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Original Article

Result of alpha track detection of radon in soil gas in the Khlong Marui Fault Zone, Southern Thailand: A possible earthquake precursor

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Abstract

Measurements of radon concentration in soil gas were conducted at ten stations (ST1-ST10), located mainly in the Khlong Marui Fault Zone, Thap Put District, Phang Nga Province over a period from 28 January to 25 April, 2007. The results of the radon concentration were presented as the variation of cumulative alpha track over a week period. At Station ST10 the radon concentrations are in general higher than those at other stations for every week. Two significant radon anomalies were found to have the concentration above the mean value plus one standard deviation. During the period of monitoring the local and regional earthquake activities were observed showing patterns consistent with the occurrence of the radon anomalies. The maximum radon concentration is interpreted to be related to a possible influence of the pressure and stress increased in the subsurface. An increase in the number of earthquakes is observed correlating to a lower radon concentration when the subsurface pressure dropped due to tectonic stress release by seismic activities. Therefore, it would be possible to use the variation of soil gas radon concentration as an earthquake precursor in the Khlong Marui Fault Zone.

Keywords: radon in soil gas, alpha track, earthquake precursor, Khlong Marui Fault Zone

1. Introduction

The Mw 9.3 Sumatra-Andaman Earthquake occurred off the West coast of Northern Sumatra, Indonesia at 3.316ºN and 95.854ºE on 26 December 2004 at 00:58:53 UTC. The earthquake triggered a series of devastating tsunamis that spread throughout the Indian Ocean, killing people and inundating coastal communities across South and Southeast Asia, including parts of Indonesia, Sri Lanka, India, and Thailand (USGS, 2005). The crustal movements related to the 26 December 2004 Earthquake resulted in an increased number of reported sinkholes in Southern Thailand (DMR, 2005; Duerrast *et al*., 2007). However, no data or evidence before suggested the occurrence of this giant earthquake.

Radon is a natural alpha-emitting radioactive gas produced from radium found in groundwater, rocks, and soils. Concentrations of some terrestrial gases in soil have been found to be anomalously high along active faults, suggesting that the faults may be pathway of least resistance for the outgassing processes of the earth. Radon in the subsurface is often studied for the investigation of specific mineral deposits but also increasingly as a possible precursor phenomenon for earthquakes. Changes of radon concentrations in soil may have been found as a possible precursors of large tectonic earthquakes (e.g. Ulomov and Mavashev, 1967; Chyi *et al*., 2001). Earthquakes by nature are associated

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with the deformation of the crust as the release of accumulated stress. These stress changes, which are related to crustal or plate movements, might be translated into changes of the radon emission coming from the subsurface, which then might be interpreted as complex short- or long-term precursory phenomena of an forthcoming earthquake (Planinic *et al*., 2004). Radon also has been used both to locate buried faults and to monitor faults in the anticipation of predicting any future earthquake activities. Several authors reported anomalously high radon concentrations along many active faults that are registered a few weeks or months before many earthquakes (e.g. Tanner, 1980; King *et al*., 1996; Planinic *et al*., 2004). However, no radon in soil gas has been studied along the important Ranong (RFZ) and Klong Marui Fault Zones (KMFZ) in Southern Thailand before the 26 December 2004 earthquake.

2. Materials and Methods

2.1 Radon measurements

The measurements of the radon concentrations in soil gas were conducted at ten stations, mainly in Thap Put District, Phang Nga Province, all distributed along the Khlong Marui Fault Zone (Figure 1). The soil gas radon detection system in this study used a solid-state nuclear track detector (SSNTD; CR-39) registering the cumulative alpha track over several weeks. The principle of the SSNTDs is based on the alpha particles emitted from radon gas collided the surface of the detector materials and produced the tracks. The CR-39, 2x2 cm detector was placed inside a vertical cylindrical tube of 2 inch (5 cm) diameter, and 1.2 m length that was put in a dug hole of 1 m depth into the ground. The detectors are placed on the top of the tube and sealed airtight against the outside air and moisture from the ground (Figure 2). The CR-39 detector was exposed to the soil gas radon for a week in undisturbed conditions. On completion of the exposure time the former detector was collected for further processing and a new detector was placed in the same manner. The CR-39 detectors at the ten monitoring sites were changed every week over a period of several weeks.

