https://doi.org/10.5194/se-2019-116
Preprint. Discussion started: 25 July 2019

Solid Earth Discussions

Alkali basalt from the Seifu seamount of the Japan Sea: post-spreading magmatism in the back-arc region

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Abstract. We report geochemical characteristics and Ar-Ar dating of a basalt dredged from the Seifu Seamount (SSM-basalt), located at northeast of the Tsushima Basin in the southwest Japan Sea, which is one of the western Pacific back-arc basin swarm. A plateau age of 8.33 ± 0.15 Ma (2σ) was obtained by the ^{40}Ar-^{39}Ar age spectrum of SSM-basalt. The SSM-basalt (8.3 Ma) was formed at an early stage after the termination of the Japan Sea back-arc opening. The SSM-basalt is high-K to shoshonitic alkaline basalt and is characterized by enrichment of light rare earth element (REE). The trace element pattern of the SSM-basalt is similar to Ocean island-type basalt (OIB) whereas Yb_{PM} (=6) is distinctively higher than that of OIB, indicating of its formation by the low degree melting of the source mantle under spinel peridotite stability field. The Nd-Sr and Pb isotope compositions of the SSM-basalt are offset from the compositional trend of the Japan Sea back-arc basin basalts. The Sr-Nd isotope relationship of the SSM-basalt suggest its source can be formed by deplete MORB mantle source mixing with EM1-like component. The SSM basalt was formed as a post-back-arc spreading magmatism by low degree of partial melting of a portion that is easily melted in the upwelling asthenosphere associated with the main back-arc magmatism.

Keywords: Back-arc magmatism, Alkali basalt, Japan Sea, Pos-backarc magmatism

https://doi.org/10.5194/se-2019-116
Preprint. Discussion started: 25 July 2019

1 Introduction

Many studies reported back-arc magmatisms during back-arc rifting/spreading (e.g., Martinez *et al.*, 2001; Pearce and Stern, 2006). Sato *et al.* (2002) proposed that "post back-arc spreading magmatism" which is the formation and eruption of enriched basalts during the last stage of back-arc basin spreading and/or after cessation of spreading, as a common process in the late stage of back-arc development. Ishizuka *et al.* (2009) also examined "post back-arc spreading magmatism" in the Shikoku Basin of the Izu-Bonin arc-back-arc system and suggested that it is characterized by two distinctive magma types.

The Sea of Japan (Japan Sea, hereafter) is located in the northern part of the western Pacific back-arc basin swarm and is regarded as one of the typical inactivated back-arc basins developed between island arc and continent (Tamaki and Honza, 1985; Uyeda and Kanamori, 1979). Numerous geophysical surveys were carried out to elucidate the architecture of the Japan Sea back-arc basin and its formation processes (e.g., Lee et al., 1999; Yoon et al., 2014; Sato et al., 2014). Geophysical data coupled with direct sampling from the ocean floor including the Ocean Drilling Program (ODP) revealed the formation process of the northern Japan Sea (Tamaki et al., 1992) (Fig. 1). The breakup of the lithosphere and oceanic floor spreading were initiated from the eastern margin of continent at 32-28 Ma, and back-arc magmatisms were terminated at 18-15 Ma (Tamaki et al., 1992). The basins are mainly composed of extended continental crust and oceanic crust. Several seamounts and islands are distributed, and form chained array (Fig. 1). The radiometric age of volcanic rocks from the seamounts in the Yamato basin is 6-13 Ma (Kaneoka et al., 1990; Kaneoka and Yuasa, 1988) whereas that of the Ulleung Island volcanism in the Tsushima basin (Ulleung Basin) is distinctively younger than 2 Ma (Kim et al., 1999a).

Pouclet et al. (1995) summarized magmatic history of the circum-Japan Sea area including the southwest Japan arc, northeast China and the back-arc basin. The alkali basalt magmatism is frequent at the southwest Japan arc after termination of the Japan Sea opening (< 4 Ma). Kim and Yoon (2017) recently suggested that the seamount chain in the Tsushima Basin was formed by the post-back arc spreading magmatism based on the geochemical data of alkali basalt samples studied by Lee et al. (2011).

A basaltic block containing peridotite xenoliths was dredged from the Seifu Seamount (Ninomiya et al., 2007), located at northeast of the Tsushima Basin in the southwest Japan Sea (Fig. 1). Radiometric dating, coupled with geochemical signatures, of volcanic rocks from the seamount would be the most direct method of addressing the tectonic and magmatic history of the southwest Japan Sea. Here, we report the petrological, geochemical and geochronological data of the basalt sample from the Seifu Seamount, in comparing with data of volcanic rocks in the circum-Japan Sea area and discuss its origin in the context of post back-arc spreading magmatism.

