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Geographical Distribution of $^3He/^4He$ Ratios in the Chugoku District, Southwestern Japan

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Abstract—We have collected 34 hot spring and mineral spring gases and waters in the Chugoku and Kansai districts, Southwestern Japan and measured the $^3He/^4He$ and $^4He/^{20}Ne$ ratios by using a noble gas mass spectrometer. Observed $^3He/^4He$ and $^4He/^{20}Ne$ ratios range from 0.054 R_{atm} to 5.04 R_{atm} (where R_{atm} is the atmospheric $^3He/^4He$ ratio of 1.39×10^{-6}) and from 0.25 to 36.8, respectively. They are well explained by a mixing of three components, mantle-derived, radiogenic, and atmospheric helium dissolved in water. The $^3He/^4He$ ratios corrected for air contamination are low in the frontal arc and high in the volcanic arc regions, which are consistent with data of subduction zones in the literature. The geographical contrast may provide a constraint on the position of the volcanic front in the Chugoku district where it was not well defined by previous works. Taking into account the magma aging effect, we cannot explain the high $^3He/^4He$ ratios of the volcanic arc region by the slab melting of the subducting Philippine Sea plate. The other source with pristine mantle material may be required. More precisely, the highest and average $^3He/^4He$ ratios of 5.88 R_{atm} and 3.8 ± 1.6 R_{atm}, respectively, in the narrow regions near the volcanic front of the Chugoku district are lower than those in Kyushu and Kinki Spot in Southwestern Japan, but close to those in NE Japan. This suggests that the magma source of the former may be related to the subduction of the Pacific plate, in addition to a slight component of melting of the Philippine Sea slab.

Key words: Helium isotopes, magma source, subduction, Philippine Sea plate.

1. Introduction

It is well documented that helium isotopic ratios can be useful for evaluating a variety of geophysical and geological environments (MAMYRIN and TOLSTIKHIN, 1984; OZIMA and PODOSEK, 2002). In the subduction zones, a clear geographical contrast of the $^3He/^4He$ ratio; lower value in the frontal arc (forearc) and higher in the volcanic arc (backarc) regions is found in northeastern Japan (SANO and WAKITA, 1985), northern New Zealand (GIGGENBACH *et al.*, 1993), and southern Italy (SANO *et al.*, 1989). The higher ratios with a mantle-derived helium in the

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volcanic arc are probably associated with the diapiric uprise of a magma and lower ratios in the frontal arc may be due to radiogenic helium produced by the decay of U and Th in the crustal and sedimentary rocks.

The Japanese Islands are divided by the "Itoigawa-Shizuoka tectonic line" (I-S TL) into major tectonic blocks, northeastern (NE) Japan and southwestern (SW) Japan (Fig. 1).

In NE Japan the old, cold and thick oceanic lithosphere of the Pacific plate subducts beneath the Eurasia plate. A well-defined island arc system feature such as a deep trench, a frontal arc region, a volcanic arc region and a backarc region is developed (MATSUDA, 1964). Geographical contrast of $^{3}He/^{4}He$ ratios was found at the volcanic front of NE Japan (SANO and WAKITA, 1985). In SW Japan, in contrast, an exceptional $^{3}He/^{4}He$ distribution pattern was observed in the Kansai district. Extraordinarily high $^{3}He/^{4}He$ ratios were found in the forearc region. The roughly circular area with the high ratio was called the "Kinki Spot". Taking into account the high ^{3}He emanation and seismic swarm activity in the region, WAKITA *et al.* (1987) suggested the presence of a shallow magma body beneath the area, and SENO *et al.* (2001) further suggested that partial melting might be induced by dehydration from the serpentinized slab mantle beneath Kii Peninsula.

In the Kyushu district, the most western part of SW Japan and a part of the Kyushu-Ryukyu arc, the contrast of $^{3}He/^{4}He$ ratios exists at the volcanic front (SANO and WAKITA, 1985; MARTY *et al.*, 1989; STURCHIO *et al.*, 1996; NOTSU *et al.*, 2001), which is similar to those observed in NE Japan. The Chugoku district is located between the Kinki Spot and the Kyushu district, where the volcanic front is not well defined (SUGIMURA, 1960). The initial purpose of the present work is to identify the front based on the geographical distribution of $^{3}He/^{4}He$ ratios. Second is to provide new information on the magma source using the highest and average $^{3}He/^{4}He$ ratio of the narrow region near the front together with the $^{87}Sr/^{86}Sr$ ratios of volcanic rocks in literature. The melting of the Philippine Sea slab is not likely to be a major magma source of the basis of the high $^{3}He/^{4}He$ ratio. We suggest that the magma source might have a deeper origin comparing the $^{3}He/^{4}He$ ratio with those of Kyushu and NE Japan.

