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Radon concentration distributions in shallow and deep groundwater around the Tachikawa fault zone

Fumiaki Tsunomori [a, *], Tomoya Shimodate [b], Tomoki Ide [c], Hidemi Tanaka [c]

[a] Geochemical Research Center, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan
[b] Collage of Liberal Arts, International Christian University, 3-10-2 Osawa, Mitaka, Tokyo 181-8585, Japan
[c] Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo, Tokyo 113-0033, Japan

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Groundwater radon concentrations around the Tachikawa fault zone were surveyed. The radon concentrations in shallow groundwater samples around the Tachikawa fault segment are comparable to previous studies. The characteristics of the radon concentrations on both sides of the segment are considered to have changed in response to the decrease in groundwater recharge caused by urbanization on the eastern side of the segment. The radon concentrations in deep groundwater samples collected around the Naguri and the Tachikawa fault segments are the same as those of shallow groundwater samples. However, the radon concentrations in deep groundwater samples collected from the bedrock beside the Naguri and Tachikawa fault segments are markedly higher than the radon concentrations expected from the geology on the Kanto plane. This disparity can be explained by the development of fracture zones spreading on both sides of the two segments. The radon concentration distribution for deep groundwater samples from the Naguri and the Tachikawa fault segments suggests that a fault exists even at the southern part of the Tachikawa fault line.

1. Introduction

The Headquarters for Earthquake Research Promotion announced that the probability of earthquake occurrence in the Tachikawa fault zone increased because the Global Navigation Satellite System revealed that the extension direction of the Earth's crust after the 2011 off the Pacific Coast of Tohoku Earthquake on March 11, 2011 was about 45° to the fault strike of the Tachikawa fault segment (Ozawa et al., 2012; The Headquarters for Earthquake Research Promotion, 2015). Since the Tachikawa fault segment, which is one of fault segments composing the Tachikawa fault zone, is thought to be located beneath a residential area, detailed information was required in order to prepare a hazard map for a possible earthquake. Japanese government and Earthquake Research Institute, the University of Tokyo surveyed the segment using seismic wave reflection and geological trenching in 2015 (MEXT Japan, 2015). They concluded that the presence of obvious geological unconformity and a clear reflection in the sedimentary layers of the northernmost 12 km part of the fault line implied the existence of a fault beneath this part. However, the absence of any such geological unconformity or reflection plane in the relatively thicker sedimentary layers of the southernmost 21 km part of the fault line implied that there was no fault beneath the southernmost part of the fault line.

Identifying the fault strike and the extent of the damage zone around the fault are essential for disaster prevention initiatives based on estimates of strong ground motion. A fault is comprised of two inhomogeneous architectures, a fault core filled with fault gouge and damage zones in which fractures develop (Caine et al., 1996; Faulkner et al., 2010). By identifying these components, the location of the fault strike can be recognized. In the case that a fault plane reaches the ground surface, the fault core can be examined by trenching. If a fault is covered by sedimentary layers, then the location of the fault plane can be recognized by seismic reflection profiling. Fault cores are impermeable to geofluids, like water and gas, while damage zones are permeable to geofluids (Faulkner et al., 2010; Morita et al., 2013; Kuo and Tsunomori, 2014). For example, Lockner et al. revealed that the permeability of rocks on both sides of the Nojima fault was considerably higher than that of the fault core (Lockner et al., 2009). The reason why helium, carbon dioxide, and radon are frequently used as indicators of fault position is

* Corresponding author.
E-mail address: eqpred@gmail.com (F. Tsunomori).

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because the concentration distribution and the values and patterns of fluxes in these gases are remarkable around faults. Consequently, the location of a hidden fault can be geochemically specified based on the distribution characteristics of geofluids around a fault (Baubron et al., 2002; Al-Hilal and Al-Ali, 2010; Walia et al., 2010; Li et al., 2013).

Recently, the gamma-ray exploration of faults is more popular than the radon exploration. This method is powerful because we need no sampling such as groundwater or soil, as a result we can carry out a "contactless" fault survey. Nevertheless there are still some technical problems to be solved (Yoshimura and Ohno, 2012). In addition, the gamma-ray method is only applicable when a fault reaches to the ground surface or the subsurface in a non-urban region, thus it is difficult to use the method if a fault is buried under thick layers in a city area. On the other hand, the radon concentration in groundwater brings directly the information of an aquifer. This radon method enables us to consider whether the aquifer is connected to a fracture zone of a fault or not. And many wells still remain even in an urban region. Therefore the radon exploration of buried faults like Tachikawa fault is still useful.

The aim of this study is to estimate the strike and the extent of the damage zone of the Tachikawa fault segment based on groundwater radon concentrations.

