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Radon anomalies precursory to the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes in Taiwan

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ABSTRACT

Contrary to the normally observed increase in groundwater radon that occurs prior to earthquakes, we have measured anomalous decreases in radon concentration prior to the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes that occurred within a 55 km radius from the Antung D1 monitoring well in eastern Taiwan. The v-shaped pattern of radon anomalies recognized at Antung is valuable for detecting the aseismic strain precursory to potentially disastrous earthquakes in a fractured aquifer surrounded by ductile aquitard in seismotectonic environments in this area.

1. Introduction

Variations in radon (^{222}Rn) content in groundwater have been observed prior to some earthquakes (Hauksson, 1981; Igarashi et al., 1993, 1995; Igarashi and Wakita, 1990; Liu et al., 1985; Noguchi and Wakita, 1977; Silver and Wakita, 1996; Teng, 1980; Wakita et al., 1980, 1989, 1991). Most of the radon anomalies from these observations indicate a radon increase prior to the earthquake. However, precursory radon declines are also known to exist. For example, Wakita et al. (1980) observed a sudden drop followed by an increase in the radon concentration that occurred prior to the 1978 Izu-Oshima-kinkai earthquake of magnitude 7.0. Unfortunately, observations like these are generally irreproducible (Roeloffs, 1999). Radon anomalies, generally at isolated locations, have been noted in several parts of the world, but this research is the first example of two anomalies occurring at the same location – and all in a period of less than four years. We have monitored groundwater radon since July 2003 at the Antung hot spring that is located near the Chihshang fault – part of the eastern boundary of the present-day plate suture between the Eurasia and the Philippine Sea plates. This paper reports two groundwater radon anomalies observed at the Antung hot spring in eastern Taiwan, located about 3 km southeast of the Chihshang fault, since July 2003 (Fig. 1). The Chihshang fault ruptured (Hsu, 1962) during two 1951 earthquakes of magnitudes $M = 6.2$ and $M = 7.0$. The annual survey of geodetic and GPS measurements has consistently revealed the active creep of the Chihshang fault that is moving at a rapid steady rate of about 2–3 cm/year during the past 20 years (Angelier et al., 2000; Lee et al., 2003; Yu and Kuo, 2001; Yu et al., 1990). Since July 2003, two anomalous declines in radon concentration were observed to precede the earthquakes of magnitudes $M_W = 6.8$, $M_W = 6.1$, and $M_W = 5.9$ that occurred on December 10, 2003, April 1 and 15, 2006 with epicenters located 20 km, 52 km, and 47 km, respectively, from the Antung radon-monitoring station.

^{222}Rn is a chemically inert radioactive nuclide with a half-life of approximately 3.8 days. The radon concentration in groundwater is proportional to the uranium concentration in adjacent rocks in an aquifer. 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 (3×10^{-10} m), 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 earthquake occurrence, when regional stress increases, formation of microcracks in rock masses could develop and thereby could cause anomalous changes in groundwater radon concentration.

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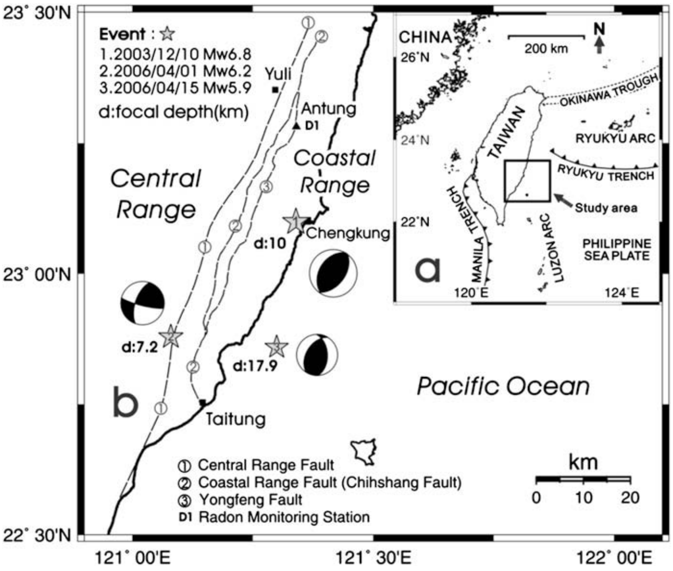

Fig. 1. Map of the epicenters of the earthquakes that occurred on December 10, 2003, April 1 and 15, 2006 near the Antung hot spring. (a) Geographical location of Taiwan. (b) Study area near the Antung hot spring.