2. Experimental

We have collected 32 hot spring and mineral spring gases and waters in the Chugoku district and 2 mineral spring gases in the Kansai district, SW Japan. Gas samples were collected by a displacement method in water using a 50 cm^3 lead glass container with vacuum valves at both ends. Spring waters were sampled in copper tubes (about 20 cm^3) when care was taken to avoid air contamination by air bubbles attaching themselves to the inner wall of the tubes. The tube was sealed at both ends using stainless-steel pinch clamps.

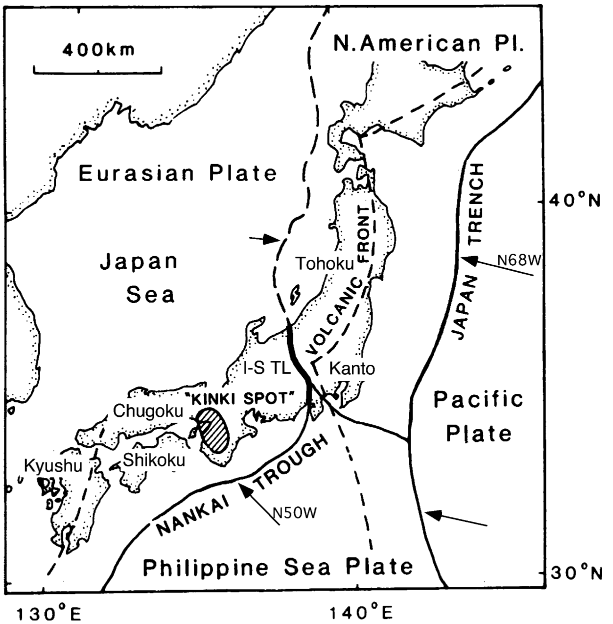

Figure 1
Plate boundaries around the Japanese Islands, trench, and volcanic front and the location of "Kinki Spot". Arrows show relative direction of the motions between the Pacific and Philippine Sea plates. Volcanic front was defined by Sugimura (1960).

The $^3He/^4He$ and $^4He/^{20}Ne$ ratios of the samples were measured by a noble gas mass spectrometer (6–60-SGA, Nuclide Co.) installed at the Center for Advanced Marine Research, Ocean Research Institute, the University of Tokyo, after purification and separation of noble gases using hot Ti-Zr getters and activated charcoal traps held at liquid N_2 temperature. Experimental errors of the helium isotopic ratio and $^4He/^{20}Ne$ ratios are about 3% and 10%, respectively, at 1σ estimated by repeated measurements of air standard gas (Sano and Wakita, 1985). Helium was not separated from Ne in the analysis, which may cause some uncertainty in absolute $^3He/^4He$ ratios (Rison and Craig, 1983; Sano and Wakita, 1988). Accordingly correction was made based on the comparison of $^3He/^4He$ ratios measured by using the VG5400 system with a cryogenic Ne separater and Nuclide mass spectrometer without the separater (Sano *et al.*, 1998).

3. *Results and Discussion*

Observed $^3He/^4He$ and $^4He/^{20}Ne$ ratios are listed in Table 1 together with the location and sample type. In the Chugoku district, SW Japan, the $^3He/^4He$ and $^4He/^{20}Ne$ ratios vary significantly from 0.054 R_{atm} to 5.04 R_{atm} (where R_{atm} is the atmospheric $^3He/^4He$ ratio of 1.39×10^{-6}) and from 0.25 to 37.7, respectively. Figure 2 shows a correlation diagram between the $^3He/^4He$ and $^4He/^{20}Ne$ ratios. The distribution of all samples in the diagram is located in a mixing region of three end-members, primordial helium derived from a mantle beneath the Chugoku district, radiogenic helium produced from uranium and thorium in crustal rocks, and atmospheric helium dissolved in water (air saturated water; ASW) at relatively low temperature compared with volcanic-hydrothermal system. This suggests that helium in the sample is well explained by a simple mixing of those which originated from the three sources (SANO and WAKITA, 1985). If there exists a tritiogenic helium (decay product of tritium, ^3H) in the sample, it should be located outside of the mixing between ASW and the mantle. However this is not the case. The contribution of a tritiogenic helium may be significantly small.

