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Estimation of fracture porosity using radon in Japan and Taiwan

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ABSTRACT

A quantitative method using the precursory radon decline as a tracer to estimate fracture porosity is presented with the help of case studies in Japan and Taiwan. In small fractured aquifers, the in-situ volatilization of dissolved radon could cause a decline of radon in groundwater precursory to an earthquake. Mathematical models have been developed to correlate the radon decline with fracture porosity and volumetric strain in the aquifer rocks based on the mechanism of in-situ radon volatilization. The anomalous decline in groundwater radon prior to the Japan 1978 M = 7.0 Izu-Oshima-kinkai earthquake has been used to estimate the fracture porosity at the Nakaizu SKE-1 well for 0.0000426. The anomalous decline in groundwater radon prior to the Taiwan 2003 M_w 6.8 Chengkung earthquake has been used to estimate the fracture porosity for 0.0001117 at the Antung D1 well.

1. INTRODUCTION

Anomalous declines in the radon concentration of groundwater precursory to nearby earthquakes have been observed in small fractured confined aquifers in both Japan and Taiwan. An anomalous radon decline from a background level of 483 ± 3 cpm to a minimum of 439 ± 7 cpm was observed at the SKE-1 well in the Izu Peninsula precursory to the 1978 M = 7.0 Izu-Oshima-Kinkai earthquake in Japan (Wakita et al. 1980). An anomalous radon decline from a background level of 791 ± 46 pCi/L to a minimum of 326 ± 9 pCi/L was also observed at the D1 well in the Antung hot spring prior to the 2003 Mw = 6.8 Chengkung earthquake in eastern Taiwan (Kuo et al. 2006). Both wells (SKE-1 and Antung D1) were completed in small fractured confined aquifers. Under such geological conditions, the dilatant expansion of pore space could induce water flow from regions of low dilation into regions of large expansion. When the rock-dilation rate is large in comparison with the water-flow rate, gas bubbles could develop and in-situ volatilization of radon could cause the anomalous declines of radon in groundwater precursory to nearby earthquakes (Kuo et al. 2006).

It is of practical interest to correlate the radon decline with the gas saturation, fracture porosity, and volumetric strain in the aquifer rocks. With the help of case studies, this paper presents a quantitative method to estimate fracture porosity using the radon declines precursory to the 1978 M = 7.0 Izu-Oshima-Kinkai earthquake in Japan and the 2003 M_w = 6.8 Chengkung earthquake in eastern Taiwan.

2. IN-SITU RADON-VOLATILIZATION MECHANISM

Radon volatilization from groundwater into the gas bubbles can explain the anomalous decreases of radon precursory to the earthquakes (Kuo et al. 2006). Gas bubbles could develop in a small fractured aquifer with undrained conditions precursory to an earthquake. Before any precursory phenomenon appears (Stage 1), there is only water phase in the aquifer. When the regional tectonic stress continues to increase and aquifer recharge is weak, the dilation of brittle rock could occur at a faster rate than the rate of groundwater recharging into the newly created micro-cracks. As a result, gas bubbles and two phases (gas and water) develop in the aquifer. The radon in groundwater volatilizes into the gas bubbles and the radon concentration in groundwater decreases. Before any precursory phenomenon appears, the aquifer is water-saturated and there is only water phase present in the fracture space. During the period of radon anomaly (Stages 2 and 3), there are two phases (gas and water) in the aquifer. Gas bubbles are present in the fracture space as a distinct gas phase. Mass transfer of radon occurs between water and gas phases during Stages 2 and 3. In Stage 2, the dilation rate of brittle rock is faster than the recharge rate of groundwater, and vice versa in Stage 3. At the end of radon anomaly, the aquifer becomes water-saturated again and the groundwater radon concentration recovers to the previous background level before the earthquake.

For a confined aquifer with undrained conditions, in-situ radon-volatilization model, Eq. (1), was developed to explain the anomalous decreases of radon precursory to the earthquakes as follows (Kuo et al. 2006).

$$C_0 = C_w (H \times S_g + 1) \tag{1}$$

where C_0 is initial radon concentration in groundwater precursory to each radon anomaly, pCi/L; C_w is the observed radon minimum in groundwater during an anomalous decline, pCi/L; S_g is gas saturation, fraction; H is Henry's coefficient for radon at aquifer temperature, dimensionless. Eq. (1) correlates the observed decline in groundwater radon with the gas saturation developed in a confined aquifer.

