

A very hydrous mantle under the western Pacific region: Implications for formation of marginal basins and style of Archean plate tectonics

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Abstract

The western Pacific region has been refrigerated by the subducting cold oceanic plates since 450 Ma. However, the region is also characterized by the presence of many oceanic microplates less than 1300 km across, as well as active magmatism; the Philippine Sea plate is representative. We have compiled and examined petrochemical characters of drilled basalts of DSDP from the Philippine Sea plate, and conclude that the source mantle for oceanic basalts is rich in water ca. 0.2 wt.%, and is 50–60 °C lower than that for MORB. The extensive melting is due to the high water content in the source mantle.

It is well known that some marginal basins apparently have greater depths than the major oceans. We calculated the age–depth correlation based on a model of transient half-space cooling at given parameters of temperatures of mantle and surface, 1280 and 0 °C, and the thermal diffusivity, $1 \text{ mm}^2 \text{ s}^{-1}$. The calculation shows the correlation of age-residual depth from a mid-oceanic ridge is $367 \sqrt{\text{age}(\text{my})}$ for the Philippine Sea, consistent with the bathymetric data. Moreover, the mid-oceanic ridge may be relatively deep because this region is underlain by the cooler mantle.

Addition of water to the mantle peridotite lowers the solidus temperature and viscosity. Melting experiments of hydrous peridotite show that addition of 0.2 wt.% H_2O content lowers the solidus temperature by 150 °C. As a result, the mantle under the region may practically correspond to a ca. 90 °C hotter mantle than normal MORB-source mantle in terms of magmatism and rheology. Numerical simulation for a hotter mantle suggests that many small plates should be formed because of extensive heat release by active magmatism, consistent with many microplates in this region. The presence of many oceanic microplates may be analogous to Archean plate tectonics, characterized by a hotter mantle.

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Keywords: Marginal basins; Refrigerated hydrous mantle; The western Pacific region; Archean plate tectonics

1. Introduction

Oceanic lithosphere is born at a mid-oceanic ridge, migrates to a trench, and subducts underneath continents. The western Pacific region has been a site of destructive plate boundaries for at least 450 Ma (Figs. 1 and 2; e.g. Isozaki and Maruyama, 1991). For the last 150 Ma, the amount of subducted oceanic lithosphere has been calculated, based on the assumption that there has been symmetrical development of magnetic stripes on already subducted plates, as expected by the present ridge systems in the Pacific, and that the hotspots have been stable and immobile among plates for the last 150 Ma. The result shows

that the subducted slabs amount to ~18,000 km long from the east and ~12,000 km long from the south (Fig. 3; Engebretson et al., 1992).

Oceanic crust is extensively hydrated by hydrothermal metamorphism at a mid-oceanic ridge (e.g. summary by Alt, 1995), in addition to regional metamorphism at a subduction zone (e.g. Miyashiro, 1973). Recent seismic observations suggest that lithospheric mantle is itself hydrated by downward-water injection even to the central portion of a plate when it bends at a trench (e.g., Maruyama and Parkinson, 2000). On the other hand, the water in slab starts to be dehydrated and released from a downgoing slab at a subduction zone. The depth of the dehydration strongly depends on the geothermal gradient at a subduction zone. An experimental result of MORB + H_2O (Poli and Schmidt, 1995; Okamoto and Maruyama, 1999) and a

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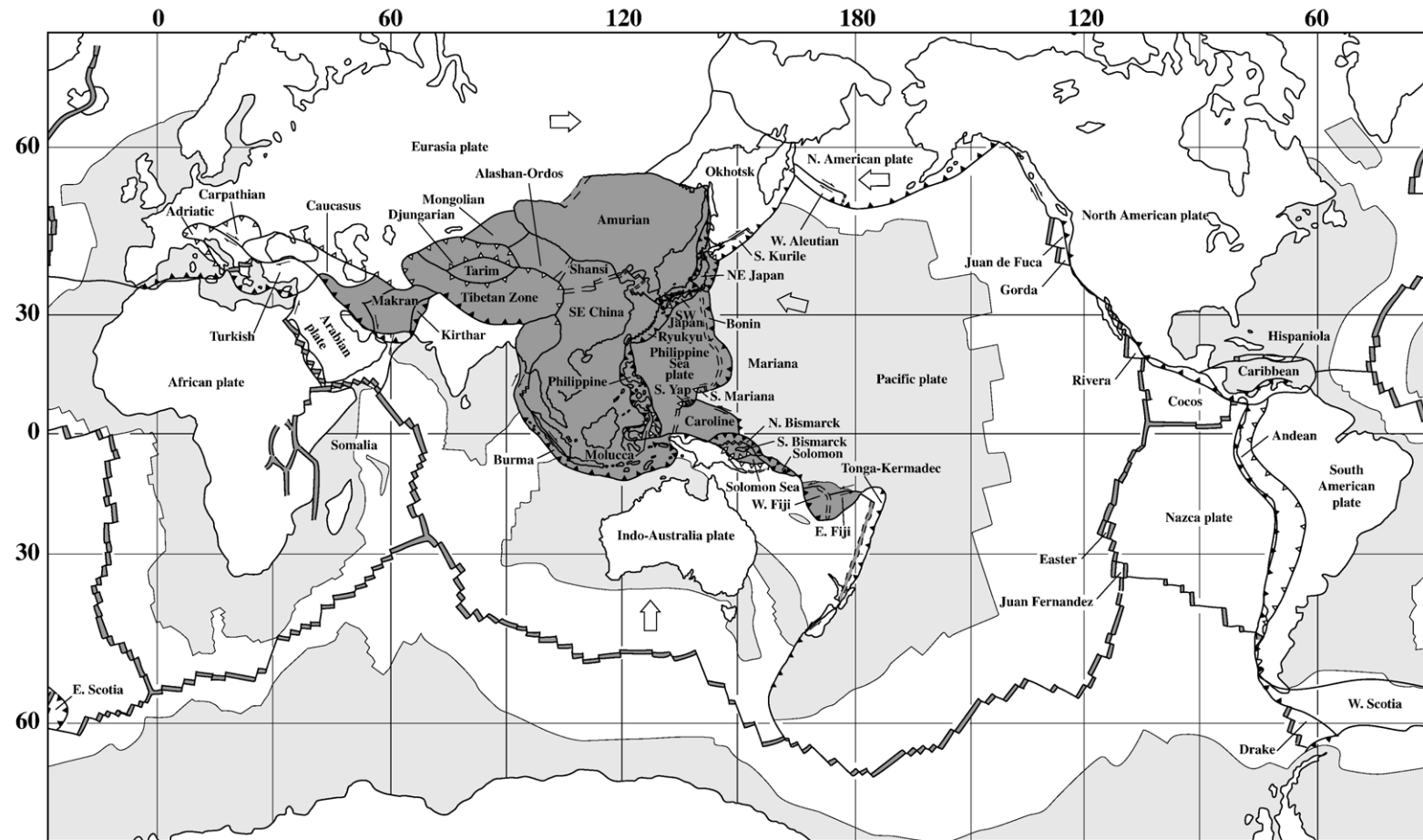


Fig. 1. Distribution of micro- and major plates, and plate geometry on the Earth. Note the dominant occurrence of oceanic microplate in the western Pacific. Shaded area indicates the region of lithospheric graveyards and the consequent probable hydrous mantle due to double subduction of old Pacific and Indo-Australian plates. Light shaded areas indicate oceanic lithosphere > 65 Ma.