Assuming that the $^4He/^{20}Ne$ ratios of mantle and radiogenic helium are significantly larger than that of ASW, it is possible to correct atmospheric helium contamination as follows (CRAIG *et al.*, 1978):

$$R_{cor} = [(^3He/^4He)_{obs} - r]/(1 - r),$$
$$r = (^4He/^{20}Ne)_{ASW}/(^4He/^{20}Ne)_{obs},$$

where R_{cor} and $(^3He/^4He)_{obs}$ denote the corrected and observed $^3He/^4He$ ratios, and $(^4He/^{20}Ne)_{ASW}$ and $(^4He/^{20}Ne)_{obs}$ are the ASW and observed $^4He/^{20}Ne$ ratios, respectively. If the observed $^4He/^{20}Ne$ ratio is close to the ASW value ($^4He/^{20}Ne$ = 0.25 at 0°C), r becomes about unity and the correction may be significantly erroneous due to an experimental error of $^4He/^{20}Ne$ ratio, that is about 10%. Sano *et al.* (1997) reported the error in the correction for ASW helium contamination as follows:

$$\sigma_{cor} = (R_{0.9} - R_{1.1})/2R_{cor},$$
$$R_{0.9} = [0.9 \times (^3He/^4He)_{obs} - r]/(0.9 - r),$$
$$R_{1.1} = [1.1 \times (^3He/^4He)_{obs} - r]/(1.1 - r),$$

where σ_{cor} denotes the error of the correction. The total error of the corrected $^3He/^4He$ ratio is defined as follows:

$$\sigma_{total} = \sqrt{\sigma_{cor}^2 + \sigma_{exp}^2},$$

where σ_{total} and σ_{exp} denote the total error of the corrected $^3He/^4He$ ratio and an experimental error of $^3He/^4He$ measurement, respectively. The error assigned to the corrected $^3He/^4He$ ratio in Table 1 includes all possible $^3He/^4He$ errors.

3.1 Volcanic Front in the Chugoku District

Based on the geographical distribution of Quaternary volcanoes in Japan, SUGIMURA (1960) has defined a volcanic front as a strikingly abrupt trenchward limit of volcanoes, which may provide evidence for partial melting in the mantle wedge beneath the volcanic arc behind the volcanic front. It was well identified in the Kurile arc, the NE Japan arc and the Izu-Ogasawara arc of NE Japan and the Kyushu-Ryukyu arc of SW Japan. In contrast the volcanic front was not identified in the Chugoku district (MATSUDA and UYEDA, 1971). Recently KIMURA *et al.* (2003a) have reported late Cenozoic volcanic activity in the Chugoku district using 108 newly obtained K-Ar ages and they suggested the position of Quaternary volcanic front in the region, which is similar to that indicated by NAKANISHI *et al.* (2002).

Figure 3 shows the corrected $^3He/^4He$ ratios and sampling sites of water and gas samples in this work together with those in Kyushu (STURCHIO *et al.*, 1996; MARTY *et al.*, 1989; NOTSU *et al.*, 2001) and Shikoku (WAKITA *et al.*, 1987). A solid circle has a higher $^3He/^4He$ ratio than the open circle, suggesting stronger mantle signature. It is noted that Quaternary volcanic front (QVF) proposed by KIMURA *et al.* (2003a) cannot match the geographical distribution of $^3He/^4He$ ratios. Several samples located in the trench side of QVF such as Tonbara, Tawara, Kakinoki and Kibedani indicate the $^3He/^4He$ ratio higher than 2 R_{atm}. Based on the distribution, we draw a helium volcanic front (HVF) in Figure 3. The HVF is located about 20 km from the south side of the QVF in the Chugoku district. This may suggest that the magma source is moving southward.

Figure 4 is the $^3He/^4He$ profile in the Chugoku district, showing corrected $^3He/^4He$ ratio versus geographic distance from the sampling site to the HVF. There is a clear contrast in $^3He/^4He$ ratio between the frontal arc and the volcanic arc regions in the district, which is consistent with those observed in the NE Japan arc and the Izu-Ogasawara arc of NE Japan and the Kyushu-Ryukyu arc of SW Japan (SANO and WAKITA, 1985). The contrast is understood to reflect the absence or presence of magma sources beneath the respective regions, since the high $^3He/^4He$ ratio can be of mantle origin and implies the close presence of a rising magma in the volcanic arc.

