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In-situ radon volatilization in an undrained fractured aquifer

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ABSTRACT

In-situ radon volatilization offers a practical mechanism for a premonitory decrease in groundwater radon. Our study on large earthquakes in Taiwan from 2003 to 2018 deciphers the mechanism of radon volatilization responsible for the recurrent radon anomalies precursory to large earthquakes, which enables an important application of the mechanism to site a well in suitable geological conditions for a premonitory decrease in groundwater radon. A small low-porosity fractured aquifer in undrained conditions near an active fault is a suitable geological site to detect precursory declines in groundwater radon prior to local large earthquakes. A suitable geological site cited here is Taiwan's Paihe limestone spring.

1. INTRODUCTION

A small low-porosity fractured aquifer surrounded by a ductile formation in undrained conditions can be used as an effective natural strain meter for earthquake warning by applying groundwater radon as a tracer. Anomalous declines in groundwater radon, greater than 25 %, were recorded at Paihe precursory to four local large earthquakes in southwestern Taiwan between 2010 and 2018. Here we decipher the mechanism of radon volatilization responsible for the above radon anomalous declines. Fig. 1 illustrates the mechanism by which the natural strain meter works to detect aseismic crustal-strain signals precursory to local large earthquakes. Fig. 1 shows the schematic diagram of a small fractured aquifer (painted in blue) situated in a brittle rock (painted in pink), which is surrounded by a ductile formation (painted in yellow) in undrained conditions. When aquifer recharge is weak and negligible, undrained conditions are valid. Fig. 1a shows that there is only water phase (painted in blue) in the aquifer before any precursory phenomenon appears. When the regional stress increases, Fig. 1b shows that dilation of brittle rock (shown in the enlarged circle) could occur at a faster rate than the rate of groundwater recharging into the newly created micro-cracks (painted in white branches). As a result, gas saturation (painted in white bubbles) and two phases (gas and water) develop in the aquifer. The radon in groundwater volatilizes into the gas phase and the radon concentration in groundwater decreases. The above mechanism is referred to as "in-situ radon volatilization" [1]. An important requisite for the application of the mechanism is to site a well in suitable geological conditions to detect radon anomalous declines precursory to local large earthquakes recurrently. A small low-porosity fractured aquifer in undrained conditions near an active thrust fault is a suitable geological site. A suitable geological sites cited in this paper is Paihe limestone spring in southwestern Taiwan (Fig. 2).

Measurement of radon concentration (Radon-222) in groundwater has been frequently used in earthquake prediction studies[2-19]. Our research effort since 2003 focuses on the anomalous declines in groundwater radon and their mechanisms precursory to large earthquakes in Taiwan[2-19]. The only clear example of anomalous decreases in the radon concentration of groundwater identified in Japan is regarding the 1978 Izu-Oshima-Kinkai earthquake[4]. The radon anomaly precursory to the 1978 Izu-Oshima-kinkai earthquake is often criticized for the irreproducibility to measure recurrences of radon anomalies, particularly at the same well. The lack of a plausible physical mechanism to explain the observed decline in radon is also criticized[20]. Here we refute the criticism by being able to measure recurrences of radon anomalies at Paihe in southwestern Taiwan (Fig. 3) precursory to four local large thrust-type earthquakes from 2010 to 2018. All global hazardous events in the subduction zone, such as 2004 Sumatra, 2011 Tohoku, 2018 Sulawesi and Alaska earthquakes, occurred without warning. Here we discover the mechanism and practical applications of in-situ radon volatilization for warning future megathrust earthquakes in the subduction zone.