3. A QUANTITATIVE METHOD TO ESTIMATE FRACTURE POROSITY

In a small low-porosity fractured aquifer under undrained conditions and compressive stress, the volumetric strain is a linear function of the gas saturation as follows (Kuo et al. 2011).

$$de \cong \phi S_g \tag{2}$$

where de is the volumetric strain of aquifer rock, dimensionless; ϕ is the initial fracture porosity of aquifer rock before dilation, fraction; S_g is gas saturation in a low-porosity confined aquifer, %. Gas saturation (S_g) can be determined using Eq. (1) with the help of an observed radon anomaly. Given the volumetric strain (de), fracture porosity (ϕ) can be estimated for a low-porosity confined aquifer using Eq. (2).

4. CASE STUDY IN JAPAN: NAKAIZU SKE-1 WELL

The M = 7.0 Izu-Oshima-Kinkai earthquake occurred at 12:24 hours (JST) on January 14 of 1978 to the east of the Izu Peninsula. The epicenter of the main shock was located at 34.8°N and 139.3°E (Fig. 1). The principal fault inferred from a seismological study (Shimazaki and Somerville 1978) was an east-trending right-lateral strike-slip fault 17 km long that was situated beneath the sea between the Izu Peninsula and Izu-Oshima Island. On the east coast of the Izu Peninsula, the western edge of the fault, ground displacement occurred along a fault trending northwest-southeast with a length of 3 km (Tsuneishi et al. 1978). The maximum displacement of the fault was 1.3 m.

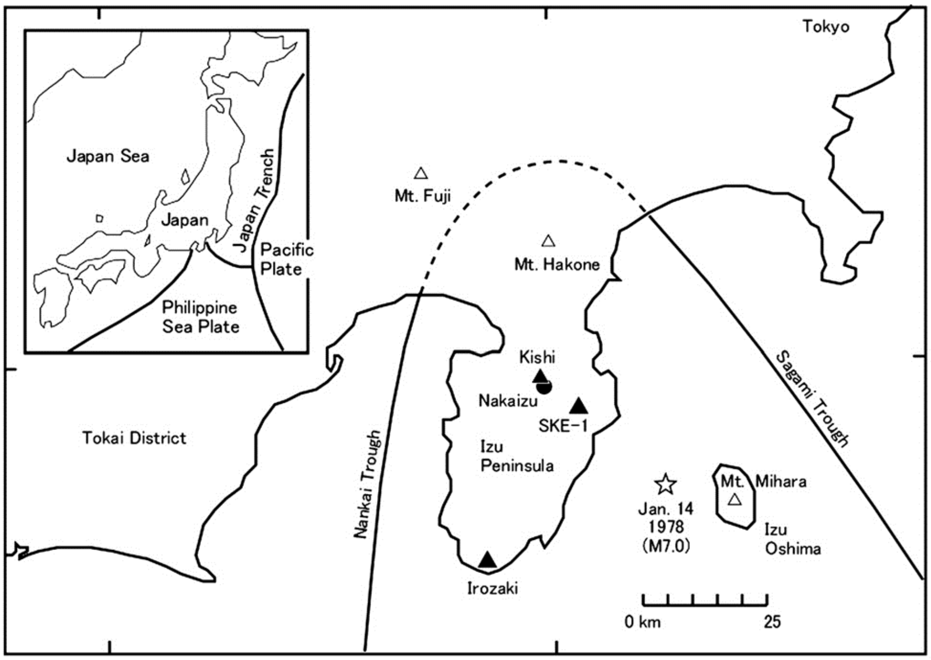

Figure 1: Map of the Izu Peninsula and the surrounding area (adapted from Wakita et al. 1980).

Figs. 2a and 2b summarized precursory changes of radon and strain for the 1978 M = 7.0 Izu-Oshima-Kinkai earthquake in, respectively (Wakita 1996). Fig. 2a shows the radon concentration recorded at the SKE-1 well. The distance from the epicenter to the radon monitoring station (SKE-1) for the 1978 Izu-Oshima-Kinkai earthquake was about 25 km. In October 1977 the radon concentration at the SKE-1 monitoring well began to decrease from a background level of 483 ± 3 cpm about eighty days before the 1978 earthquake (Fig. 2a). In early December the radon concentration further decreased and reached a minimum level of 439 ± 7 cpm in January 1978. Then the concentration reversed and began to increase rapidly five days before the main shock and reached a higher level than the previous background level.