3.2 Helium and Strontium Isotope Signature of the Chugoku District

In order to discuss the geochemical characteristic of the magma source in NE Japan, SANO and WAKITA (1985) showed the variations in the $^3He/^4He$ ratios in narrow areas along the volcanic front, parallel to the trench axis. Data were selected for samples collected in the transition region with a width of 25 km, 5 km on the frontal arc side, and 20 km on the backarc side of the volcanic front. Significant variation of $^3He/^4He$ ratio among various arcs was observed, that is, relatively lower ratios ($\sim$3.6 R_{atm}) in the NE Japan arc and higher ($\sim$5.3 R_{atm}) in the Izu-Ogasawara arc. Similar variation in $^{87}Sr/^{86}Sr$ ratios of volcanic rocks, higher ratios (0.7038–0.7045) in the former arc and lower ratios (0.7032–0.7038) in the latter was reported by NOTSU (1983). Less radiogenic contamination (high $^3He/^4He$ and low $^{87}Sr/^{86}Sr$ ratios) of the magma source in the Izu-Ogasawara arc than the NE Japan arc was attributable to the geotectonic

Table 1

$^{3}He/^{4}He$, $^{4}He/^{20}Ne$, *and corrected* $^{3}He/^{4}He$ *ratios of hot spring gas and water samples in SW Japan*

No.	Sample	Prefecture	Type	Location (°N	°E)	$^{3}He/^{4}He$ (R_{atm})	$^{4}He/^{20}Ne$	$^{3}He/^{4}He_{cor}$ (R_{atm})	Error	Ref.
	Kansai									
1	Shiota	Hyogo	G	34.95	134.70	0.757	19	0.753	0.023	1
2	Shikano	Hyogo	G	34.92	134.88	1.186	110	1.19	0.04	1
3	Yumura	Hyogo	G	35.55	134.48	3.850	59	3.87	0.12	1
4	Inagawa	Hyogo	G	34.12	134.67	0.830	36	0.829	0.025	
5	Ishimichi	Hyogo	G	34.15	134.58	1.090	251	1.09	0.03	
	Shikoku									
6	Muroto	Kochi	G	33.30	134.13	1.657	7.9	1.69	0.05	2
7	Umaji	Kochi	G	33.57	134.07	1.036	2.2	1.04	0.03	2
8	Okudogo.4	Ehime	G	33.87	132.83	1.264	14	1.27	0.04	2
9	Okudogo.8	Ehime	G	33.87	132.83	1.264	10	1.27	0.04	2
10	Okudogo.K	Ehime	G	33.87	132.83	1.271	16	1.28	0.04	2
11	Yunotani	Ehime	G	33.88	133.17	1.686	17	1.70	0.05	2
12	Bessi	Ehime	G	33.90	133.32	2.214	830	2.22	0.07	2
13	Kamiyama	Tokushima	G	33.97	134.37	0.986	5.9	0.985	0.030	2
	Chugoku									
14	Misasa	Tottori	G	35.40	133.88	5.271	6.3	5.50	0.17	2
15	Sekigane	Tottori	G	35.35	133.77	4.300	30	4.34	0.13	2
16	Koyahara	Shimane	G	35.15	132.58	4.171	59	4.19	0.13	2
17	Tonbara	Shimane	G	35.07	132.80	2.586	18	2.61	0.08	2
18	Tamatsukuri	Shimane	W	35.40	133.02	3.086	29	3.10	0.09	2
19	Yunotsu	Shimane	W	35.08	132.35	4.699	1.01	5.92	0.24	
20	Asahi	Shimane	W	34.87	132.27	3.053	1.39	3.50	0.12	
21	Aribuku	Shimane	W	34.93	132.20	2.338	2.05	2.52	0.08	
22	Mimata	Shimane	W	34.88	132.23	5.038	1.45	5.88	0.24	
23	Kakinoki	Shimane	W	34.43	131.87	4.743	5.92	4.91	0.15	
24	Sanbe	Shimane	W	35.12	132.62	0.847	0.49	0.688	0.040	
25	Mito	Shimane	W	34.68	132.02	1.546	0.82	1.79	0.06	
26	Kibedani	Shimane	W	34.42	131.90	2.331	0.35	5.52	1.24	
27	Yobizuru	Yamaguchi	W	34.03	131.95	1.662	2.48	1.74	0.05	
28	Yumoto	Yamaguchi	W	34.23	131.17	3.150	1.64	3.54	0.12	
29	Kawatana	Yamaguchi	W	34.13	130.93	2.793	2.9	2.96	0.09	
30	Ichinomata	Yamaguchi	G	34.27	131.07	1.594	16.4	1.61	0.05	
31	Ganseiju	Yamaguchi	W	34.43	131.77	4.370	25.8	4.40	0.13	
32	Tawarayama	Yamaguchi	W	34.28	131.10	2.986	3.17	3.16	0.10	
33	Yuno	Yamaguchi	W	34.08	131.68	1.997	37.7	2.00	0.06	
34	Jiseiji	Yamaguchi	W	34.03	131.27	1.818	3.0	1.89	0.06	
35	Yutani	Yamaguchi	W	34.10	131.10	2.169	3.89	2.25	0.07	
36	Suo	Yamaguchi	W	33.95	132.18	0.875	0.30	0.292	0.251	
37	Yumen	Yamaguchi	W	34.35	131.25	1.135	0.27	2.83	0.93	
38	Yuda	Yamaguchi	W	34.15	131.45	0.800	0.48	0.583	0.051	
39	Tawara	Hiroshima	W	34.73	132.43	2.007	2.18	2.14	0.07	
40	Yusaka	Hiroshima	W	34.42	132.83	0.054	12.1	0.034	0.002	
41	Yunoyama	Hiroshima	W	34.48	132.28	0.215	4.21	0.166	0.007	
42	Rakan	Hiroshima	W	34.35	132.07	1.422	4.47	1.45	0.04	
43	Ushiobara	Hiroshima	W	34.47	132.12	1.859	23	1.87	0.06	
44	Yano	Hiroshima	W	34.67	133.10	1.663	8.53	1.68	0.05	

