Geographical distribution of $^3\text{He}/^4\text{He}$ ratios and seismic tomography in Japan

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The $^3\text{He}/^4\text{He}$ ratios ($Ra$) of natural gas, volcanic fluid, and groundwater are compiled in the Japanese Islands and their geographical distributions are discussed in the tectonic framework of subduction zone together with precisely-determined seismic velocity structures. In Northeastern (NE) Japan where typical island arc signatures are developed, there is a clear contrast of $^3\text{He}/^4\text{He}$ ratios perpendicular to the trench axis, low-$Ra$ in the frontal arc and high-$Ra$ in the volcanic arc. This may reflect the presence or absence of magma with high-$Ra$ in the shallow crust. As a carrier of primordial helium, source melt may be generated in low-V zone of the wedge mantle by dehydration of Pacific slab at about 150 km deep and may flow upward sub-parallel to the slab, which is well constrained by S-wave velocity perturbation. In the Chugoku and Shikoku districts of Southwestern (SW) Japan, there is a geographical contrast of $Ra$ similar to NE Japan except for the region at about 100 km from the volcanic front where medium-$Ra$ was found. High-$Ra$ observed in volcanic arc of the Chugoku district may be attributable to the mantle helium derived from the magma source generated below the Philippine Sea slab. Medium-$Ra$ in the Shikoku district is explained by dehydration of the young slab with a moderate aging effect. These features are again consistent with the results of seismic tomography. In the Kinki district of SW Japan, anomalously high-$Ra$ was observed in the frontal arc region that was called by “Kinki Spot”. Since the high-$Ra$ is located at much wider region from the volcanic front when compared with NE Japan, the melt generated below the Philippine Sea slab may penetrate into the fissure of the slab tear and may arrive at the shallow crust by upwelling flow.

Keywords: helium isotopes, seismic tomography, Japanese islands, geotectonics, arc magma

INTRODUCTION

After the pioneer work of Sano and Wakita (1985), many $^3\text{He}/^4\text{He}$ ratios of volcanic fluids and natural gases were obtained throughout the Japanese Islands. These data have provided new knowledge of geophysics and geochemistry of the subduction zone. However most of them were focused on the regional interest such as Hokkaido island (Sano and Wakita, 1988), Kinki district (Wakita et al., 1987; Matsumoto et al., 2003; Umeda et al., 2006), Chugoku district (Sano et al., 2006), and Shikoku island (Dogan et al., 2006). The other data were related to single volcanoes such as Oshima (Sano et al., 1988), Hakone (Sakamoto et al., 1992), Kusatsu–Shirane (Sano et al., 1984) and Ontake (Sano et al., 1998) in Japan. Since a lot of helium isotopes have been published, it is timely to compile the data and discuss their relation with tectonic settings of island arc as a whole.

The recent development of dense regional high-sensitivity seismograph network (up to about 900 stations) has provided high-quality data and a large amount of travel-time data is available in Japan. Based on the large number of earthquakes, the precise travel-time tomography was performed using high-quality P- and S-wave arrival times. Such 3D seismic velocity structure of the upper mantle beneath the Northeastern (NE) Japan was well documented by a research group of Tohoku University (Zhao and Hasegawa, 1993; Nakajima et al., 2001; Hasegawa and Nakajima, 2004). Recently Nakajima and Hasegawa (2007) have reported seismic tomography beneath the Southwestern (SW) Japan and suggested that a large low-velocity anomaly beneath the Philippine Sea slab is the source of arc magma.

In this study we compile helium isotope data of Japan available in literatures. Based on the geographical distribution of the $^3\text{He}/^4\text{He}$ ratio corrected for air contamination and precise 3D seismic velocity structure using high-quality travel-time data, we discuss an island arc tectonics and magma genesis in the subduction zone.
HELIUM ISOTOPES AND ARC MAGMA GENESIS IN NE JAPAN

The Japanese Islands are divided into two major blocks, NE Japan and SW Japan by Itoigawa–Shizuoka tectonic line (Fig. 1). NE Japan is considered as a well-defined island arc system with a deep trench, a frontal arc, a volcanic arc, and a back arc region with a marginal sea (Kaizuka, 1972). Perpendicular to the trench axis, geophysical data such as terrestrial heat flow, gravity anomaly and seismic velocity vary significantly across the island arc (Yoshii, 1977). These geographical and geophysical signatures were well explained by the subduction of the Pacific plate beneath the NE Japan. On the other hand, there are few geochemical data with across the arc variation (Kuno, 1966; Notsu, 1983; Shibata and Nakamura, 1997) and they were limited to within a volcanic arc.

