EXPRESS LETTER

On the change of $^3\text{He}/^4\text{He}$ ratios in hot spring gases after The Iwate–Miyagi Nairiku Earthquake in 2008

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The Iwate–Miyagi Nairiku Earthquake in 2008 (M7.2) occurred on June 14th 2008 in the northeastern Japan, Iwate Prefecture. We collected water and gas samples in hot springs from seven localities around the epicenter of the earthquake on June 21st and 22nd, one week after the earthquake, and measured the $^3\text{He}/^4\text{He}$ ratio and He and Ne concentrations of the dissolved gases. We found 10–85% increases in $^3\text{He}/^4\text{He}$ ratios in five hot springs, while we found 11–35% decrease in two others. The positive anomalies were interpreted as upwelling of aqueous fluid containing mantle ^3He beneath the earthquake region. It is possible that ascending fluids triggered the earthquake.

Keywords: helium isotopes, noble gas, earthquake, epicenter, Japan

INTRODUCTION

Recent geophysical research in northeastern Japan suggest that aqueous fluids supplied by the subducting slab are transported upward to shallow levels where they may weaken the surrounding crustal rocks, resulting in local compressional/tensional deformation and increasing the local crustal contraction rate (e.g., Hasegawa *et al.*, 2005). Thus ascending fluids of mantle origin may trigger shallow crustal earthquakes by the mechanism of pore-pressure diffusion (i.e., relaxation) (Parotidis *et al.*, 2005). However, the presence of fluids is generally inferred by seismic velocity anomalies and stochastic modeling (Hainzl and Ogata, 2005). It is difficult to directly detect the presence of enhanced upwelling fluid flow using geophysical techniques.

Helium isotopic ratio could be a good tracer to identify the uprising of deep-seated fluids. These fluids often contain measureable traces of mantle-derived helium, particularly in volcanic areas as Japan (e.g., Sano and Wakita, 1985). Mantle helium is characterized by the occurrence of primordial ^3He with a typical $^3\text{He}/^4\text{He}$ ratio of 8 Ra (1 Ra = 1.4×10^{-6} ; Ra means the $^3\text{He}/^4\text{He}$ ratio of the atmosphere). This is very different from the low $^3\text{He}/^4\text{He}$ ratio in the crust (10^{-2} – 10^{-1} Ra) because of the addition of large amounts of ^4He produced via the radioactive decay of Th and U contained in the crustal rocks.

In the northeastern Japan, where a typical island arc structure is developed on the subduction zone, there is a clear trend in the $^3\text{He}/^4\text{He}$ ratio values which is perpendicular to the arc axis; low $^3\text{He}/^4\text{He}$ ratios in the front arc and high $^3\text{He}/^4\text{He}$ ratios in the volcanic arc (Sano and Wakita, 1985; Sano and Nakajima, 2008). However, this typical trend across the island arc is not well observed throughout all of northeastern Japan. For example, all the samples in the volcanic arc for 38–39°N have values between 2 to 5 Ra, but those in the 39–39.5°N area have ratios as low as 1 Ra; this indicates the presence of crustal material under the arc, which agrees well with the underground structure obtained from seismic velocity data (Horiguchi, 2008). *The Iwate–Miyagi Nairiku Earthquake in 2008* occurred in such a low $^3\text{He}/^4\text{He}$ ratio area, and thus $^3\text{He}/^4\text{He}$ ratios could be a good tracer to identify the origin of the aqueous fluid.

Here we present some helium isotopic data measured in hot springs from the Iwate Prefecture in a radius of about 40 km around the epicenter of *The Iwate–Miyagi Nairiku Earthquake in 2008* which suggests a primary role of mantle-derived fluids in triggering the earthquake.

SAMPLES AND He MEASUREMENTS

The Iwate–Miyagi Nairiku Earthquake in 2008 occurred on June 14th 2008. The epicenter was 39°1.7' N 140°52.8' E with a magnitude M7.2 and a depth of 8 km (source: Japan Meteorological Agency). Horiguchi (2008) collected hot spring and gas samples throughout this region in May and July in 2006 and measured He isotopic

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Fig. 1. The sampling locations (open circles) and the epicenter (star mark) of the Iwate–Miyagi Nairiku Earthquake in 2008. The inset shows the epicenter location relative to the entire Japanese island chain. Thick lines show the location of active Quaternary faults. The filled triangles are Quaternary volcanoes, and the line with triangles shows caldera rim (from Maps of Active Faults in Japan). The gray area shows the epicenters of the aftershocks (source: Japan Meteorological Agency). The $^3\text{He}/^4\text{He}$ ratio (corrected for air component; see text) after the earthquake and the increase rate (in the parenthesis) of the $^3\text{He}/^4\text{He}$ ratio relative to that before the earthquake are given.

ratios and He and Ne concentrations. For the present study, we collected samples in seven localities around the epicenter on June 21st and 22nd 2008, only a week after the earthquake. The sampling localities are given in Fig. 1. All samples are hot spring water except for Onikobe, where gas samples were collected using a water displacement method and stored in a container with vacuum valves at both ends (e.g., Sano *et al.*, 1986; Matsumoto *et al.*, 2003). Two kinds of glass containers were used; lead glass with a volume of 50 cm³ and Pyrex with a volume of 100 cm³. The gas dissolved in the water samples was extracted by pouring the water into a connecting glass container under vacuum at the laboratory.