2 Geological background and sample description

The Seifu Seamount is located at the northeastern margin of the Tsushima Basin, where is a junction of three basins between continental crustal fragments (Fig. 1). The Tsushima Basin is now geomorphologically connected to southwestern margin of the Japan Basin by the Ulleung Interplain Gap (UIG) and is separated from the Yamato Basin by the Yamato Rise and the Oki

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Bank. A studied basalt sample was dredged from the Seifu Seamount by the KT85-15 cruise of R/V Tansei-maru of the Ocean Research Institute, University of Tokyo, in 1985 (Dredge Station No. KT85-15 D-3: 38°12.20'-12.80'N, 132°34.70'E) (Shimamura et al., 1987). Lee et al. (1999) proposed that the basement of the Tsushima Basin is thick oceanic crust formed by incomplete spreading as well as extending of continental crust caused by westward propagation of spreading during the Japan Sea opening. The direction of the Tsushima Basin opening is N-S, evidenced from the NE-SW orientation of ridge-like feature parallel to the Yamato Basin spreading (Lee et al., 1999). Kim et al. (2011) revealed that the chained seamounts buried by sediments are placed along the UIG. They expected that the volcanic ages of the UIG seamount chain are the same as that of the Yamato Seamount chain (Kim et al., 2011a). The Seifu seamount is seated on the Japan Basin of further ENE part of the UIG seamount chain.

The basalt sample contains peridotite xenoliths with variable size from a few millimetres to usually < 3cm (up to 10 cm) and their-derived xenocrysts (Ninomiya et al., 2007). The basalt sample shows porphyritic texture. The phenocrysts of the basalt sample are mainly olivine with small amounts of plagioclase, orthopyroxene, clinopyroxene and spinel. Plagioclase phenocryst shows anhedral with albite twins, oscillatory zoning and dusty zone, and is sometimes surrounded by tiny plagioclase crystals that is the same size as the groundmass. Orthopyroxene phenocrysts are rimmed by fine-grained mineral aggregate, which is similar to those found in orthopyroxene in peridotite xenoliths, indicating that all orthopyroxene phenocrysts are of xenocryst origin. Spinel phenocryst, up to 0.5 mm in size, shows anhedral and rounded in shape. The groundmass of the sample is crystalline and shows intersertal textures mainly consisting of prismatic plagioclase with small amounts of olivine now partly serpentinized/altered, opaque mineral (ilmenite and titanomagnetite), apatite and clinopyroxene. The prismatic plagioclase crystals in the groundmass sometimes show weak trachytic texture.

3 Geochemistry and dating

3.1 Analytical method

In preparation of the powdered sample, crustal and mantle xenolith fragments were removed as possible. Whole rock major- and trace-element compositions of basalt from the Seifu Seamount (SSM-basalt) are determined by EPMA and LA-ICP-MS at Kanazawa University. For EPMA and LA-ICP-MS measurements, fused whole-rock glass prepared by a direct fusion method was also used. Details are shown in Tamura et al. (2015). The major-element composition was also determined by XRF in Senshu University (Sato, 2010). The analytical procedure used for chemical separation and mass spectrometry for Sr, Nd and Pb isotope determinations was outlined by Yoshikawa and Nakamura (1993), Shibata and Yoshikawa (2004) and Miyazaki et al. (2003). Mass spectrometry was performed on a Thermo-FinniganMAT262 equipped with nine Faraday cups, using a static multi-collection mode. Normalizing factors used to correct for isotopic fractionation in the Sr, Nd and Pb isotope analyses were $^{86}Sr/^{88}Sr = 0.1194$, $^{146}Nd/^{144}Nd = 0.7219$, and 0.061 per atomic mass unit, respectively. Measured isotopic ratios for standard materials were $^{87}Sr/^{86}Sr = 0.710261 \pm 0.000018$ ($2\sigma_m$) for NIST 987, $^{143}Nd/^{144}Nd = 0.511842 \pm 0.000018$ ($2\sigma_m$) for La Jolla and $^{206}Pb/^{204}Pb = 16.937 \pm 0.006$ (2σ), $^{207}Pb/^{204}Pb = 15.491 \pm 0.0048$($2\sigma$), $^{208}Pb/^{204}Pb = 36.721 \pm 0.026$ (2σ) for

NIST 981. Total procedural blanks for Sr, Nd and Pb were less than 100, 10 and 10 pg, respectively. The geochemical data of the SSM-basalt is summarized in supplementary table S1.

We conducted the $^{40}Ar/^{39}Ar$ incremental heating analysis to obtain the radiometric age. The sample were crushed into a few mm grains, and separated fresh groundmass. Samples were wrapped in Al foil and contained in an Al capsule (70 mm in length, 10 mm in diameter) with flux monitors biotite of EB-1 (91.4 ± 0.5 Ma; Iwata, 1997), K_2SO_4 and CaF_2. The samples were irradiated for 24 hours in the Japan Material Testing Reactor (JMTR). During the irradiation, the samples were shielded by Cd-foil in order to reduce thermal neutron-induced ^{40}Ar from ^{40}K (Saito, 1994). The Ar extraction and Ar isotopic analyses were done at Radioisotope Center, University of Tokyo. During incremental heating, gases were extracted in 8 steps between 600 and 1300°C. The analytical methods are described by Ebisawa et al. (2004).