2. RESULTS

Recurrent anomalous decreases in the concentration of groundwater radon were observed prior to the 2003 M_w 6.8 Chengkung, 2006 M_w 6.1 and M_w 5.9 Taitung, 2008 M_w 5.4 Antung, 2011 M_w 5.0 Chimei, 2015 M_w 6.2 Green Island, and 2018 M_w 5.1 Changbin earthquakes. Regarding a physical basis that explains the characteristic radon decline, an in-situ volatilization mechanism was presented based on radon phase behavior and the geological conditions of the Antung hot spring[1]. The Antung hot spring is a low-porosity fractured isolated aquifer situated in an andesitic block and surrounded by a ductile mudstone of the Lichi mélange[21]. Under these geological conditions, the development of new cracks in the aquifer rock could occur at a rate faster than the recharge of pore water. In an aquifer with such un-drained conditions, gas saturation and two phases (vapor and liquid) could develop in the rock cracks[22-24]. Meanwhile, the radon in groundwater volatilizes and partitions into the gas phase and the concentration of radon in groundwater decreases. The above mechanism is referred to as “in-situ radon volatilization” [1]. An important requisite for the application of the mechanism is to site a well in suitable geological conditions to detect radon anomalous declines precursory to local large earthquakes recurrently.

Based on gathered learnings from southeastern Taiwan’s Antung hot spring, we proposed a similar monitoring site in southwestern Taiwan at Paihe. Paihe fulfills the geological requisites for a suitable monitoring site. In November 2009, we initiated an observation of groundwater radon at the Paihe spring (P1) which is from a small limestone aquifer[25]. We hoped to prove again that a small limestone aquifer with undrained conditions can be used as an effective natural strain meter for earthquake warning by applying radon as a tracer. There were four main earthquakes (M_w > 6.0) that occurred in southwestern Taiwan between November 2009 and November 2018. Fig. 3 shows the location of the Paihe spring (P1) and the epicenters of the 2010 M_w 6.3 Jiasian, 2013 M_w 6.0 Jenai, 2013 M_w 6.3 Fishpond, and 2016 M_w 6.4 Meinong earthquakes. Recurrent groundwater radon anomalies were again consistently observed at the Paihe spring (P1) prior to all the above thrust-type earthquakes in southwestern Taiwan.

As shown in Fig. 4a-c, the concentration of groundwater radon at Paihe decreased from background levels of 144 ± 7, 134 ± 5, and 137 ± 8 pCi/L to minima of 104 ± 8, 85 ± 4, and 97 ± 9 pCi/L prior to the 2010 Jiasian, 2013 Jenai and Fishpond and 2016 Meinong earthquakes, respectively. Based on epicenter locations and earthquake occurrence time, we consider the 2013 M_w 6.3 Fishpond earthquake that occurred on June 2, 2013 triggered by stress transfer in response to the 2013 M_w 6.0 Jenai earthquake that occurred on March 27, 2013. As shown in Fig. 3, Event 1, 2, 3, and 4 are all thrust-type earthquakes. The data collected in southwestern Taiwan again supports that all large thrust-type earthquakes (M_w > 6) can be warned through a long-term monitoring of precursory declines in groundwater radon at Paihe. Table 1 summarizes the observed radon background, radon minimum, percent of radon decline, precursory time, and epicenter distance from the Paihe spring (P1) precursory to large (M_w > 6.0) thrust-type earthquakes in southwestern Taiwan between November 2009 and November 2018. The effective radius of detecting radon precursory phenomena at the Paihe spring (P1) is 87 km and the precursor time is usually 2 to 6 months. The precursor time for radon is an important quantitative parameter to make a short-term earthquake warning.

Table 1 summarizes important parameters from the radon anomalous declines recorded at Paihe precursory to four large thrust-type earthquakes in southwestern Taiwan between 2010 and 2018. By utilizing Table 1 and an anomalous radon decline recorded at Paihe, we can make a short-term earthquake warning for southwestern Taiwan (Fig. 3).

Recently, an anomaly (Fig. 4d) was observed at Paihe when the radon concentration started to decline on September 6, 2018 from a background level of 142 ± 2 pCi/L to a minimum of 93 ± 9 pCi/L. The v-shaped patterns of radon anomalies recognized in Fig. 4d, Fig. 4a, and Fig. 4b are similar. Table 1 shows that the precursory time is 80 days, 104 days, and 171 days prior to the 2010 M_w 6.3 Jiasian, 2013 M_w 6.0 Jenai, and 2013 M_w 6.3 Fishpond earthquakes, respectively. Therefore, we can make a short-term earthquake warning of a large thrust-type earthquake (M_w > 6) likely to occur in southwestern Taiwan with a similar precursory time between 80 days and 171 days after September 6, 2018 when the radon concentration started to decline.

