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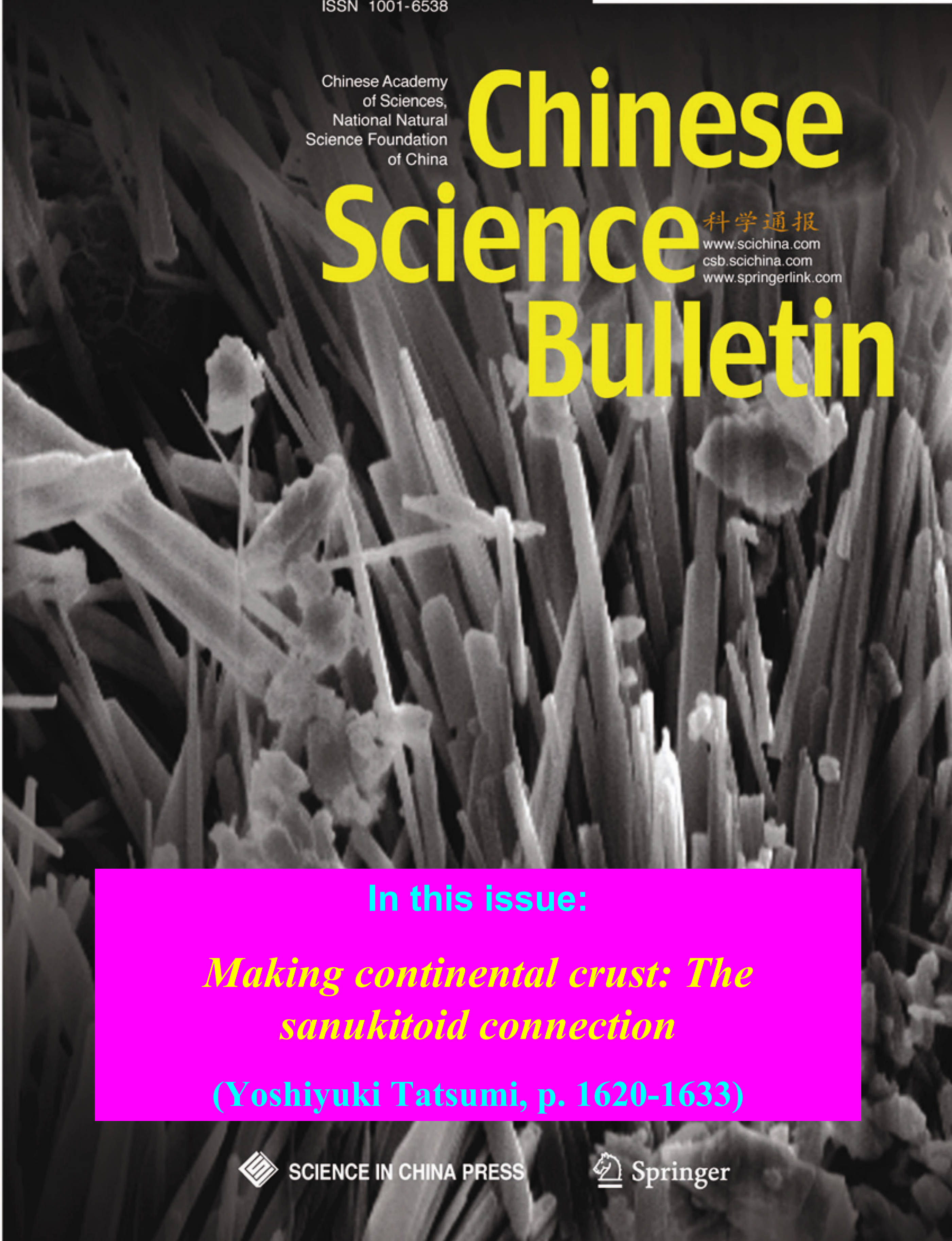

In this issue:

Making continental crust: The sanukitoid connection

(Yoshiyuki Tatsumi, p. 1620-1633)

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REVIEW

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Editor's note

Yoshiyuki (Yoshi) Tatsumi is currently the Program Director of the Institute for Research on Earth Evolution of Japan Agency for Marine-Earth Science and Technology (IFREE/JAMSTEC). He received a BSc in Geology with honors (1978) and an MS (1980) from Kyoto University, and a PhD in Earth Sciences from the University of Tokyo in 1983. He held research/visiting positions at the University of Manchester, UK (1983—1984) and the University of Tasmania, Australia (1989—1990) while holding Assistant and Associate Professorships at Kyoto University (1983—1996). He has been full Professor of School of Earth Sciences, Institute of Geothermal Sciences at the Kyoto University, and Ocean Research Institute at the University of Tokyo since 1996. Yoshi is a world-renowned igneous petrologist and authority on magma generation and evolution associated with subduction zones. He uses magmatism as a tool to understand the evolution of the solid Earth. He has published over 120 research papers in leading journals such as *Nature*, *Science*, *Geology*, *Earth and Planetary Science Letters*, *Journal of Geophysical Research*, *Journal of Petrology*, *Contributions to Petrology and Mineralogy*, *Chemical Geology*, etc. Every igneous petrologist today, in particular those who study the petrogenesis of subduction-zone igneous rocks, is impressed with and influenced by Yoshi's classic book 《Subduction Zone Magmatism》 (Tatsumi Y. and Eggins S., Blackwell Publishing, 1995, 1—224), which has been widely cited in research papers and used in classrooms. His thinking goes beyond magmatism. He offers insights into mantle wedge thermal structure, origin of back-arc basins, chemical stratification of the upper mantle, mantle plume hypothesis, and the chemical and physical significance of seismic structure of island arc crust. He has been an international leader advocating how continental crust is actually being generated today above subduction zones in the western Pacific, especially along the Izu-Bonin-Mariana arc system. His overview of "Subduction factory: How it operates in the evolving Earth" (*GSA Today*, 2005, 15: 4—10) has concisely summarized our state-of-the-art thinking on the petrological, geochemical and geophysical consequences of subduction-zone factories, and elucidated the significance of such factories in the evolution of the solid earth through creating continental crust and deep mantle geochemical reservoirs. Yoshi is also one of the major driving forces behind the Integrated Ocean Drilling Program (IODP). He is one of the very first lecturers of the Distinguished Researcher & International Leadership Lecture Series (DRILLS) of the IODP (http://www.iodp.org/drills/), currently touring Europe and presenting "Drilling into the Memory of Earth".

I am delighted that Yoshi Tatsumi accepted the invitation to contribute an article to *Chinese Science Bulletin* on the possible genetic link of subduction-zone magmatism and continental crust formation. The broad similarity in trace element geochemistry between bulk continental crust and volcanic arc rocks led to the conjecture that continental crust is formed by subduction-zone magmatism. However, the bulk-arc crust is basaltic whereas bulk continental crust composition is andesitic. Removal of mafic/ultramafic lower arc crust cumulate has thus been invoked, but physical mechanisms for such removal are unknown. Furthermore, arc andesites are too depleted in Mg, Ni and Cr to account for the bulk continental crust composition. To resolve this dilemma, Yoshi argues that sanukitoids or high Mg andesites (HMAs) produced by subducting-slab melting and melt-mantle interaction are ideal andesitic melts with high Mg, Ni and Cr to meet the required bulk continental crust composition. He used sanukitoids from the Setouchi volcanic belt in SW Japan as well as literature data from the Aleutians as examples and demonstrated quantitatively that bulk composition of continental crust can be readily produced by differentiation of HMA sanukitoids. This sanukitoid hypothesis is very attractive, and is apparently superior to the traditional island arc model for continental crust. Nevertheless, it remains unclear how "isolated" intra-oceanic arcs will contribute to continental crust growth because back-arc basins spread and ocean ridges spread also. Furthermore, it is still debatable whether arc crust production is indeed mass balanced by subduction erosion and sediments recycling. There is no doubt that science cannot advance without debate. It is thus my hope that this paper will offer an impetus that encourages Chinese scientists, in particular the younger generations, to participate in this exciting debate.