2. Materials and methods

2.1. Site description

We initiated an observation of groundwater radon in July 2003 at a well D1 located at the Antung hot spring (Fig. 1). The observation well is located approximately 20 km north of the epicenter of the magnitude $M_W = 6.8$ earthquake that occurred at 4:38 am on December 10, 2003 (UT). On the basis of the distribution of the aftershocks, the faulting generated by the earthquake extended close to the observation well. Discrete samples of geothermal water have been collected from a well at the Antung hot spring for analysis of radon (^{222}Rn) content. The water is pumped from an interval ranging from 167 m to 187 m below ground surface. The water from the well was pumped more or less continuously.

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. A minimum of three well-bored volumes were purged before taking samples for radon measurements.

2.2. Radon analysis

The liquid scintillation method was adopted to determine the activity concentration of ^{222}Rn in groundwater (Noguchi, 1964). Radon was partitioned selectively into a white mineral-oil based scintillation cocktail (Perkin Elmer) immiscible with the water samples, and then assayed with a liquid scintillation counter (LSC). The results were corrected for the amount of radon decay between sampling and assay.

A calibration factor for the LSC measurements of $193 \pm 1.4\ \mathrm{c\,min^{-1}\,Bq^{-1}}$ was calculated using an aqueous ^{226}Ra calibration solution, which is in secular equilibrium with ^{222}Rn progeny. The background for the LSC was $5.5 \pm 0.22\ \mathrm{c\,min^{-1}}$. For a count time of 50 min and background less than $6\ \mathrm{c\,min^{-1}}$, a detection limit below $0.67\ \mathrm{Bq\,dm^{-3}}$ was achieved using the sample volume of $15\ \mathrm{cm^3}$. Routine checks for LSC measurements were made to ensure that the calibration factor was $>189\ \mathrm{c\,min^{-1}\,Bq^{-1}}$ and the background was $<6\ \mathrm{c\,min^{-1}}$.

3. Results and discussion

Two groundwater radon anomalies were observed to precede the earthquakes of magnitude $M_W = 6.8$, $M_W = 6.1$, and $M_W = 5.9$ that occurred on December 10, 2003, April 1, 2006, and April 15, 2006 near Antung in eastern Taiwan. Fig. 2 shows the radon concentration data since July 2003 at the monitoring well D1 in the Antung hot spring. Radon concentration errors are ±1 standard deviation after simple averaging of triplicates. All the anomalous decreases observed at Antung follow the same v-shaped progression and are marked with shaded inverted triangles in Fig. 2(a). The large background variation in radon data is a natural phenomenon and indicates that the groundwater radon in the Antung hot spring formation is sensitive to crustal strain near an active tectonic plate boundary. Four local earthquakes with magnitudes $M_W = 5.4$, $M_W = 5.2$, $M_W = 6.2$, and $M_W = 5.3$ occurred on December 10, 2003, January 1, 2004, May 19, 2004, and September 26, 2005, respectively. Based upon their magnitudes and locations, we consider these as aftershocks of the 2003 Chengkung earthquake. The large scatter in radon data between the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes appears to be related to these aftershocks. Table 1 shows the locations of all the epicenters and their distances from the Antung D1 monitoring well. Table 1 also