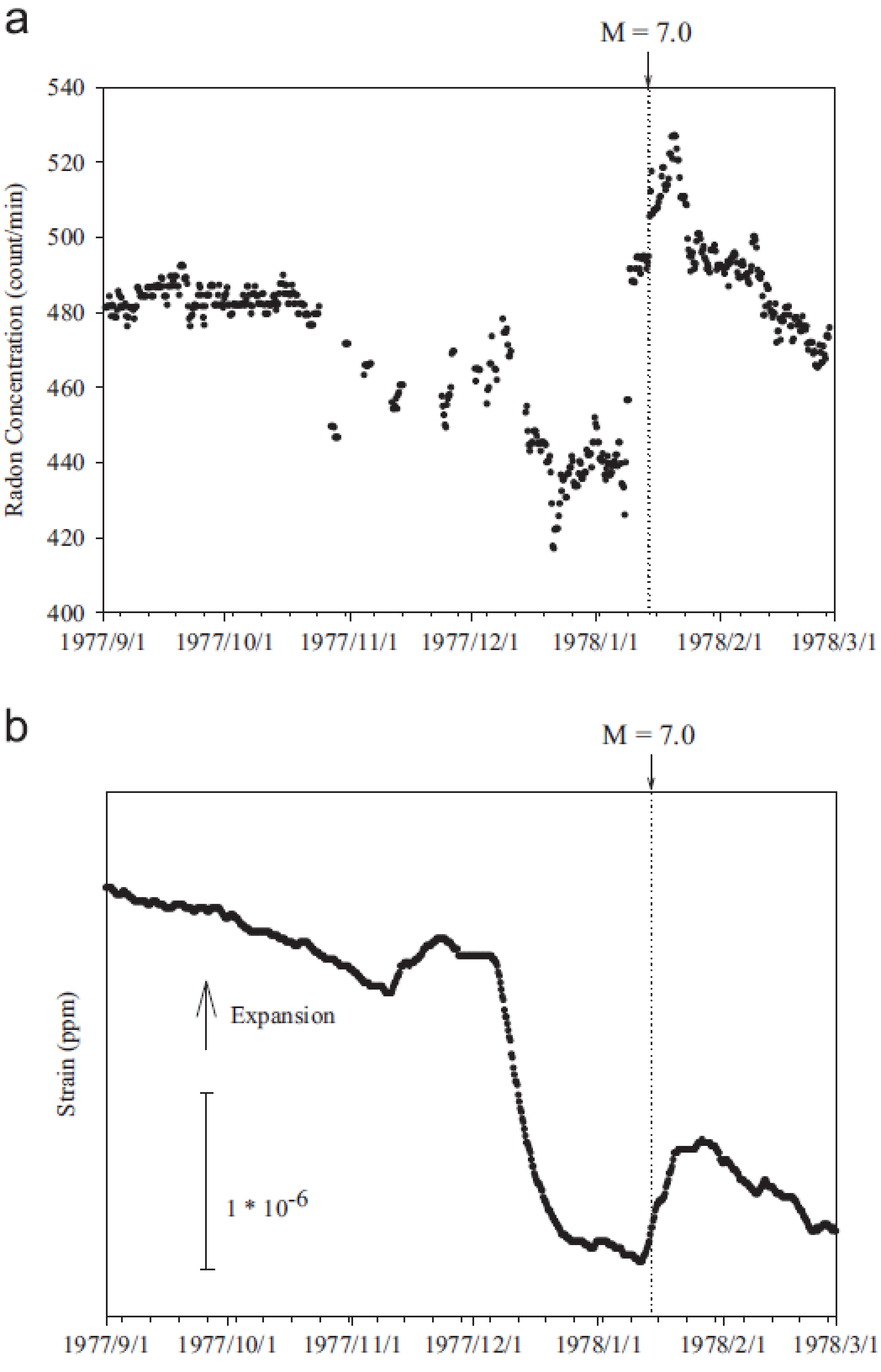

Figure 2: Precursory changes of the 1978 Izu-Oshima-Kinkai earthquake (adapted from Wakita 1996). (a) Radon concentration changes observed at the SKE-1 well (350 m deep) with a distance from the epicenter (D) = 25 km. (b) Record of the volumetric strainmeter at Irozaki with D = 50 km.