(Yaoling Niu, Department of Earth Sciences, Durham University, UK)

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Making continental crust: The sanukitoid connection

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The average continental crust possesses intermediate compositions that typify arc magmatism and as a result it is believed to have been created at ancient convergent plate boundaries. One possible mechanism for intermediate continental crust formation is the direct production of andesitic melts in the upper mantle. Sanukitoids, which characterize the Setouchi volcanic belt, SW Japan, include unusually high-Mg andesites (HMA). They were generated by slab melting and subsequent melt-mantle interactions under unusual tectonic settings such as where warm lithosphere subducts into hot upper mantle. Such conditions would have existed in the Archean. Hydrous HMA magmas are likely to have solidified within the crust to form HMA plutons, which were then remelted to produce differentiated sanukitoids. At present, generation and differentiation of HMA magmas may be taking place in the Izu-Bonin-Mariana arc-trench system (IBM), because (1) HMA magmatism characterizes the initial stages of the IBM evolution and (2) the IBM middle crust exhibits V_p identical to that of the bulk continental crust. V_p estimates for plutonic rocks with HMA compositions support this. However tonalitic composition for middle-crust-forming rocks cannot be ruled out, suggesting an alternative possibility that the continental crust has been created by differentiation of mantle-derived basaltic magmas.

high-Mg andesite, sanukitoid, boninite, slab melting, continental crust

1 Introduction

Although the continental crust represents only 0.4% of the total mass of the solid Earth, it is a huge geochemical reservoir of incompatible elements, containing, for example, over 40% of the Earth's potassium. In addition, it contributed significantly to the removal of CO_2 from atmosphere and hydrosphere of the early Earth and has been the stage for terrestrial life. The continental crust therefore played a key role in the evolution of the Earth system, yet how it was created remains a matter of much debate. It is well established that the bulk continental crust possesses an intermediate composition similar to tonalite or andesite[1−3]. Such a composition is the basis for believing that convergent plate margins have been the major site of continental crust formation, because andesitic magmatism typifies such a tectonic setting. However, mantle-derived magmas produced in the modern arc-trench system are mostly mafic or basaltic. This is probably the greatest dilemma facing those interested in the origin of continental crust.

One possible solution to this dilemma is direct production of andesitic magmas in the mantle, not differentiation of basaltic magmas. Since the pioneering article by Nicholls and Ringwood[4], experimental studies have repeatedly shown that partial melting of subducted basaltic crust, either with or without subsequent melt-mantle interactions, yields "primary" andesitic magmas[5−7]. The majority of continental crust formed in the Archean, when the mantle temperature may be higher, and slab melting, instead of slab dehydration as at present, may be responsible for the production of dominantly andesitic magmas[8−11]. Kelemen[10] emphasized that the composition of bulk continental crust is similar

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to those of Mg-rich andesites, rather than those of "normal" andesites and favored mantle-derived Mg-rich andesitic magma as a potential source of the continental crust.

Shirey and Hanson[12] first recognized a suite of intrusive and volcanic rocks from the Superior Province, which have some similar characteristics to Tonalite-Trondhjemite-Granodiorite (TTG), the major component of Archean juvenile continental crust. These rocks are referred to as "Archean sanukitoids", as they have distinctive major- and trace-element characteristics, enriched in Mg, Cr, and Ni similar to the high-Mg andesites (HMA), known as sanukitoids in the Setouchi volcanic belt, SW Japan. HMA sanukitoids have been explained as mantle-derived primary andesitic magmas. Since then, in addition to the Superior Province, Archean sanukitoids have been documented from other Late Archean terranes, e.g., Baltic shield[13], South India[14], and the central Pilbara Craton[15]. Understanding the origin of sanukitoids and the genetic linkage between sanukitoids and TTGs should provide a key to decoding the processes responsible for continental crust formation.

The term sanukitoid was first used by Koto[16] for compact volcanic rocks that are comagmatic with "sanukite" in the Sanuki region of NE Shikoku, SW Japan. Sanukite was first defined by Weinschenk[17] as gray- and black-coloured, lustrous, aphanitic, and compact volcanic rocks containing needle-like bronzite phenocrysts. It is difficult, however, to identify the genetic connection between sanukite and other sanukitoids. Thus, it may be practical to use the term sanukitoids for black-colored, phenocryst-poor (generally, total phenocrysts <10%), plagioclase-aphyric, compact volcanic rocks occurring typically in the SW Japan arc[18,19]. If this terminology is accepted, then the term sanukitoid for intrusive and plutonic rocks is not recommended, because sanukitoids are defined as volcanic rocks macroscopically and petrographically rather than by major element compositions.

In order to assess the role of high-Mg andesite magmas in the continental crust formation, this article reviews the genesis of sanukitoids in the Setouchi volcanic belt and its tectonic setting. The contribution of high-Mg andesite magmatism to the evolution of modern intra-oceanic arc crust is also examined, as such arcs are thought to be a possible site for generating juvenile continental crust.

2 Setouchi volcanic belt-analogue to an Archean arc?

In the forearc region of the SW Japan arc, i.e., between the Quaternary volcanic front and the Nankai Trough, characteristic volcanic rocks such as pitchstone, garnet-bearing dacite, and sanukitoids were sporadically emplaced during the middle Miocene and form the Setouchi volcanic belt (SVB), extending for ~600 km with five major volcanic groups (Figure 1). Recent K-Ar dating[20−25] confirmed an age of (13.7±1.0 (1)) Ma for SVB magmatism[19]. Almost synchronous ((14.2±0.8) Ma[21,26]) with this magmatism, felsic volcano-plutonic complexes formed on the near-trench side of the SW Japan arc (Figure 1). The arrangement of dual magmatic zones, both parallel to the arc-trench system (Figure 1), suggests the involvement of plate subduction. However, the occurrence of volcanic rocks distinct from those found in "normal" volcanic arcs implies that the subduction was unusual. In the following, the unusual conditions of the tectonic setting are reviewed.

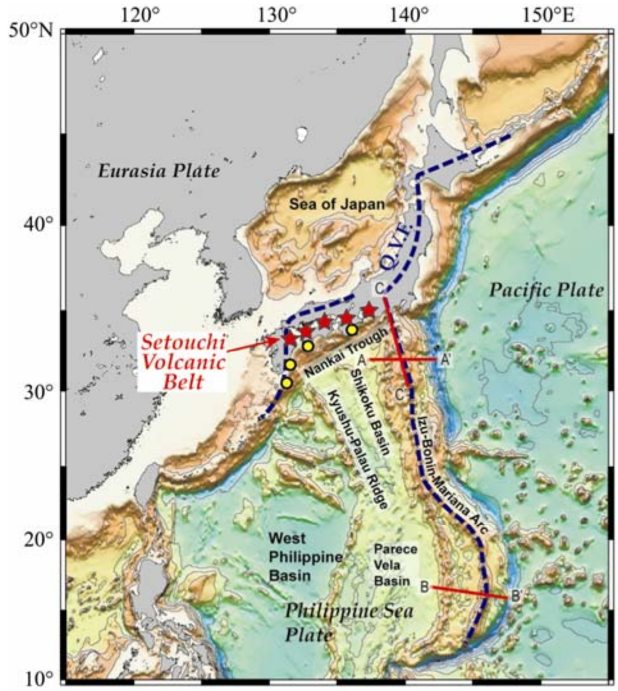

Figure 1 The Setouchi volcanic belt (red stars) and the near-trench felsic volcano-plutonic complexes (yellow circles), both formed in the present fore-arc of the SW Japan arc. The Shikoku Basin and the Sea of Japan are backarc basins created north and south of the SW Japan arc, respectively. Blue broken lines indicate the Quaternary volcanic fronts (QVF). The seismic crust/mantle structure along red lines (A-A′, B-B′, C-C′) are shown in Figure 9.