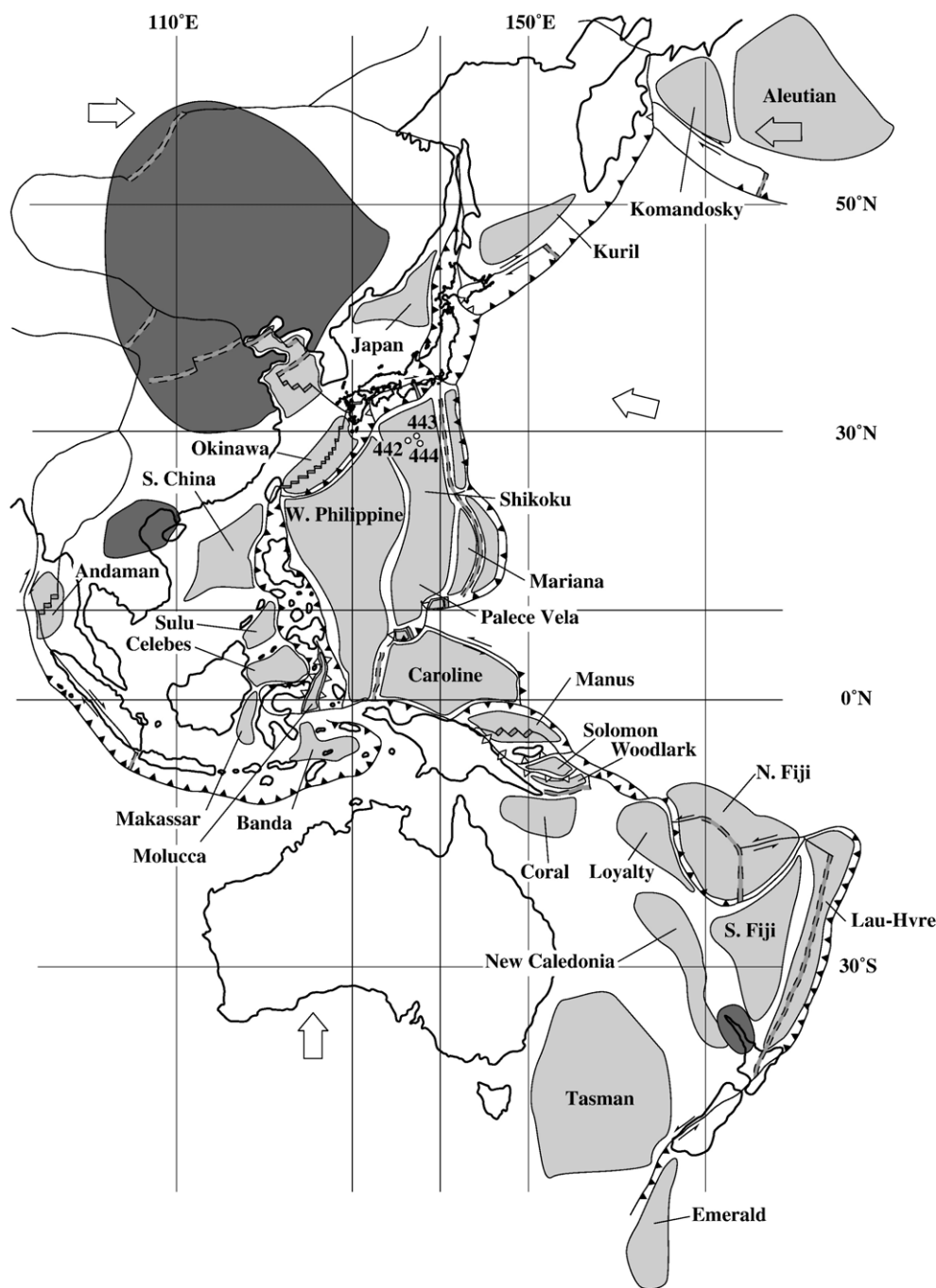


Fig. 2. Distribution of marginal basins around the western Pacific. Light shaded areas indicate the post-Cretaceous marginal basins. Shaded areas indicate Cenozoic basalts and active rift system in the northeast China region and Quaternary subduction-unrelated volcanism in the northwestern part of New Zealand (Tatsumi et al., 1990).

numerical simulation of slab dehydration (Iwamori, 1998; Harry and Green, 1999) indicates that subduction of a younger slab tends to supply much larger amounts of water to the hanging wall at a shallow level. In contrast, the subduction of old, cold oceanic lithosphere allows much water to be transported to deeper mantle up to the mantle transition zone at 410–660 km. Consequently, mantle wedges should be extensively hydrated with time.

On the other hand, water in the mantle moves to the surface with the magma generated from the mantle at a mid-oceanic

ridge, hotspot or subduction zone. The water content of primary magma found at MORs, hotspots and subduction zones is approximately, 0.1–0.5 (Sobolev and Chaussidon, 1996), 0.5–1.1 (Clague et al., 1991; Bureau et al., 1998) and up to 6.0 wt.% (Sisson and Layne, 1993; Sobolev and Chaussidon, 1996; Roggensack et al., 1997; Roggensack, 2001), respectively. Calculation of the total output of water brought to the surface by magma at different tectonic settings amounts to 2.33×10^8 tons per year, and about $1/5$ of 11.2×10^8 tons per year moves down into the mantle by subduction (Maruyama, 1997, 1999).

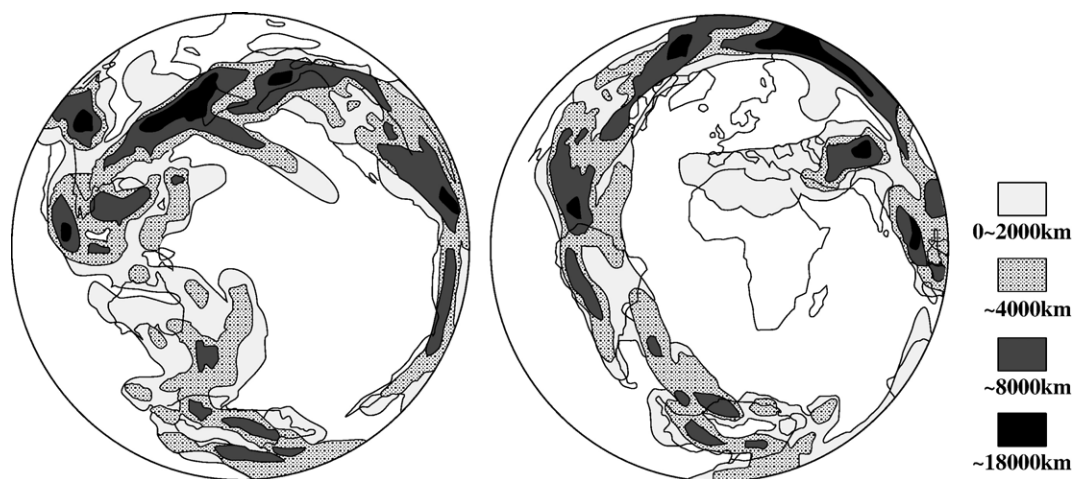


Fig. 3. Distribution of lithospheric graveyard during the last 150 Ma on the Earth, after Engebretson et al. (1992). The numbers mean length of subducted slab. Note that the largest amount of subducted lithosphere is the western Pacific.

If this process has long continued, all the surface water must have been swallowed into the mantle because plate tectonics has been in operation since the Early Archean (e.g. Komiya et al., 1999a). This paradox is explained by the changing geothermal gradient at subduction zones with time. The compilation of Archean to modern subduction zone metamorphism (Maruyama et al., 1996; Hayashi et al., 2000; Komiya et al., 2002a) suggests that a higher geothermal gradient at subduction zones in the Archean to Proterozoic, caused by subduction of young oceanic plates and hotter potential temperature of the mantle, resulted in shallower de-volatilization and even partial melting of oceanic crust in the Archean. No water was transported into the deeper mantle until 750 Ma (Maruyama, 1997). Surface water may have increased by the continuous and extensive magmatism in the Archean to the Proterozoic, and it decreased after 750 Ma.

The presence of water in the mantle has a remarkable influence on magma genesis and mantle rheology, because of the depression of the solidus temperature and the lowering viscosity of the mantle with added water. For example, the addition of 0.5 wt.% H₂O to the mantle makes a solidus temperature of the mantle up to 200 °C lower than that of dry mantle (Hirose, 1997a), and the strain rate of olivine is an order of magnitude higher, corresponding to that at ca. 100 °C higher under dry condition (Karato et al., 1982; Kohlstedt et al., 1995).

More than 75% of the marginal basins in the world are concentrated in the western Pacific region (Figs. 1 and 2; Tamaki and Honza, 1991). Some of them apparently have greater depths than the major oceans such as the Pacific and Atlantic oceans (a summary by Tamaki and Honza, 1991). The curves of age and depth correlations are represented by a $\text{depth} = 2500 + 350 \sqrt{\text{age}(\text{my})}$ for a major ocean and by a $\text{depth} = 3222 + 366 \sqrt{\text{age}(\text{my})}$ for the Philippine Sea (Tamaki and Honza, 1991). The reason for such a difference is still controversial. Moreover, marginal basins share some distinct characteristics (Tamaki and Honza, 1991): (1) they are, of course, smaller than major oceans. (2) The active duration of marginal basins is short, usually less than 25 m.y. (3) Most

basins are younger than 80 Ma. (4) Most marginal basins are apparently related to subduction.

This work presents evidence for a highly hydrated mantle under the western Pacific region. We will discuss the origin and characteristics of marginal basins, from the standpoint of an upper mantle hydrated by subduction. The implication for Archean plate tectonics is also given.

2. Petrology of tholeiitic basalts in the Shikoku basin

2.1. Data treatment and compilation

Most oceanic ridge basalts have experienced some shallow-level fractionation in a crustal magma chamber or in conduits, and some may have suffered even high-pressure fractionation. These processes modify the abundance of all major elements derived from their parental magmas. A necessary first step, therefore, is correct for the effects of shallow-level fractionation in order to estimate the pressure, temperature, and composition of the source mantle, including the water content. Two approaches were used to infer the major element chemistry of parental magmas from a suite of variably fractionated basalts. The first is to consider only compositions with high MgO contents, which are likely to have experienced minor fractionation. The other is the method that major element abundances at a given MgO content are calculated from a liquid line of descent of a suite of relatively primitive basalts (e.g. Klein and Langmuir, 1987). They choose 8.0 and 15 wt.% as the given MgO content for MORB and plume-related basalt, respectively (Klein and Langmuir, 1987, 1989; Scarrow and Cox, 1995). The second approach is often used for geochemical studies of MORB because the number of ridge segments that can be studied through the first approach is limited; only evolved basalts have been recovered from many regions. In the present study, the first approach was used because high MgO samples are available in the region.