3. CONCLSIONS

Under suitable geological conditions - a small fractured aquifer such as Taiwan’s Paihe limestone spring with undrained conditions - groundwater radon is a sensitive tracer for strain changes in the crust associated with earthquake occurrences. Our paper makes a significant advance in the understanding of the geological conditions and physical basis for in-situ radon volatilization. Prior to our study, the geological conditions necessary to apply anomalous decrease in groundwater radon for earthquake warning were unknown. Here, we outline the geological requisites to site a radon-monitoring well.

Recent destructive megathrust earthquakes near Anchorage, Alaska and on Indonesia’s Sulawesi Island indicate the difficulty of forecasting earthquakes. Here, we discover quantitative applications of radon anomalous declines consistently recorded at Paihe precursory to four large thrust-type earthquakes in southern Taiwan between 2010 and 2018. Via a long-term monitoring of groundwater radon at a small brittle aquifer in other areas of the world on the subduction plate boundary; future destructive megathrust earthquakes, such as 2018 Alaska and Sulawesi, can be warned months ahead of quake occurrence. A reliable short-term warning yields important implications for hazard mitigation.

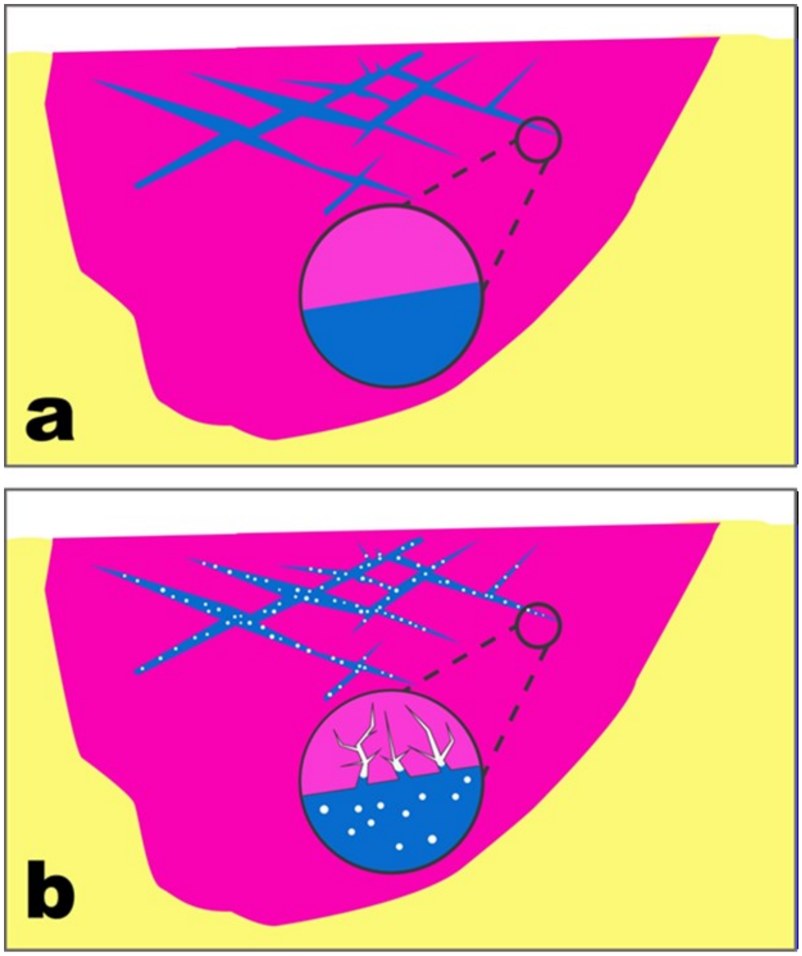

Figure 1: A small fractured aquifer in undrained conditions. (a) Before micro-cracks develop, the aquifer is one-phase. (b) After micro-cracks develop, the aquifer is two-phase.