The $^3\text{He}/^4\text{He}$ ratio and the concentrations of He and Ne were determined using a noble gas mass spectrometer VG5400 installed at Osaka University. All measurements

were carried out within two weeks after the sample collection. Helium analyses were calibrated against the HESJ (Helium Standard of Japan; 20.63 ± 0.10 Ra) to determine the isotopic discrimination (Matsuda *et al.*, 2002). The $^3\text{He}/^4\text{He}$ ratios of air were 1.002 ± 0.056 Ra and 0.989 ± 0.053 Ra during the measurement period, confirming that the obtained values were identical with the real air value (1 Ra) within errors. Results are reported in Table 1. For the Onikobe and Kamihata sites we made measurements twice for different glass containers, and the obtained results agree well each other (Table 1). For the samples collected before the earthquake, only the lead glass containers were used and the measurements were carried out at the Ocean Research Institute of The University of Tokyo. The details of the measurements are given in Horiguchi (2008) and those values are also given in Table 1.

RESULTS AND DISCUSSION

To avoid the effect of air contamination during the sampling and/or in the sample itself we corrected the obtained $^3\text{He}/^4\text{He}$ ratio using the $^4\text{He}/^{20}\text{Ne}$ ratios (Table 1). The $^3\text{He}/^4\text{He}$ ratio in air is 1 Ra and its $^4\text{He}/^{20}\text{Ne}$ ratio is 0.318. We assumed the $^4\text{He}/^{20}\text{Ne}$ ratios of the mantle and the crust to be 5000 (Horiguchi, 2008). We made the following calculation;

$$(^3\text{He}/^4\text{He})_c = (1/5000 - 1/0.318)/(1/(^4\text{He}/^{20}\text{Ne})_m) \times ((^3\text{He}/^4\text{He})_m - 1) + 1$$

where $(^3\text{He}/^4\text{He})_c$ is the corrected $^3\text{He}/^4\text{He}$ ratio and the subscript “m” indicates the measured value. The calculated $(^3\text{He}/^4\text{He})_c$ should represent only the mixture of the mantle and crustal helium (Table 1).

We plotted $(^3\text{He}/^4\text{He})_c$ after the earthquake and the percentage of variation in the ratio in Fig. 1. Among the samples, the sampling locations at Sugo were different, although belonging to the same hot spring area. Thus, it may not be accurate to compare directly the pre- and post-earthquake $(^3\text{He}/^4\text{He})_c$ for Sugo hot spring.

For Onikobe, Yabitsu, Kamihata and Tsunatori and Sawanouchi samples, we observed an increase in the $^3\text{He}/^4\text{He}$ ratios ranging from 10 to 85% (Fig. 1 and Table 1). In contrast, the ratio at Yunohara decreases by 35%. It is noteworthy that Yunohara is a cold spring (temperature lower than 20°C), while all other springs have higher temperatures up to 40°C. Thus, the origin of the springs may be different only for Yunohara. Yunohara is at the western side and is just on the active fault that is not related the earthquake in this time (Fig. 1). It is very likely that some different mechanism to release radiogenic ^4He occurred in this site. The Iwate–Miyagi Nairiku Earthquake in 2008 is supposed to be associated with a reverse fault

Table 1. $^3\text{He}/^4\text{He}$ and $^4\text{He}/^{20}\text{Ne}$ ratios and the increase rate of the $^3\text{He}/^4\text{He}$ ratio after the earthquake

Sample location ^{*1}	$(^3\text{He}/^4\text{He})_{\text{m}}$ ^{*2} (Ra)	$(^4\text{He}/^{20}\text{Ne})$	$(^3\text{He}/^4\text{He})_{\text{c}}$ ^{*3} (Ra)	$(^3\text{He}/^4\text{He})_{\text{c before}}$ ^{*4} (Ra)	Increase rate ^{*5} (%)
Sawauchi	1.018 ± 0.026	0.637	1.036 ± 0.053	0.686 ± 0.031	51 ± 10
Tsunatori	0.951 ± 0.044	70.4	0.951 ± 0.044	0.848 ± 0.020	12 ± 6
Sugo	0.832 ± 0.019	1.09	0.763 ± 0.027	0.854 ± 0.049	-11 ± 6
Yunohara	1.258 ± 0.014	16.5	1.263 ± 0.015	1.940 ± 0.031	-35 ± 1
Kamihata	0.273 ± 0.012	2.98	0.186 ± 0.013	0.102 ± 0.027	82 ± 50
	0.285 ± 0.015	2.72	0.190 ± 0.017	0.102 ± 0.027	87 ± 52 (84 ± 36)
Yabitsu	0.367 ± 0.019	4.26	0.316 ± 0.020	0.258 ± 0.022	23 ± 13
Onikobe	2.320 ± 0.061	0.872	3.077 ± 0.096	2.722 ± 0.014	13 ± 4
	1.983 ± 0.041	0.663	2.890 ± 0.079	2.722 ± 0.014	6 ± 3 (10 ± 2)
Air		0.318	1		

^{*1}The second values of Kamihata and Onikobe are for the sample in the lead-glass container. All others are for the sample in the Pyrex glass container.