3.2. Results

The SiO_2 and TiO_2 contents of the SSM-basalt are 49 wt% and 1.9 wt%, respectively. Total alkali content ($Na_2O + K_2O$) is 5.8 wt% (Na_2O and K_2O are 4.0 wt% and 1.8 wt%, respectively). The SSM-basalt corresponds to alkaline basalt in terms of total alkali vs. SiO_2 discrimination diagram (Miyashiro, 1978) (Fig. 2) and high-K to shoshonitic composition subdivided by Le Maitre (1989). Primitive mantle normalized trace-element pattern is shown in Figure 3. The trace-element composition of the SSM-basalt is characterized by enrichment of light rare earth element (REE) and no apparent anomalies in high-field strength elements (HFSE) relative to neighbouring REEs. $La_{PM=\text{primitive normalized value}}$ and $(La/Yb)_{PM}$ ratio are 54 and 9, respectively. $(Nb/La)_{PM}$ and $(Ta/La)_{PM}$ are around 1.5 (Fig. 4a). The trace element patterns of the SSM-basalt is equivalent to those of ocean Island-type basalt (OIB). However, Yb_{PM} (=6) is distinctively higher than that of OIB (Fig. 4b). Isotopic ratios of $^{143}Nd/^{144}Nd$ and and $^{87}Sr/^{86}Sr$ are 0.512903 and 0.703476, respectively (Fig, 5). Pb isotopic ratio of the SSM basalt is $^{206}Pb/^{204}Pb = 17.664$, $^{207}Pb/^{204}Pb = 15.434$ and $^{208}Pb/^{204}Pb = 37.308$ (Fig. 5).

The ^{40}Ar-^{39}Ar age spectrum of SSM-basalt shows a plateau age of 8.33 ± 0.15 Ma (2σ) in 6 fractions at lower temperature (Fig. 6), where the age should be accepted as the best estimate because the initial $^{40}Ar/^{36}Ar$ ratio corresponds to the atmospheric ratio (295.5) in the inverse isochrones (Fig. 6).

4 Discussions

4.1 Timing of the SSM basaltic magmatism

Basalt intervals were recovered from the Japan Sea basin by the ODP Leg 127/128 cruises: the Yamato Basin (Site 794 and Site 797) and Japan Basin (Site 795) (e.g., Tamaki et al., 1992) (Fig. 1). The Ar-Ar dating of these basalts indicated that they were formed as back-arc magmatism at 18-21 Ma (Yamato Basin) and 15-25 Ma (Japan Basin), respectively (Kaneoka et al., 1992). The back-arc basin basalt (BABB) magmatism also caused the extension of continental crust until 15 Ma (e.g., Tamaki et al., 1992; Kaneoka et al., 1992). The Ar-Ar dating of andesitic rocks from the Yamato Basin seamounts is 11-17 Ma (Kaneoka et al., 1990). A volcanic age of the SSM-basalt (8.3 Ma) indicates that the SSM was formed by the magmatism at

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an early stage after termination of the Japan Sea opening and is clearly distinguished form the volcanisms of the Ulleung and Jejudo islands (< 2 Ma).

4.2. Origin of the SSM basalt and its tectonic setting

The trace-element patterns of the SSM alkali basalt is characterized by non-depletion of Nb and Ta relative to light-REE (e.g., Nb_{PM}/La_{PM} = 1.5), and by high heavy-REE abundances (e.g., Yb_{PM} = 6) (Fig. 4). They are similar to OIB-type alkali basalts from oceanic islands (e.g., Ulleung Island) and the continental region of the east China whereas the high HREEs abundance distinguishes the SSM basalt from other alkali basalts in the circum-Japan Sea area (Fig 4). Alkali basalts with high Nb/La ratio and high-HREEs abundance have been also reported from the South Korean Plateau, located at the east of the SSM (Lee et al., 2011) (Fig. 4c). Relatively high HREEs in the SSM basalt suggest that garnet was not a residual phase in the source mantle. The high-Nb SSM basalt with a high-HREEs can be formed by the low degree melting of the source mantle under pressure conditions shallower than garnet peridotite stability field.