The SKE-1 well is situated near Nakaizu in the Izu Peninsula in a fractured confined aquifer of volcanic basalt rocks, which display brittle deformation. Based on laboratory observations of rock dilatancy (Brace et al. 1966), it is assumed that dilation of the rock mass occurred in the Izu Peninsula precursory to the 1978 Izu-Oshima-Kinkai earthquake. The SKE-1 well is located in the valley of an isolated mountainous area. Under such geological conditions, dilation of the rock mass could occur at a rate faster than the rate at which pore water could flow into the newly created pore volume when regional stress increases (Nur 1972; Scholz et al. 1973). Meanwhile, gas bubbles and two phases (vapor and liquid) could develop in the rock cracks and the radon in groundwater could volatilize into the gas bubbles (Kuo et al. 2006). Therefore, the concentration of radon in groundwater decreases. The sequence of events for radon data prior to the 1978 Izu-Oshima-Kinkai earthquake (Fig. 2a) can be interpreted in three stages. From September 1, 1977 to October 24, 1977 (Stage 1), radon was fairly stable (around 483 ± 3 count/min). During Stage 1, there was an accumulation of tectonic strain, which produced a slow, steady increase of effective stress. About eighty days before the magnitude (M) 7.0 earthquake, i.e. Stage 2, the concentration of radon started to decrease and reached a minimum level of 439 ± 7 count/min during a 60-day period. During Stage 2, dilation of the rock mass occurred and gas bubbles developed in cracks in the rock and radon volatilized into the gas bubbles. Stage 3 started at the point of minimum radon concentration when water saturation in cracks and pores began to increase. About five days before the 1978 Izu-Oshima-Kinkai earthquake, the radon concentration reversed suddenly and then recovered rapidly to the previous background level.

The physical mechanism of groundwater-radon volatilization can be applied to explain the anomalous declines in groundwater radon observed prior to the 1978 Izu-Oshima-Kinkai earthquake (Tsunomori and Kuo 2010). Eq. (1) can be applied to quantify gas saturation developed in aquifer prior to the 1978 Izu-Oshima-Kinkai earthquake. Henry's coefficients (H) for radon at aquifer temperature (14 ℃) is 3.27 (Weigel 1978). Based on the anomaly data in Fig. 2a, groundwater radon concentration declined from a background level of 483 ± 3 cpm to a minimum level of 439 ± 7 cpm. Applying Eq. (1), the gas saturation developed near the SKE-1 well prior to the 1978 Izu-Oshima-Kinkai earthquake can be estimated. Precursory to the 1978 Izu-Oshima-Kinkai earthquake, a gas saturation of 3.07 % developed in aquifer (Tsunomori and Kuo 2010).

A precursory strain change of about 1 ppm was also measured by the Sacks-Evertson borehole strainmeter at Irozaki located 50 km from the epicenter of the 1978 Izu-Oshima-Kinkai earthquake (Furuya and Fukudome 1986). Figs. 2a and 2b show precursory changes of groundwater radon and volumetric strain for the 1978 Izu-Oshima-Kinkai earthquake, respectively (Wakita 1996; Furuya and Fukudome 1986).

A gas saturation (S_g) of 3.07 % was determined in the SKE-1 aquifer precursory to the 1978 Izu-Oshima-Kinkai earthquake using Eq. (1) and radon anomaly. A precursory strain (de) of about 1 ppm was measured at Irozaki. A fracture porosity (ϕ) of 0.0000426 can be estimated near the SKE-1 well using Eq. (2) (Kuo and Tsunomori 2014).

5. CASE STUDY IN TAIWAN: ANTUNG D1 WELL

The 2003 M_w 6.8 Chengkung earthquake, which occurred on December 10, 2003, was the strongest earthquake near the Chengkung area in eastern Taiwan since 1951. The Antung radon-monitoring well D1 was located 24 km from the epicenter. Approximately 65 days prior to the 2003 M_w 6.8 Chengkung earthquake, groundwater radon started to decrease from a background level of 787 pCi/L to a minimum concentration of 326 pCi/L.