We compiled basaltic glasses and whole rock analyses of basalts with MgO contents between 5 and 10 wt.% from Sites

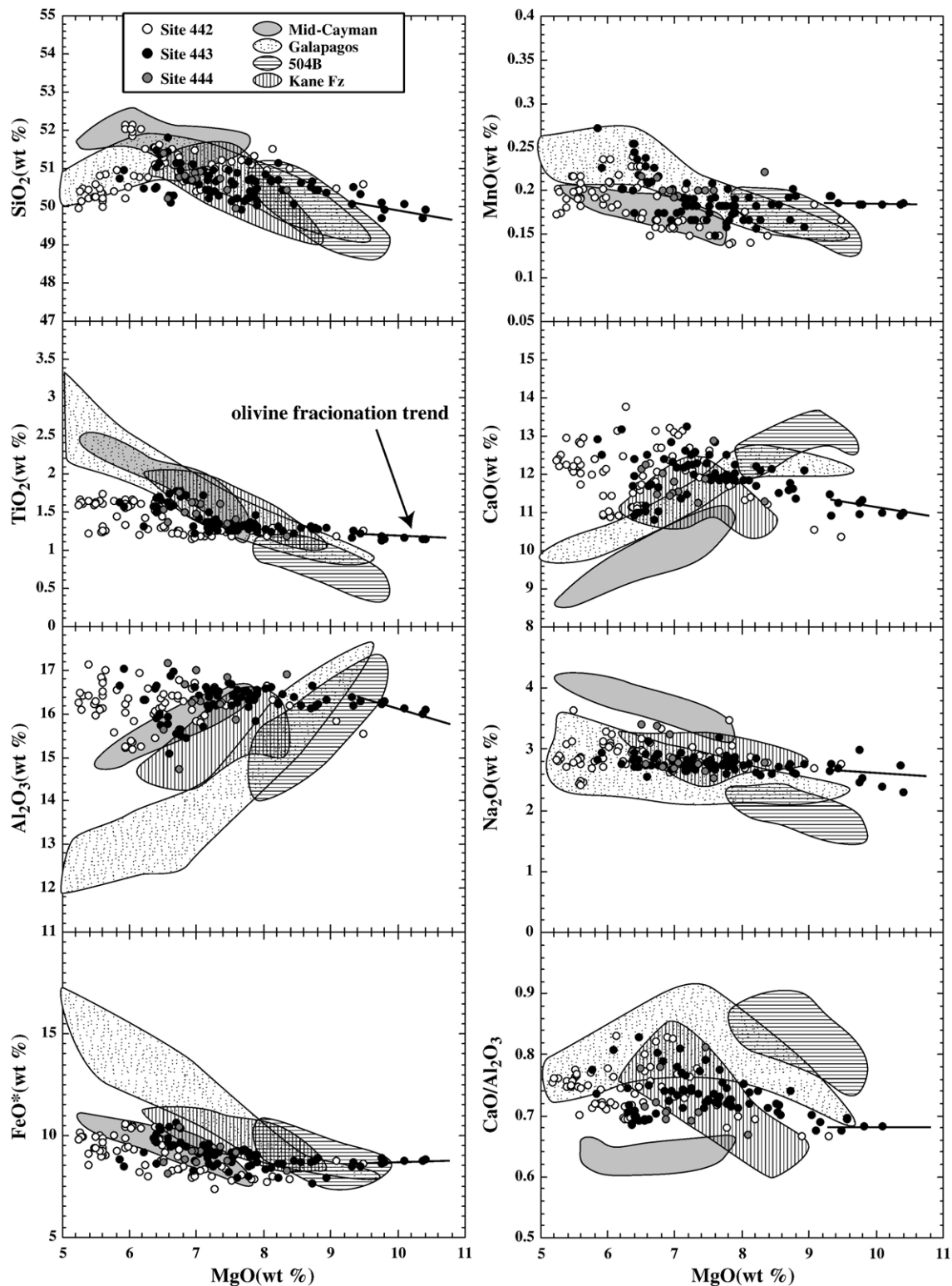


Fig. 4. MgO variation diagrams of major elements for tholeiitic basalts from the Shikoku Basin, compared with other MORBs from the Mid-Cayman Rise, the East Galapagos Rift, the Site 504B, and the Kane Fracture Zone (Melson et al., 1976; Melson and O'Hearn, 1979; Dick et al., 1980; Marsh and Dick, 1980; Wood et al., 1980; Clague et al., 1981; Fornari et al., 1983; Sparks, 1995; Elthon et al., 1995). Symbols are shown in the inset.

442, 443, and 444 in the Shikoku Basins (Dick et al., 1980; Marsh and Dick, 1980; Wood et al., 1980) to estimate the potential temperature and water content of the mantle under the western Pacific region (Fig. 2). For samples whose information

on the extent of whole rock alteration and their modal abundances were given, whole rock analyses of highly altered samples or highly phyrlic samples were excluded from our computations. Although minor alkali basalt occurs as well as

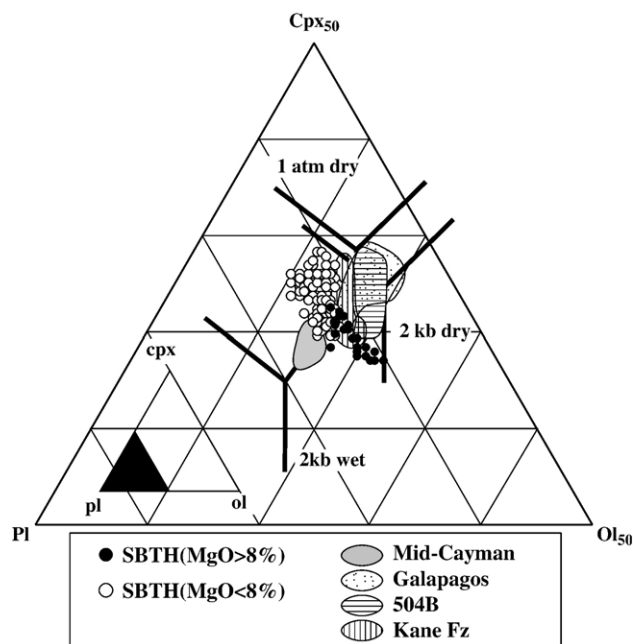


Fig. 5. Normative composition of SBTH on the pseudo-ternary Cpx–Pl–Ol diagram, calculated by the projection scheme by Kinzler and Grove (1992). MORBs from the Mid-Cayman Rise, the East Galapagos Rift, the Site 504B, and the Kane Fracture Zone are also shown on the diagram. The pseudo-invariant points under the anhydrous and hydrous conditions at 1 atm and 2 kb are estimated from previous melting experiments (Tormey et al., 1987; Gaetani et al., 1993). Symbols are shown in the inset.

tholeiitic basalt at Site 444 of DSDP (Dick et al., 1980), it is excluded from our compilation.

2.2. Chemical characteristics of basalts in the Shikoku Basin

2.2.1. Major elements

Fig. 4 shows MgO versus major element diagrams of basaltic rocks from Sites 442, 443 and 444 in the Shikoku Basin, along with basaltic rocks in other ocean basins, Kane Fracture Zone (Melson et al., 1976; Melson and O'Hearn, 1979), the Eastern Galapagos Rift (Clague et al., 1981; Fornari et al., 1983), Hole 504B to the south from the Costa Rica Rift Zone (Sparks, 1995) and Mid-Cayman Rise in the Caribbean plate (Elthon et al., 1995). These compositions were compared after normalizing nine major element concentrations to 100%. For tholeiitic basalts in the Shikoku basin (thereafter SBTH), samples with higher MgO contents (> ca. 7.5 wt.%) plot roughly along olivine fractionation curves on the MgO variation diagrams as follows: SiO₂, TiO₂, Al₂O₃, CaO, and Na₂O contents increase with decreasing MgO; FeO*, and MnO contents and CaO/Al₂O₃ ratios remain almost constant or slightly increase (Fig. 4). These correlations suggest that the chemical variations of SBTH at higher MgO contents are mainly controlled by olivine fractionation; clinopyroxene fractionation plays a minor role. The decrease of Al₂O₃ and CaO contents, and the CaO/Al₂O₃ ratio indicate that fractionation of plagioclase and clinopyroxene become more significant at lower MgO contents. Scatters in the data, especially in Al₂O₃ and CaO contents, are larger at lower MgO

content, suggesting small differences in the timing and extent of the fractionation of plagioclase and clinopyroxene. These characteristics are similar to those in MORB in major oceans (e.g. Klein and Langmuir, 1987).