Table 1

(Contd.)

No.	Sample	Prefecture	Type	Location (°N	°E)	$^3He/^4He$ (R_{atm})	$^4He/^{20}Ne$	$^3He/^4He_{cor}$ (R_{atm})	Error	Ref.
45	Konu	Hiroshima	W	34.70	133.08	0.773	1.03	0.700	0.023	
46	Hiwa	Hiroshima	W	35.00	133.00	1.127	36.8	1.13	0.03	
47	Buttsuji	Hiroshima	W	34.45	133.02	0.975	0.28	0.769	0.435	
48	Yoro	Hiroshima	W	34.43	133.20	1.294	0.39	1.82	0.17	
49	Harada	Hiroshima	W	34.48	133.20	0.975	0.27	0.663	0.513	
50	Iwakura	Hiroshima	W	34.37	132.13	1.033	0.25	–	–	
51	Chiyoda	Hiroshima	W	34.65	132.53	1.504	0.55	1.93	0.10	
	Kyushu									
52	Southern Beppu	Oita	G	33.28	131.38	6.390	4.64	6.79	0.21	3
53	Northern Beppu	Oita	G	33.28	131.38	6.070	4.81	6.43	0.20	3
54	Yufuin	Oita	G	33.27	131.05	6.420	17.1	6.52	0.20	3
55	Kuju	Oita	G	33.08	131.25	5.829	83	5.85	0.18	4
56	Obama	Nagasaki	G	32.72	130.20	4.320	93.6	4.33	0.13	5
57	Unzen	Nagasaki	G	32.73	130.27	5.230	67.8	5.25	0.16	5
58	Shimabara	Nagasaki	G	32.77	130.37	7.060	178	7.07	0.21	5
59	Aso,Yunotani	Kumamoto	G	32.88	131.10	4.529	36	4.56	0.14	4
60	Ebino	Miyazaki	G	31.93	130.85	5.993	37	6.04	0.18	1
61	Shinmoedake	Kagoshima	G	31.90	130.88	6.108	25	6.17	0.19	1
62	Iodani	Kagoshima	G	31.88	130.83	3.683	8.3	3.79	0.11	1
63	Yunotani	Kagoshima	G	31.88	130.80	4.655	2.3	5.24	0.17	1
64	Ramune	Kagoshima	G	31.82	130.73	5.324	4.2	5.68	0.18	1
65	Shikine	Kagoshima	G	31.70	130.78	2.496	27	2.51	0.08	1
66	Sakamoto	Kagoshima	G	30.78	130.28	5.266	3.1	5.75	0.18	1
67	Satsumaiodake	Kagoshima	G	30.78	130.32	6.863	17	6.98	0.21	1