2.1 Shallow slab

The Quaternary volcanic front of SW Japan arc, which forms by subduction of the Philippine Sea plate underneath the Eurasian plate (Figure 1), lies ~100 km above the surface of the subducting plate[27]. Although the depth to the top of the subducting lithosphere ranges from 72 to 173 km beneath the volcanic front[28], it is rather constant beneath the central part of most volcanic arcs (105—110 km[29]). On the other hand, Miocene magmatism in the SW Japan arc, such as the SVB and the felsic volcanic-plutonic belt, are distributed in the forearc region of the Quaternary arc-trench system (Figure 1). It is likely that the depth of the slab surface is much shallower (~30—50 km, the values of the present height) for the Miocene magmatic belts than for the Quaternary volcanic belt. The reason for believing so is twofold. First, the trench-fill sediments have been accreted to the SW Japan arc to form subduction zone complexes, suggesting the paleo-Nankai Trough would be located closer to the SW Japan arc. Second, the angle of subduction for the Miocene SW Japan would be shallower than that of the Quaternary arc because of its young age (see below).

The linkage between magma generation and the depth of slab top beneath volcanoes has been an unsolved problem[28,30]. One possible explanation for the normal depth (~110 km) between the volcanic front of the central part of volcanic arcs and the underlying surface of the subducted oceanic crust may be the pressure-dependent breakdown of chlorite and amphibole in the down-dragged hydrous peridotites layer at the base of the mantle wedge[29,31,32]. Although aqueous fluids are also supplied to the mantle wedge underneath the forearc region, the mantle wedge temperature is not high enough to cause partial melting. For melting to occur as required to generate the near-trench magmatism of the Miocene SW Japan arc, temperature in the mantle wedge and/or in the subducting slab must be unusually high.

2.2 Backarc spreading and a young slab

The subducting slab beneath most of the of SW Japan arc is the lithosphere of the Shikoku Basin, the backarc basin created behind the Izu-Bonin-Mariana (IBM) arc (Figure 1). On the basis of geomagnetic anomalies and ocean bottom topography data[33−35], the following scenario is now widely accepted as the evolutionary history of the Shikoku Basin (Figure 2):

(1) ~30 Ma——rifting of the Kyushu-Palao paleo-arc commenced;

(2) ~27 Ma——spreading and subsequent oceanic crust creation propagated to the south at 10 cm/yr;

(3) ~23—20 Ma——changing in spreading direction and rate;

(4) ~15 Ma——spreading stopped and the Kinan seamount chain formed.

The oceanic crust of Shikoku Basin began to form at

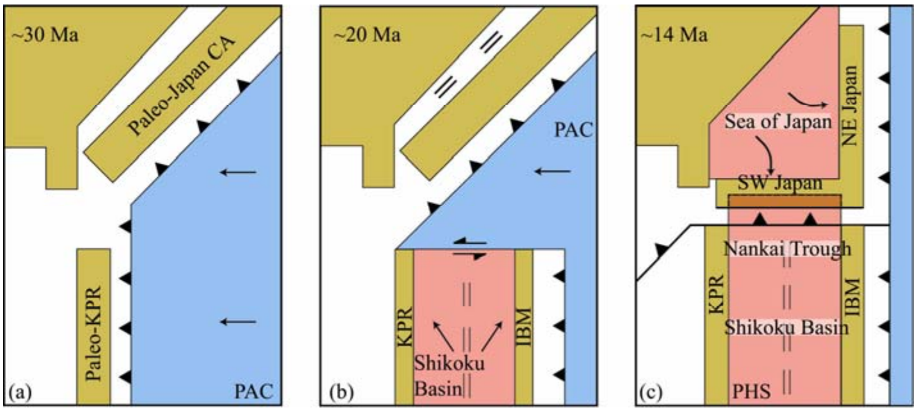

Figure 2 Tectonic evolution of backarc-arc-trench systems at the eastern margin of the Asian continent since 30 Ma[60]. Backarc spreading at Sea of Japan resulted in southward migration of SW Japan arc slivers, causing "obduction" of that arc sliver on a newly-born, "hot", and buoyant Shikoku Basin lithosphere. These tectonic settings including subduction of a hot lithosphere into the hot upper mantle, which triggered unusual Setouchi sanukitoid magmatism, may be analogous to those in the Archean when much of the continental crust was created. (a) Formation of Paleo-Kyushu-Palau Ridge (KPR) arc and Paleo-Japan continental arc (CA). (b) Spreading of Shikoku Basin and subsequent eastward migration of IBM (Izu-Bonin-Mariana) arc from KPR. Rifting at Asian continental margin. (c) Opening of Sea of Japan backarc basin and rotation of SW and NE Japan arc slivers, clockwise and anti-clockwise, respectively. Southward migration of SW Japan arc sliver resulted in "obduction" of that sliver onto a young, hot, and hence buoyant Shikoku Basin lithosphere.

~27 Ma and was 14 million years old or younger when the SVB became activating at 13－14 Ma. Subduction of such a young (<14 Ma) lithosphere may be responsible for the unusually shallow angle subduction beneath the Miocene SW Japan arc. Subduction of a young and "hot" plate may have caused slab melting. Based on numerical simulation, Furukawa and Tatsumi[36] demonstrated that the temperature of the slab surface at a depth of 40 km beneath the SVB is >300 K higher than that beneath the present NE Japan arc, resulting in partial melting of both the downgoing sediments and altered oceanic crust.

In the usual scenario, older oceanic lithosphere can be subducted into the mantle because it becomes increasingly cold and dense with age. A young and hence "hot" plate, such as the Shikoku Basin lithosphere, is more buoyant and as a result cannot be easily subducted. How was subduction of such a young lithosphere initiated beneath the SW Japan arc?

2.3 Backarc spreading, drift and obduction of an arc sliver and high-T mantle wedge

The Sea of Japan, located behind the SW and NE Japan arcs, is also a backarc basin, created by rifting of the eastern margin of the Asian continent. Ocean Drilling Program Legs 127 and 128 successfully recovered basaltic basement rocks from the Sea of Japan[37]. Ar-Ar dating of these rocks, together with the ages of fossils from sediments that directly cover the basaltic basement suggests that the Sea of Japan backarc basin formed at 30－15 Ma[37,38]. The opening of this backarc basin caused drifting together with clockwise and anti-clockwise rotations of SW and NE Japan arc slivers respectively at ~15 Ma[39] (Figure 2). Consequently, the young, "hot" lithosphere of Shikoku Basin confronted the sliver of the SW Japan arc that was rotating and drifting to the south. Thus, it may be reasonable to infer that the arc sliver obducted onto the newly-born oceanic lithosphere, forcing a buoyant plate to be subducted beneath the arc (Figure 2). It is important to stress that the magmatism both in the Setouchi and the near-trench region of the SW Japan arc is almost synchronous with the rotation of the arc sliver.

The principal cause of the backarc rifting is controversial; it may be triggered "passively" by trench retreat or "actively" by injection of asthenosphere into the mantle wedge[40]. In each case, however, backarc basin formation should involve upwelling of asthenospheric material that ultimately makes oceanic crust and yields upper mantle temperatures higher than those in a normal subduction system without backarc basin opening. Tatsumi et al.[41] confirmed this idea numerically and demonstrated, for example, that the temperature of the mantle wedge at 40 km depth beneath the backarc region of the NE Japan arc was ~200 K higher during the opening of the Japan Sea than at present.

2.4 Archean-like thermal regime

In conclusion, the possible tectonic explanation for why magmatism at the SVB generates sanukitoids, distinct from normal modern arc magmatism is: subduction of an unusually high-T lithosphere into an unusually high-T upper mantle. Although it is still debatable whether the modern-day plate tectonics began in the Archean or later[42], such conditions would have been ubiquitous during the Archean when the upper mantle was much warmer than at present. Therefore magma generation in the SVB could be considered a modern equivalent to Archean arc magmatism. This is further supported by the widespread occurrence of plutonic rocks with compositions similar to sanukitoids in Archean terranes[12－15]. Importantly, Archean times marked one of the peak periods of continental formation[43,44]. The compositional similarity between continental-crust-forming rocks and sanukitoids suggest most sanukitoid magma genesis could be closely related to the process of continental crust formation.