The geology at well D1 at the Antung hot spring is instrumental to site a well for monitoring anomalous declines in groundwater-radon concentration. Fig. 3 shows the geological map and cross section near the radon-monitoring well D1, which is about 3 km southeast of the Longitudinal Valley Fault (Chen and Wang 1996). The Longitudinal Valley Fault is the present-day plate suture between the Eurasian and the Philippine Sea plates. The Longitudinal Valley Fault (Hsu 1962) ruptured during two 1951 earthquakes of magnitude (M) 6.2 and (M) 7.0. Four stratigraphic units are present near the Antung hot spring. The Tuluanshan Formation consists of Miocene volcanic rocks such as lava and volcanic breccia as well as tuffaceous sandstone. The Fanshuliao and Paliwan Formations consist of Plio-Pleistocene mudstone turbidites with rhythmic sandstone. The Lichi mélange occurs as a highly deformed mudstone that is characterized by penetrative foliation visible in outcrop.

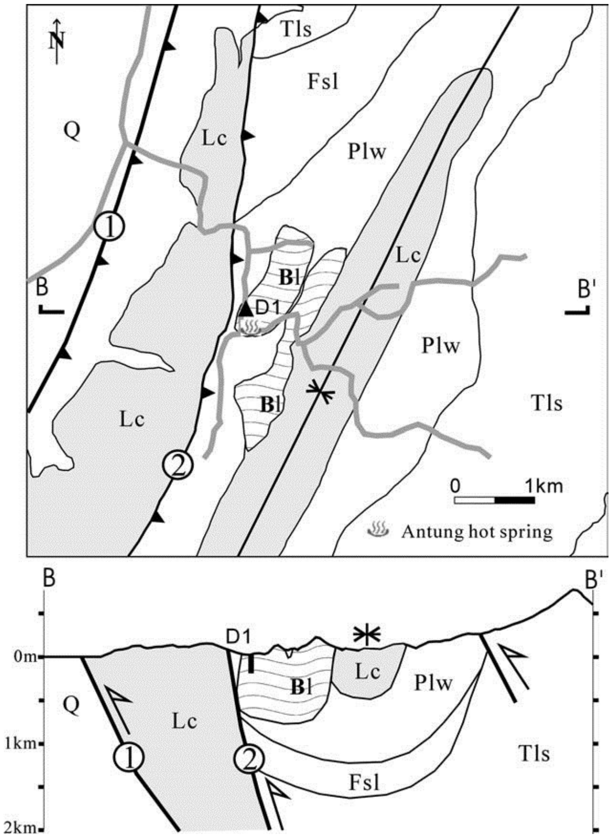

Figure 3: Geological map and cross section near the radon-monitoring well in the area of Antung hot spring (Q: Holocene deposits, Lc: Lichi mélange, Plw: Paliwan Formation, Fsl: Fanshuliao Formation, Tls: Tuluanshan Formation, Bl: tuffaceous fault block, D1: radon-monitoring well, ①: Chihshang, or, Longitudinal Valley Fault, ②: Yongfeng Fault) (adapted from Kuo et al. 2006).

The Antung hot spring is situated in an exotic brittle tuffaceous-sandstone block surrounded by a ductile mudstone of the Paliwan Formation and the Lichi mélange (Chen and Wang 1996). The exotic block extends about 1 or 2 km. Aquifer size at Antung well D1 is small.

Fig. 3 shows that the Antung hot spring is situated at the hanging wall along the Yongfeng fault and the Longitudinal Valley fault. Both faults are thrust faults. Along a thrust fault, rock dilation is likely to take place at the hanging wall (Doglionia et al. 2011). When the regional stress increases to about half the fracture stress, dilation of brittle rock initiates and micro-cracks develop in aquifer rock (Brace et al. 1966; Nur 1972; Scholz et al. 1973). When aquifer is small, the development of new cracks could occur at a rate faster than the recharge of pore water in a small brittle aquifer. Prior to local large earthquakes, gas bubbles and two phases (gas and water) are likely to develop in the newly created micro-cracks near Antung well D1. As gas phase develops in rock fractures, the groundwater-dissolved radon volatilizes into the gas phase and the radon concentration in groundwater decreases. The above mechanism is referred to as "in-situ radon volatilization" (Kuo et al. 2006). The mechanism provides the physical basis to interpret the anomalous decline in groundwater radon before earthquake occurrence. The in-situ radon-volatilization mechanism also helps select a suitable monitoring site to catch the anomalous decline in groundwater radon as an earthquake precursor.

