Seismic Response of Dissolved Gas in Groundwater

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Abstract

We share three examples of earthquake response of gas and radon concentrations in groundwater, and discuss how we reveal a mechanism of such phenomena for the earthquake forecast. Groundwater radon concentration which had been monitored at the Kashima observatory on the Futaba fault indicated no pre-seismic response to "the 2011 Pacific Offshore of Tohoku Earthquake", though the observatory is located at 180 km distance from the epicenter of the earthquake. Observation in the Kashima observatory was stopped because of catastrophic damages to instruments. On the other hand, a gas composition in groundwater recorded at the Atotsugawa observatory on the Atotsugawa active fault pre-seismically changed before the earthquake. Especially, helium concentration clearly indicated precursory change, and responded in concert with small-scale earthquakes happened along active faults. Even though both observatories are placed on the active fault, the reason why the latter case showed the precursory change would be that the Atotsugawa fault is more active rather than Futaba fault. Groundwater radon concentration, which was recorded at the Nakaizu observatory in the Izu Peninsula, moderately-elevated from a half year before the earthquake. The radon concentration recently reached to the original level. Seismo-geochemical changes in an aquifer above might have been triggered by a stress change due to a tectonic deformation after and/or before earthquakes. Unfortunately, we have only some conceptual model to evaluate the precursory changes. In order to develop a more realistic model to express the mechanism of precursors, we would like to discuss a strategy of study.

1. INTRODUCTION

It is good time to restart the seismo-geochemical monitoring to realize the earthquake forecast. A big earthquake of Mw=9.0 hit Tohoku and Kanto area in Japan at 14:46:18, 11, March 2011 (JST). The big earthquake was named as "the 2011 Pacific Offshore of Tohoku Earthquake" (3.11 earthquake). Big tsunamis followed by the 3.11 earthquake killed many peoples and catastrophically broke cities on the coastal part of the Pacific Ocean. We believe that the seismo-geochemical studies have a potential to prevent seismic disasters. As you know, the radon concentration in groundwater sometimes indicates precursory change for big earthquake (e.g., Wakita et al. (1980); Igarashi et al.

(1995); Sugusaki et al. (1996); Virk et al. (2001); Kuo et al. (2006)). Though Yasuoka's model (Yasuoka et al., 2006) and Sornette's model (Sornette, 1999) are simple and powerful, but it is difficult to connect model parameters to the actual hydrological and tectonic parameters. The essential point is to express the radon concentration by observable parameters related to hydrology and tectonics. Kuo's model (Kuo, 2006) gave an important view for explanation of the radon decline. This idea will make a breakthrough on the mechanism study of precursors. In this paper, we share three examples of earthquake response of gas and radon concentrations in groundwater, and discuss how we reveal a mechanism of such phenomena for the earthquake forecast.

2. OBSERVATION

The Kashima observatory (KSM, N37.69, E140.89) is located in the eastern part of Fukushima Prefecture. The observation well is a 200-m deep artesian well which was directly drilled on the Futaba active fault. The upper layer of the Kashima site is composed of sandstone and shale, and mylonitic granodiorite layers are found deeper than 130 m. Groundwater, which drains out from a branch tube on a well casing pipe at a flow rate of about 30 mL/min, was directly introduced into a ZnS(Ag) scintillation detector chamber (Noguchi and Wakita, 1977). Radon gas was extracted passively from groundwater in the detector chamber.

The Atotsugawa observatory (ATG, N36.34, E137.18) is located in the northern part of Gifu Prefecture and south-western end of the Atotsugawa active fault. The observation well is a 300-m deep well drilled directly on the Atotsugawa fault, and the strainer depth is 170 m. Groundwater was siphoned directly from an aquifer at a flow rate of about 250 mL/min. Gas dissolved in groundwater was extracted by a depressurization method, and was dried by a dryer system. Dehumidifed gas was fed into a quadrupole mass spectrometer (Takahata, et al., 1997; Tsunomori and Notsu, 2008) to analyze a gas composition. Gas composition was calculated from a mass spectrum in consideration of effects of fragmentation and ionization cross section.