Although the extent of differentiation, namely MgO content, varies among sites, there are no systematic chemical differences at a given MgO content (Fig. 4), indicating that temperature and pressure of partial melting and composition of the source mantle are similar. The observation is reasonable, because they were derived from similar ridge segments with different age (deV. Klein et al., 1978). Some compositional variations are observed for MORBs, which were interpreted in many previous works as differences mainly in potential temperature of source mantle (e.g. Klein and Langmuir, 1987, 1989; Klein et al., 1991). SBTH is enriched in SiO₂ at a higher MgO content, relative to MORBs in major oceans. SiO₂ content of SBTH overlaps other MORBs at an intermediate to low MgO content. TiO₂ content of SBTH is higher in primitive samples with over 9 wt.% MgO content, whereas it is lower at evolved samples. The similar feature is apparent in FeO*, MnO, and Na₂O content. Al₂O₃ content of SBTH is lower than that of MORBs in the Eastern Galapagos Rift and the Site 504B at a high MgO content, whereas it is higher in intermediate and low MgO contents. Some SBTH forms a similar compositional variation of Al₂O₃ content in MORBs from the Mid-Cayman Rise and the Kane Fracture Zone, while others are enriched in Al₂O₃ content, relative to the latter. Al₂O₃ content of SBTH is lower than that of MORBs in

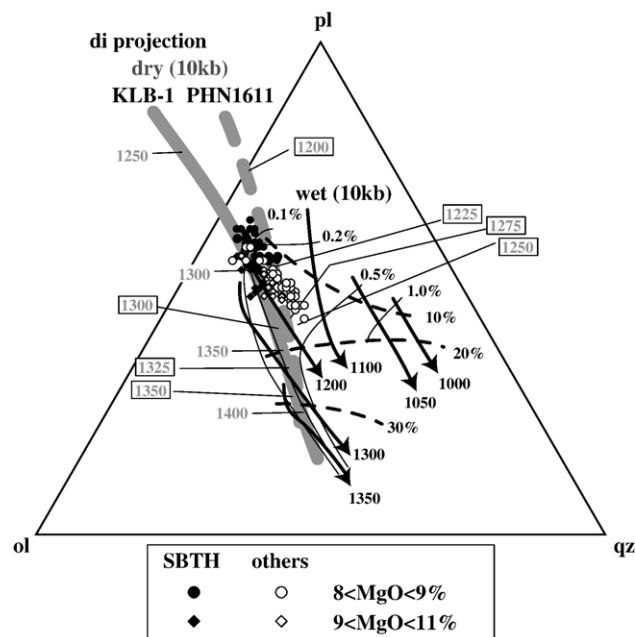


Fig. 6. Normative composition of primitive SBTH on the Walker's pl–ol–qz, projected from di (Walker et al., 1979). Primitive MORBs from the Mid-Cayman Rise, the East Galapagos Rift, the Site 504B, and the Kane Fracture Zone are also shown on the diagram. Compositional trends of experimental melts from anhydrous peridotite of KLB-1 (solid gray line) and PHN1611 (broken gray line) and hydrous peridotite of KLB-1 + H₂O (solid black lines) are also shown in the diagram. Attached numbers are melting temperature (1000–1400 °C), water content in hydrous peridotite (0.1–1.0%), and degree of melting (10–30%). Symbols are shown in inset.

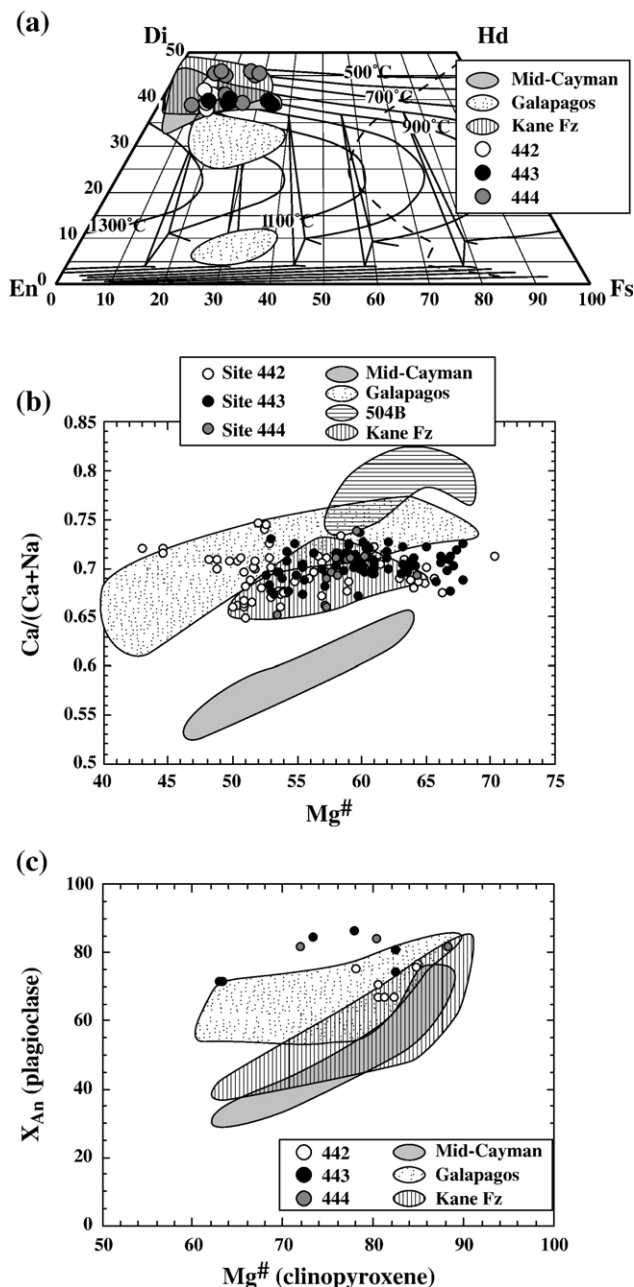


Fig. 7. (a) Compositional plots on Lindsley's quadrilateral diagram for clinopyroxenes from SBTH, the Mid-Cayman Rise, the East Galapagos Rift, and the Kane Fracture Zone. Symbols are shown in the inset. (b) Plot of $\text{Ca}^\#$ ($=\text{Ca}/(\text{Ca}+\text{Na})$) vs. $\text{Mg}^\#$ for SBTH. Shown for comparison are MORBs from the Mid-Cayman Rise, the East Galapagos Rift, the Site 504B, and the Kane Fracture Zone. (c) X_{An} of plagioclase plotted against $\text{Mg}^\#$ of clinopyroxene for SBTH. Shown are compositions of plagioclases and clinopyroxenes within MORBs from Mid-Cayman Rise, East Galapagos Rift, and Kane Fracture Zone.

the Eastern Galapagos Rift and the Site 504B in a high MgO content, whereas is higher in intermediate and low MgO contents. Some SBTH form a similar compositional variation of Al_2O_3 content in MORBs from the Mid-Cayman Rise and the Kane Fracture Zone, while others are enriched in Al_2O_3 content, relative to the latters. In CaO contents, SBTH is enriched relative to Kane Fracture Zone and Mid-Cayman Rise, and is depleted

compared to the Site 504B and the Eastern Galapagos Rift. CaO content of SBTH is higher than other MORBs in intermediate to low MgO contents. $\text{CaO}/\text{Al}_2\text{O}_3$ ratio of SBTH is lower than MORBs from the Site 504B and the Eastern Galapagos Rift, and higher than MORBs from the Mid-Cayman Rise.

2.2.2. Comparison of SBTH with melts in hydrous melting experiments

Fig. 5 shows normative compositions of SBTH, and MORBs in other four regions on pseudoternary diagrams of clinopyroxene (Cpx)–plagioclase (Pl)–olivine (Ol) projected from quartz (Qz), following the projection scheme of Kinzler and Grove (1992). Projected positions of Fo–Di–An piercing point of dry melts at 1 atm and 2 kb, and an H_2O -saturated melt at 2 kb, coexisting with Ol–Cpx–Pl are also shown on the figure (Tormey et al., 1987; Gaetani et al., 1993). The pseudoinvariant point moves toward Ol_{50} with increasing pressure under the anhydrous condition (Grove et al., 1992), whereas it does towards Pl under the hydrous condition (Gaetani et al., 1993). In the latter case, crystallization of plagioclase follows that of clinopyroxene (Gaetani et al., 1993).

SBTH forms a compositional trend at the intermediate field between 1 atm anhydrous and 2-kb hydrous conditions. MORBs from the East Galapagos Rift (MgO 5–9.6% MgO), the Hole 504B (7.4–9.8% MgO), and the Kane Fracture Zone (6.3–8.9% MgO) are plotted almost along a multisaturation boundary of Ol–Pl and the pseudoinvariant point under the anhydrous condition at 1 atm. MORBs from the Mid-Cayman Rise (5.4–7.7% MgO) appear to be distributed on a pseudounivariant line of Ol–Cpx–melt under hydrous condition at 2 kb.

The compositions of primitive SBTH and other MORBs are plotted on Fig. 6 — Walker's ol–pl–qz ternary projection (Walker et al., 1979). Chemical trends of melts from anhydrous peridotite and hydrous peridotite with 0.1% to 1% H_2O at 10 kb are shown in the figure (Hirose and Kushiro, 1993; Hirose and Kawamoto, 1995; Hirose, 1997a). SBTH is distributed off to the ternary plane di–pl–ol, compared with other MORBs. In the case that SBTH is derived from anhydrous peridotite, SBTH is formed at slightly lower temperature, ca. 20 °C, than other MORBs. In a case of hydrous melting, however, SBTH is derived from hydrous peridotite with up to 0.2% H_2O , at up to 100 °C lower temperature. The degree of melting of SBTH is estimated much lower than that of other MORBs in the former case, but it is equivalent or higher in the latter.

2.2.3. Mineral composition of tholeiitic basalts in the Shikoku Basin

Many of the basalts are only sparsely phyrlic or even aphyric, and aphyric samples are dominant. Major phenocrysts are plagioclase, olivine, and pyroxene, with accessory chromian spinel and magnetite. Many have only plagioclase as phenocrysts, followed by samples with both plagioclase and olivine, or with both plagioclase and clinopyroxene (Dick et al., 1980; Marsh and Dick, 1980). Olivine from pillowed basalt in Site 442 shows a small variation in composition ($\text{Fo}_{82.3}$ – $\text{Fo}_{82.9}$), while olivine from pillows and sills in Site 443 has a larger variation ($\text{Fo}_{81.3}$ – $\text{Fo}_{86.6}$). Olivine from Site 444A is fayalitic and has a wide range of composition ($\text{Fo}_{69.7}$ – $\text{Fo}_{85.3}$).