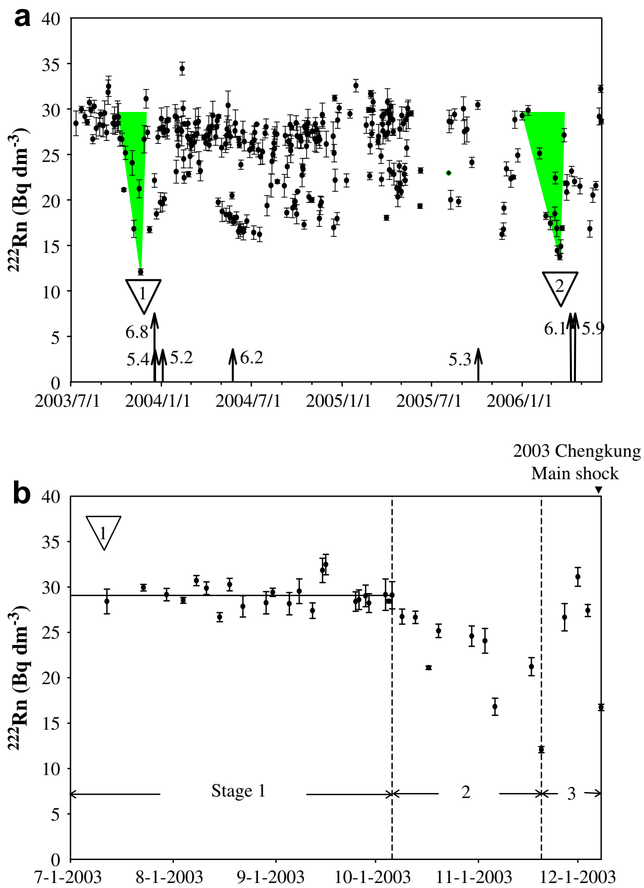

Fig. 2. (a) Radon concentration data at the monitoring well D1 in the Antung hot spring (open inverted triangles: anomalous radon minima; long arrows: mainshocks; short arrows: aftershocks; earthquake magnitude *M*w shown beside arrows). (b) Observed radon concentration data prior to the 2003 $M_W = 6.8$ Chengkung earthquake.

Table 1
Epicenter locations of all the earthquakes ($M_W > 5$) that occurred between December 10, 2003 and April 15, 2006 near the Antung hot spring.

UT:Date	Time	Longitude	Latitude	Depth (km)	M_w	Epicenter distance (km)
2003/12/10	38:15.2	121.336	23.102	10	6.8	20
2003/12/11	01:49.8	121.423	22.781	12.6	5.4	56
2004/1/1	15:18.5	121.624	23.38	17.8	5.2	31
2004/5/19	04:12.0	121.387	22.697	8.7	6.2	65
2005/9/26	50:20.4	121.408	23.209	9.4	5.3	11
2006/4/1	02:19.4	121.124	22.83	10	6.1	55
2006/4/15	40:54.0	121.311	22.849	11.7	5.9	48

indicates that tectonic stress can migrate from the epicenters toward the radon-monitoring station at least for a 55 km radius near the Antung area. The sequence of events for radon anomalies prior to the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes were characterized with three stages (Fig. 2(b)). During Stage 1, the radon concentration in groundwater was fairly stable and there was an accumulation of tectonic strain, which produced a slow, steady increase of effective stress. The Antung hot spring is a fractured aquifer with limited recharge surrounded by ductile mudstone. Under these geological conditions, dilation of brittle rock masses occurred and gas saturation developed in rock cracks during Stage 2. The radon in groundwater volatilized into the gas phase. The radon concentration of groundwater started to decrease and reached a minimum value. Stage 3 started at the point of minimum radon concentration; the water saturation in rock cracks and pores began to increase again. During Stage 3, the radon concentration in groundwater increased and recovered to the previous background level before the earthquake. The coseismic drop of radon concentration could be caused by the jerk motion in crust near the hypocentral area at the mainshock.