Sano and Wakita (1985) reported the 3He/4He and 4He/20Ne ratios of 115 natural gas and volcanic fluids in Japan. Helium in these samples is well explained by the mixing of three end members: the upper mantle helium with the 3He/4He ratio of about 8 Ra and the 4He/20Ne ratio of 1000; the radiogenic helium with the 3He/4He ratio of 0.02 Ra and the 4He/20Ne ratio of 1000; the atmospheric helium with 1 Ra and 4He/20Ne ratio of 0.318. The mixing hypothesis has successfully applied to their data as well as many other data obtained in Japan (Wakita et al., 1987; Sano and Wakita, 1988; Dogan et al., 2006). One can distinguish air helium from the mixture of the mantle and radiogenic helium based on the 4He/20Ne ratio. Actually it is possible to correct air helium contamination using following equations (Craig et al., 1978).

\[
R_{\text{corr}} = \left[ \left( \frac{3\text{He}}{4\text{He}} \right)_{\text{obs}} - r \right] / (1 - r),
\]

\[
r = \frac{\left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{air}} / \left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{obs}}}{r \left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{air}} / \left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{obs}}},
\]

where \( R_{\text{corr}} \) and \( \left( \frac{3\text{He}}{4\text{He}} \right)_{\text{obs}} \) denote the corrected and observed \( \frac{3\text{He}}{4\text{He}} \) ratios, and \( \left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{air}} \) and \( \left( \frac{4\text{He}}{20\text{Ne}} \right)_{\text{obs}} \) are the air and observed \( \frac{4\text{He}}{20\text{Ne}} \) ratio. After correcting the air helium contribution, we define here the \( \frac{3\text{He}}{4\text{He}} \) ratio of samples as follows:

- **high-Ra** \( \frac{3\text{He}}{4\text{He}} > 4\text{Ra} \) more than 50% mantle contribution
- **medium-Ra** \( 4\text{Ra} > \frac{3\text{He}}{4\text{He}} > 2\text{Ra} \) between 50% and 25% mantle contribution
- **low-Ra** \( 2\text{Ra} > \frac{3\text{He}}{4\text{He}} \) less than 25% mantle contribution

where high-Ra is principally found in volcanic region with high heat emission such as hot springs and geothermal activity, while low-Ra is tend to be observed in non-volcanic region.

We have compiled helium isotopes data in the Tohoku and Hokkaido districts of NE Japan (Sano and Wakita, 1985, 1988) and plotted in the map based on the definition above after the correction for air contamination (see Fig. 2a). It is apparent that low-Ra samples is locating everywhere while medium-Ra and high-Ra fluids distribute limitedly within the volcanic arc region. Figure 2b shows the relationship between the distance from the quaternary volcanic front and the \( \frac{3\text{He}}{4\text{He}} \) ratio expressed in the unit Ra. Sano and Wakita (1985) have emphasized that these is a geographical difference of Ra between the frontal arc and volcanic arc; lower in the trench side and higher in the back arc side in NE Japan. This trend is not changing at the present case (Fig. 2b). Their interpretation was that the uprising magma is a unique material which brings primordial helium from the upper mantle to the shallow crust. The volcanic front was formed at the location below which subducting slab reaches the depth where hydrous volatiles supplied from the slab lowers the solidus temperature of mantle materials and generates a partial melting (Tatsumi et al., 1983; Tatsumi, 1986). Thus geographical contrast of Ra has constrained the magma genesis immediately below the volcanic front. Another important feature of the geographical distribution is that medium-Ra and high-Ra situate relatively narrow region with about 110 km wide from the volcanic...
There is no high-Ra in the area of more than 110 km far from the front in the back arc side (Fig. 2b). This trend may provide another constraint on the arc magma genesis in NE Japan.