The $Mg^{\#}$ ($=100 \times Mg/(Mg+Fe^*)$) of calcic clinopyroxenes ranges from 78.0 to 84.8, 62.9 to 82.4, and 61.8 to 88.2 in Sites 442, 443 and 444, respectively. The “Quad” components range from 86.4 to 92.0, 86.1 to 92.6, and 74.6 to 93.8, respectively. The major “other” component in most samples is Ca–Tschermak molecule, but the CaTi molecule is predominant in some samples, especially from Site 444. Calculated compositions of the pyroxenes according to Lindsley (1983) are plotted onto the Di–En–Hd–Fs pyroxene quadrilateral, along with pyroxenes from basaltic rocks in other ocean basins, the Kane Fracture Zone, the Eastern Galapagos Rift, the Hole 504B and the Mid-Cayman Rise (Fig. 7a). Clinopyroxenes from SBTH are enriched in Wo component, relative to those from the Mid-Cayman Rise and the East Galapagos Rift. Although $Mg^{\#}$ of clinopyroxenes from SBTH is lower than that from the Kane Fracture Zone, the former almost overlaps the latter.

X_{An} ($=100 \times Ca/(Ca+Na)$) of plagioclase from Sites 442, 443, and 444 is in the range 44.8 to 88.0, 46.7 to 86.5, and 37.3 to 84.5, respectively (Dick et al., 1980). Fig. 7(c) shows X_{An} of plagioclase plotted against $Mg^{\#}$ of the coexisting clinopyroxene from SBTH, along with that from the Kane Fracture Zone, the Eastern Galapagos Rift, Hole 504B and the Mid-Cayman Rise. X_{An} of plagioclase from the East Galapagos Rift is higher than that from other regions at a given $Mg^{\#}$ of clinopyroxene. X_{An} of plagioclase from SBTH is higher. Fig. 7(b) shows a plot of $Ca/(Ca+Na)$ vs. $Mg^{\#}$ for SBTH and other MORBs. Although a similar offset can be seen for basalts from Mid-Cayman Rise, East Galapagos Rift, and Kane Fracture Zone, SBTH does not show such an offset.

3. Discussion

3.1. Water content of suboceanic mantle in the western Pacific region

It is well known that the vesicularity of pillowed basalts in the Shikoku basin is much higher than that of typical MORBs erupted at similar abyssal depths (e.g. Dick, 1980). Vesicularity depends mainly on solubility of water in melts, which is dependent on pressure, melt composition, and temperature. For example, more water can be dissolved in a komatiitic melt than in a basaltic melt. However, high vesicularity of the SBTH should reflect higher water content than typical MORBs, because the differences in major element concentrations between the SBTH and other MORBs are small (Fig. 4), as suggested by previous work (Dick, 1980).

It is also well known that melt from hydrous mantle is different in composition from that from anhydrous mantle (e.g. Kushiro, 1972, 1974). Hydrous melts are enriched in SiO_2 and Al_2O_3 , and depleted in MgO and CaO , relative to anhydrous melts, after normalization of the major element concentration to 100%. Without the normalization, the hydrous melts are depleted in all of values (Gaetani and Grove, 1998). However, the compositional differences decrease at a higher temperature, and a similar composition of melt can be produced from both anhydrous and hydrous peridotite at a given degree of melting (Hirose and Kawamoto, 1995; Hirose, 1997a). But the tem-

perature of anhydrous melting is, of course, much higher than that of hydrous melting (Hirose and Kawamoto, 1995; Hirose, 1997a). Moreover, the liquid line of descent of hydrous melt is different from that of anhydrous melt, because addition of water lowers the appearance temperature of the silicate phases to varying degrees at crystallization (Kushiro, 1974; Gaetani et al., 1993; Parman et al., 1997). This effect increases from olivine through clinopyroxene to plagioclase (Kushiro, 1974; Gaetani et al., 1993; Parman et al., 1997), and may be caused by decrease of the activity of SiO_2 in the melt (Parman et al., 1997).

The liquid line of descent of SBTH is similar to that of other MORBs at a glance, but some obvious differences exist among them (Fig. 4). The decrease of Al_2O_3 content of the SBTH around 8 wt.% MgO is absent (Fig. 4). Sudden increases of TiO_2 , FeO^* , MnO , and Na_2O contents around 8 wt.% MgO are also not obvious in the SBTH. The increases result from onset of fractionation of plagioclase, together with decrease of Al_2O_3 content in the crystal fractionation (e.g. Klein and Langmuir, 1987). The evidence of delay of onset of plagioclase crystallization suggests fractionation of plagioclase of SBTH is minor, relative to that of typical MORBs. Composition of primary melts and pressure affect the onset of precipitation of plagioclase as well as addition of water. However, primitive SBTH is similar in Al_2O_3 content to primitive MORBs from the Mid-Cayman Rise and the Kane Fracture Zone (Fig. 4). Moreover, the CaO/Al_2O_3 ratio of SBTH is lower than that of MORBs from the East Galapagos Rift and Site 504B (Fig. 4). The evidence indicates that the compositional effect is insignificant. Increase of pressure causes not only the suppression of crystallization of plagioclase but also the promotion of crystallization of clinopyroxene (Fig. 5, and Grove et al., 1992). These characteristics are often described as evidence of high-pressure fractionation in some MORBs (e.g. Mid-Cayman Rise: Grove et al., 1992). However, the pseudoternary Cpx–Pl–Ol diagram indicates that the pseudoinvariant point of Ol–Pl–Cpx is offset towards the Pl apex rather than to the point Ol_{50} (Fig. 5). Although the lack of further experimental data does not allow us to estimate the accurate water content, the offset is consistent with the crystallization of a hydrous melt. Degassing on eruption, indicated by great amount of vesicles, possibly leads to a relatively weak influence of addition of water on the crystallization, especially in evolved samples.

Addition of water changes the composition of crystallized phases such as clinopyroxene and plagioclase. Delay of onset of precipitation of clinopyroxene due to addition of water, relative to olivine, results in crystallization of clinopyroxene with lower $Mg^{\#}$ and higher Wo content than that under anhydrous conditions (Parman et al., 1997). Although the clinopyroxene phenocrysts from SBTH, except for some lower $Mg^{\#}$ clinopyroxenes, almost overlap those from the Kane Fracture Zone on Lindsley’s quadrilateral, they are enriched in Wo component, relative to those from the East Galapagos Rift (Fig. 7a). The evidence supports that SBTH has a higher water content than MORBs from the East Galapagos Rift, and possibly from the Kane Fracture Zone. Composition of plagioclase depends on composition of melt, pressure, and H_2O content (Panjasawatwong et al., 1995). X_{An} of plagioclase increases with increasing $Ca^{\#}$ ($=100 \times Ca/(Ca+Na)$) of melt

(Panjasawatwong et al., 1995). Moreover, the higher degree of partial melting increases $\text{Ca}^\#$, and eventually X_{An} of plagioclase (Dick and Natland, 1996). $\text{Ca}^\#$ of SBTH overlaps that of MORBs from the Kane Fracture Zone, and is lower than that of MORBs from the East Galapagos Rift (Fig. 7b). The evidence suggests that the degree of melting of SBTH is similar to that of MORBs from the Kane Fracture Zone, and $\text{Ca}^\#$ in the melt plays an insignificant role for X_{An} of plagioclase among them. X_{An} of plagioclase from SBTH is higher than that of MORBs from the Kane Fracture Zone at any $\text{Mg}^\#$ of clinopyroxene, and even that

of East Galapagos Rift MORBs at intermediate to low $\text{Mg}^\#$. A similar relationship is also found between MORBs and arc-front tholeiites (Ishiwatari et al., 1990). The evidence indicates that SBTH contains more water than other MORBs even during fractional crystallization.

In spite of depletion of all major elements on a volatile-free basis (Gaetani and Grove, 1998), addition of water causes the enrichment of SiO_2 and Al_2O_3 in melts, especially at a low degree of melting (e.g. Kushiro, 1974; Hirose, 1997a). The compositional change is obvious on Walker's ternary projection ol–pl–qz from di (Fig. 6, modified from Fig. 3 of Hirose, 1997a). The normative composition of experimental melts from a hydrous peridotite increases normative quartz, with increasing water content on the figure. But, the experimental melts from hydrous melting with 0.1 wt.% H_2O may be enriched in normative ol, compared with anhydrous melting (Fig. 6). The composition moves towards the di–ol–qz plane with increasing temperature. SBTH is offset towards the ternary plane di–pl–ol, relative to other MORBs (Fig. 6). The difference indicates that assuming anhydrous melting, the potential temperature of the source mantle of SBTH may be ca. 20 °C lower than that of normal mantle under other mid-oceanic ridges.