Some of the characteristics of the radon concentrations observed for the Chengkung quake of Taiwan can be compared to those of the Izu-Oshima-kinkai tremor of Japan. For example, the distance from the epicenter to the radon-monitoring station for the 2003 $M_W = 6.8$ Chengkung earthquake was about 20 km; this distance is quite similar to the epicenter–station distance of 25 km for the 1978 $M = 7.0$ Izu-Oshima-kinkai earthquake of Japan. The observed radon anomaly precursory to the 2003 Chengkung earthquake (Kuo et al., 2006) also behaved similarly to that observed precursory to the 1978 Izu-Oshima-kinkai earthquake (Wakita et al., 1980). Sixty-five days before the 2003 Chengkung earthquake (Fig. 2(b)), the radon concentration of groundwater started to decrease. Similarly, about seventy-five days before the 1978 Izu-Oshima-kinkai earthquake, the radon concentration started to decrease. Nine days before the 2003 Chengkung earthquake (Fig. 2(b)), the radon concentration recovered to the previous background level. Similarly, about five days before the 1978 Izu-Oshima-kinkai earthquake, the radon concentration recovered to the previous background level. Both the radon-monitoring wells D1 at Antung and SKE-1 at Izu are in fractured aquifers of brittle volcanic rocks. In addition, the strain record at Irozaki in the Izu Peninsula showed a precursory strain change of about 1 ppm and revealed a rock dilation process prior to the $M = 7.0$ earthquake.

Specifically, radon decreased from background levels of 28.9 and 28.1 Bq dm^{-3} to minima of 12.1 ± 0.3 and 13.7 ± 0.3 Bq dm^{-3} prior to the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes, respectively. Environmental records such as atmospheric temperature, barometric pressure, and rainfall were examined to check whether the radon anomaly could be attributed to these environmental factors (Fig. 3). The atmospheric temperature, barometric pressure, and rainfall are periodic in season. It is difficult to explain such a large radon decrease by these environmental factors. There was also no heavy rainfall responsible for the radon anomaly. The observations at the Antung hot spring suggest that radon concentrations in groundwater under similar geological conditions can be a sensitive indicator of strain changes in the crust preceding an earthquake.

The epicenters of the earthquakes of magnitude $M_W = 6.8$, $M_W = 6.1$, and $M_W = 5.9$ that occurred on December 10, 2003, April 1, 2006, and April 15, 2006 and their associated precursory radon anomalies are plotted in Figs. 1 and 2, respectively. On December 10, 2003, the Chengkung earthquake ($M_W = 6.8$) occurred on the Chihshang fault approximately 20 km from the Antung hot spring. The epicentral distributions of the 2003 Chengkung aftershocks reveal the close relationship between seismicity and the Chihshang fault. The Chihshang fault extends to about 30 km in depth and dips approximately 50° to the southeast from the surface to approximately 20 km in depth. Between the depths of 20–30 km, the fault changes dip to approximately 20° to the southeast. Based on focal mechanism studies, the Chengkung quake occurred on a thrust fault with strike of N36°E and dip of 50°SE (Kuochen et al., 2007). Two earthquakes, with magnitudes $M_W = 5.2$ and $M_W = 6.2$, occurred on January 1, 2004 and May 19, 2004. Based upon their