Nakajima et al. (2001) reported both P- and S-wave velocity structures beneath NE Japan by applying a travel-time tomography method. Figure 3 shows a vertical cross-section of S-wave velocity perturbations along line A–A′ in the map of Fig. 2a. Low-velocity zone (both P- and S-waves) were extensively distributed along the volcanic front in the uppermost mantle and are expanding downward to the back arc side in the mantle wedge across the arc. They suggested that the partial melting zones existed...
in the mid-crust right beneath active volcanoes. Taking into account of these tomography studies, Hasegawa and Nakajima (2004) have presented a schematic diagram of vertical cross-section of the crust and upper mantle beneath NE Japan where genesis of arc magma was well explained.

Figure 4 shows a schematic diagram of NE Japan which describes geographical distribution of helium isotopes. This is principally the same as the Plate 5 of Hasegawa and Nakajima (2004) with some modifications to accommodate with helium isotopes in the back-arc region. Aqueous fluids with low-$^{87}\text{R}_\text{a}$ are supplied from subducting Pacific Plate at several depths. The cause of the low-$^{87}\text{R}_\text{a}$ in the oceanic crust will be given later. More precisely at about 80–130 km deep of NE Japan the fluids are derived from a metamorphic reaction of jadeite lawsonite blueschist to lawsonite amphibole eclogite. At about 100–150 km deep another dehydration of lawsonite amphibole eclogite to eclogite may occur and the fluids are again supplied (Hacker et al., 2003). These fluids may react with overlying mantle materials and form secondary hydrous minerals such as serpentine and chlorite in the mantle wedge (Iwamori, 1998), which could make helium isotopes medium-$^{87}\text{R}_\text{a}$. As following the subducting slab, fluids hosted in hydrous minerals may have been dragged down to depths of 150–200 km where breakdown of these secondary minerals may occur (Iwamori, 1998). The breakdown may release a large amount of aqueous fluids which may move upward and probably initiates partial melting in the inclined low-V zones with high-$^{87}\text{R}_\text{a}$. The melt is transported sub-parallel to the subducting slab by the upwelling flow and finally meets the Moho beneath the volcanic front. Then the melt separates from the flow and distributes below the Moho along the volcanic front. This is the principle source of high-$^{87}\text{R}_\text{a}$ magma in NE Japan. A part of the flow may arrive at the Moho of the back-arc side and the separated melt may lead to the source magma of volcanism in the back-arc region (see Fig. 3). There is a constraint that the partial flow can travel about 100 km from the volcanic front in horizontal direction based on the high-$^{87}\text{R}_\text{a}$ distribution (see Fig. 2b). Anyway the upwelling flow with low velocity signature is the principle carrier of the mantle helium with high-$^{87}\text{R}_\text{a}$.

**HELIUM ISOTOPES IN CHUGOKU AND SHIKOKU OF SW JAPAN**

In SW Japan a well-defined island arc system has not developed. The volcanic front is not as clear as in NE Japan except Kyushu and heat flow values are relatively high in the trench region (Yamano et al., 1984). These features are generally attributable to the subduction of the young and warm lithosphere of the Philippine Sea plate beneath the Eurasian plate (Shiono and Sugi, 1985). In addition the Pacific plate descends from the east beneath the Philippine Sea and Eurasian plates. This has resulted in a complicated surface geology (Taira et al., 1989) and lateral heterogeneity in the upper mantle structure of SW Japan (Nakajima and Hasegawa, 2007). Helium isotope data were significantly lacking in the Chugoku and Shikoku districts until year 2005 (Sano and Nakajima, 2004).
so simple as described by Dogan (1985; Wakita et al., 1987). Recently Dogan et al. (2006) have reported 38 3He/4He and 3He/20Ne ratios of gas and water samples from the Shikoku district. At the same time Sano et al. (2006) have published 34 helium isotope data in the Chugoku district. We have compiled these data and plotted them in the map as following above definition of helium isotopes (Fig. 5a). It is apparent that high-Ra is located only in the volcanic arc while low-Ra fluids occur everywhere. The tendency is significantly similar to that of NE Japan. On the other hand several medium-Ra are found in the frontal arc region of Shikoku district, which is discrepant from NE Japan. Similar medium-Ra was reported in the frontal arc region of the North Island, New Zealand (Sano et al., 1987).