After exposing to radon, the detector was chemically etched to enlarge the latent tracks in 6.25 N NaOH solutions for 100 min. at 85°C. The alpha tracks in the detector were counted under an optical microscope (OLYMPUS-BHC) at 100x magnification. The track densities were counted ran-

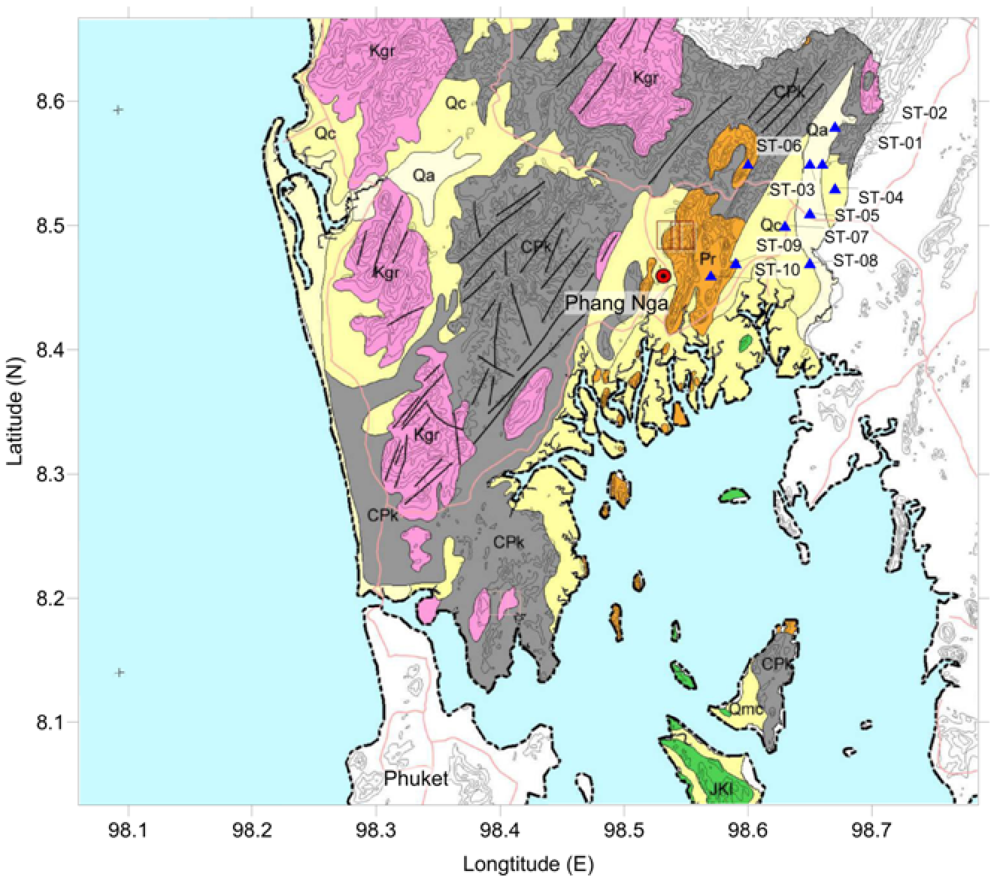

Figure 1. Radon measuring stations in relation to the geology of Phang Nga Province. KGr=Cretaceous granite; CPk=Permo-Carboniferous mudstone; Pr=Permian limestone; Qa, Qc, Qmc=Quaternary unconsolidated sediments. Geological map redraw from DMR (2007).