According to key element ratios for detecting of slab-derived components in volcanic rocks, the SSM basalt is located on global MORB-OIB compositions whereas the Japan Sea BABB is geochemically characterized by MORB (D-type) to island arc tholeiite–ocean island tholeiite (E-type) compositions (Allan and Gorton, 2006; Hirahara et al., 2015) (Fig. 5). The Nd-Sr-Pb isotopic compositions of the SSM basalt are depleted and are more similar to depleted (D)-type of the Japan Sea BABB than those of other circum-Japan alkali basalts (Fig. 5). The SSM basalt source can be formed by Depleted MORB Mantle (DMM) mixing with enrich mantle portion of the EM1-like source in the Sr-Nd isotope diagram (Fig. 5). Hirahara et al. (2015) suggested that geochemical characteristics of the Japan Sea BABB are plotted at between depleted mantle component and slab-derived component. The D-type basalt was formed from depleted mantle source with very minor to nil contributions from the slab-derived component. Forward model calculations on the Japan Sea BABB indicated that the melting conditions for the D-type basalts are deeper and hotter than those of MORB (Hirahara et al., 2015). These geochemical characteristics of the SSM basalt suggest that slab-component contributions to the origin of the SSM basalt was very minor, indicating that magmatism for the formation of the SSM basalt melt was likely caused by a source heterogeneity in the asthenospheric mantle. The age and geochemical constraints of the SSM basalt suggest that upwelling of the Japan sea back-arc asthenosphere continued even after the main volcanism of back-arc spreading, so that a low degree of partial melting occurred in a mantle component, which is easily melted, of the upwelling asthenosphere.

The Nd, Sr and Pb isotopic compositions of the SSM-basalt are also clearly different from those of alkali basalts in the circum-Japan Sea area (Fig. 5). The SSM-basalt has depleted isotopic compositions: high-$^{143}Nd/^{144}Nd$ and low-$^{87}Sr/^{86}Sr$ ratios. In the Nd-Sr and Pb isotope diagrams, the SSM-basalt is plotted slightly offset from the compositional trend of the Japan Sea BABB (Fig. 5). The alkali basalts from the South Korean Plateau also have distinctive Nd-Sr compositions similar to the SSM basalt (Fig. 5a) whereas their Pb isotopic compositions are comparable to the compositional trend of Japan sea BABB (Fig. 5bc). Remarkably, the isotopic compositions of the SSM basalt are comparable to those of 6-13 Ma trachyandesite from seamounts in the Yamato basin (Tatsumoto and Nakamura, 1991).

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Based on the geochemical data of the South Korean Plateau basalt (SKP basalt) and the tectonic history of the Tsushima basin, Kim and Yoon (2017) concluded that the SKP-basalt was a product of post-spreading magmatism. The age of SKP basalts has not been, however, determined yet. Many submarine volcanoes including seamounts buried by sediments were discovered in the Japan Sea Basin (e.g., Kim et al., 2011b; Kimura et al., 1987) (Fig, 1). These submarine volcanoes and seamounts were also likely formed by the post back-arc spreading.

Sato et al. (2002) reported post-spreading magmatism that formed the seamounts composed of the enriched basalt magma in the back-arc region of the Shikoku basin during and/or after the last stage of the back-arc spreading. They pointed out that the post-spreading magmatism is a common process at the back-arc basins in the western Pacific region. For example, in contrast to the spreading magmatism (30-15 Ma), enriched basalt volcanisms (Kinan Seamount Chain of Fig. 1: 7-15 Ma) were reported as the post-spreading magmatism in the Shikoku Basin in the Izu-Bonin back-arc system (Sato et al., 2002; Ishizuka et al., 2009). The age of the SSM basalt (8.3 Ma), which is about ~7 Mys after termination of the Japan Sea opening (~15 Ma), is comparable to the period of the post-spreading magmatism in the Shikoku Basin. Ishizuka et al., (2009) invoked that the post back-arc spreading magmatism in the Shikoku Basin is caused by heterogeneities of the asthenospheric mantle, which is upwelling and produces BABB melts beneath the back-arc spreading center. It is interesting to note that trace element compositions of the Kinan Seamount Chain alkali basalts are similar to those of the SSM basalt.

Because of the very minor contributions of slab component to the SSM basalt source, the SSM basalt is a window to explore mantle components beneath the Japan Sea back-arc region of the western Pacific region. Alkali basalts were also reported from the Philippine Sea plate (Kinan Seamount Chains: Sato et al., 2002; Ishizuka et al., 2009) and the Pacific plate (Petit spot magmas, see Fig. 1: Hirano et al., 2006; Machida et al., 2009) near the Japan Sea in the western Pacific region. The geochemical characteristics of the SSM basalt are similar to those of the Kinan Seamount Chains in the Philippine sea plate, but different from those of the petit spot magmas in the Pacific plate (Figs. 3,4,5). The involvement of EM1 component in melt source is minor but is widely observed both in the Japan Sea and Shikoku basin in the western Pacific region.