Fig. 8 shows primitive magmas of the SBTH and MORBs along with the compositional variation of experimental melts obtained by “diamond aggregate methods” (Hirose and Kushiro, 1993; Baker and Stolper, 1994; Kushiro, 1996) in binary diagrams of MgO vs. SiO_2 and FeO^* , and SiO_2 vs. FeO^* . The “diamond aggregate methods” is a configuration of high-pressure experiment, which a small chip of loosely sintered diamond aggregates is embedded in the sample powder in order to make large melt ponds (Hirose and Kushiro, 1993). The melting experiments show MgO content in melts is proportional to melting temperature and the consequent degree of melting. In contrast, SiO_2 content in melt decreases with increasing pressure, whereas SiO_2 content in melt is almost constant across a wide temperature range, except for very low or high degrees of melting (e.g. Hirose and Kushiro, 1993; Kushiro, 1996). The melting experiments indicate that “average” melting pressures of both SBTH and other MORBs can be estimated to be about 10 to

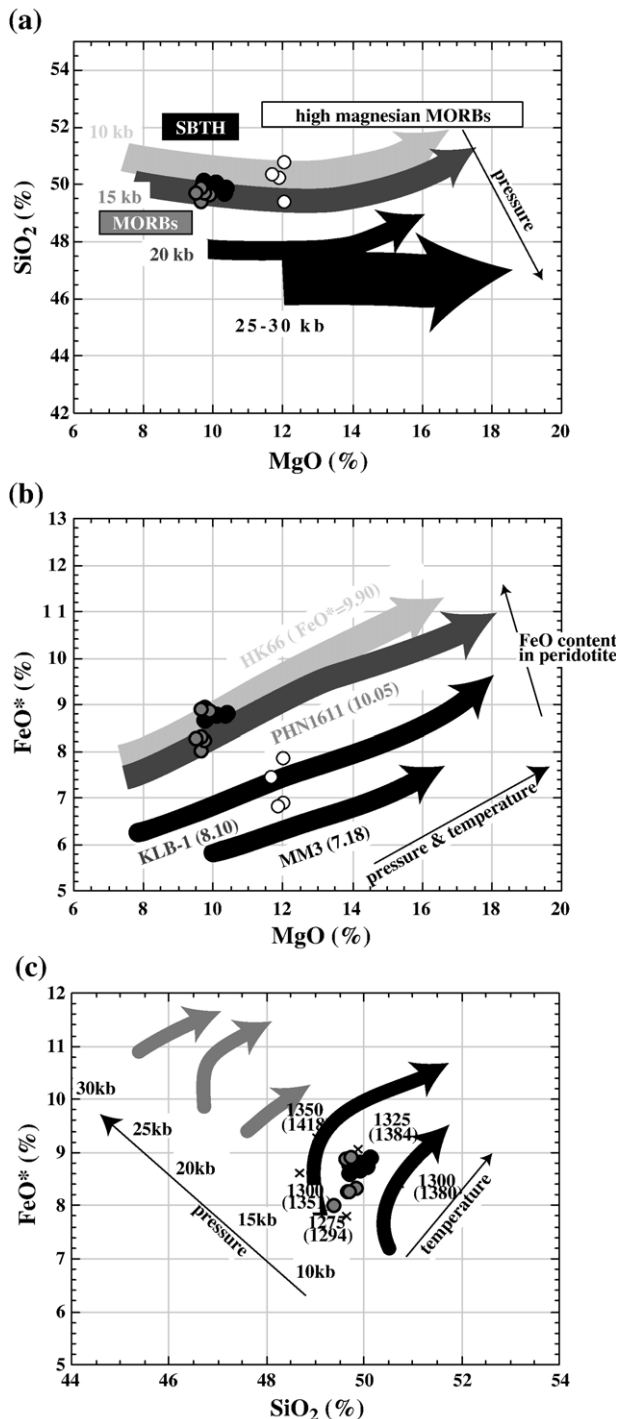


Fig. 8. Comparison of primitive SBTH (solid black circles) with partial melts formed from mantle peridotite by diamond methods. Shown for comparison are primitive MORBs (solid gray circles) from the East Galapagos Rift and Site 504B, and the most primitive MORBs (open circles) from other region. (i) SiO_2 – MgO diagram. Thick arrows indicate compositional variation of partial melts produced from four mantle peridotites at different pressure, 10 kb for light gray, 15 kb for gray, 20 kb for dark gray and 25–30 kb for black arrow respectively. This diagram indicates that both SBTH and other MORBs were formed at 10 to 15 kb. (ii) MgO – FeO diagram. Thick arrows indicate compositional variation of partial melts produced at 10–15 kb from four different mantle peridotites, HK66 for light gray, PHN1611 for gray, KLB-1 for dark gray and MM3 for black arrow, respectively. This diagram indicates that FeO content of mantle source of both SBTH and MORBs from the East Galapagos Rift and Site 504B is comparable to HK66 and PHN1611, whereas that of most primitive MORBs is comparable to KLB-1. (iii) SiO_2 – FeO diagram. Thick arrows indicate compositional variation of partial melts produced from PHN1611 at 10 to 15 kb for black, and at 20 to 30 kb for gray arrow, respectively. This diagram indicates that assuming anhydrous condition, melting pressure and temperature of SBTH was around 10–15 kb and 1350 °C, and was higher than those of other MORBs from Galapagos and Site 504B.

15 kb because both SBTH and other MORBs overlap experimental melts at 10 and 15 kb on the MgO vs. SiO₂ diagram (Fig. 8a). Moreover, the FeO* content or Mg[#] of source mantle can be similarly estimated from comparison between compositions of SBTH and experimental melts. The FeO content in melts depends on pressure and temperature of melting, and on the FeO content of source mantle. FeO* content in melts increases with increasing melting pressure, up to at least 3 GPa. Although the FeO* content in melts is constant or even decreases with increasing temperature at high degree of melting (>ca. 35 vol. %), it similarly increases with temperature at low to moderate degrees of melting. As a result, the FeO content in experimental melts from a peridotite apparently forms a single compositional trend with increasing melting temperature and pressure on the MgO vs. FeO diagram (Fig. 8b). FeO content in melt increases with increasing FeO content in the source mantle (Fig. 8b). FeO content in the source mantle can be well evaluated using the melting experiments at 10 and/or 15 kb, because melting pressure, at 10–15 kb can be estimated from the SiO₂ content in melt (Fig. 8b). Fig. 8b indicates that both SBTH and other MORBs were derived from a FeO-enriched peridotite, such as HK66 and PHN1611. Kushiro (1998) estimated Mg[#] of MORB-source peridotite to be 85 to 89 from compilation of experimental data and MORB data, consistent with our estimate of FeO* content of the source mantle of other MORBs. Comparison of SBTH and other MORBs with experimental melts generated from a FeO-rich peridotite PHN1611 on a SiO₂ vs. FeO* diagram (Fig. 8c) indicates that, assuming dry melting, SBTH is formed from a hotter mantle (PMT=ca. 1380 °C) than the source mantle of other MORBs (PMT=ca. 1350 °C). The calculation is not consistent with the estimate from Walker's pl–ol–qz ternary diagram. The effect of the addition of CO₂ to the source mantle is not fully considered in this paper, because addition of CO₂ qualitatively produces highly different melts from SBTH (Hirose, 1997b). Namely, the above evidence indicates that an assumption of an anhydrous condition is inappropriate for magma genesis of SBTH.

A slightly higher SiO₂ content of SBTH than other MORBs is consistent with melts from a hydrous peridotite with over 0.1 wt.% H₂O (Hirose, 1997a). Moreover, most SBTH can be produced from a hydrous peridotite with up to 0.2 wt.%, but slightly normative qz-enriched SBTH can be derived from a little more hydrous peridotite (Fig. 6).

The interpretation that a hydrous mantle with 0.1–0.2 wt.% H₂O exists under the western Pacific region is quite natural because a primary magma derived from hydrous mantle with 0.2 wt.% H₂O contains at most 2-wt.% H₂O at 10-vol.% of degree of melting. In addition, FTIR analyses of H₂O content in basalt glasses from Southwest Pacific back-arc basins shows that primitive basalts contain 0.83% and 1.9% H₂O in Lau Basin and Woodlark Basin, respectively (Danyushevsky et al., 1993). Danyushevsky et al. (1993) showed that mantle underneath marginal basins in western Pacific region was metasomatized by subduction-related component, and contains high H₂O content, about 0.1–0.2 wt.% H₂O at 10-vol.% of degree of melting (Danyushevsky et al., 1993). The results also supports that mantle under the western Pacific region has much water content, ~0.2 wt.%.

3.2. Effect of compositional difference of source mantle

The binary diagram MgO vs. FeO* indicates that source mantle of other MORBs is similar to that of PHN1611, especially in FeO content, rather than to KLB-1, as discussed above (Fig. 8b). No melting experiment of PHN1611+H₂O is available. However, according to melting experiments of hydrous KLB-1, any hydrous melt corresponds to a certain anhydrous melt in composition at a high degree of melting after normalization of the major element concentration to 100% (Hirose, 1997a). In such a case, the melting temperature of a hydrous melt is, of course, much lower than that of the anhydrous melt with the same composition (Hirose, 1997a). Similarly, melts from PHN1611+H₂O may be expected to be similar in composition to melts from anhydrous PHN1611 at a relatively high degree of melting. In this case, the source mantle of SBTH is estimated to be similar to PHN1611+H₂O, because the SBTH overlap compositional trends of PHN1611 as well as other MORBs (Fig. 8a,b).