Fig. 4 shows the radon anomaly observed at Antung well D1 prior to the 2003 Chengkung earthquake. The radon anomaly clearly progresses in a sequence of three stages. Stage 1 is buildup of elastic strain. During Stage 1, the radon concentration in ground water was fairly stable at 787 ± 42 pCi/L. When the regional stress continued to increase, dilation of brittle rock masses occurred. Stage 2 is development of cracks and gas bubbles in the brittle aquifer. During Stage 2, the radon in ground water volatilizes into the gas bubbles. The radon concentration of ground water starts to decrease and reaches a minimum value at 326 ± 9 pCi/L. Stage 3 is influx of groundwater. Stage 3 starts at the point of minimum radon concentration. During Stage 3, the radon concentration in ground water increases and recovers to the previous background level before the earthquake.

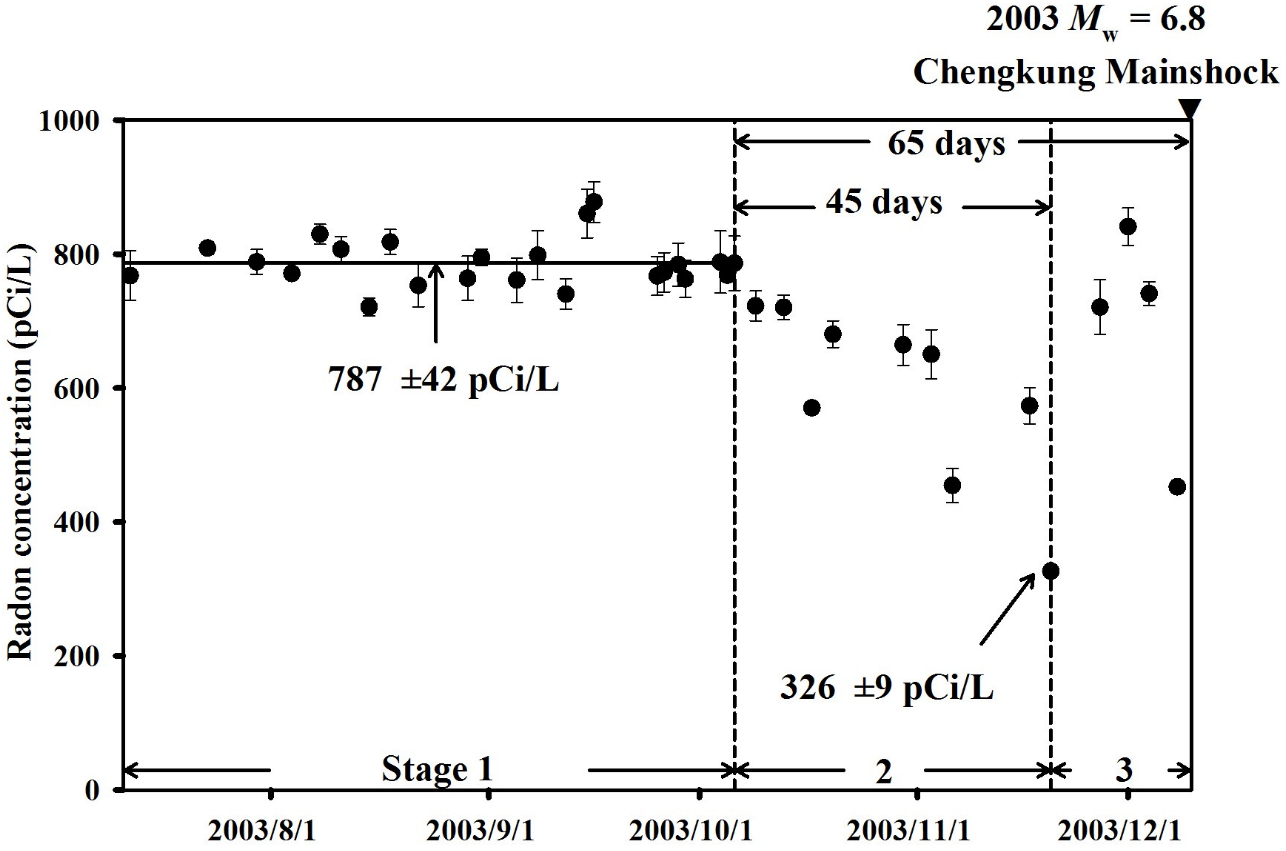

Figure 4: Radon concentration data at the monitoring well (D1) in the Antung hot spring. Stage 1 is buildup of elastic strain. Stage 2 is dilatancy and development of cracks and gas saturation. Stage 3 is influx of ground water and diminishment of gas saturation (adapted from Kuo et al. 2006).