3 Sanukitoid genesis

Sanukitoids in SVB includes volcanic rocks exhibiting different phenocryst assemblages and chemistry: augite-olivine basalt, augite-olivine andesite, bronzite-olivine andesite, augite-bronzite-olivine andesite, hornbrende-olivine andesite, augite-bronzite andesite, bronzite andesite, and aphyric andesite. Among these, most olivine-bearing sanukitoids can be classified as high-Mg andesite (HMA), which is herein defined as Mg-rich (MgO > 5 wt%) andesites with FeO*/MgO (FeO*, total iron as FeO)<1.0. The reason for defining so is that the melt with such composition is in equilibrium with Mg-rich mantle olivine based on the following three assumptions: (1) Fe/Mg exchange partition coefficient ($[Fe/Mg]^{Olivine}/[Fe/Mg]^{Melt}$) of 0.3[45], (2) mantle olivine having Mg/[Mg+Fe] > 0.87, and (3) $Fe^{2+}/(Fe^{2+}+Fe^{3+})$ of 0.9 in a magma. Sanukitoids that do not belong to HMAs are hereafter referred as to differentiated sanukitoids.

3.1 Geochemical characteristics of sanukitoids

Sanukitoids form a broad calc-alkalic trend (Figure 3). It should be stressed that some differentiated sanukitoids have compositions identical to that of the bulk continental crust. As Shirey and Hanson[12] pointed out, Late Archean rocks from the Superior Province broadly share the major element characteristics with sanukitoids, although they exhibit diversity in Na_2O (Figure 3).

HMA sanukitoids are not olivine cumulative because (1) they are poor in phenocryst and (2) olivine phenocryst, if present, has Fe/Mg ratio in equilibrium with the host melt[18,19]. Low FeO*/MgO, high Ni (>100 μg/g) and Cr (>200 μg/g) concentrations in those sanukitoids thus suggest that they represent primary andesitic melts derived from the upper mantle, consistent with mineralogical data showing high NiO in olivine (> 0.4 wt%) and high $Cr/(Cr+Al+Fe^{3+})$ in chromite inclusions[18,19].

Of the known HAM occurrences, those from SVB, the Bonin Islands (boninites[46]), and western Aleutians[47] have been extensively studied. Among these, Setouchi and Aleutian HMAs have similar major element compositions except K_2O. Boninites, however, are low in TiO_2, Al_2O_3, Na_2O, and K_2O and rich in FeO* and MgO compared with the Setouchi and Aleutian HMAs[19].

HMAs generally show incompatible trace element patterns that typify subduction zone magmas, i.e., relative depletions of immobile high-field-strength elements such as Nb and Ti and relative enrichment of mobile large-ion-lithophile elements such as Cs, Rb, and K, and a positive Pb anomaly. Setouchi HMAs are further distinct in having higher concentrations of incompatible elements than Aleutian and Bonin HMAs and possess compositions similar to those of the bulk continental crust (Figure 4). Consistent with their highly enriched incompatible element characteristics, HMA sanukitoids possess enriched Sr-Nd-Pb-Hf isotopic characteristics (Figure 5). The origin of these enriched signatures is

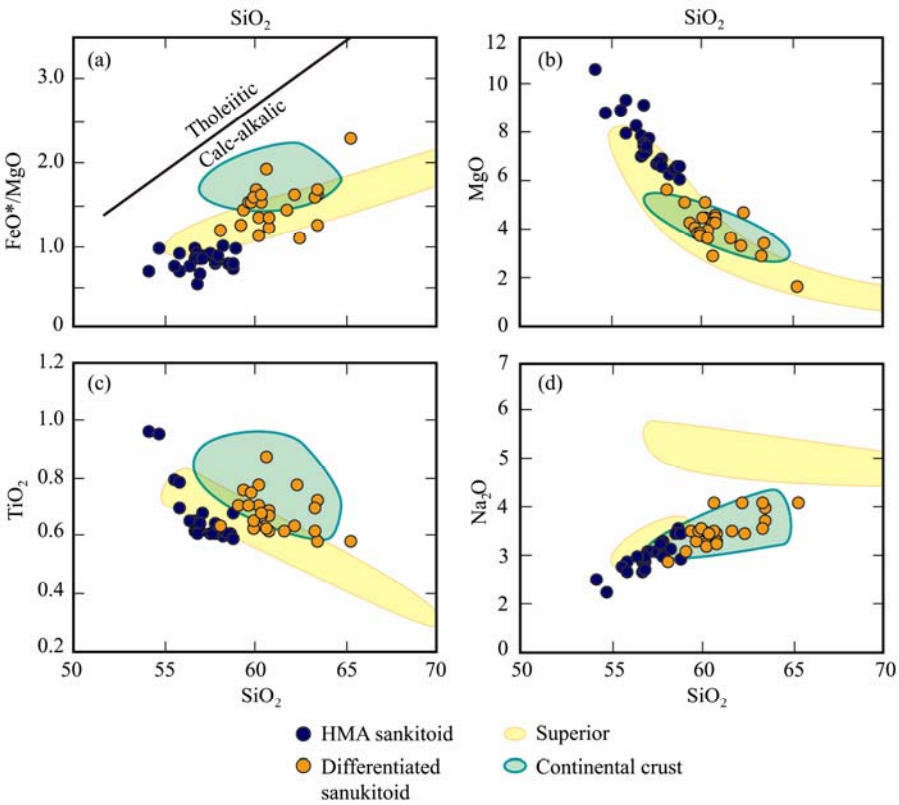

Figure 3 Major element characteristics of HMA and differentiated sanukitoids in the Setouchi volcanic belt[24,57,63], “sanukitoids” in the Superior Province[12], and the average continental crust[1−3]. Setouchi sanukitoids, especially differentiated sanukitoids, possess compositions close to those of continental crusts, suggesting that these may be produced by a similar process.

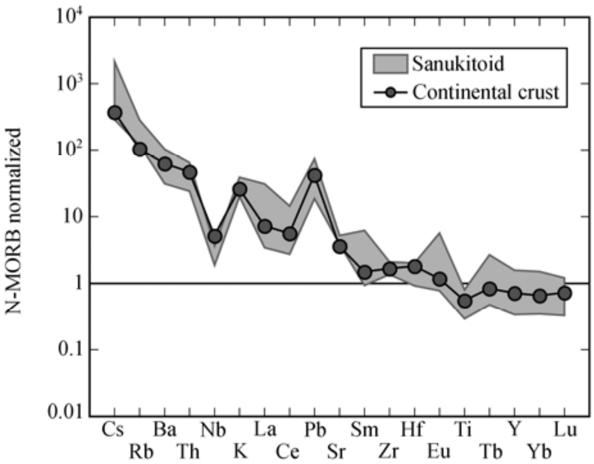

Figure 4 Incompatible elements characteristics of Setouchi sanukitoids (data from Shimoda et al.[63]; Tatsumi et al.[24]). They exhibit N-MORB normalized pattern typical of arc lavas and identical to the average continental crust[2]. This compositional overlap strongly suggests a common formation mechanism in operation for Setouchi and continental crust magmatism.

discussed later.

Adakites are believed to represent partial melts of the downgoing oceanic crust[48,49], because adakites have unusually higher Sr/Y ratio than typical arc magmas, and because of selective partitioning of Y into residual garnet within the subducting oceanic crust[50]. Setouchi HMAs, as well as those from the Bonin and Aleutian islands, do not show this adakitic signature. If slab melting was involved in Setouchi HMA magma formation, then the subducting slab may have melted at depths shallower than the garnet stability field.

3.2 Origin of HMA sanukitoids

(i) P-T-H_2O conditions of HMA magma generation

Petrographic and chemical characteristics of HMA sanukitoids suggest that they represent nearly-primary magmas in equilibrium with upper mantle peridotites. It has been well established experimentally that partial melting of peridotites under H_2O-rich conditions at mantle pressures can produce melts with andesitic, not basaltic, compositions[51−53]. These earlier results were further confirmed by direct analyses of partial melts from hydrous peridotites[54]. These experiments, however, only provide limited information on P-T-H_2O conditions for HMA magma genesis.