^{*2}The measured $^3\text{He}/^4\text{He}$ ratio.

^{*3}Corrected $^3\text{He}/^4\text{He}$ ratio for the air component using $^4\text{He}/^{20}\text{Ne}$ ratio (see text).

^{*4}Corrected $^3\text{He}/^4\text{He}$ ratio before the earthquake (from Horiguchi, 2008).

^{*5}The value in the parenthesis is the mean value of two measurements.

movement due to E-W compression. The surface slip direction at the earthquake was perpendicular to the axis (NNE-SSW) of the epicenter region of the aftershocks (Fig. 1). One may think that the increase/decrease of the $^3\text{He}/^4\text{He}$ ratio is related with compressional/extensional feature of the region. However, all the sampling locations including Yunohara are supposed to be in compression field, and the decrease of the $^3\text{He}/^4\text{He}$ ratio in Yunohara is not related with this feature. The $^4\text{He}/^{20}\text{Ne}$ ratio of Yunohara is as high as 16.5 although it is not so high as 70.4 of Tsunatori that is at the north side of the epicenters of the aftershocks (Fig. 1). We have not made an accurate quantitative analysis of the ^4He concentration of Yunohara, but it is estimated to be higher than that of other samples by about an order of magnitude, judging from the peak intensity at the measurement. Thus, it is likely that some radiogenic ^4He from the crustal rocks was supplied in this sample.

Anyway, our results suggest that the $^3\text{He}/^4\text{He}$ ratios increased by 10–85% in most of the hot springs in this region after the earthquake (Fig. 1 and Table 1). We do not think this is due to the normal variance. The sampling seasons are almost the same before and after the earthquake, so we can not expect large isotopic variations caused by changes in the hydrologic cycle. If the variation is due to the normal variance, the change (increase or decrease) of the $^3\text{He}/^4\text{He}$ ratios should be at random. The probability that the He ratio in five hot spring increases is $1/32$, that in five of six hot springs is $6/64$ (in case including Yunohara).

Previous studies on the change of the $^3\text{He}/^4\text{He}$ ratios before and after an earthquake show that they can both

increases and decreases after an earthquake. For the 1995 South Hyogo Prefecture Earthquake (M7.2), the $^3\text{He}/^4\text{He}$ ratios of ground water samples decreased by about 20–40%, which was interpreted as being due to the release of radiogenic ^4He as a result of micro-fracturing of rocks (Sano *et al.*, 1998). The basement in the South Hyogo Prefecture is granitic, possibly enhancing the radiogenic production of ^4He from the decay of U and Th. Igarashi *et al.* (1995) also reported the increase of radon in ground-water before the 1995 South Hyogo Prefecture Earthquake, which is also due to the formation of micro-cracks in the aquifer system.

In contrast, after the 1984 Western Nagano Earthquake (M6.8) the $^3\text{He}/^4\text{He}$ ratios of four bubbling gas increased at hot springs located less than 10 km from the newly formed fault (comparison between 1981 and 1984 after the earthquake), indicating that the earthquake was triggered by an upward migration of the ^3He -containing fluids associated with magma intrusion beneath the source region (Sano *et al.*, 1986). The three samples of which $^3\text{He}/^4\text{He}$ ratios decreased after the earthquake were located more than 10 km from the fault although one sample shows the increase of the ratio in this area. A similar increase of $^3\text{He}/^4\text{He}$ ratios was also reported after The Niigataken Chuetsu-oki Earthquake in 2007 (Horiguchi, 2008) where the $^3\text{He}/^4\text{He}$ ratios of gas well increased in all six sampling sites, indicating the intrusion of magmatic fluid to the crustal shallow part.

Our results show $^3\text{He}/^4\text{He}$ variations in a similar fashion to those observed during the 1984 Western Nagano Earthquake (Sano *et al.*, 1986) and The Niigataken Chuetsu-oki Earthquake in 2007 (Horiguchi, 2008). For

comparison, we can speculate that upwelling of the deep-seated fluids containing primordial ^3He excess produced the observed He isotopic variations in the hot springs of Iwate Prefecture.

The injection of large amount of deep-seated fluids could have triggered the earthquake. The Emergency Observation Group (Tohoku University) for *The Iwate–Miyagi Nairiku Earthquake in 2008* gave a preliminary short report of their seismological research for the Coordinating Committee for Earthquake Prediction (CCEP material #178) on the internet website (http://www.aob.geophys.tohoku.ac.jp/download/yochiren/siryo/178_1.pdf) on August 18th. A vertical cross-section of S-wave perturbations along the earthquake region (figure 7e of the report) showed the occurrence of a low-velocity layer corresponding to the upwelling channel of aqueous fluid under the main shock epicenter region (Okada *et al.*, 2007, 2008). Thus, our geochemical observations related to the upwelling of mantle-derived fluids seem to be much compatible with the seismological data.

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