Radon volatilization from groundwater into the gas phase can explain the anomalous decreases of radon precursory to the earthquakes (Kuo et al. 2006). For a confined aquifer with undrained conditions, Eq. (1), in-situ radon-volatilization model, correlates the observed decline in groundwater radon with the gas saturation developed in a confined aquifer. Based on Weigel equation (1978), the Henry's coefficient (*H*) at aquifer temperature (60 ℃) is 7.91 for radon. Using the data of radon background and minimum from Fig. 4 and Eq. (1), the gas saturation developed in Antung fractured aquifer can be determined, S_g = 17.9 % prior to the 2003 M_w 6.8 Chengkung earthquake.

Wu et al. (2006) investigated the dislocation fault model of the 2003 Chengkung earthquake using a computer code by Okada (1992). Figure 5 shows the calculated coseismic strain distribution due to the 2003 Chengkung earthquake based on the dislocation fault model (Wu et al. 2006). The calculated compression strain (*de*) is about 20 ppm near the Antung hot spring for the 2003 M_w 6.8 Chengkung earthquake (Kuo et al. 2006).

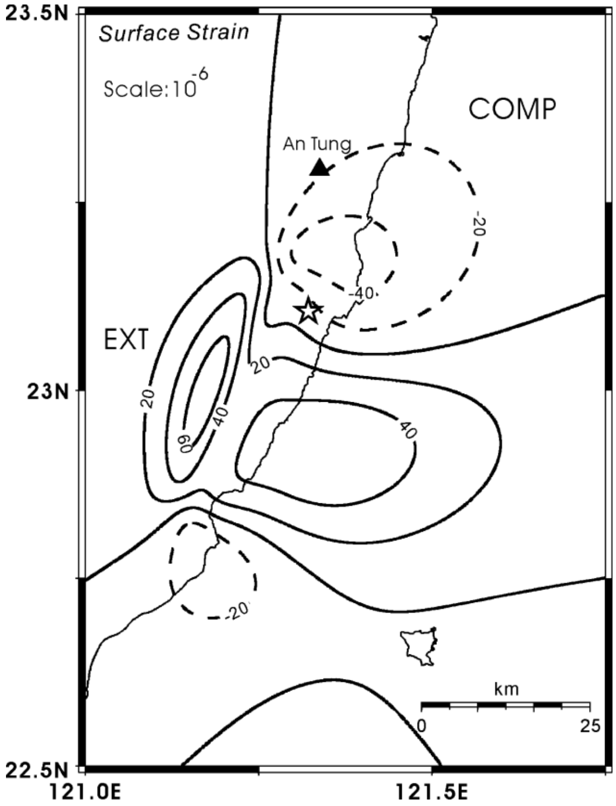

Figure 5: Distribution of coseismic surface strain (ppm) calculated based on the computer code for dislocation models by Okada (1992). Positive and negative values mean dilatation and contraction, respectively. The filled star denotes the 2003 mainshock. The filled triangle denotes the radon-monitoring well (D1). EXT and COMP denote dilatation and contraction, respectively (adapted from Kuo et al. 2006).

A gas saturation (S_g) of 17.9 % developed in aquifer near the Antung well D1 precursory to the 2003 M_w 6.8 Chengkung earthquake (Kuo et al. 2006). Given a precursory strain (de) of about 20 ppm estimated near the Antung hot spring, a fracture porosity (ϕ) of 0.0001117 can be estimated near Antung well D1 using Eq. (2).

6. CONCLUSIONS

1. A quantitative method has been developed to estimate fracture porosity using the anomalous radon declines precursory to earthquakes in Japan and Taiwan.

2. The anomalous decline in groundwater radon prior to the 1978 M = 7.0 Izu-Oshima-kinkai earthquake has been used to estimate the fracture porosity. A fracture porosity of 0.0000426 can be estimated near the SKE-1 well.

3. The anomalous decline in groundwater radon prior to the 2003 M_w 6.8 Chengkung earthquake has been used to estimate the fracture porosity. A fracture porosity of 0.0001117 can be estimated near Antung well D1.

4. A small low-porosity fractured aquifer near an active fault can be an ideal natural strain meter to site a radon-monitoring well for earthquake warning.

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