In order to explain the medium-Ra in Shikoku, Dogan et al. (1987) have suggested two mechanisms. First a major active fault in Japan called “the Median Tectonic Line” can provide an efficient path for the mantle helium which was liberated from the Philippine Sea plate, which is similar to the explanation of medium-Ra in New Zealand by Giggenbach et al. (1993). Second hydrous fluids again derived from the descending slab may cause fracturing within the crust, thereby easing the transfer of the medium-Ra to the surface. This means that the uprising fluids themselves made the path to the surface which is supported by the evidence that non-volcanic deep tremors occur, about 30 km deep in the region (Obara, 2002). If the latter is the case, medium-Ra should be found in the other region where the long-period tremors occur in SW Japan such as southwestern Tokai area. However Byakko and Yuya springs of the Tokai area showed low-Ra (0.79Ra and 1.24Ra, respectively from Sano and Wakita, 1985). Thus the mechanism of medium-Ra is not so simple as described by Dogan et al. (2006).

Figure 5b indicates the relationship between the distance from the helium volcanic front and the 1He/4He ratio expressed in the unit Ra. This front was defined by the geographical distribution of helium isotopes in Chugoku district (Sano et al., 2006). It is noted that medium-Ra found in Shikoku is located relatively narrow region at about 100 km from trench side of the front. This suggests that the medium-Ra is somehow related to the depth of the upper surface of the Philippine Sea plate. The helium may be derived from the aqueous fluids expelled from the subducting slab. It is necessary to calculate the magma aging effect which may lower the helium isotopes significantly from the original MORB-type helium.

Sano et al. (2006) have reported high-Ra in the volcanic arc region of Chugoku district and have described that it is impossible to explain the high-Ra by the slab melting of the descending Philippine Sea plate based on the magma aging effect. The other source with pristine mantle material was required. They further suggested that the magma source is related to the Pacific plate at the great deep when taking into account of the highest and average helium isotopes as well as strontium isotopes of volcanic rocks.

**Magma Aging Effect on Helium Isotopes**

Above discussions on medium-Ra in Shikoku and high-Ra in Chugoku require the evaluation of the magma aging effect. Therefore we have re-calculated the decrease of helium isotopes (Ra) by addition of radiogenic helium with time. The method is principally the same as the magma aging reported by Torgersen and Jenkins (1982). The initial condition of tholeiite magma such as U, Th and 3He contents are referred from Tatsumoto (1966) and Dymond and Hogan (1974). We follow the radiogenic production of 4He from the equation by Craig and Lupton (1976). We assume that production ratio of 3He/4He based on the nuclear reaction: 6Li(n,α)3H is 0.03Ra (or 4.17 × 10^-4) as described by Mamyrin and Tolstikhin (1984). Then we calculate helium isotope variation with time. It is noted that the variation of nucleogenic production ratio of 3He/4He does not affect the result significantly.

Figure 6 shows the magma aging effect on helium isotopes of holocrystalline and glassy tholeiite as defined by Torgersen and Jenkins (1982) where initial 3He contents are 7 × 10^-13 and 7 × 10^-11 ccSTP/g, respectively. The helium isotopes of holocrystalline tholeiite start to decrease...
even after 1000 year, while the ratio of glassy tholeiite
does not change until $10^7$ year. We should assume the ini-
tial content of $^3$He in bulk oceanic crust. It is unrealistic
to take the initial contents of holocrystaline or glassy
tholeiite. Probably the actual value exists between those
values of $7 \times 10^{-15}$ and $7 \times 10^{-11}$ ccSTP/g. Kumagai
et al. (2003) have reported helium contents of gabbros and
peridotites recovered from oceanic core complex on the
Southwest Indian Ridge. They admitted that total helium
abundances of these samples are lower than MORB
glasses (glassy tholeiites) by two to three orders of mag-
nitude. We calculate the average of $^3$He contents in their
gabbros as $7 \times 10^{-13}$ ccSTP/g except for the sample with
very low $^3$He/$^4$He ratio. The standard deviation of the
contents indicates the variation of factor three at the maxi-
mum. Taking into account of these data, we assume that
the initial $^3$He content of bulk oceanic crust is $7 \times 10^{-13}$
ccSTP/g with uncertainty of factor three at the maxi-
mum. In NE Japan descending Pacific plate is old and cold.
Formation age of the oceanic crust at the trench is esti-
mated about 130 Ma by the magnetic anomalies
(Nakanishi et al., 1992). Magma aging calculation leads to
the $^3$He/$^4$He of values between 0.10Ra and 0.65Ra, sig-
nificantly lower than the low-Ra with 25% mantle con-
tribution. Therefore the low-Ra is dominant component
in the frontal arc region of NE Japan, even though aque-
ous fluids derived from the Pacific plate may arrive at
the shallow crust.

