmatism in Cenozoic arcs and in Phanerozoic ophiolites [Cameron, 1985; Jenner, 1981, Encarnación et al., 1999; Tatsumi and Maruyama, 1989, Cameron, 1989; Crawford et al., 1989]. This probably reflects the difficulty in promoting shallow melting of residual harzburgite under the influence of typical arc geotherms, and the generation of other Cenozoic boninite suites may reflect operation of tectonic phenomena that can only locally elevate the geotherm to a sufficient degree. Proximity to a magmatic rift or spreading centre in the overriding plate, or the subduction of young oceanic lithosphere are among the most popular theories for providing excess heat to convergent margins [Hickey-Vargas, 1989; Pearce et al., 1992; Taylor et al., 1994; Tatsumi and Maruyama, 1989].

One example of present interaction between a plume-tail and a subduction zone may be in the Tonga arc. Elevated $^3He/^4He$ ratios in magmatism from the northern Lau Basin are believed to represent Samoan hotspot material that entered the mantle beneath the Tonga Trench around the start of the Pliocene and subsequently migrated a short distance to the south [Poreda, 1985]. High-Ca boninites have been dredged from the northern termination of the Tonga arc and have been interpreted to result from interaction between hot, depleted mantle from the Samoan hotspot and the northern Tonga subduction zone [Falloon and Danyushevsky, 2000].

Examples of Late Archean plume-subduction zone interaction have been postulated in the greenstone belts of North America. Boninitic-type lavas are interbedded with calc-alkaline and komatiitic lavas in the Abitibi Belt in Canada [Wyman, 1999]. Temporal associations of the different types of lavas vary between different locations leading Wyman [Wyman, 1999] to suggest that a single plume may have interacted with different arcs over a period of approximately 50 Ma. Interaction between a thermal anomaly and subduction zones as outlined above for the Philippine Sea Plate and Caroline Plate suggests the western Pacific may provide a suitable modern analogue for the Archean Abitibi Belt.

Summary

Boninites occur in restricted volumes in several Cenozoic locations [Crawford et al., 1989] but the large areal extent of the IBM boninite suite is problematic and requires an unusual geodynamic setting in the western Pacific during the Middle Eocene. This paper provides a model that explains the voluminous IBM boninitic magmatism in the context of other, simultaneous tectonic events in the region. The model suggests that *widespread* boninitic magmatism of the IBM forearc is the result of interaction between a subduction zone and a thermal anomaly, rather than a characteristic of infant subduction zones. This model may not apply to all locations in which boninites are found but may be relevant to northern Tonga and to Archean magmas with boninitic affinities.

Plate tectonic reconstruction suggests that OIB-style magmatism and uplift of the northern rift margin accompanied rifting in the West Philippine Basin. The location of these events lies close to a point in the mantle where a thermal anomaly is presently inferred from petrology and geochemistry. Furthermore, an aseismic ridge, the Eauripik Rise, lies on the part of the Caroline plate that passed over the same point during the Oligocene and Miocene. These facts suggest that excess magmatism may have been generated close to this particular location from the Middle Eocene until the present day. The region of high heat-flow during the Early Eocene may have interacted with an existing but restricted subduction zone, or zones, leading to development of a 2000km magmatic arc and generation of the IBM boninite suite. The absence of analogous extensive boninitic suites in the Phanerozoic rock record may result from the unusual juxtaposition of zones of upwelling (hotspots) and downwelling (subduction) in the mantle. The more restricted volumes of boninite suites found elsewhere in the Cenozoic reflect interaction between hot mantle and subduction on much smaller scales or the operation of other mechanisms that facilitate a suitable combination of sources and geotherms in subduction zones.

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Figure Captions

Figure 1. Map of the western Pacific and SE Asia. The Philippine Sea Plate is outlined by the dashed line. Relevant geographic and bathymetric features are labelled. Abbreviations: WPB, West Philippine Basin; NWSB, Northwest sub-basin; SSB, southern sub-basin, RT, Ryukyu Trench; Phil T., Philippine Trench. Symbols represent DSDP/ODP drill sites and Izu-Bonin-Mariana boninite series sampling sites of Middle Eocene magmatism. Different symbols represent petrogenetic types identified using trace element characteristics [Hickey-Vargas, 1989; DeBari et al., 1999; Hickey-Vargas, 1998; Hickey-Vargas, 1991]; see Figure 2 for key. Thin lines represent magnetic anomalies from Hilde and Lee [Hilde and Lee, 1984].