1: SANO and WAKITA (1985); 2: WAKITA *et al.* (1987); 3: STURCHIO *et al.* (1996); 4: MARTY *et al.* (1989); 5: NOTSU *et al.* (2001). G: gas sample; W: water sample.

setting of the former arc such as the steeper dip angle of the Wadati-Benioff zone and thinner crust over the mantle wedge (SANO and WAKITA, 1985).

Table 2 lists the average and highest $^3He/^4He$ ratios of samples collected in the transition region of the NE Japan arc, the Izu-Ogasawara arc, Chugoku district and the Kyushu district together with those of the Kinki spot. The $^{87}Sr/^{86}Sr$ ratios of volcanic rocks are also referred from the literature (NOTSU, 1983; KIMURA *et al.*, 2005). Both the average and highest $^3He/^4He$ ratios are significantly lower in the Chugoku district than the Kyushu district. The $^3He/^4He$ signature of the district is consistent with that of the NE Japan arc. In contrast the $^{87}Sr/^{86}Sr$ ratios of volcanic rocks in the Chugoku district resemble those of the Kyushu district, but are significantly higher than those of the Izu-Ogasawara arc. Therefore the geochemical environment of the magma source in the transition region of the Chugoku district may be similar to that of the NE Japan arc and they are more contaminated by crustal materials than the Kyushu district in terms of helium isotopes. On the other

Table 2

The average and highest $^3He/^4He$ *ratios and* $^{87}Sr/^{86}Sr$ *ratios of NE and SW Japan samples*

	Number of samples	Average $^3He/^4He$ (R_{atm})	Highest $^3He/^4He$ (R_{atm})	$^{87}Sr/^{86}Sr$
NE-Japan arc[(a)]	5	3.6 ± 0.7	4.33	0.7038–0.7045
Izu-Ogasawara arc[(a)]	6	5.3 ± 1.1	6.80	0.7032–0.7038
Kinki spot[(b)]	11	4.7 ± 1.5	6.97	
Chugoku district[(c)]	15	3.8 ± 1.6	5.80	0.7035–0.7053
Kyushu district[(d)]	16	5.6 ± 1.3	6.98	0.7038–0.7054

(a) SANO and WAKITA (1985); NOTSU (1983).
(b) WAKITA *et al.* (1987).
(c) this work; NOTSU *et al.* (1990); KIMURA (2005).
(d) MARTY *et al.* (1989); NOTSU *et al.* (1990); STURCHIO *et al.* (1996); NOTSU *et al.* (2001).

hand, the $^3He/^4He$ ratios of backarc region volcanoes were higher than those of the transition region in the NE Japan arc (SANO and WAKITA, 1985), while this is not the case in the Chugoku district. The $^3He/^4He$ ratios of the backarc region in the Chugoku district are lower than those of the transition region (see Fig. 4). The geochemical environment of the magma source in the backarc region of the Chugoku district should be discrepant from that of the NE Japan arc.

3.3 Implications for the Magma Source of the Chugoku District

Geotectonic settings of the Chugoku district are different from those of the NE Japan arc. It is well documented that subduction of young plates manifest different geophysical processes than subduction of old plates (e.g., SHIONO, 1988; OKINO *et al.*, 1994). Volcanism in the NE Japan arc is explained by partial melting of the mantle wedge due to dehydration of serpentine, which in turn is hydrated by the dehydration of the slab (IWAMORI, 1998). On the other hand the dehydration of the Philippine Sea slab beneath southwest Japan occurs at a shallow depth (SENO *et al.*, 2001; YAMASAKI and SENO, 2003) and it seems difficult to explain the Quaternary volcanism in this region by dehydration from the subducted crust. Especially beneath Kinki Spot, the dehydration from the serpentinized mantle may have induced incipient partial melting of the mantle wedge (SENO *et al.*, 2001). Melting of the subducted slab is one possibility (NAKANISHI *et al.*, 2002). DEFANT and DRUMMOND (1990) explained the volcanic rocks, Adakites, by partial melting of young subducted slabs. MORRIS (1995) reported that chemical characteristics of volcanic rocks from Sambe and Daisen volcanoes are similar to Adakites, and NAKANISHI *et al.* (2002) suggested the aseismicity of the Philippine Sea slab at depths exceeding 60 km represents melting of the slab. Although it is tenuous whether the P-T path of the crust of the subducting Philippine Sea slab at present passes through the solidus of amphibolite or not (YAMASAKI and SENO, 2003), it is likely to have passed through the solidus for the geological past (FURUKAWA and TATSUMI, 1999).