The Nakaizu observatory (SKE, N34.93, E 139.04) is located in the central part of Izu Peninsula. The observation well is a 350-m deep artesian well drilled in a brittle stratum surrounded by a ductile one. Groundwater was directly drawn out from inside of a well casing by a pump at a flow rate of about 1 L/min because the flow rate of groundwater from the well head is about 300 L/min. Groundwater sampled was injected into an active radon exchanger (Fig. 1) which uses atmospheric air as a blank gas because the radon concentration of air is negligibly low rather than that of groundwater. Radon concentration was measured by a hand-crafted ZnS(Ag) scintillation chamber. In the case of the active extraction of radon, the radon concentration in groundwater calculated from that in air must be corrected by flow rates of groundwater and air in the chamber as follows,

$$C_{w,0} = C_a \left(\frac{F_a}{F_w} + D \right), \tag{1}$$

where C_a, $C_{w,0}$, F_a, F_w, and D denote respectively a radon concentration of an extracted gas, a radon concentration of groundwater, a flow rate of groundwater in the exchanger, a flow rate of air as a blank gas in the chamber, and partition coefficient. The partition coefficient was evaluated by a conventional equation (Cosma et al. (2008); Hunyadi et al. (1999)),

$$D = 0.105 + 0.403\mathrm{Exp}(-0.0502T), \tag{2}$$

where T is the groundwater temperature in Celsius' temperature scale.

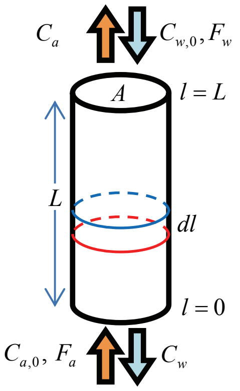

Fig. 1: Diagrammatic illustration of an active radon exchanger.

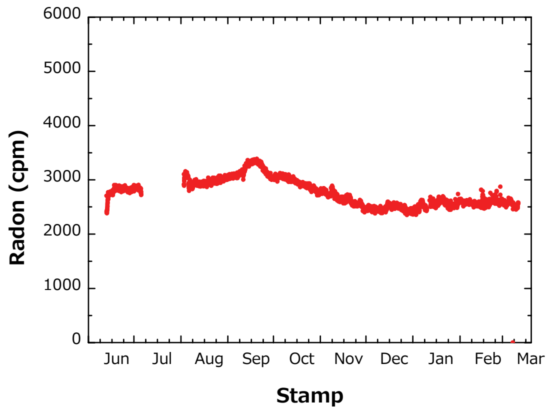

Fig. 2: The radon concentration change of the KSM site from Jun. 2010 to Mar. 2011

3. RESULTS AND DISCUSSIONS

3.1 Radon concentration at Kashima

The radon concentration during 10 months before the earthquake also showed same behavior that the radon concentration in groundwater of the KSM site shows high concentration in summer season and low concentration in winter season (Igarashi and Wakita, 1990). According to the criterion reported by Igarashi and Wakita (1990), we should be able to expect an anomaly in the radon concentration. However, although the KSM site is located on the Futaba active fault and the epicentral distance is about 180 km, the radon concentration did not indicate preseismic anomalous change (Fig. 2).

As Igarashi pointed out, there is a possibility that the sensitivity of the radon concentration to big earthquakes is variable with time (Igarashi et al, 1993). This suggests that the responsibility of the radon concentration to the tectonic deformation is also variable, thus the KSM site became silent.