For discussion, experimental data of KLB-1 were used rather than PHN1611 because only experimental data of KLB-1+H₂O are available to us. However, it does not affect the previous discussion, because source mantles of both SBTH and other MORBs are similar to PHN1611 in composition. The source mantle of SBTH should be more hydrous than that of other MORBs. However, the estimated potential temperature from PHN1611 may be still lower than that from experimental data of KLB-1, because PHN1611 is more fertile than KLB-1. Moreover, it should be noted that both SBTH and other MORBs are better plotted on a compositional trend at 10 kb based on experimental melts from PHN1611 rather than KLB-1 (Fig. 6).

3.3. Potential temperature of the mantle under the western Pacific region

We estimated the potential temperature of the source mantles of SBTH and other MORBs using thermodynamic parameters from experimental data of anhydrous and hydrous KLB-1 (Hirose and Kushiro, 1993; Hirose and Kawamoto, 1995), because those of PHN1611 are not available. Assuming 0.6 °C/km for adiabat slope, 590 kJ/kg for heat of fusion, and 1.26 kJ/kg°C for heat capacity in anhydrous melting (Hirose and Kushiro, 1998), and 0.6 °C/km for adiabat slope, 590 kJ/kg for heat of fusion, and 1.18 kJ/kg°C for heat capacity in hydrous melting (Iwamori et al., 1995), the potential temperature of the source mantle of SBTH and other MORBs are about 1280 and 1340 °C, respectively. The water content of the source mantle of SBTH is assumed to be 0.2 wt.%, as shown above. Actually, the potential mantle temperatures are lower than the estimates, because both source mantles have similar composition to PHN1611.

Some marginal basins including the Shikoku basin apparently have greater depths than the major oceans (Park et al., 1990; Tamaki and Honza, 1991). The curves of age and depth correlations are represented by $\text{depth} = 2500 + 350 \sqrt{\text{age}(\text{my})}$ for a major ocean and by $\text{depth} = 3222 + 366 \sqrt{\text{age}(\text{my})}$ for the Philippine Sea (Park et al., 1990; Tamaki and Honza, 1991). The origin of the difference is still controversial. We calculated the

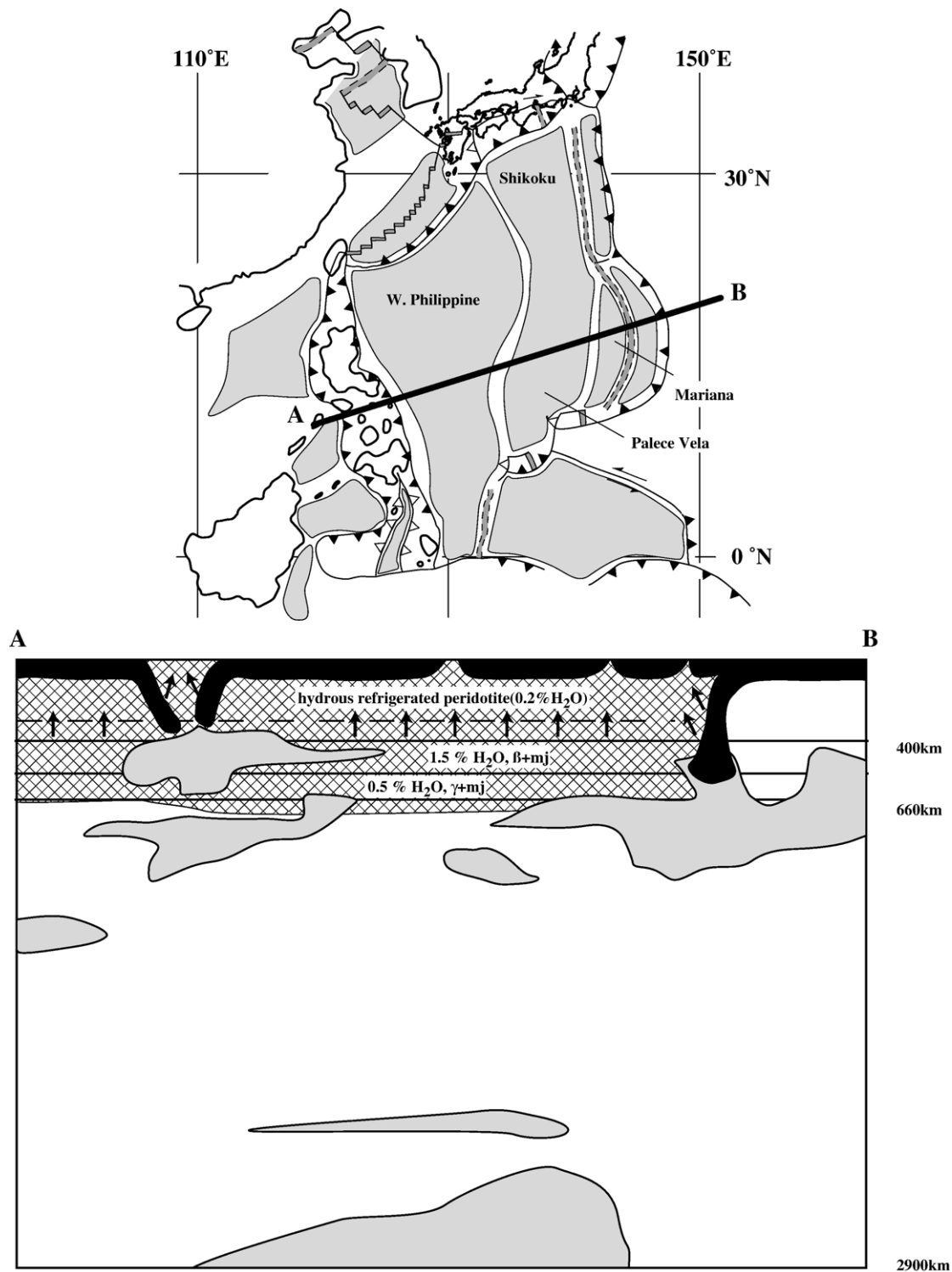


Fig. 9. Above: a simplified tectonic map of the western Pacific region. Symbols are the same as in Fig. 2. Below: a schematic profile of the mantle along the cross section from A to B. Shaded fields show P-wave high velocity anomalies (Fukao et al., 1994), presumably corresponding to the subducted lithospheres. They are located at two stratigraphic regions, around the mantle transition zone and core–mantle boundary. The field with cross stripes indicates the region of hydrous mantle. The Upper mantle is refrigerated by the successive subduction of old and cold oceanic lithosphere, and is hydrated by degassing from the subducted lithosphere. The subduction of the old oceanic lithosphere can carry H_2O to mantle transition zone, and may form the hydrated mantle with much amount of H_2O because β - and γ -spinel can contain more H_2O than olivine, pyroxene and garnet (Kawamoto et al., 1996). Arrows show direction of movement of H_2O .

age–depth correlation based on a model of transient half-space cooling (Turcotte and Schubert, 1982), at given parameters of temperatures of mantle and surface, 1340 and 0 °C for normal

ocean, and 1280 and 0 °C for the western Pacific region, respectively. The thermal diffusivity is given as $1 \text{ mm}^2 \text{ s}^{-1}$ (Turcotte and Schubert, 1982). Assuming 3.43 and 3.30 g/cm^3 for

densities of lithosphere and asthenosphere, respectively, it is shown by calculation that the correlations of age-residual depth from a mid-oceanic ridge are $346 \sqrt{\text{age}(\text{my})}$ for normal oceans and $367 \sqrt{\text{age}(\text{my})}$ for the Philippine Sea, respectively. The calculation is consistent with the bathymetric data (Park et al., 1990).

Bathymetric difference at spreading centers of the Philippine Sea and a normal ocean can be also explained by the difference between the potential temperature of their underlying mantle. We also assumed that the isostasy achieves from ridge to subduction zone for these calculation (e.g. Kono and Yoshii, 1975). Bulk density of the mantle decreases by about 0.2% with increasing temperature from 1280 to 1340 °C (Fei, 1995). In this case, the depth of compensation is calculated to be ca. 300 km. This value is higher than the thickness (ca. 100-km) of MORB-source mantle estimated from mantle tomographies (e.g. Anderson et al., 1992; Fukao et al., 1994). The discrepancy may be due to underplating of cooler mantle under the SBTH source mantle. Mantle tomography shows that a “hotter” region with slow seismic velocity is distributed there (e.g. Fukao et al., 1992, 1994). However, mantle tomography can measure seismic velocity within a region, and the seismic velocity depends on not only temperature but also its composition including H₂O within the region. Even if the temperature is the same, addition of water possibly lowers the seismic velocity. Therefore, the interpretation that the cooler mantle underlies the SBTH source mantle is necessarily not inconsistent with the mantle tomography. In addition, lateral variation in density of the Earth’s mantle was recently calculated from free-oscillation data (Ishii and Tromp, 1999). In spite of scanty data, the calculation supports the idea that a denser region is below the western Pacific region.

