Anomalous decrease in groundwater radon before the Taiwan M6.8 Chengkung earthquake

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Abstract

On December 10, 2003, an earthquake of magnitude (M) 6.8, the strongest since 1951, occurred near the Chengkung area in eastern Taiwan. Approximately 65 d prior to the 2003 Chengkung earthquake, precursory changes in the groundwater radon concentration were observed at the Antung radon-monitoring station located 20 km from the epicenter. The radon anomaly was a decrease from a background level of 28.9 Bq L\(^{-1}\) to a minimum of 12.2 Bq L\(^{-1}\). Observations at the Antung hot spring suggest that the groundwater radon, when observed under suitable geological conditions, can be a sensitive tracer for strain changes in the crust preceding an earthquake.

Keywords: Radon-222; Fault; Groundwater; Earthquake

1. Introduction

Radon (\(^{222}\)Rn) is a radioactive nuclide with a half-life of approximately 3.8 d. The radon concentration in groundwater is proportional to the uranium concentration in adjacent rocks in an aquifer. Radon is chemically inert. The transport behavior of radon in geological
environments can be described on the basis of physical processes such as fluid advection, diffusion, partition between liquid and gas phases, and radioactive decay. Because of radon’s short recoil length \(3 \times 10^{-8} \text{ cm}\), only atoms produced at the surface of rock grains are released to the surrounding groundwater. Thus, the radon concentration in groundwater is largely dependent on the surface area of rocks (Torgersen et al., 1990). Before the occurrence of an earthquake, when regional stress increases, formation of microcracks in rock masses could cause an increase in the surface area of rocks. As a result, radon concentration rises in the groundwater (Igarashi et al., 1995; Teng, 1980).

Measurement of \(^{222}\text{Rn}\) in groundwater has been performed for earthquake prediction (Igarashi et al., 1995; King, 1978; Liu et al., 1986; Noguchi and Wakita, 1977; Roeloffs, 1999; Silver and Wakita, 1996; Teng, 1980; Wakita et al., 1980). According to a worldwide survey (Hauksson, 1981), most radon \((^{222}\text{Rn})\) anomalies showed an increase in the radon content of groundwater. Contrarily, few anomalies manifested a decrease in the radon content of groundwater.

To accumulate data on groundwater radon concentration, we began to study the Antung hot spring in eastern Taiwan in July 2003. An anomalous decrease in the concentration of \(^{222}\text{Rn}\) in groundwater was observed to precede the earthquake of magnitude (M) 6.8 that occurred on December 10, 2003 near Chengkung in eastern Taiwan. The anomalous decrease in radon concentration observed at the Antung hot spring suggests that the groundwater radon, when observed at suitable sites, can be a sensitive tracer for strain changes in crust associated with earthquake occurrences (Roeloffs, 1999; Silver and Wakita, 1996).

2. Materials and methods

2.1. Radon-monitoring station

The Chihshang Fault is the most active segment of the Longitudinal Valley Fault which is the present-day plate suture between the Eurasian and the Philippine Sea plates (Fig. 1). The Chihshang Fault (Hsu, 1962) ruptured during two 1951 earthquakes of magnitude (M) 6.2 and (M) 7.0. The annual survey of geodetic and GPS measurements has consistently revealed that the active creeping Chihshang Fault has been moving at a rapid steady rate, about 2–3 cm y\(^{-1}\) during the past 20 y (Angelier et al., 2000; Yu and Kuo, 2001).

Fig. 2 shows the surface slip history of the Chihshang Fault from mid-1986 to December 2004. The dashed line represents the results of direct measurements of offsets during the period 1986–1997 (Angelier et al., 1997; Angelier et al., 2000). The solid line shows the results of creepmeter monitoring during the period 1998–2003 (Lee et al., 2005). The average creeping rate was 27 mm y\(^{-1}\) and 22 mm y\(^{-1}\) in 1986–1992 and in 1992–1997, respectively. The creepmeters installed in 1998 revealed a significant decrease in creeping rate of the Chihshang Fault during the 5.5 y preceding the 2003 Chengkung earthquake. The average creeping rate was 14 mm y\(^{-1}\) in 2000–2003. The decreasing creeping rate since year 2000 suggested increasing seismic hazard along the Chihshang Fault. The Antung hot spring located approximately 3 km southeast of the Chihshang Fault was selected for the radon-monitoring site.

A 10-month observation started in July 2003 at a well (D1) located in the Antung hot spring. The filled triangle in Fig. 1 is the radon-monitoring well (D1). The monitoring well (D1) is located roughly 20 km north of the hypocenter of the magnitude (M) 6.8 earthquake that occurred at 4:38 am on December 10, 2003 (UT).