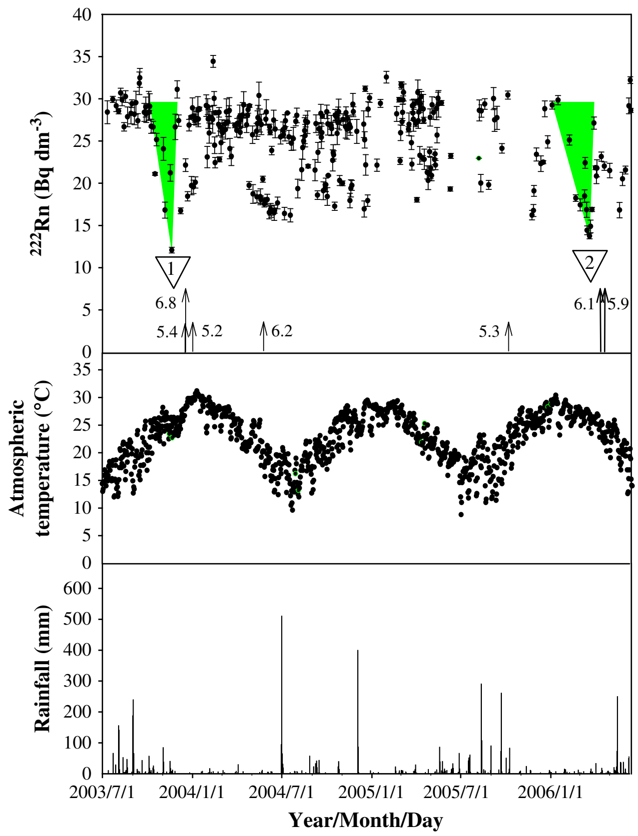

Fig. 3. Comparison of Radon concentration, atmospherical temperature, and rainfall data (open inverted triangles: anomalous radon minima; long arrows: mainshocks; short arrows: aftershocks; earthquake magnitude Mw shown beside arrows).

magnitudes and locations, we consider these as aftershocks of the Chengkung earthquake of December 10, 2003. On April 1, 2006, the Taitung earthquake ($M_W = 6.2$) occurred in the Central Range approximately 55 km from the Antung hot spring. Based on a seismic dislocation model for the Taitung event, the mainshock involved a west-dipping oblique slip fault, with predominantly left-lateral strike-slip motion, and it occurred on the western side of the plate suture (Wu et al., 2006). Fifteen days later (April 15, 2006), another large earthquake ($M_W = 5.9$) occurred in the Pacific Ocean about 48 km south of the Antung hot spring. This quake occurred on the opposite (east) site of the plate boundary. We consider the $M_W = 5.9$ earthquake that occurred on April 15, 2006 as being triggered by stress transfer in response to the 2006 $M_W = 6.1$ Taitung earthquake. The observed precursory minimum in radon concentration decreases as the earthquake magnitude increases and as the distance between the hypocenter and the Antung radon-monitoring station decreases. For example, the radon minimum of 12.1 ± 0.3 Bq dm^{-3} that occurred prior to the 2003 $M_W = 6.8$ Chengkung earthquake is lower than 13.7 ± 0.3 Bq dm^{-3} that occurred prior to the 2006 $M_W = 6.1$ Taitung earthquake.

An understanding of the geological rock settings near the Antung hot spring would help explain the radon anomalous declines precursory to nearby large earthquakes. The studied region (Fig. 4) occupies an unusual tectonic setting in the Coastal Range Tectonic Province that is located at the plate suture between the Eurasia and Philippine Sea plates. Four stratigraphic units are present in the study area: (1) the Tuluanshan Formation consists of volcanic units such as lava and volcanic breccia as well as tuffaceous-sandstone; (2) the Fanshuliao and (3) Paliwan Formations consist of rhythmic sandstone and mudstone turbidites; and (4) the Lichi mélange occurs as a highly deformed mudstone that is characterized by penetrative foliation visible in outcrop. The Antung hot spring is situated in a brittle tuffaceous-sandstone block surrounded by a ductile mudstone of the Paliwan Formation (Chen and Wang, 1996). Well-developed minor faults and joints are common in the tuffaceous-sandstone block that displays intensively brittle deformation. It is possible that these fractures reflect deformation and disruption by the nearby faults. Hence, geological evidence suggests the tuffaceous-sandstone block displays intensively brittle deformation and develops in a ductile-deformed mudstone stratum. Groundwater flows through the fault zone and is then recharged into the block along the minor fractures.