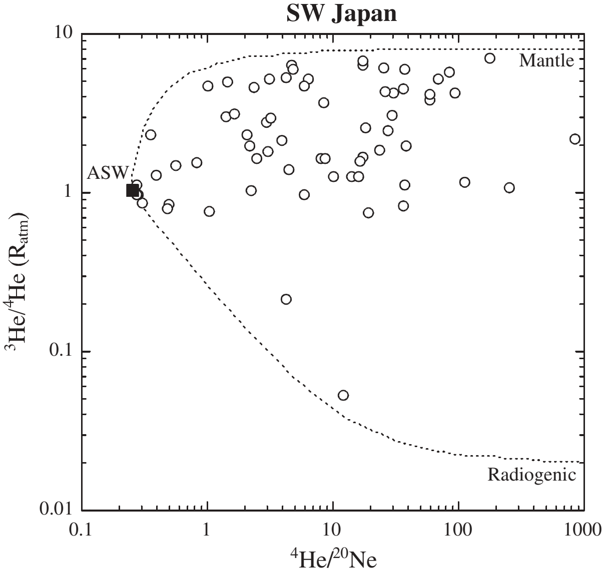

Figure 2
A correlation diagram between the $^3He/^4He$ and $^4He/^{20}Ne$ ratios of hot spring gas and water samples in SW Japan. Dotted lines show the mixing lines between mantle derived helium and air saturated water at 0 °C (ASW) and between radiogenic helium and ASW.

We examine here whether the slab melting produces the recent volcanism of the region in terms of the aging effect on the helium isotopes. Formation age of the Shikoku Basin, which is a part of the subducting Philippine Sea plate, is about 20 to 30 Ma (KOBAYASHI and NAKADA, 1978) or about 15 to 25 Ma (SHIH, 1980). Then it is definitely older than 10 Ma. TORGERSEN and JENKINS (1982) reported helium isotope decline due to magma aging. If we assume the holocrystalline Tholeiite as a representative material of the Shikoku Basin, uranium and thorium abundances are 0.1 and 0.18 ppm, respectively (TATSUMOTO, 1966). Again if the magma which consists of the Shikoku Basin evolves as a closed system, the $^3He/^4He$ ratio decreases with geological time due to radiogenic production of ^4He. Assuming that the initial $^3He/^4He$ ratio and ^3He content in the holocrystalline tholeiite are 8 R_{atm} and 1.6×10^{-10} cm^3STP/g (OZIMA and PODOSEK, 2002), respectively, the estimated $^3He/^4He$ ratios of 1 Ma and 10 Ma magma are 0.24 R_{atm} and 0.086 R_{atm}, respectively. The highest (5.8 R_{atm}) and average (3.8 R_{atm}) $^3He/^4He$ ratio of the transition region in the Chugoku district are significantly higher than the value of 0.086 R_{atm} estimated in 10 Ma magma. This suggests that the slab melting alone cannot account for the helium isotope data in the region. New and pristine mantle material with a high $^3He/^4He$ ratio should be involved in the magma source of the Chugoku district.

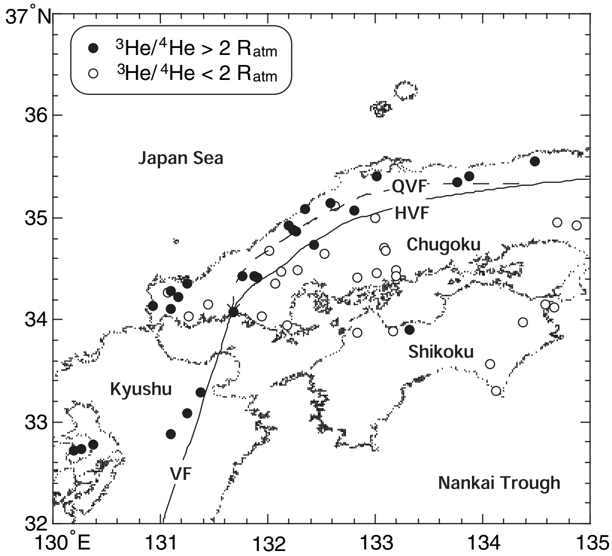

Figure 3
Locations of sampling sites and corrected $^{3}He/^{4}He$ ratios. Solid circles indicate that the $^{3}He/^{4}He$ ratio is higher than 2 R_{atm}, and open circles show that the ratio is lower than that. Quaternary volcanic front (QVF) reported by KIMURA *et al.* (2003a) does not agree with Helium Volcanic Front (HVF) defined in this work.