2.2. Sample collection

Discrete samples of geothermal water have been collected from the monitoring well (D1) for analysis of radon \((^{222}\text{Rn})\) content. The production interval of the well ranges from 167 m to 187 m below ground surface. The well was pumped more or less continuously. The sampling frequency was twice per week.
Every sampling starts with flushing the stagnant water in the monitoring well and in the screen zone. An insufficiently purged volume represents a major source of error, because the water sample would contain a mixture of stagnant water from the monitoring well, pore water from the filter gravel and groundwater influenced by the natural emanation rate of the aquifer. Freyer et al. (1997) reported the behavior of radon concentration in the pumping flow during continuous sampling in a monitoring well. In the first stage of flushing, the radon concentration of the water samples is practically zero and then increases rapidly to approach a constant value. A minimum of three well-bored volumes were purged before taking samples for radon measurements.

It is important to ensure the radon not to escape during the sampling procedure and the sample transportation and preparation. A 40 ml glass vial with a TEFLOW lined cap was used for sample collection. After collecting a sample, the sample vial was inverted to check for air bubbles. If any bubbles were present in the vial, the sample water was discarded and sampling was repeated. The date and time of sample collection were recorded. The samples were stored and transported in a cooler. Counting radioactivity was done within 4 d.

2.3. Radon determination

To determine the concentration of $^{222}$Rn in groundwater, the method described by Prichard and Gesell (1977) was modified and adopted. Radon is partitioned selectively into a mineral-oil scintillation cocktail.

Fig. 1. (a) Tectonic setting of Taiwan (study area: location of b). (b) Location map of the Longitudinal Valley Fault area. The open star is the 2003 mainshock; filled stars are 1951 mainshocks; filled triangle is radon-monitoring station.
immiscible with the water sample (Noguchi, 1964). The sample is dark-adapted, equilibrated, and then counted in a liquid scintillation counter (LSC) using a region or window of the energy spectrum optimal for radon alpha particles (Lowry, 1991).

Radon concentrations were determined by drawing a 15 ml sample directly from a field sample into a clean syringe. Care was taken to prevent aeration of the samples in the process. The samples were then injected beneath a 5 ml layer of mineral-oil-based scintillation solution in 24 ml vials. The vials were vigorously shaken to promote phase contact, dark-adapted and held for at least 3 h to ensure the attainment of equilibrium between $^{222}$Rn and its daughters, and then assayed with a liquid scintillation counter. The results were corrected for the amount of radon decay between sampling and assay.

A calibration factor for the LSC measurements of $193 \pm 1.4$ cpm Bq$^{-1}$ was calculated using an aqueous $^{226}$Ra calibration solution, which is in secular equilibrium with $^{222}$Rn progeny. The background for the LSC was $5.5 \pm 0.22$ cpm. For a count time of 50 min and background less than 6 cpm, a detection limit below 0.67 Bq L$^{-1}$ was achieved using the sample volume of 15 ml (Prichard et al., 1992).

3. Results and discussion

The radon concentration in groundwater was fairly stable (28.9 Bq L$^{-1}$ in average) in the period from July 2003 to September 2003 (Fig. 3). Sixty-five days before the magnitude (M) 6.8 earthquake (December 10, 2003), the radon concentration in groundwater started to decrease for 45 d. Twenty days prior to the earthquake, the radon concentration reached a minimum value of 12.2 Bq L$^{-1}$ and then started to increase again. Six days before the earthquake (December 10, 2003), the radon concentration recovered to the previous background level of 28.9 Bq L$^{-1}$. Radon-concentration errors shown in Fig. 3 are ±1 standard deviation after simple averaging of triplicates.
Environmental records such as temperature and rainfall were examined to check if the radon anomaly could be attributed to these environmental factors. The temperature of the groundwater was very stable during the observation period. There was no heavy rainfall responsible for the radon anomaly. It is also difficult to explain such a large radon decrease by the mixing of groundwater.

The magnitude (M) 6.8 mainshock occurred on the Chihshang Fault which has a faulting surface extending about 30 km in depth and dips approximately 50° to southeast. Focal mechanism of the mainshock is a thrust striking N36°E and dipping 50°SE. The Antung hot spring is about 3 km southeast of the Chihshang Fault. The anomalous decrease in radon concentration observed at the Antung hot spring suggests that the groundwater radon, when observed at suitable sites, can be a sensitive tracer for strain changes in crust associated with earthquake occurrences.

Fig. 2 shows the surface slip history of the Chihshang Fault from mid-1986 to December 2004. We interpret the diminution in creeping rate in 2000–2003 and the anomalous decrease in groundwater radon from October 2003 to November 2003 as evidences of strain change prior to the 2003 Chengkung earthquake. We do not have the data for the short-term change of creeping rate contemporaneous with the radon anomaly. However, we do have data from the long-term monitoring of creeping rate by creepmeters, which did help us select the radon-monitoring site. The radon anomaly is a near-term precursory change induced by an earthquake occurrence. Both the creepmeter and radon monitoring are complementary to each other. Although it is difficult to draw definite conclusions, we would like to point out that groundwater radon and creepmeter monitoring deserve consideration in such seimotectonic environments, as they contribute usefully to seismic hazard mitigation.

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