Figure 2. Plate reconstruction of Southeast Asia and the western Pacific at 50 Ma, at the start of the Middle Eocene [Hall, 1996]. The locations of the Izu-Bonin and Mariana arcs are indicated, along with estimated extents of pre-Middle Eocene crust of the Amami-Oki Daito Province and the Southern sub-basin of the West Philippine Basin (WPB). Sampling sites of Middle Eocene magmatism on the present day Philippine Sea Plate (PSP) and the IBM forearc are shown with symbols representing the geochemical nature of the magmas erupted during the Middle Eocene. The I-MORB sample from the Izu-Bonin Trench wall is probably pre-Middle Eocene [DeBari et al., 1999]. Radiometric ages of most of the plotted WPB lavas are within error of 50Ma [Ozima et al., 1977, Hickey-Vargas, 1998, McKee and Klock, 1980]. Ages for the IBM boninite suite vary between 55 and 44 Ma with a mode at 45 Ma [Cosca et al., 1998]. Classification of these lavas as MORB, E-MORB or OIB is based on trace element characteristics [Hickey-Vargas, 1989; DeBari et al., 1999; Hickey-Vargas, 1998; Hickey-Vargas, 1991]. Small diamonds represent sites where

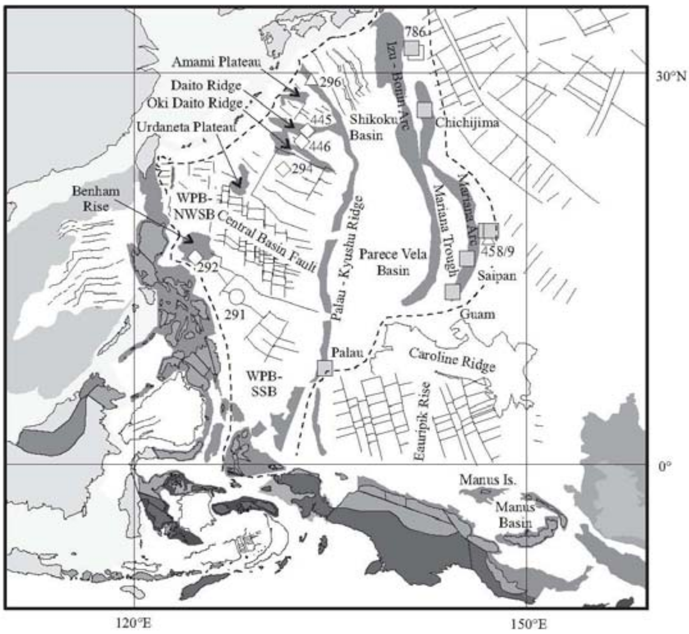
trace element data are not available but ocean island magmatism is inferred from the petrology and major element chemistry. The inferred location of the Manus Basin hotspot centre is plotted and has been migrated such that it remains fixed with respect to the Hawaiian hotspot. A small circle of 750 km radius is drawn around this point to represent the size of the plume-head inferred for the Afar plume [Ebinger and Sleep, 1998].

Figure 3. Initial $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ isotope ratios of lavas from the West Philippine Basin, the Izu-Bonin-Mariana forearc, the Palau-Kyushu Arc, Oligocene to Miocene backarc basins of the eastern Philippine Sea Plate and the Manus Basin [Hickey-Vargas, 1989; Stern et al., 1991; Pearce et al., 1992; Hickey-Vargas and Reagan, 1987; Taylor et al., 1994; Pearce et al., 1999; Woodhead et al., 1999; DeBari et al., 1999; Hickey-Vargas, 1998; Hickey-Vargas, 1991]. Ranges of modern Pacific and Indian MORB are shown for comparison. Classification of Philippine Sea Plate lavas as MORB, E-MORB or OIB is based on trace element characteristics [Hickey-Vargas, 1989; DeBari et al., 1999; Hickey-Vargas, 1998; Hickey-Vargas, 1991].

Figure 4. Map of western Pacific and SE Asia showing the 55 Ma-present track of a thermal anomaly currently located beneath the Manus Basin calculated from the tectonic reconstruction of Hall [Hall, 1996]. Labelled yellow squares show positions at 5 Ma intervals and red circles are positions at intervening 1 Ma intervals from 55 Ma to 30 Ma. A yellow line links subsequent 5 Ma intervals. There are two segments from 50 Ma to 45 Ma since the track can be calculated for either the northern or southern segments of the West Philippine Basin, which was actively spreading at that time. The northern track is further divided into two parts due to subsequent spreading in the Parece Vela Basin and Mariana Trough. From 45 Ma to 33 Ma the track is not

marked since it would have been located on Pacific Plate lithosphere that has now been subducted. Calculation of the 10 Ma to present day section (dotted line) is complicated by tectonics (see text for discussion).

Figure 1


Amami Plateau
Daito Ridge
Oki Daito Ridge
Urdaneta Plateau
Benham Rise
WPB-NWSB
Central Basin Fault
292
291
WPB-SSB
296
445
446
294
Shikoku Basin
Izu - Bonin Arc
786
Chichijima
Palau - Kyushu Ridge
Parece Vela Basin
Mariana Trough
Mariana Arc
458/9
Saipan
Guam
Palau
Caroline Ridge
Eauripik Rise
Manus Is.
Manus Basin
30°N
0°
120°E
150°E