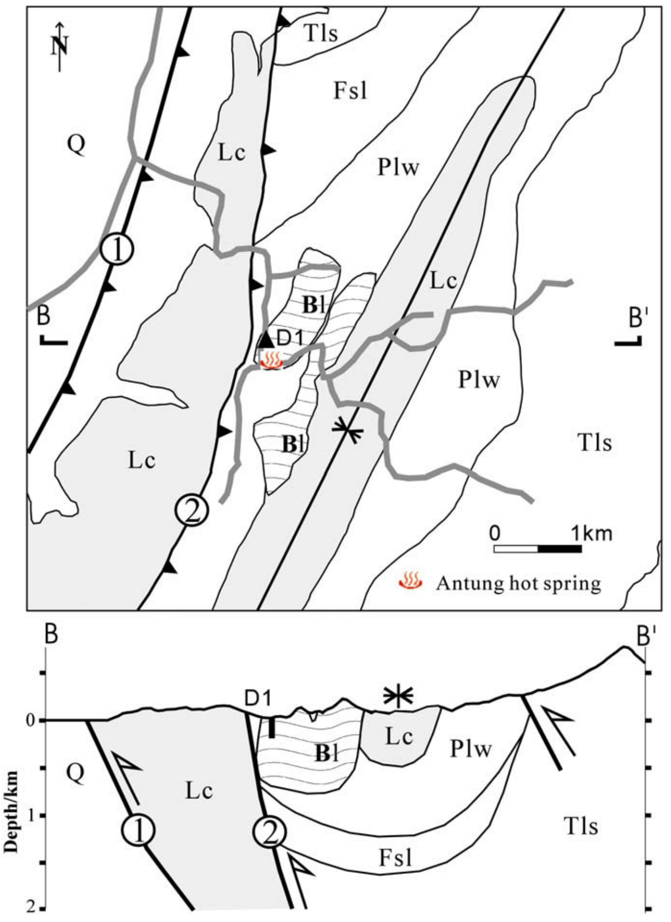

Fig. 4. (Top) Geological map near the radon-monitoring well D1 in the area of Antung hot spring (Q: Holocene deposits, Lc: Lichi mélange, Plw: Paliwan Formation, Fsl: Fanshuliao Formation, Tls: Tuluanshan Formation, Bl: tuffaceous fault block, D1: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault). (Bottom) B–B' cross section passing through the monitoring well D1 (Adapted from Kuo et al., 2006).

Because the Antung hot spring is situated in a fractured tuffaceous-sandstone block inside mudstone, the aquifer recharge is limited. Under geological conditions such as those of the Antung hot spring, we hypothesized that when regional stress increases, dilation of the rock mass occurs (Brace et al., 1966; Scholz et al., 1973). During this stage, gas saturation and two phases (vapor and liquid) develop in rock cracks and pores. Meanwhile, the radon in groundwater volatilizes and partitions into the gas phase. Therefore, the radon concentration in groundwater decreases during this stage. Thus, under suitable geological conditions, groundwater radon can be a sensitive tracer for strain changes in the crust associated with earthquake occurrences.

Although the Japanese earthquake mentioned earlier recorded a similar decrease in radon concentration prior to a large earthquake (Wakita et al., 1980), the significance of our research is that it is the first documented case of two (recorded by the same groundwater monitoring station) precursory decreases in radon anomalies associated with large magnitude earthquakes.

4. Conclusions

We have monitored groundwater radon since July 2003 at a well D1 located at the Antung hot spring. The following conclusions are based on the results of the data consisting of the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes.

1. For the first time, two anomalous decreases in radon concentration have been recorded prior to the 2003 $M_W = 6.8$ Chengkung and 2006 $M_W = 6.1$ Taitung earthquakes that occurred within a 55 km radius from the Antung D1 monitoring well in eastern Taiwan.
2. The v-shaped pattern of radon anomalies recognized at Antung is valuable for detecting the aseismic strain precursory to potentially disastrous earthquakes in this area.
3. The observations at the Antung hot spring suggest that radon concentrations in groundwater under similar geological conditions can be a sensitive tracer of strain changes in the crust preceding a nearby large earthquake. Groundwater radon monitoring is recommended in a fractured aquifer surrounded by ductile aquitard in seismotectonic environments for seismic hazard mitigation.

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