In order to estimate conditions of HMA magma generation more quantitatively, melting experiments, including the analysis of "multiple-saturation of mantle phases", have been conducted. Figure 6(a) shows the melting phase relations for a Setouchi HMA sanukitoid SD-261[55]. In the presence of 20 wt% H_2O, i.e., under H_2O-oversaturated conditions, olivine is the liquidus phase at pressures < 1.5 GPa, and is replaced by clinopyroxene at higher pressures. At 1.5 GPa, orthopyroxene, in addition to the above two phases, appears on the liquidus. These liquidus phases have compositions similar to those in mantle peridotites. It is thus suggested that the HMA SD-261 can be in equilibrium with mantle lherzolite at 1.5 GPa and ~1030℃ under H_2O-oversaturated conditions. This HMA is also multiply saturated with lherzolitic minerals under H_2O-undersaturated conditions (Figure 6(a)). Since the Moho pressure beneath the SVB is ~1.0 GPa, the minimum H_2O content in that mantle-derived HMA magma would be ~8 wt%.

At least two other HMAs from SVB (TGI[56]) and the Islands Bonin (CH414[57]) have been examined in terms of the multiple-saturation of mantle phases. The residual mineral assemblages change during peridotite melting from lherzolitic, via harzburgitic, to dunitic with increasing temperature or melt fraction. The experimental results for the above two HMAs indicate that these HMAs may be produced at higher temperatures than that for HMA SD-261, leaving harzburgitic minerals as melting residues (Figure 6(b)), which is consistent with lower FeO*/MgO ratios for TGI and CH414 than for SD-261. These experimental results may suggest a rather simple mechanism of HMA magma generation that addition of a significant amount of H_2O from the subducting lithosphere to the overlying mantle wedge to cause hydrous partial melting[58,59]. However, experimental results provide constraints solely for the conditions of final equilibration of HMA melts with mantle peridotite and do not necessarily suggest the above simple mechanism.

(ii) Geochemical constraints on HMA magma production mechanism: Slab melting or dehydration?

H_2O and melts, more precisely silica-rich aqueous fluids and/or H_2O-rich silicate melts, are metasomatic agents derived from the subducting slabs, which transfer slab components to the mantle wedge and facilitate mantle melting for arc magmas. The role of these two possible metasomatic agents in HMA magma genesis has been examined quantitatively by geochemical formulation of dehydration, partial melting and melt-solid reaction by Tatsumi and Hanyu[60]. Their modelling is based on compositions of subducted sediments and al-

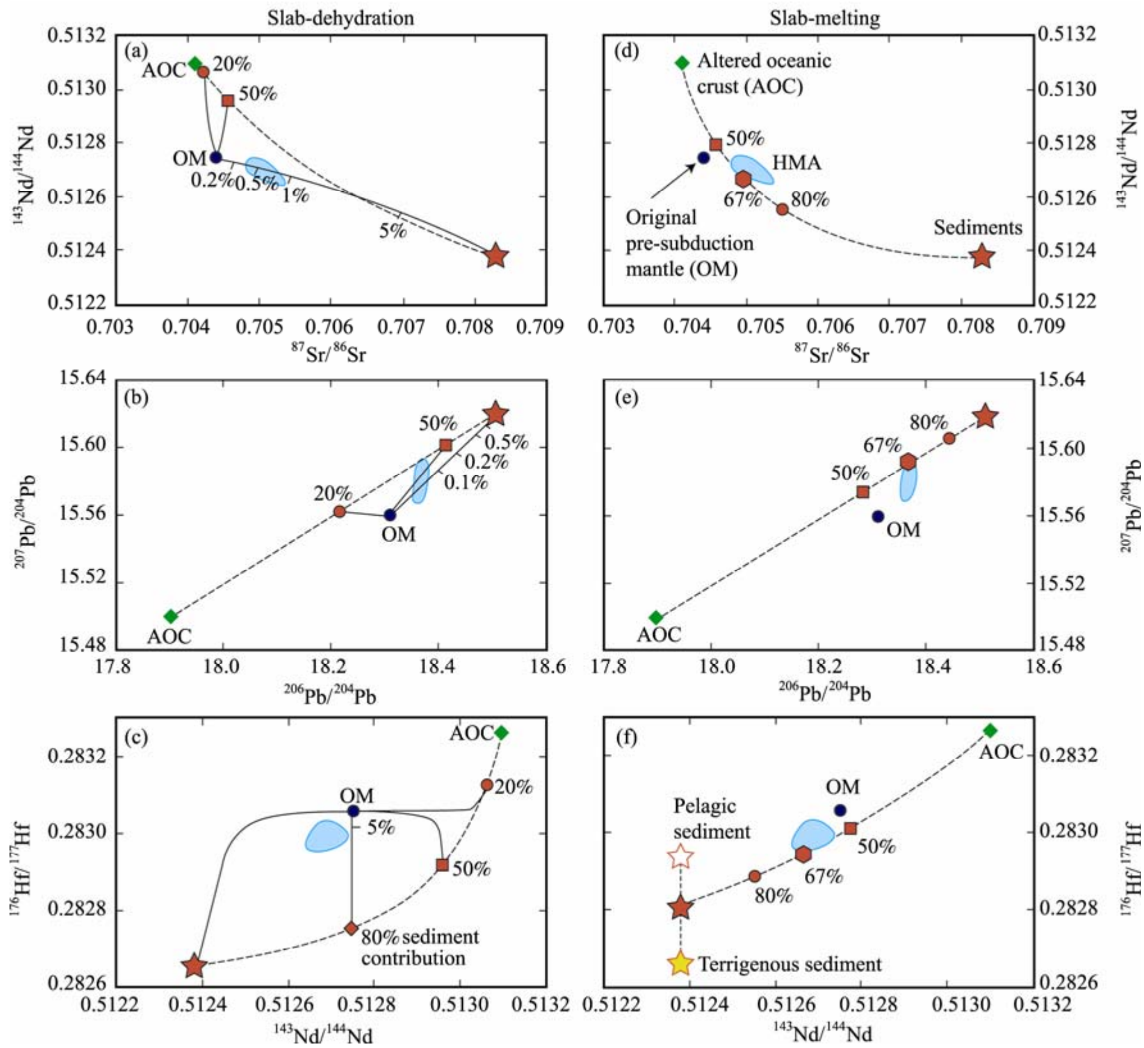

Figure 5 Sr-Nd-Pb-Hf isotopic characteristics of Setouchi HMAs (blue) and results of geochemical modelling for HMA magma production via slab-hydration ((a)—(c)) and slab-melting ((d)—(f)) after Tatsumi and Hanyu[60]. Element transport via slab-dehydration cannot quantitatively explain isotopic compositions of HMAs. On the other hand, melting of subducted altered oceanic crust (AOC) and sediments (sediment contribution is shown in numbers) can provide isotopic compositions of magmas close to Setouchi HMAs.

tered oceanic crust of the Shikoku Basin[61−63], experimentally/theoretically-derived solid-fluid and solid-melt partition coefficients[60,64,65], and the least metasomatized magma source composition estimated on SVB basalt compositions[60].

The results indicate that the incompatible trace element characteristics of HMA sanukitoids, which is similar to those of average continental crust (Figure 4), are well reproduced either by fluxing of slab-fluids or slab-melts that cause partial melting of the metasomatized mantle or by melt-mantle interaction, respectively. Can isotopic modelling identify a likely mechanism of producing HMA sanukitoid magmas?