3.2 Gas composition at Atotsugawa

The gas composition in groundwater might have indicates preseismic change not only before the 3.11 earthquake but also before small earthquakes along the ATG site. Especially, the helium concentration gradually decreased before earthquakes, and it gradually increased to an original level after earthquakes (Fig. 4). In this study, the extracted gas from groundwater was dried by a dehumidifier system. This process is important to analyze the helium concentration because the helium signal in a mass spectrum sometimes is distorted by a huge signal of H_2 due to the fragmentation of H_2O molecules with the electron ionization. As shown in Fig 3., the H_2O signal of sample gas is as same as that of blank gas. This made the helium signal clear.

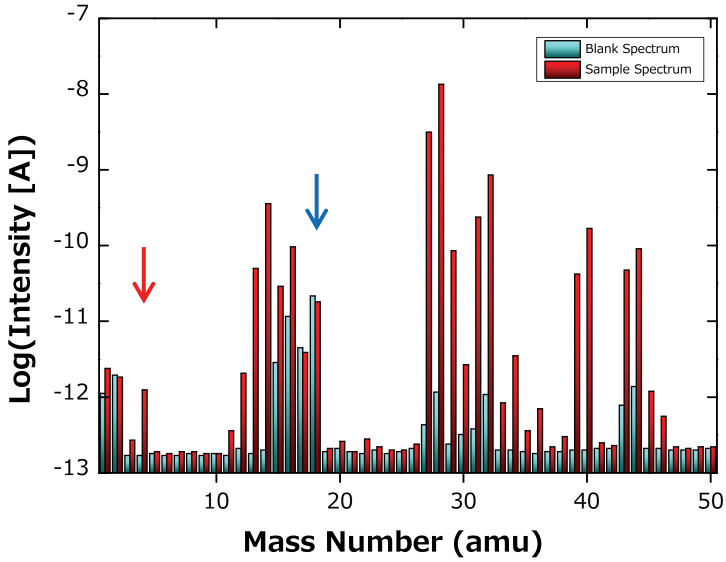

Fig. 3: A typical mass spectrum of gas extracted from groundwater of the ATG site. A blue arrow indicates a signal of H_2O, and a red arrow does the helium signal.

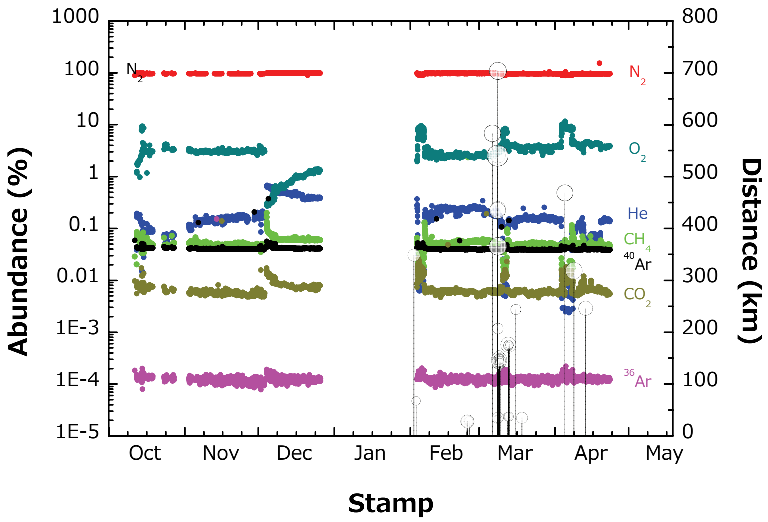

Fig. 4: Composition change of gas concentration dissolved in groundwater recorded from Oct. 2010 to Apr. 2011. Circles indicate earthquakes, its radius reflects the magnitude and height shows the epicentral distance.