In SW Japan subducting Philippine Sea plate is young
and warm. The age of the slab at the trench is estimated
15–25 Ma (Shih, 1980) and about 20 Ma by the magnetic
anomalies (Okino et al., 1994). The calculated $^3$He/$^4$He
ratios vary from 0.40Ra to 3.4Ra, suggesting that medium-Ra
is available in aqueous fluids derived from the descending slab in some case. On the other hand, it is
difficult to maintain the high-Ra in the oceanic crust.

Figure 7 shows a vertical cross-section of S-wave ve-
locity perturbations along line B–B’ in the map of Fig. 5a
(Nakajima and Hasegawa, 2007). This indicates the ex-
istence of a large low-velocity anomaly below the Phil-
ippine Sea slab in the Chugoku and Shikoku districts at
least down to depths of 300 km. Nakajima and Hasegawa
(2007) have inferred that the low-velocity zone is an
upwelling flow from great deep. There is a shallow low-
velocity zone toward the Quaternary volcanoes in
Chugoku which is connecting with the large anomaly
below the Philippine Sea slab as going around the tip of
the plate.

Figure 8 indicates a schematic diagram of Chugoku
and Shikoku of SW Japan which explains geographical
distribution of helium isotopes. This is basically the same
as figure 10A of Nakajima and Hasegawa (2007) with
some modifications to accommodate with helium isotopes in Shikoku. Based on the magma aging calculation, it is possible to maintain medium-$^{40}$Ra in the subducting Philippine Sea plate at present. Aqueous fluids supplied from the oceanic crust at the depth between 30–50 km by metamorphic dehydration reactions (Hacker et al., 2003; Yamasaki and Seno, 2003) may be the principle source of medium-$^{40}$Ra in Shikoku. In the case of NE Japan, expelled fluids produce secondary minerals which may have been dragged down to deep in the mantle. In the SW Japan, the fluids may have hardly chance to form secondary minerals at such shallow depth and may move upward by their buoyancy. This aqueous uprise may cause the non-volcanic deep tremors in the region (Obara, 2002). Medium-$^{40}$Ra is located narrow region at about 100 km trench side of the front (see Fig. 5b), which is well explained by the hydration hypothesis since the depth of the Philippine Sea plate may arrive at 30–50 km in the area. Magma aging effect suggests that high-$^{40}$Ra in the volcanic arc of Chugoku is not attributable to the re-melting of the oceanic crust and pristine mantle material was required (Sano et al., 2006). An upwelling flow from great deep, probably related to the Pacific plate, could be the carrier of such high-$^{40}$Ra in the shallow crust of the region.

**HELIUM ISOTOPES AND KINKI SPOT IN SW JAPAN**

Sano and Wakita (1985) found anomalously high $^{3}$He/$^{4}$He ratio in the frontal arc region of the Kinki district, SW Japan. Since the high-$^{40}$Ra was locating in roughly circular area, they called this “Kinki Spot”. Wakita et al. (1987) reported additional helium data as well as microseismic activity continuing over a long period at shallow depths. Taking into account of high terrestrial heat flow, hypocentral distribution of micro-earthquakes, and the presence of molten materials inferred from the characteristic phases of SxP and SxS reflected waves in microseismograms, they suggested the existence of a shallow magma body beneath the area. Matsumoto et al. (2003) have confirmed high-$^{40}$Ra in the “Kinki Spot” and inferred that the mantle helium was derived from the dehydration of young and warm Philippine Sea Plate. They further suggested that the occurrences of non-volcanic deep tremors in the Kii Peninsula were caused by the movement of fluids derived from the subducting slab. Recently Umeda et al. (2006) have reported again high-$^{40}$Ra emanation and conductive anomaly in the region. They have attributed these features into the aqueous fluids expelled from the Philippine Sea Plate. However the magma aging effect indicates that it is difficult to maintain the high-$^{40}$Ra in the Philippine Sea Plate as discussed above. It is not likely that the high-$^{40}$Ra was derived from the dehydration suggested by Matsumoto et al. (2003) and Umeda et al. (2006). In addition the slab melting can not account for the high-$^{40}$Ra. The other source with pristine mantle material is definitely needed in the region.