5 Conclusion

A basaltic block containing peridotite xenoliths was dredged from the Seifu Seamount located at the northeastern margin of the Tsushima Basin of the Japan Sea. Geochemical and geochronological data of the Seifu Seamount basalt sample (SSM-basalt) are summarized as follows. The SSM-basalt is high-K to shoshonitic alkaline basalt with enrichment of light rare earth element (REE) having no anomalies of high-field strength elements (HFSE) relative to neighbouring REEs. The trace element patterns of the SSM-basalt is equivalent to those of ocean Island-type basalt (OIB). The SSM-basalt is, however, characterized by high heavy-REE abundances: La_{PM} and $(La/Yb)_{PM}$ ratio are 54 and 9, respectively. Isotopic ratios are $^{143}Nd/^{144}Nd = 0.5129$, $^{87}Sr/^{86}Sr = 0.703476$, $^{206}Pb/^{204}Pb = 17.664$, $^{207}Pb/^{204}Pb = 15.434$ and $^{208}Pb/^{204}Pb = 37.308$. The ^{40}Ar-^{39}Ar of SSM-basalt shows a plateau age of 8.33 ± 0.15 Ma (2σ).

The age of the SSM basalt (8.3 Ma) is about ~7 Mys after termination of the Japan Sea opening (~15 Ma). Trace element patters of the SSM basalt can be formed by the low degree of partial melting under pressure conditions shallower than

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garnet peridotite stability field. We concluded that the SSM basalt was a result of post back-arc magmatisms of the Japan sea back-arc spreading. The magmatism for the formation of the SSM basalt melt was likely caused by a source heterogeneity in the asthenospheric mantle. The SSM basalt source has geochemical characteristics of Depleted MORB Mantle (DMM) mixing with enrich mantle portion of the EM1-like source. Geochemical similarities of the post back-arc magmatisms in the Japan Sea and Shikoku basin of the Philippine Sea suggest that the EM1 component is minor but is likely widely spread to melt source in the western Pacific region.

6 Acknowledgements

We are grateful to Captain K. Miki, Mr. T. Kato and the other crew members of the R/V Wakashio Maru, Captain H. Igarashi and the crew members of the R/V Tansei Maru, and scientists on these scientific cruises. We also thank T. Ishii for providing the studied samples. This work is partly supported by Kanazawa University SAKIGAKE 2018 (T.M.) and a Grant-in-Aid for Scientific Research of the Ministry of Education Culture, Sports, Science and Technology of Japan (No. 16H05741 & 19H01990: T.M.).

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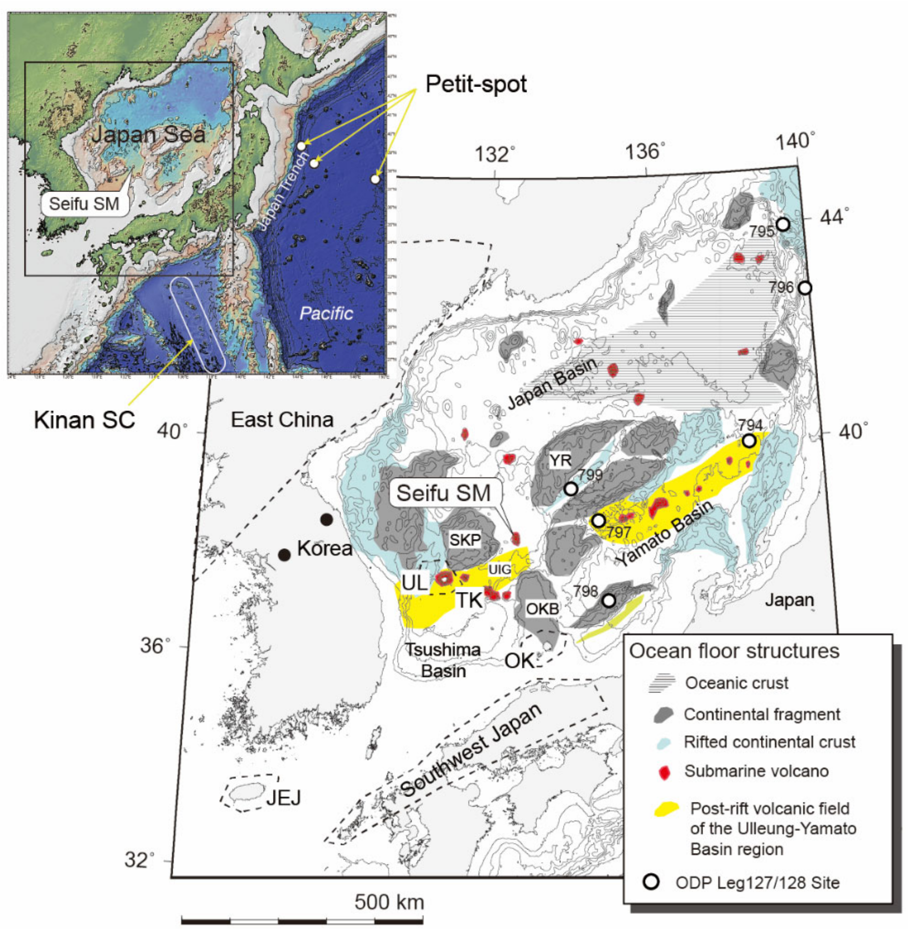