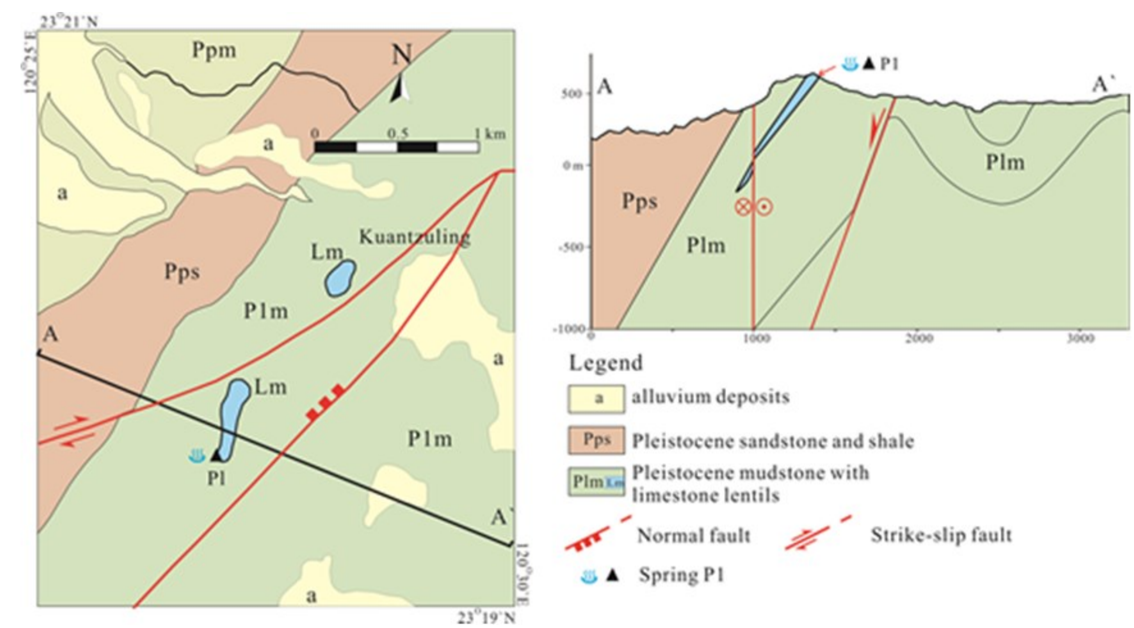

Figure 2: Geological map and cross section near the Paihe spring (P1).

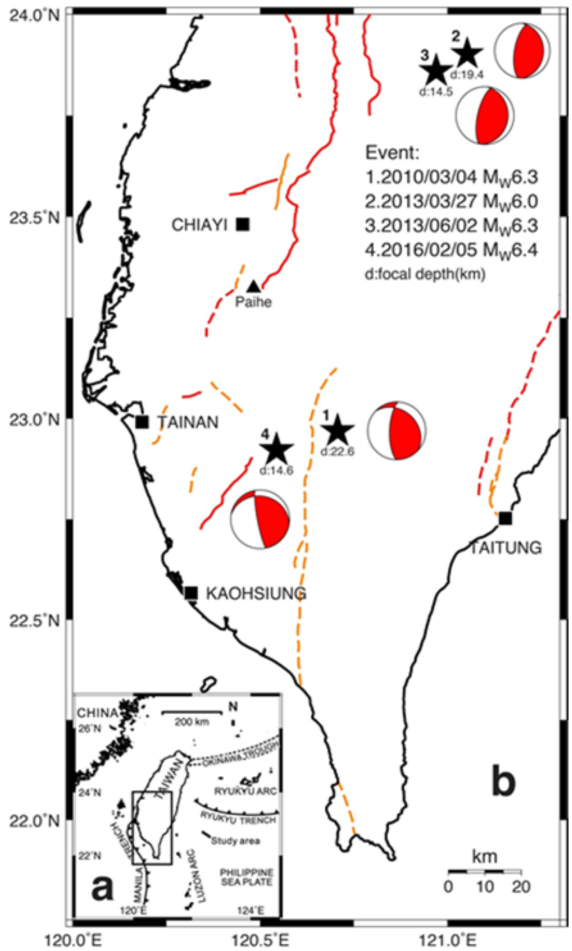

Figure 3: Map of the epicenters of the large earthquakes that occurred near Paihe from 2010 to 2018. (a) map of Taiwan. (b) study area near Paihe (filled stars: mainshocks, filled triangle: Paihe spring P1).