We have compiled helium isotopes data in the Kinki district of SW Japan (Sano and Wakita, 1985; Wakita et
and plotted in the map based on the above definition (Fig. 9a). The volcanic front is not really defined in northern Kinki region. We tentatively extend the volcanic front from the Chugoku district to the northern Kinki. It is apparent that medium-Ra and high-Ra are locating even in frontal arc region, which is completely different from geographical distributions of helium isotopes in NE Japan (Fig. 2a), and Chugoku and Shikoku, SW Japan (Fig. 5a). Figure 9b shows the relationship between the distance from the hypothetical volcanic front and the \(^{3}\text{He}/\(^{4}\text{He}\) ratio expressed in the unit Ra. This helium profile is apparently anomalous compared with those of NE Japan, and Chugoku and Shikoku, SW Japan. In order to describe the cause of high-Ra in the frontal arc of SW Japan, Sano and Wakita (1985) proposed newly developing volcanism in the region by moving of the volcanic front. If this is the case, it is necessary to explain the observation that high-Ra is located at about 250 km wide region across the island arc system. This is significantly wider than those in NE Japan, about 100 km (see Fig. 2b) and in the Chugoku district, less than 100 km (see Fig. 5b). Breakdown of secondary minerals may not produce aqueous fluids from the descending slab with such a long distance and/or variable depth (Iwamori, 1998). Thus the magma genesis model of NE Japan (Fig. 4) may not be easily applicable to the Kinki district.

Figure 10 indicates a vertical cross-section of S-wave velocity perturbations along line C–C’ in Fig. 8a (from Nakajima and Hasegawa, 2007). This indicates the existence of a large low-velocity anomaly below the Philippine Sea slab, very similar to those of the Chugoku and Shikoku districts. Taking into account of the absence of a high-velocity anomaly corresponding to the subducted Philippine Sea slab beneath the Kii Peninsula, Nakajima and Hasegawa (2007) have suggested that the shallow low-velocity zone is connecting with a large low-velocity anomaly below the Philippine Sea plate somewhat passing through the slab. Figure 11 shows a schematic diagram of the Kinki district of SW Japan which explains geographical distribution of helium isotopes. There may be a large fissure of the Philippine Sea slab tear induced by the different dip angle of the subducting ocean plate. Upwelling mantle materials with high-Ra may penetrate through the fissure and may arrive at the shallow crust of the region. The fissure might have occurred along the fossil spreading ridge of the Shikoku Basin that is now subducting beneath the Kii Channel. Even though this model is highly schematic and admittedly oversimplified, this can explain the observation of significantly wide distribution of high-Ra across the island arc. In order to constrain the model more precisely, extensive sampling and analysis of helium isotopes in northern Kinki region are highly desirable together with more tomographic researches.
CONCLUSIONS

This paper describes a geographical distribution of helium isotopes in Japan compiled from literatures and presents new interpretation on the magma genesis based on the precise seismic tomography data. In NE Japan, a carrier of the primordial helium is well visualized by low-velocity upwelling flow in the upper mantle generated in dehydration of Pacific slab. The source magma may be separated from the flow in the lower crust immediately below the volcanic front. Radiogenic helium in frontal arc is simply attributable to the absence of the magma. In volcanic arc of Chugoku, SW Japan, the mantle helium may be derived from the upwelling flow originated beneath the Philippine Sea plate, which looks passing through the tip of the plate by a contour of low velocity anomaly. In Shikoku of SW Japan medium values of helium isotopes are situating at the area about 100 km from the volcanic front. The helium characterized by significant mantle component may be attributed to the dehydration of the young slab with a moderate aging effect. We try to explain the cause of “Kinki Spot” by fissure type tear of the subducting Philippine Sea slab. However it is not fully resolved in this work. Extensive sampling and analysis of helium isotopes in the region are needed to constrain the formation mechanism of high-Ra in the frontal arc in addition to tomographic analysis in future.

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