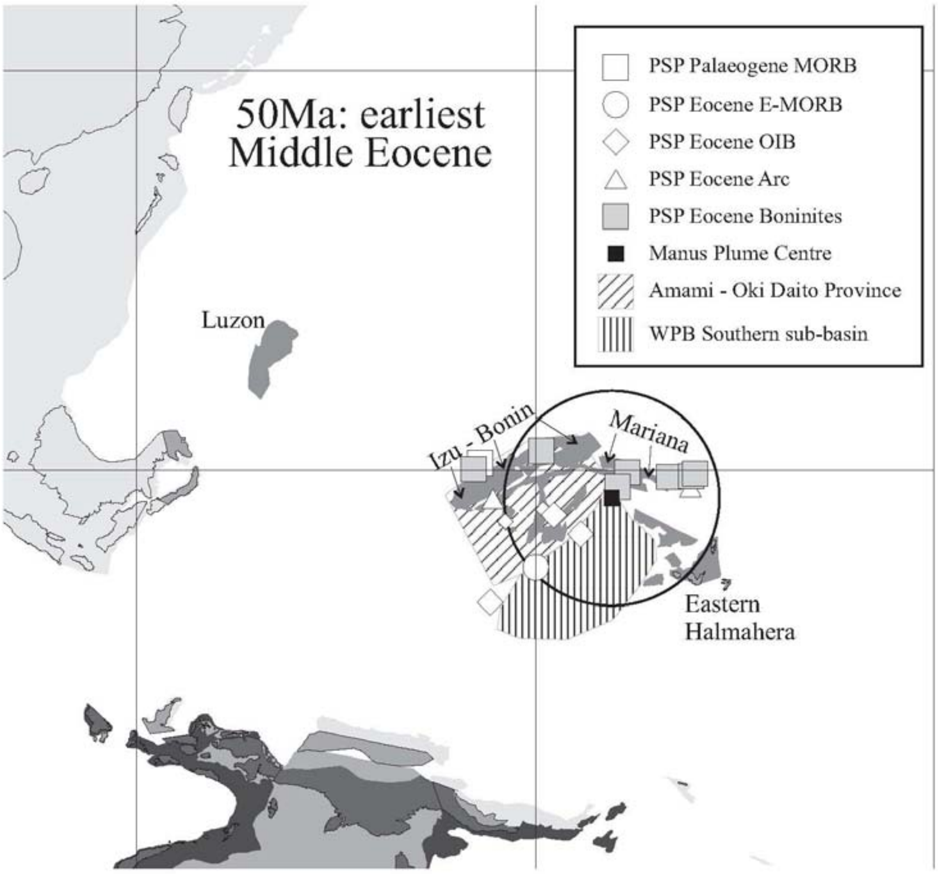

50Ma: earliest
Middle Eocene
PSP Palaeogene MORB
PSP Eocene E-MORB
PSP Eocene OIB
PSP Eocene Arc
PSP Eocene Boninites
Manus Plume Centre
Amami - Oki Daito Province
WPB Southern sub-basin
Luzon
Izu - Bonin
Mariana
Eastern
Halmahera

Figure 2

Figure 3

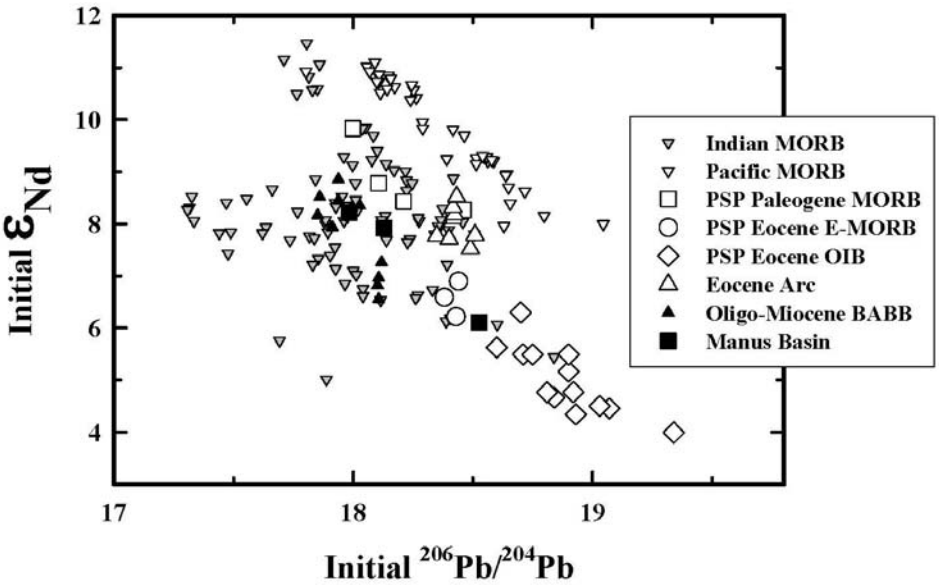

12
10
8
6
4
17
18
19
Initial ε_{Nd}
Initial $^{206}Pb/^{204}Pb$
Indian MORB
Pacific MORB
PSP Paleogene MORB
PSP Eocene E-MORB
PSP Eocene OIB
Eocene Arc
Oligo-Miocene BABB
Manus Basin

Figure 4