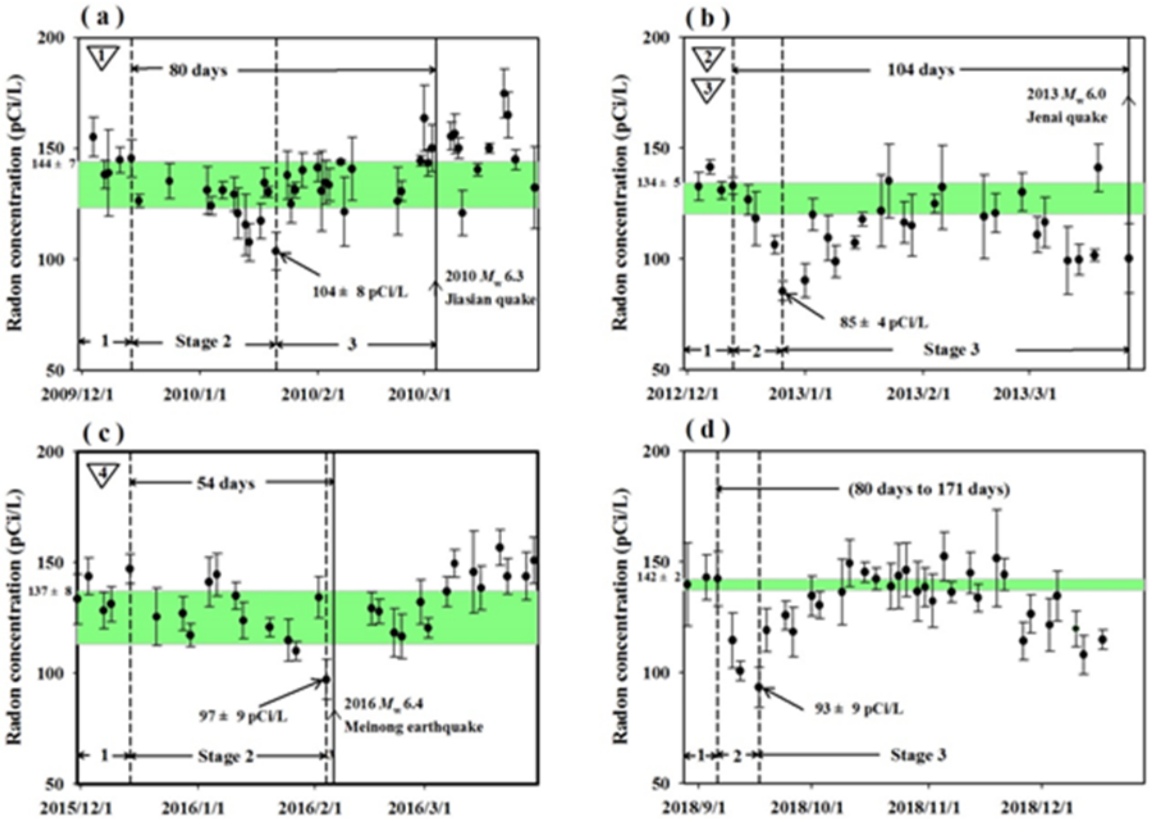

Figure 4: Radon concentration data at Paihe spring P1 prior to (a) 2010 Jiasian, (b) 2013 Jenai and Fishpond, (c) 2016 Meinong earthquakes, and (d) 2018 radon anomaly. Green rectangles show radon concentration between the mean radon concentration and three standard deviations below the mean. Stage 1 is buildup of elastic strain. Stage 2 is development of cracks. Stage 3 is influx of groundwater. Numbers in inverted triangles correspond to earthquake event in Fig. 3.

Earthquake	Magnitude (M_w)	Radon background (pCi/L)	Radon minimum (pCi/L)	Percent of decline (%)	Precursory time (day)	Epicenter distance (km)
2010 Jiasian	6.3	144	104	28	80	46
2013 Jenai	6.0	134	85	37	104	87
2013 Fishpond	6.3	134	85	37	171	78
2016 Meinong	6.4	137	97	29	54	45

Table 2: Important parameters from the radon anomalous declines recorded at Paihe precursory to four large thrust-type earthquakes in southern Taiwan between 2010 and 2018.

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