The results of isotopic mixing calculations for the slab-dehydration model with different sediment contributions to slab-fluid formation are shown in Figures 5(a)—(c). Sr and Nd isotopic compositions of HMA sanukitoids can be quantitatively reproduced by 0.5% to 1% addition of sediment-derived aqueous fluids to the original, pre-subduction mantle (Figure 5(a)). However, a significantly smaller amount of sediment-derived fluid (<0.1%) is adequate to quantitatively account for Pb isotopic compositions of HMA sanukitoids (Figure 5(b)). Furthermore, to reproduce Hf isotopic characteristics of Setouchi HMAs, higher contributions from altered oceanic crust (~20%) is required (Figure 5(c)), which is inconsistent with modelling results on other isotopes. The modelling exercise therefore indicates that although a

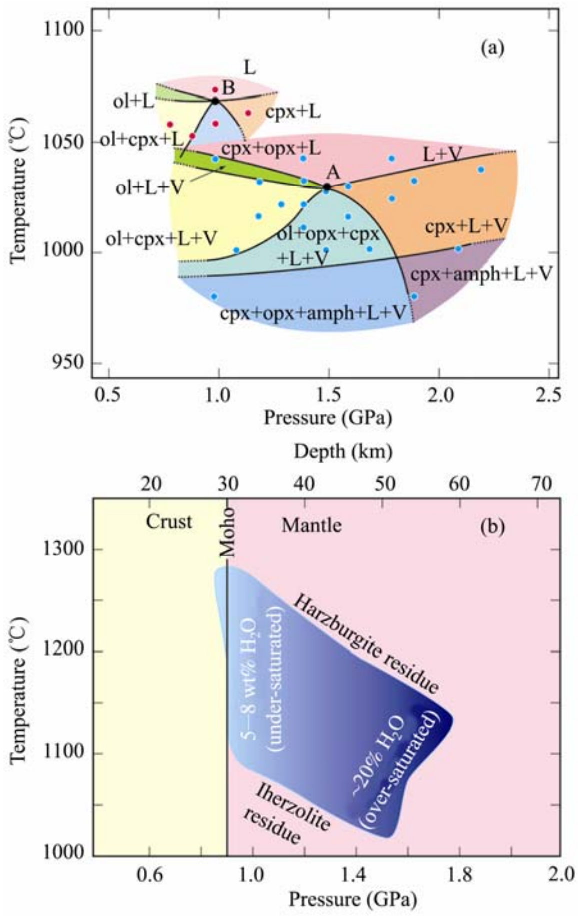

Figure 6 (a) Melting phase relations of HMA sanukitoid SD-261 under H_2O-oversaturated (~20% H_2O; blue points) and H_2O-undersaturated (~7% H_2O; red points) conditions[55]. Under these conditions, olivine, orthopyroxene and clinopyroxene are multiply saturated on the liquidus (A and B). L, liquid; V, vapour. (b) P-T-H_2O conditions of equilibration between HMA magmas and mantle peridotites[55−57].

mechanism including slab-dehydration and associated element transport can account for major and trace element characteristics of HMA sanukitoids, it fails to reproduce Sr, Nd, Pb, and Hf isotopic characteristics of HMA altogether.

The isotopic modelling results for slab melting (Figure 5(d)—(f)) demonstrate that the subducting altered oceanic crust (AOC) component, in addition to subducting sediments (a sediment contribution of 60%—70%), is required in slab-derived partial melts to reproduce the Sr-Nd-Pb isotopic characteristics of the HMA sanukitoids (Figure 5(d), (e)). The modelling based on $^{176}Hf/^{177}Hf$ compositions further suggests the involvement of subducted pelagic sediments, which possess similar Sr-Nd-Pb isotopic compositions but higher $^{176}Hf/^{177}Hf$ ratios than terrigenous sediments do (Figure 5(f)). It may thus be concluded that partial melting of subducting altered oceanic crust and terrigenous/pelagic sediments (a relative contribution of 1∶2) and subsequent melt-mantle interaction (1.08 of the residual melt fraction relative to the initial amount of slab-melt and 1.137 of the ratio of assimilation and crystallization increments[60]) can altogether explain the Sr-Nd-Pb-Hf isotopic and major/trace element compositions of HMA sanukitoids.

The geochemical modelling for HMA sanukitoid generation therefore favours a mechanism including partial melting of subducting sediments and altered oceanic crust, subsequent interaction of hydrous slab-melts with overlying mantle wedge peridotite. It should be stressed that the slab-derived melt finally equilibrate, via melt-mantle interactions, with peridotite at P-T-H_2O conditions as suggested by multiple-saturation experiments. The major and trace element modelling of the above processes[60,66] suggests ~5 wt% H_2O in the final melt, consistent with the experimental results (Figure 6). Although slab-melting is less likely in most modern subduction zones where rather old and cold lithosphere is downgoing, it may have taken place beneath the SVB because a young and “hot” lithosphere of the Shikoku Basin has been subducting beneath the arc[36,60].

3.3 Origin of differentiated sanukitoids

HMAs in SVB are temporally and spatially related to more differentiated sanukitoids, which possess major element compositions similar to average continental crust, and often form, together with differentiated sanukitoids, composite lava flows or dykes that show systematic changes in modal and chemical compositions within a single flow or a dyke. Such composite lavas may thus provide key constraints on differentiation processes of sanukitoid magmas and on continental crust formation.

The most spectacular example of a sanukitoid composite lava flow is the Oto-Zan lava flow on Shodo-Shima Island[67], which is up to 100 m in thickness and is composed of augite-olivine HMA at its base, via olivine-augite-orthopyroxene andesitic sanukitoid, to augite-orthopyroxene andesitic sanukitoid upwards (Figure 7). Elemental abundances also change accordingly with changing phenocryst assemblage although Sr-Nd-Pb isotopic compositions remain constant throughout the thickness of flow unit (Figure 7).

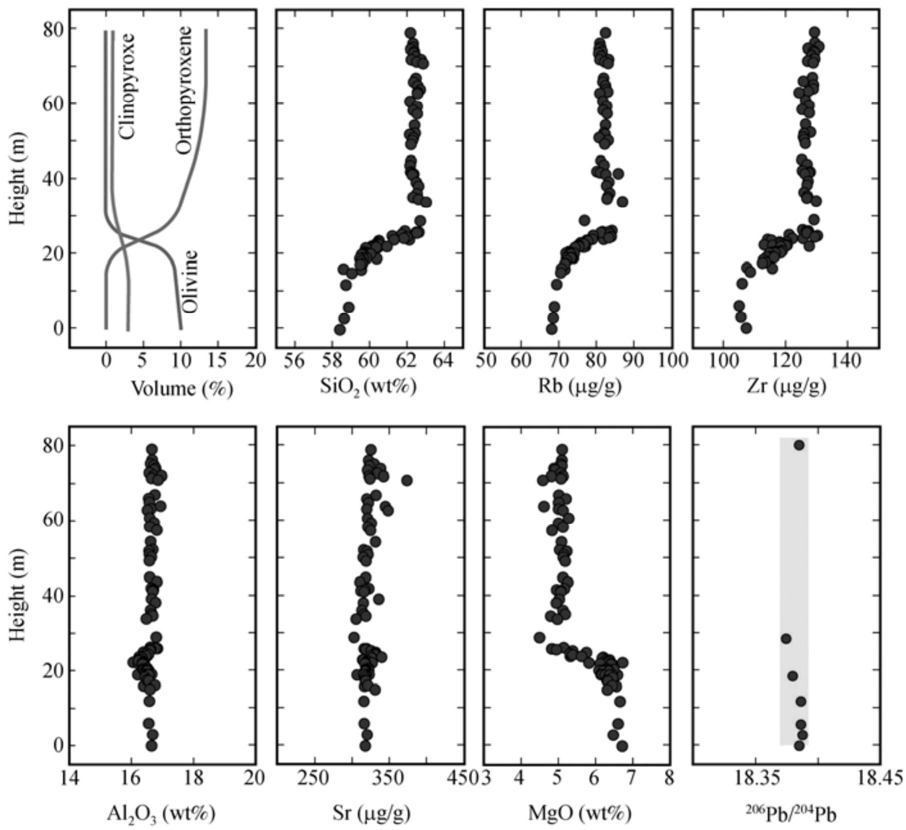

Figure 7 Variations of modal and chemical compositions throughout the Oto-Zan composite lava flow as a function of thickness from the base[67]. This lava flow includes HMAs at its base and differentiated sanukitoids in middle and upper parts of a single flow.