Figure 1: Location of the Seifu Seamount (SM) and distributions of ocean floor structures (YR: Yamato Rise, OKB: Oki Bank, SKP: South Korea Plateau, and UIG: Ulleung Interplain Gap) in the Japan Sea (modified after Tamaki 1988; Tamaki et al., 1992; Kim et al., 2011). The oceanic crust is only distributed in the Japan Basin. Note that the Seifu Seamount is built on the extended continental crust (white area) in the Japan Basin, where is between the seamount chains (submarine volcanos) of UIG and Yamato Basin, such as the post-rift volcanic field (Kim et al., 2011). ODP Leg 127/128 Sites recovering "back-arc basin basalt (BABB)" from the Yamato Basin (Tamaki et al., 1992) and main localities of basalts in the circum-Japan Sea area are shown (Southwest Japan including San-in, San-yo and NW Kyushu, OK: Oki Island, UL: Ulleung Island, CHJ: Cheju Island, TK: Takesima Island, Korea and East China). Petit-spot and Kinan SC (Seamount Chain) are localities of alkali basalts from Pacific and Philippine Sea plates, respectively (Hirano et al., 2006; Ishizuka et al., 2009). The topographic and bathymetric maps were prepared using GeoMapApp (Ryan et al., 2009).

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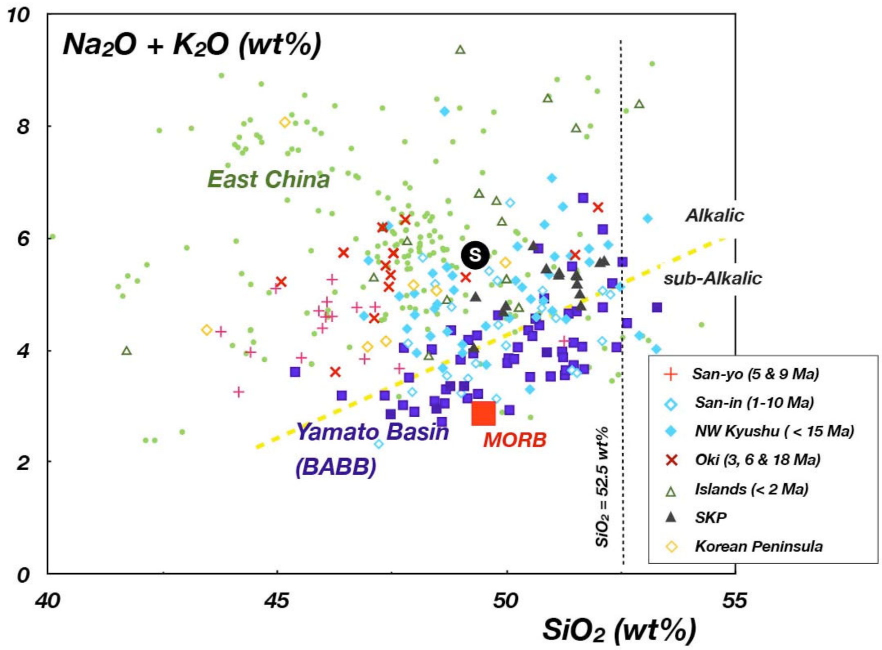

Figure 2: Whole-rock SiO_2 and total alkali (Na_2O+K_2O) contents of basalt from the Seifu Seamount (black circle with S). Alkali and sub-alkali boundary lines from Miyashiro (1978). Basalts from the circum-Japan Sea area are shown for comparison. BABB: back-arc basin basalt from the Yamato Basin and Japan Basin. Data source: Dostal et al. (1988), Nakamura et al. (1989, 1990), Allan and Gorton (1992), Iwamori (1992), Miyake (1994), Uto et al. (1994 , 2004), Basu et al. (1991), Chung (1999), Kim et al. (1999b), Pouclet et al. (1995), Zou et al. (2000), Zhang et al. (2002), Choi et al., (2006), Yan and Zhao (2008), Lee et al. (2011) and Hirahara et al. (2015).