2. Location and methods

2.1. Geological setting and location of sampling wells

The Tachikawa fault segment in the Tachikawa fault zone, which has a northwest-southeast strike direction (Yamazaki, 1978; Takahashi et al., 1992; Togo et al., 1996), is located in the western part of the Kanto plain in central Japan. The bedrock reaches the surface in a mountainous area on the western side of the Kanto plain. The bedrock in the northwestern area is a Jurassic accretionary complex, and that in the southeast is a Cretaceous accretionary complex. No igneous rock is present in the plane and mountain areas. According to a study on the Bouguer anomaly in this region (Suzuki, 1999, 2002), the bedrock surface lies a few thousand meters below the thick sedimentary layers of the plain.

We selected 30 sampling sites for the collection of shallow groundwater samples and 19 wells for the collection of deep groundwater samples (see Fig. 1). Sampling sites for shallow groundwater collection were selected so that they would cover both the Tachikawa fault segment and the sample sites described in Saito and Takata's report (Saito and Takata, 1994). The sampling wells for deep groundwater samples were selected based on whether the strainer depth was deeper than 1000 m. Almost all deep wells were drilled to supply public bath facilities with hot spring water. Thus, the geology at the strainer depth in each well was not disclosed, and the pipeline configurations of the wells were not standardized.

2.2. Sampling and radon measurement

Groundwater was allowed to flow from the drain valves for a few minutes to ensure that it was as fresh as possible before sampling. A 1.0 L volume of groundwater was collected in a 2.2 L plastic bottle, which was then sealed with a screw cap bearing two tube connectors. The bottled groundwater was strongly agitated for three minutes to achieve gas-liquid equilibrium as quickly as possible. The following assumptions were made in this study: 1) atmospheric air is radon free, and 2) a 3-min agitation period is sufficient for achieving the gas-liquid equilibrium. A closed system for the radon measurement was configured as shown in Fig. 2. The inner diameter and the total length of silicone tubes were 3 mm and 1 m, respectively. The air in the gas phase in the bottle was introduced into a radon monitor (RTM1688, SARAD GmbH) by a diaphragm pump after being dehumidified by passing through a DRIERITE® drying column with a void volume of 270 mL. Radioactive aerosols contained in the gas phase were caught using a filter unit connected to the inlet of the radon monitor. Gas exhausted from the outlet of the radon monitor was returned to the bottle. No bubbling setup was included in our system because we already confirmed that the equilibrium transfer is negligible under the circulation time and the temperature conditions in this study according to the quality control experiment carried out previously. Recirculation of the air phase was performed for 5 min at a rate of 15 L/min, after which radon measurements were started. The number of alpha particles emitted from radon daughters was counted continuously for 15 min. All measurements were carried out in-situ.

The air phase volume, V_a, was the total volume of the closed system, i.e., the sum of the measurement system and the gas phase in the plastic bottle. The volume of the water phase V_w was 1.0 L. The radon concentration C_a in the air phase was measured after the air-water distribution of radon reached equilibrium. The radon concentration in the water phase C_w was estimated by Weigel's equation (Weigel, 1978),

$$K_d = \frac{C_w}{C_a} = 0.105 + 0.403\exp(-0.0502T), \tag{1}$$

where K_d denotes the distribution coefficient, and T is temperature. Even though T should be in equilibrium between the two phases, we adopted the temperature when a groundwater was sampled.

If the initial radon concentration in the air and water phases before agitation was C_{a0} and C_{w0}, respectively, then the conservation equation for radon can be written as

$$C_{a0}V_a + C_{w0}V_w = C_aV_a + C_wV_w. \tag{2}$$

As the initial radon concentration in the air phase must be zero, the C_{w0} value is obtained as

$$C_{w0} = C_a\left(\frac{V_a}{V_w} + K_d\right). \tag{3}$$

By the way, radon can permeate into a lot of materials; not only plastics but also metal. According to Jiranek and Hulka (Jiranek and Hulka, 2000), a diffusion coefficient of radon into polymer materials is about $10\times10^{-12}\ m^2s^{-1}$. The relaxation time of radon in a permeable hollow tube can be roughly evaluated by $\tau = r^2/(\pi^2 D)$, where r is the radius of the hollow tube, and D is the diffusion coefficient. The relaxation time evaluated by our experimental setup is about 23,000 s, which is much longer than the measurement time 1200 s for each groundwater sample in our study. Therefore we ignored the permeation of radon into the tube in this study.

We also measured the pH of the shallow groundwater samples at the time of collection. For deep groundwater samples, the electrical conductivity, the oxidation-reduction potential and the Cl^- concentration were measured in addition to the temperature and pH.

3. Results and discussion

3.1. Radon concentration in shallow groundwater

We surveyed the distribution of the radon concentration in shallow groundwater samples around the Tachikawa fault segment, and compared our results with the previous study by Saito et al.