Since the dehydration from the crust occurs at shallow depths, and the dehydration from the serpentinized mantle is limited beneath SW Japan (SENO *et al.*, 2001), typical island-arc volcanism is not expected. Another candidate to provide the mantle helium should be required in addition to the possible slab melting of the Philippine Sea plate with a low $^{3}He/^{4}He$ ratio. Recently the geometry of the subducting Pacific slab beneath SW Japan has been estimated, by a high density seismic network, to be a continuation of that beneath NE Japan along the same strike (UMINO *et al.*, 2002; SEKINE *et al.*, 2002). The depth of the slab surface is between 400 km and 500 km in the Chugoku district. We suggest that dehydration and fluid migration in the deep mantle associated with the subduction of the Pacific plate beneath SW Japan could be one possible source of pristine magmas beneath the Quaternary volcanic front of SW Japan (IWAMORI, 1991). Although it is not well known whether such deep phenomena may be consistent with the geochemical characteristics of the magma source, it is consistent with IWAMORI's (1992) inference that the source is estimated to be deep in the mantle, based on the incompatible element concentrations. Because the physical and chemical mechanism to link such deep processes to the slab melting and surface volcanism is not understood and beyond the scope of the present paper, further discussion of the problem is needed.

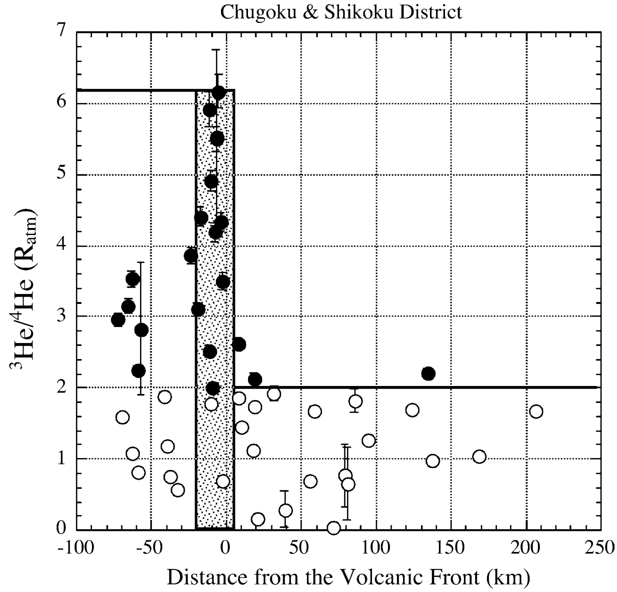

Figure 4
The $^{3}He/^{4}He$ profile in the Shikoku-Chugoku district, showing corrected $^{3}He/^{4}He$ ratio versus geographic distance from sampling site to Helium Volcanic Front (HVF in Fig. 3). Dotted region shows a transition region of $^{3}He/^{4}He$ ratios with a width of 25 km.

4. Conclusion

A clear geographical contrast of $^{3}He/^{4}He$ ratio was observed in the Chugoku district, SW Japan, which may provide a constraint on the position of volcanic front in the region where it was not well defined by previous works. Higher $^{3}He/^{4}He$ ratios found in the volcanic arc side cannot be explained by the slab melting of the subducting Philippine Sea plate because of the magma aging effect. New and pristine mantle component is required. The lower $^{3}He/^{4}He$ ratios in the narrow regions near the volcanic front of the Chugoku district than those ratios of the Kyushu district indicate that the magma source of the former is currently affected by more radiogenic contamination than the latter. The $^{3}He/^{4}He$ ratios near the volcanic front of the Chugoku district are rather close to those near the volcanic front of NE Japan, which suggests that the magma source may be related to the Pacific plate subduction, even though the mechanism is not well understood at present.

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