There were three big event groups during an observation period from October 2010 to April 2011 (Fig. 4). The first event occurred in the beginning of February 2011 just after a restart of observation. The second event was the 3.11 big earthquake and aftershocks. The third one happened in the beginning of April 2011. Concentrations of O_2, CH_4, ^{40}Ar, CO_2 and ^{36}Ar jumped coincidentally with three events. These changes recovered to original concentrations several days after events. The helium concentration gradually decreased before a few weeks at least in the second and third events. Subsequently, it co-seismically dropped at the events, and followed by gradual increase of concentration. In these behavior, the gentle decrease before the events might be precursors relating to crustal deformation before the earthquake.

3.3 Radon concentration at Nakaizu

The radon concentration monitored at the SKE site might have indicated a preseismic change before the 3.11 earthquake. The radon concentration of the SKE site had shown precursory change (Wakita, 1980) before the Izu-Oshima-Kinkai earthquake in 1978. At that time, the radon concentration gradually declined before the event with a lot of evidences, that is, the strain, the groundwater temperature, and the water level which are recorded on different sites behaved similarly to the radon concentration (Wakita et al., 1988). In this time, the radon concentration moderately increased during about a half-year before the 3.11 earthquake. The radon concentration remained in the high level during the aftershock activity was high, and it returned to the initial level when the aftershock activity became low. The deformation process of the earth's crust in this time must be different from the case in 1978 (Tsunomori and Kuo, 2010).

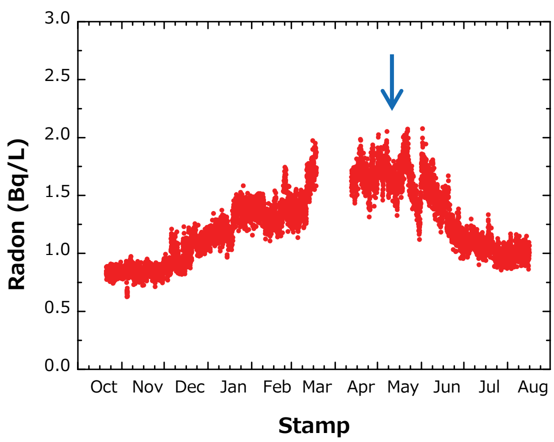

Fig. 5: Radon concentration change recorded at the SKE site form Oct. 2010 to Aug. 2011. The arrow indicates the 3.11 earthquake.

3.4 Challenge to Reveal Mechanism

We demonstrated here two precursory changes before a big earthquake. As you know, during the past four decades, many precursors had been reported. The number of literatures must be larger than 150.

However, the mechanism of precursory change remains a conceptual model. It is necessary to start to reveal mechanism as soon as possible. The fundamental ideas had been produced by Igarashi and Wakita (1990), Wylie and Wood (1990), Roeloffs (2006) and Kuo et al. (2006). The concentration of the crust-derived gas such as radon and helium is proportional to a ratio of the surface area S and the pore volume V in a fracture system of an aquifer as follows,

$$C_w = \tau E \frac{S}{V}, \tag{3}$$

where τ and E are respectively the half-life of radon in second and the production rate of radon in $Bq \cdot m^{-2} s^{-1}$, and both parameters of τ and E can be assumed as constant. The parameter S/V indicates a mean thickness of the fractures, thus the ratio would be proportional to the hydraulic conductivity if the deformation of the fracture system is small. Therefore it is important to establish an observation technique to monitor the hydraulic conductivity of an aquifer with the gas composition and/or the radon concentration for revealing the mechanism of precursors. If the radon concentration is related to the hydraulic conductivity, we might be able to construct a framework to forecast big earthquake by equation (3).

4. CONCLUSIONS

- There is no distinguishable change in the radon concentration in groundwater recorded at the KSM site.
- The gas composition, especially the helium concentration, monitored at the ATG site showed precursory change before the 3.11 earthquake.
- The radon concentration in groundwater recorded at SKE site indicated a precursory change during a half-year before the 3.11 earthquake.
- It is very important to establish an observation method to monitor the hydraulic conductivity as a probe of the surface area of a fracture system in an aquifer with the gas composition and/or the radon concentration.

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