Melting experiments on the Oto-Zan HMA at 0.3 GPa in the presence of 0.7 to 2.1 wt% H_2O, i.e., H_2O-undersaturated conditions[67] define a liquid line of descent for this HMA magma (Figure 8), which does not fit with the compositional trend for Oto-Zan sanukitoids. It thus suggests that a simple crystallization differentiation is not a process for producing these magmas.

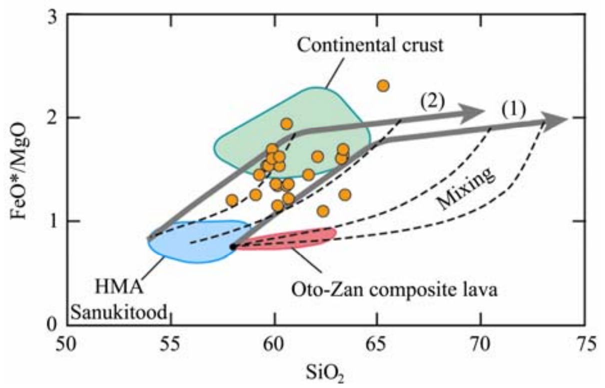

Figure 8 Compositions of HMA and differentiated sanukitoids (blue and orange) in the Setouchi volcanic belt, Oto-Zan composite lava flow, and continental crusts. Liquid lines of descent for two different HMAs derived from melting experiments[67] are shown by lines (1) and (2). Petrographic and compositional characteristics of differentiated sanukitoids can be best explained by mixing between HMA and its daughter felsic magmas, both produced by remelting of a solidified HMA pluton.

An important observation of the relatively differentiated sanukitoids is the fact that the upper portion of the Oto-Zan composite lava flow shows disequilibrium petrographic signatures, such as the occurrence of reversely and normally zoned pyroxene phenocrysts in a single specimen. One possible explanation for this observation is mixing of two magmas that have different compositions and temperatures. Constant isotopic compositions throughout the lava flow may suggest that mafic and felsic end-member magmas for mixing are co-magmatic. These observations, together with an experimentally-defined liquid line of descent and an observed compositional trend, led Tatsumi et al.[67] to the conclusion that Oto-Zan differentiated sanukitoid magmas are produced by mixing between a HMA sanukitoid melt and its differentiation product (Figure 8). However, we now face with a dilemma. Although HMA sanukitoid magmas should contain 5－8 wt% H_2O when they equilibrates with mantle peridotites, sanukitoids including those from Oto-Zan composite lava flow contain very little H_2O and are phenocryst-poor. In order to overcome this and to account for the above-mentioned magma mixing process, a possible scenario of emplacement, differentiation, and mixing of HMA sanukitoid magma is proposed:

(1) A hydrous HMA magma crystallizes extensively within the crust, resulting in the formation of HMAs pluton and causing liberation of H_2O from the magma system.

(2) The HMA pluton, in which interstitial rhyolitic melts still remain, is then heated from the base by intrusion of a high-T basalt magma, forming a H_2O-deficient HMA magma at the base of the pluton.

(3) During ascent, this secondary HMA magma entrains the overlying interstitial rhyolitic melt, resulting in varying extent of "self-mixing" and formation of a zoned magma reservoir, comprising more felsic magmas upwards.

(4) More effective upwelling of more mafic and hence less viscous magmas through a propagated vent finally results in the emplacement of the composite lava flow.

Differentiated sanukitoids in the SVB and the Oto-Zan sanukitoids generally share the same petrographic features, such as being compact, phenocryst poor, nearly dry, and containing disequilibrium phenocrysts. The chemical compositions of those differentiated sanukitoids can also be reasonably explained by self-mixing between a re-molten HMA magma and a differentiated residual melt that are produced within a HMA pluton (Figure 8). If we accept the assumption that magmas having similar compositions are produced by a similar process, then the bulk continental crust, whose compositions overlaps with those of differentiated sanukitoids, may also be created from HMA magmas via self-mixing processes. On the other hand, as the inferred liquid line of descent goes though the bulk continental crust compositions (Figure 8), it is also possible that the continental crust may be created by simple fractionation of HMA magmas[10,12].

4 Izu-Bonin-Mariana arc——a site of modern continental crust formation?

The previous section has reviewed the genesis of sanukitoids in SVB and its possible link to continental crust formation. Herein this mechanism, in which HMA plays a major role in making intermediate continental crust, is tested by examining crustal structure of the Izu-Bonin-Mariana (IBM) arc, an intra-oceanic arc extending 2800 km south of Japan (Figure 1). The reason for selecting IBM as a target is twofold. First, HMA (boninites) is the major lithology that characterizes magmatism at the initial stage of IBM evolution (~50 Ma), suggesting the possibility of the presence of boninitic rocks as one major lithology of the deep crust. Second, IBM is an arc with a well-developed middle crust with V_p = 6.0—6.3 km/s, which is identical to V_p of average continental crust[1], and hence possibly has a composition similar to average continental crust.

4.1 Seismic structure of IBM

An arc-crossing wide-angle OBS experiment at 32°15′N[68,69] defined ~ 20 km thick arc crust composed of four layers (Figures 1 and 9). The upper layer (V_p = 1.5—5.8 km/s) comprises sediments and volcanic rocks above a middle-crustal layer (V_p = 6.0—6.5 km/s). The lower crust has an upper layer (V_p = 6.8—6.9 km/s) overlying a thick basal crust layer (V_p = 7.1—7.3 km/s). The grossly layered structure of IBM crust discovered a decade ago is recently confirmed by a high-resolution seismic survey across the Mariana arc[70] (Figures 1 and 9). This survey also suggests a low seismic velocity in the uppermost mantle (V_p = 7.6—7.7 km/s), significantly slower than normal uppermost mantle (V_p = 8.0 km/s). This crustal structure has been identified along-strike beneath the northern and central IBM arc[71] (Figures 1 and 9). This characteristic middle crust layer has been also recognized elsewhere such as in the Tonga[72] and Kurile[73] arcs.

The 6.0—6.5 km/s mid-crustal layer is especially important because this velocity corresponds to a wide range of intermediate plutonic rocks and is close to that of continental crust (V_p = 6.4 km/s[1]). Plutonic xenoliths in arc lavas[74] also confirm the felsic to intermediate lithologies of the IBM middle crust. Furthermore, dredges from fault scarps both at IBM and Kyushu-Palau Ridge (KPR), a remnant paleo-IBM arc separated by Shikoku-Parece Vela Basin backarc rifting (Figure 2), sampled extensive exposures of tonalites[75]. A seismic study across the remnant KPR arc documented a velocity structure that is similar to that of the active IBM arc, including a 6 km/s middle crust layer and a thick, high velocity lower crust (Japanese Continental Shelf Project, unpublished data). The observed