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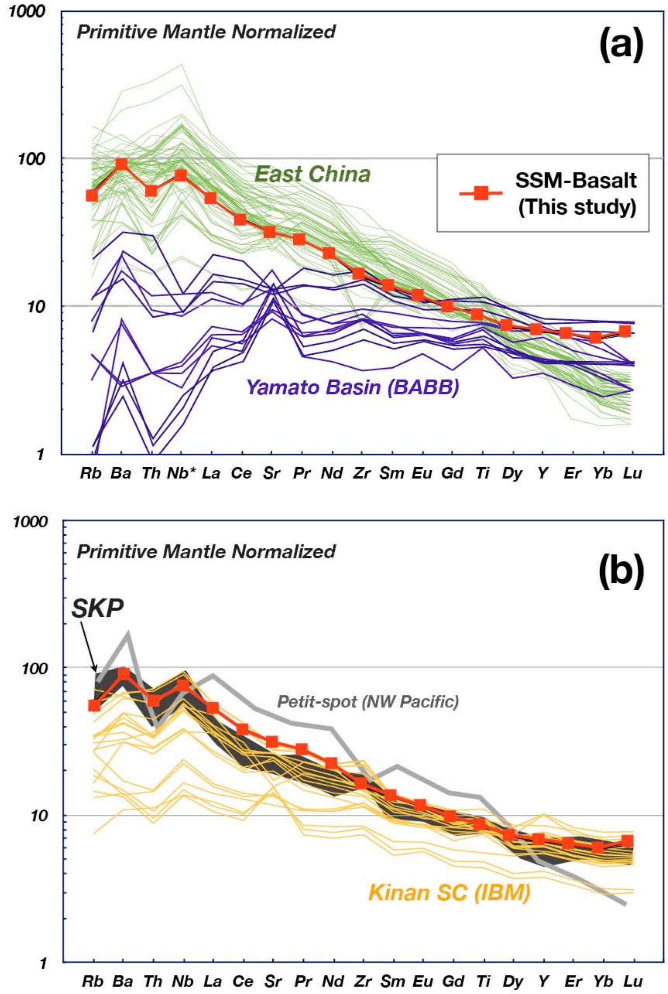

Figure 3: Primitive mantle normalized trace-element pattern of basalt from the Seifu Seamount (SSM-basalt). Normalized values (primitive mantle) from Sun and McDonough (1989). Representative basalt from the circum-Japan Sea area are shown for comparison (see Figure 2 for data source); back-arc basin basalt (BABB) from Yamato Basin and alkali basalt from east China in (a). Alkali basalt from South Korean Plateau (SKP) (black field) in (b). In (b), Kinan SC (seamount chain) in Shikoku basin (Izu-Bonin-Mariana region) and Petit-spot in northwestern Pacific Plate are from Ishizuka et al. (2009) and Hirano et al. (2006), respectively. Nb* in (a) : Ta data is used for no Nb data provided in references, assuming that $Nb_{PM}/Ta_{PM}=1$.

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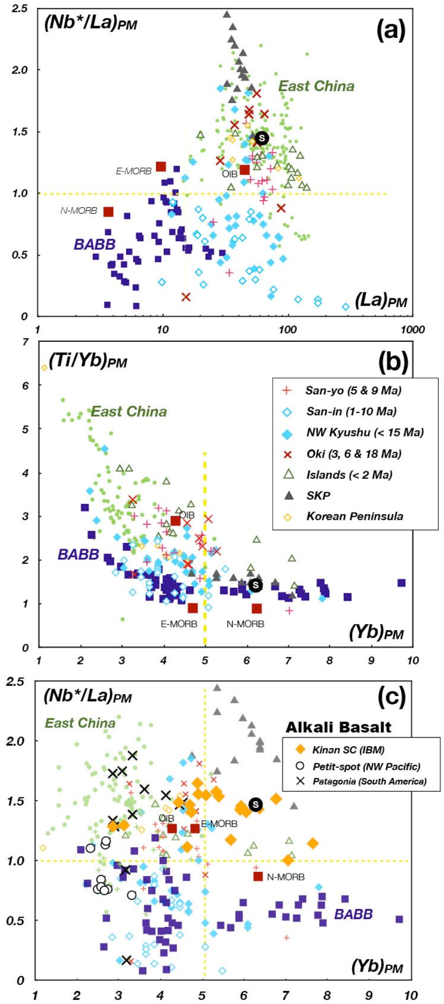

Figure 4: Compositional relationship between HFSE and REE of SSM-basalt (black circle with S) and basalts form the circum-Japan Sea area (SiO_2 < 52.5 wt%). Islands: Ulleung Island, Jejudo Island and Takeshima Island. SKP: South Korean Plateau. Normalized values (primitive mantle) and reference basalt data (MORB and OIB) form Sun and McDonough (1989). (a) Nb-La diagram. Nb*: Ta data is used for no Nb data provided in references, assuming that Nb_{PM}/Ta_{PM}=1. (b) Ti-Yb diagram. For reference data source, see Figures 2. (c) Discrimination of basalts based on compositional relationships in (a) and (b). Note that high-Nb/La ratio and -Yb basalts are rarely reported form the circum-Japan Sea area. Alkali basalts from the Kinan Seamount Chain (SC) in the Shikoku basin (Izu-Bonin-Mariana region) (Ishizuka et al., 2009), Petit-spot at northwestern Pacific plate (Hirano et al., 2006) and Patagonia (south America) (Stern et al., 1990) are shown for comparison.