3.4. Origin of high water content in the upper mantle of the western Pacific

In this section, we shall discuss the origin of water in the western Pacific region. A subduction zone provides an entrance for water into the mantle. The distribution of subduction zones on the Earth is rather simple, one extends along the margin of the Pacific Ocean, and another from the Mediterranean through Indonesia to the Fiji islands to connect with the Pacific subduction zone ring. The gross picture of the distribution of subduction zones clearly indicates that the western Pacific region is rimmed by double subduction zones where the Pacific plate subducts from the east at a speed 10 cm/yr and the Indo-Australian plate subducts from the south at a speed of 7–8 cm/yr (Figs. 1 and 2). The western Pacific is hence a place where the largest amounts of oceanic slab are subducting now with estimated lengths up to 30,000 km (18,000 km from the east, and 12,000 km from the south) during the last 150 Ma (Fig. 3; Engebretson et al., 1992).

This fact suggests that the upper mantle of the western Pacific region must have been more effectively refrigerated than that of any other region during the last 150 Ma. Therefore, volcanism and tectonics should be least extensive among all consuming plate boundaries. Yet, the western Pacific region has been most active zone of magmatism and tectonics to form a series of

opened marginal basins since the Cretaceous (Fig. 2; Tamaki and Honza, 1991). This may be due to the significant water transported into the upper mantle in the western Pacific region.

The amount of water to be transported into deeper mantle such as the mantle transition zone at 410–660 km depends largely on the age of the subducting slab with a subordinate role for speed of subduction and others. Recent high-pressure experiments of MORB showed that lawsonite eclogite is stable up to 10 GPa and 600 °C, indicating that basaltic crust of old oceanic plate can transport significant amount of water to 10 GPa (Okamoto and Maruyama, 1999). Subsequently, the water dehydrated from the subducted basaltic crust is trapped in hydrous minerals of overlying mantle wedge because dense hydrous magnesium minerals (DHMSs) are still stable in peridotite system under the condition (Komabayashi et al., 2004). Consequently, the down-going hydrous mantle on the subducting lithosphere is capable to carry water to the mantle transition zone (Komabayashi et al., 2004). If the age of oceanic lithosphere is older than ca. 50 Ma, the hydrated water can be transported into the mantle transition zone, hence 3/4 of the total length of the subduction zones (37,000 km) on Earth provides an entrance for water into deeper mantle. The western Pacific region is also characterized by the subduction of old slabs; 150–200 Ma-old Pacific plate from the east, and 100–200 Ma-old Indo-Australian plate from the south. These old plates may be hydrated even into the central portion of the oceanic lithosphere, transporting more water into deeper mantle (Omori et al., 2004). In addition, Bina and Navrotsky (2000) implied that much water is carried to deep mantle as high-pressure ice in cold subducting slabs if geothermal gradient is quite low at subduction zone. All of these facts support the idea that the western Pacific region is the place where most abundant water has been transported into the mantle during the last 150 Ma.

Fig. 9 shows a schematic profile of the mantle along the line from A to B under the western Pacific region. Three major oceanic lithospheres subduct underneath the region, from the south (the Indo-Australian), the east (the Pacific), and the west (the SE China). The Indo-Australian and the Pacific plates are old enough to carry much H₂O into deeper mantle, even to the mantle transition zone, as well as to refrigerate the mantle wedge. The mantle transition zone is composed mainly of β - or γ -spinel, which can contain much H₂O, up to ca. 3.3 wt.% (Kawamoto et al., 1996). Therefore, much H₂O may be stored in the region during the subduction of a cold oceanic lithosphere. Much H₂O is released from the region to the upper part of the upper mantle, as well as directly from the subducted slab. The process of H₂O supply possibly produces the hydrous peridotite with 0.2 wt.% H₂O in the region. Recently, Huang et al. (2005) estimated that water content in the transition zone reaches 0.1–0.2 wt.% from electrical conductivity of wadsleyite and ringwoodite, consistent with our estimate of water content under the western Pacific region.

3.5. Implications for Archean plate tectonics

The estimated potential temperature of the mantle beneath the western Pacific region is ca. 60 °C lower than that of mantle

under mid-ocean ridges elsewhere in the world. However, addition of 0.2 wt.% H₂O to a peridotite lowers the solidus temperature by ca. 150 °C (Hirose, 1997a). Consequently, the mantle under the western Pacific region may correspond to a ca. 90 °C hotter mantle than normal MORB-source mantle in terms of magmatism. Moreover, the addition of water also decreases the viscosity of peridotite (Karato et al., 1986; Kohlstedt et al., 1995). Therefore, addition of water to the mantle may also be qualitatively equivalent to a higher temperature mantle in terms of mantle rheology.

It has been qualitatively considered that the potential temperature of Archean mantle was much higher than present mantle because more radiogenic elements were present and more gravitational energy of accreting planetesimals and core formation were preserved in the Archean (e.g. Turcotte, 1980). Recently, the temperature of Archean mantle was evaluated based on petrological investigation of komatiites of several ages (Nisbet et al., 1993). However, the temperature of Archean upper mantle was still ambiguous, because the komatiites may have been derived from plume-magmatism (Campbell et al., 1989). To resolve this problem, application of accretionary geology established in the circum-Pacific orogenic belts to some Archean greenstone belts is a key to identify Archean MORBs from Archean greenstone belts based on the field occurrence of the greenstones (Taira et al., 1992; Kimura et al., 1993; Ohta et al., 1996; Komiya et al., 1999a, 2002b). Potential temperatures of Archean MORB-source mantle were estimated to be ca. 1450 to 1480 °C from comparison of the composition of the Archean MORBs and recent melting experimental data (Ohta et al., 1996; Komiya et al., 1999b, 2002b, 2004; Komiya, 2004). The estimates indicate that Archean upper mantle was 120 to 150 °C hotter than modern mantle. Therefore, hydrous mantle under the western Pacific region may be analogous to Archean mantle.

In the western Pacific region, there are over 75% of marginal basins in the world (Tamaki and Honza, 1991). The plates in the area are less than ca. 1300 km across and much smaller than major plates ca. 6000 km across in other areas. This size characteristic may be similar to that of Archean plates. Previous workers qualitatively speculated from numerical simulations that Archean plates were smaller than the present (e.g. Hargraves, 1986; Ida and Maruyama, 1992; de Wit and Hart, 1993). Moreover, the formations of small plates in the Archean are considered to be caused by higher temperature of the mantle, hence a longer total length of mid-oceanic ridge would yield extensive heat release by active magmatism (e.g. Hargraves, 1986; Ida and Maruyama, 1992). Similarly, active magmatism due to the addition of water to the mantle possibly results in formations of small oceanic plates in the western Pacific region (Fig. 2).

The mantle in the western Pacific region is practically hotter by ca. 90 °C than normal upper mantle as shown above. Moreover, the plates in the region are less than ca. 1300 km across. If the small size of plates is caused by active magmatism due to the addition of water to the mantle, the size of the plates can be estimated from comparison between effective temperature of mantle in the western Pacific region and the estimated potential temperature of Archean upper mantle. The size of plates decreases from 6000 to 1300 km across with increasing

temperature of the mantle by 90 °C. The number of plates consequently increases from about 15 to 300 at a rough estimate. Assuming that the spreading rate of Archean oceanic plates was similar to that of Phanerozoic oceanic lithosphere, an average life-span of Archean oceanic plate is estimated to be 15 m.y.

4. Conclusions

Compilation and examination of petrochemical characters of drilled basalts from the Shikoku Basin, the Philippine Sea plate, indicate that the source mantle for the oceanic basalt is rich in water at ca. 0.2 wt.%, and is 50–60 °C lower than that for MORB. The extensive melting is due to the high water content in the source mantle.

Assuming 3.43 and 3.30 g/cm³ for densities of lithosphere and asthenosphere, we calculate the age–depth correlation based on a model of transient half-space cooling at given parameters of temperature of mantle and surface at 1280 and 0 °C, and for a thermal diffusivity of 1 mm² s^{−1}. The calculation shows the correlations of age-residual depth from a mid-oceanic ridge are $367 \sqrt{\text{age}(\text{my})}$ for the Philippine Sea, consistent to the bathymetric data of the greater age-residual depth for the Philippine Sea (Park et al., 1990). Moreover, the bulk density of a mantle peridotite increases by about 0.2% with decreasing temperature from 1340 to 1280 °C. Assuming that isostasy is satisfied from ridge to subduction zone, the difference of depth at a mid-oceanic ridge between 2500 km for major oceans and 3222 km for the Philippine Sea corresponds to the ca. 300-km compensation depth. The relatively large water depth at the mid-oceanic ridge in the Philippine Sea may also be because a cooler mantle peridotite underlies the western Pacific.

Although the mantle under the region is 50–60 °C lower than source mantle of other MORBs, it practically corresponds to a ca. 90 °C hotter mantle than normal MORB-source mantle in terms of magmatism. This is the reason why recent melting experiments of hydrous peridotite show that an addition of 0.2 wt.% H₂O-content lowers the solidus temperature by 150 °C (Hirose, 1997a). According to numerical simulations (e.g. Hargraves, 1986; Ida and Maruyama, 1992), hotter mantle causes the formation of more and smaller plates because of extensive heat release by active magmatism. Over 75% of marginal basins in the world are concentrated in the western Pacific region (Tamaki and Honza, 1991). The presence of many small oceanic microplates may be analogous to the Archean plate tectonic regime, because the potential temperature of Archean upper mantle was ca. 150 °C higher than that of modern upper mantle (Ohta et al., 1996; Komiya et al., 2002b, 2004; Komiya, 2004). Assuming that the spreading rate was similar between the present and the Archean, the average life-span of Archean oceanic lithosphere should be ca. 15 m.y.

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