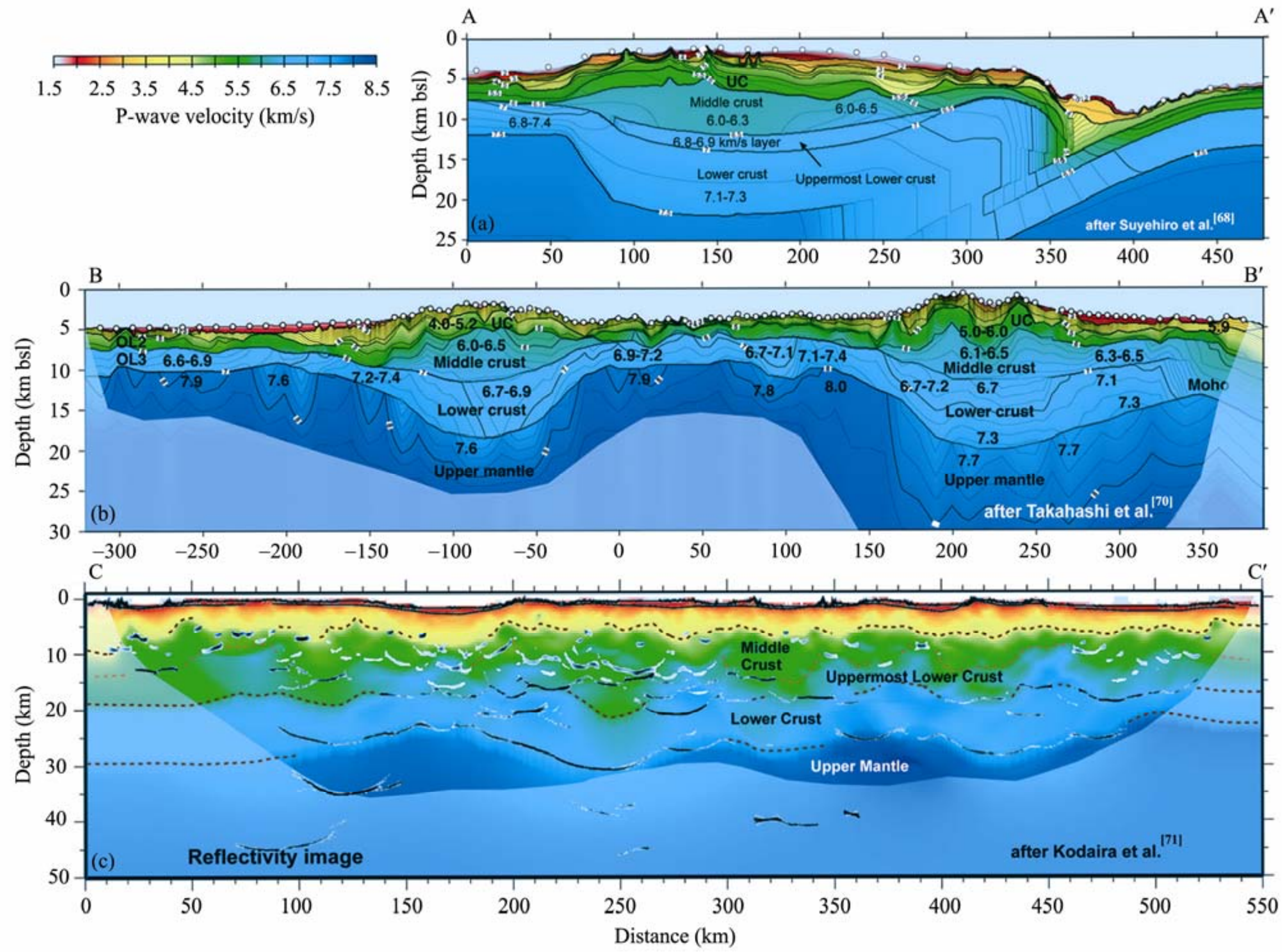

Figure 9 Seismic structure of the crust and upper mantle obtained for two across-arc sections (A-A′ and B-B′ in Figure 1) and one along-arc section (C-C′ in Figure 1)[68−71]. The IBM arc is characterized by the occurrence of middle crust layer having V_p of 6.0−6.5 km/s, the value close to V_p of the average continental crust[1].

structural and plutonic rock similarities of IBM and KPR suggest that formation of the intermediate middle crust may have begun prior to the opening of the Shikoku basin ~25 Ma, early in the evolution of the IBM arc system.

4.2 Seismic velocity estimates for IBM middle crust

As emphasized in Section 3.3, mantle-derived, H_2O-rich HMA magmas crystallize extensively within the crust, resulting in the formation of a HMA pluton. It is thus reasonable to speculate that the characteristic IBM middle crust is composed of such HMA plutons produced by solidification of boninitic magmas at the initial stage of IBM arc evolution. In order to test this hypothesis, seismic velocity (V_p) structure of the HMA plutons with compositions identical to a Setouchi HMA sanukitoid SD-261 and a boninite CH414) was estimated by assuming the following:

(1) 5 wt% H_2O is assumed for primary HMA magmas; it is the minimum H_2O content in mantle-derived primary HMA magmas as inferred from the results of melting experiments;

(2) the subsolidus mineral assemblage at an ideal middle crust condition (i.e., 10 km depth and 500℃) is modelled by using the free energy minimization algorithm, Perple_X[76];

(3) V_p of a HMA middle crust layer composed of inferred mineral assemblages is then calculated following the method of Hacker et al.[77].

The mineral assemblages and V_p of inferred HMA plutons are given in Table 1. Although V_p for a boninitic plutonic rock (6.7 km/s) is higher than the observed values, the calculated V_p is broadly close to both the observed V_p for the IBM middle crust and the average V_p of the continental crust, suggesting that HMA pluton is a good candidate for middle-crust-forming lithology. On the other hand, V_p of tonalite, which are often found from the submarine IBM or as xenoliths within IBM lavas, was measured at middle crust temperatures and pressures by Kitamura et al.[78]. The value (V_p = 6.3—6.6 km/s) is also consistent with the observed V_p of the middle crust layer. It thus suggests that lithologies of the IBM middle crust cannot be specified solely on the basis of seismic velocity data. Recently, Takahashi et al.[70] and Tatsumi et al.[79] examined evolution of IBM arc crust and subarc mantle by petrologic modelling and suggested that the tonalitic middle crust model can well explain the seismic velocity structure of this arc. An IODP (Integrated Ocean Drilling Program: http://www.iodp.org) drilling project is planned to directly sample the middle crust rocks and to test the hypothesis.

Table 1 V_p calculations for HMAs

	Boninite	Sanukitoid
SiO_2	55.2	54.8
Al_2O_3	10.6	15.2
FeO*	8.4	6.1
MgO	11.8	7.1
CaO	7.4	6.9
Na_2O	1.6	2.8
K_2O	0.0	2.2
H_2O	5.0	5.0
Total	100.0	100.0
Pressure (GPa)	0.33	0.33
Tempreature (℃)	500	500
Quartz	28.7	21.2
Plagioclase	0.6	15.2
K-feldspar	0.0	5.9
Hornbrende	53.5	45.0
Phlogopite	0.0	5.9
Muscovite	0.0	6.8
Clinoclore	17.2	0.0
Total	100.0	100.0
V_p (km/s)	6.67	6.33
V_s (km/s)	3.99	3.68

5 Discussion and summary

Setouchi sanukitoids including HMAs are distinct petrographically in that they are less-porphyritic (generally <10% total phenocrysts), plagioclase-aphyric, and compact, and are produced by a complex combined processes of slab melting, melt-mantle reactions, solidification within the crust, re-melting of HMA plutons, and melt mixing between felsic and intermediate compositions. Melting, not dehydration, of subducted sediments and oceanic crust took place beneath the SVB under unusual Archean-like tectonic settings that include subduction of a young and "hot" slab into hot upper mantle. This tectonic feature, together with the compositional similarity between differentiated sanukitoids and bulk continental crusts, suggests an important role of HMA magmatism in the continental crust formation.

The IBM, where HMA magmatism took place at the early stage of arc evolution, may be the site of modern continental crust creation; the presence of volumetrically significant middle crust with V_p close to that of average continental crust. This characteristic V_p can be explained by the emplacement of either HMA or tonalitic plutons. The tonalitic middle crust model is more likely because (1) tonalitic rocks have been commonly dredged in the IBM whereas (2) the boninitic magmatism is limited to the early stage of the IBM arc evolution. However, further effort for direct sampling of the middle crust layer is needed for identifying the mechanism of continental crust formation.

If we accept slab-melting-induced HMA sanukitoid magma generation and differentiation as an effective mechanism of early continental crust formation, then the melting residue within the subducting lithosphere would have been stored somewhere in the deep mantle and could form a distinct deep mantle geochemical reservoir. Geochemical modelling of isotopic signatures of such melting residues[80] suggests that the isotopic characteristics of slab residues do not fit with those of any known geochemical reservoir in the deep mantle, such as EMI, EMII, or HIMU that have been proposed for explaining the compositional diversity of ocean island basalts. In order to better understand the role of HMA magmatism in continental crust formation, the origin of Archean HMAs and the geochemical characteristics of recycled crustal materials should be further examined.

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