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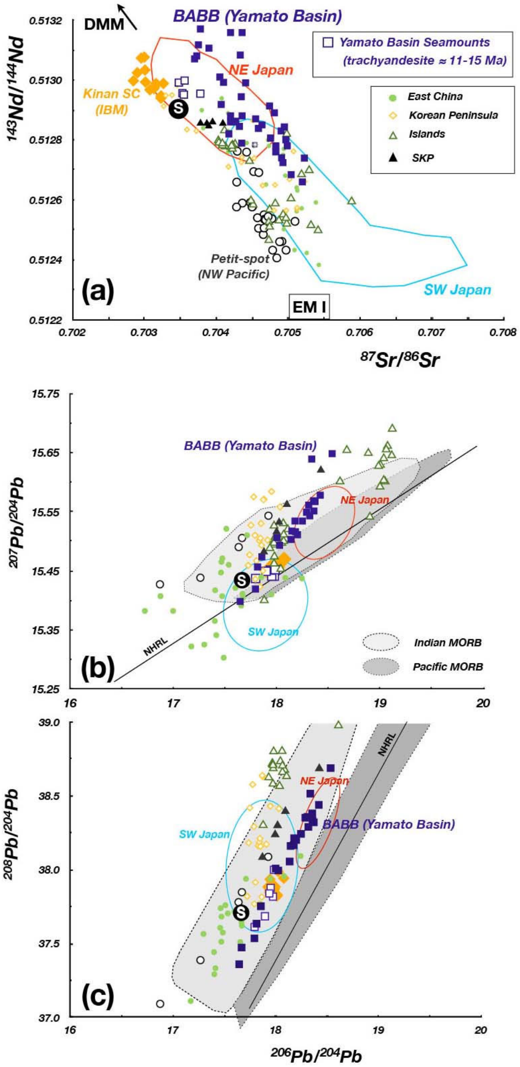

Figure 5: Nd-Sr-Pb isotopic compositions of SSM-basalt (black circle with S). (a) Sr and Nb isotopic compositions. (b) $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{208}Pb$. (c) $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$. Reference data and data fields are from Basu et al. (1991), Tatsumoto and Nakamura (1991), Cousens and Allan (1992), Nohda et al. (1992), Pouclet et al. (1994), Lee et al. (2001), Park et al. (2005), Choi et al. (2006), Ishizuka et al. (2009), Machida et al. (2009, 2015) and Hirahara et al. (2015). Indian and Pacific MORB fields in (b) and (c) are from Miyazaki et al. (2015). The North Hemisphere Reference Line (NHRL) is from Hart (1984).

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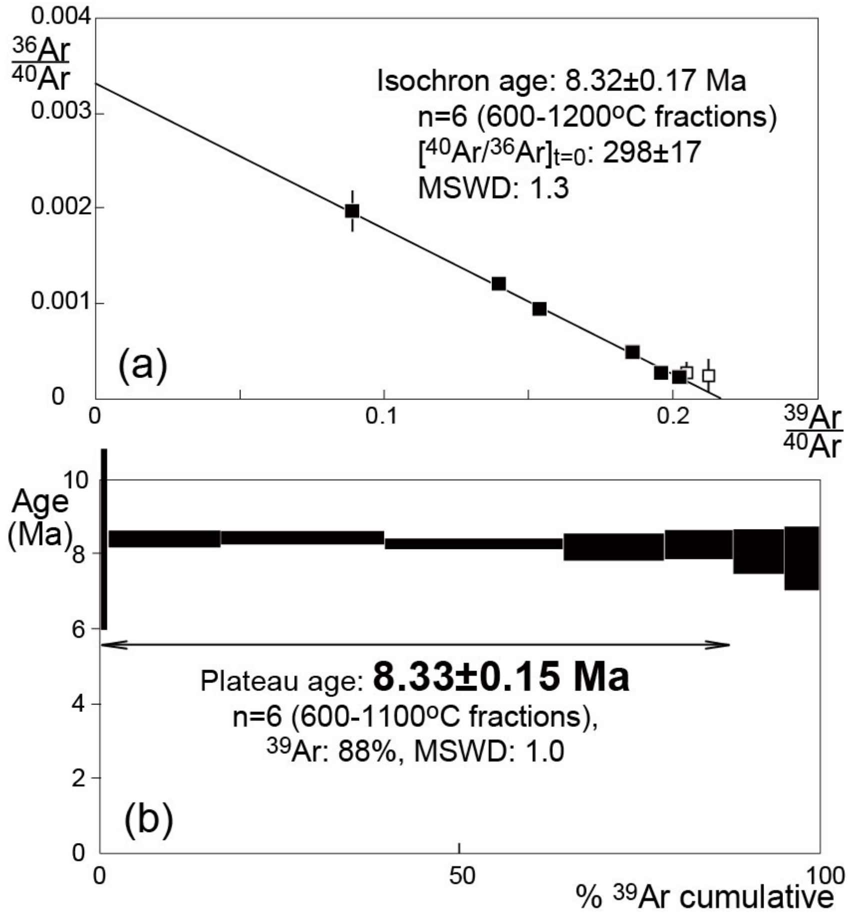

Figure 6: Inverse isochron (a) and ^{40}Ar-^{39}Ar age spectrum (b). The MSWD means the mean squared weighted deviations, MSWD=SUMS/(n-2) (York, 1968). All errors are shown in 2 sigma.