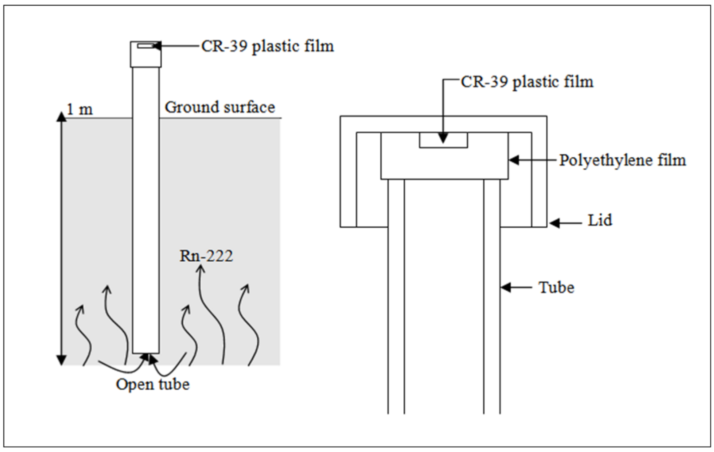

Figure 2. Schematic sketch showing the soil gas radon detection system.

domly over the CR-39 detector surface and then using statistical analysis of the data for the determination of the average track density for each CR-39 detector.

2.2 Standard calibration

The calibration procedure aims at finding the relationship between the alpha track density on the SSNTD detector after etching and the standard radon concentration of known activity. In this study, the track detector has been calibrated using a known activity of radium solution. The detector geometry and environment was constantly controlled throughout the calibration procedure. The standard radon concentrations of 564 and 1,700 Bq/m^3 are calibrated with the track density counted as a function of exposure time. The calibration equation obtained in this study is as following:

$$\text{Rn Conc. (Bq/m}^3\text{)} = \frac{106.524 \times \text{Corr.TD (T/cm}^2\text{)}}{\text{Exposure Time (day)}} \quad (1)$$

where *Rn Conc.* is the concentration of radon in soil gas (Bq/m^3), *Corr.TD* is the corrected alpha track density by subtraction of the average background track density (track/cm^2), *Exposure Time* is in the unit of day for radon exposure to the SSNTDs detector, and the value 106.524 is the calibration constant for the detection system used here.

2.3 Earthquake measurements

The earthquake monitoring site was carefully selected in the Khlong Marui Fault Zone at 8°33' N and 98°39' E, in Thap Put District, about 20 km ESE from the Phang Nga city. The seismic recording system consists of Mark L-4-3D seismometers with a 1 Hz natural frequency, and containing three geophones in three perpendicular directions, N-S, E-W, and Z components. The seismometer was connected via a data cable to the Orion datalogger, manufactured by Nanometrics, Canada. Inside the Orion is a data cartridge with a recording hard disk of 1.99 GB memory space. Therefore, during this study the data on the Orion data cartridges had to be transferred via an SCSI-cable to a computer every two weeks.

From 14 January to 21 April 2007, the short period seismic station in Thap Put could detect 135 local earthquakes, with a local magnitude (Ml) ranged from -1.6 to 3.1. Additionally, 33 man-made events were determined, probably from blasting in rock quarries nearby (see Dangmuan, 2008), and several further distance (mainly regional) earthquakes. After the data processing the analysis and interpretation of the seismic events was done with Seisan software (Havskov and Ottemöller, 2005) using all three components. After the phase identification, the time between the S- and P-wave arrival was determined (delta time). With this information and the travel-time tables given by Jeffreys and Bullen (1967) the distance of the earthquake from the seismic station could be determined. The distance was used as the criteria for the separation of the regional (> 500 km) and local (< 500 km) events. For the local earthquakes the local magnitude (Ml, or Richter scale) was determined according to Hutton and Boore (1987). The final location of each earthquake was determined from the distance to the seismic station and the back azimuth, based on the first P-wave arrival in all three components. The available data and the interpretation procedure do not allow determining the earthquake depth. As the depth of the local earthquakes can be assumed very shallow the depth was set at zero kilometers. Figure 3 shows the distribution of the local earthquakes determined from this study in relation to their magnitude.

For the correlation between radon concentration in soil gas and earthquake activities the complete data set of the regional earthquakes were taken from the United States Geologial Survey (USGS) database (USGS, 2008). In the period between 14 January 2007 and 4 May 2007 altogether 198 regional earthquakes occurred in the area between 3º S to 12º N and 90º E to 105º E (Figure 4). These earthquakes are either related to the Sunda Subduction Zone (SSZ) or the adjacent fracture zones in the Indian Ocean.

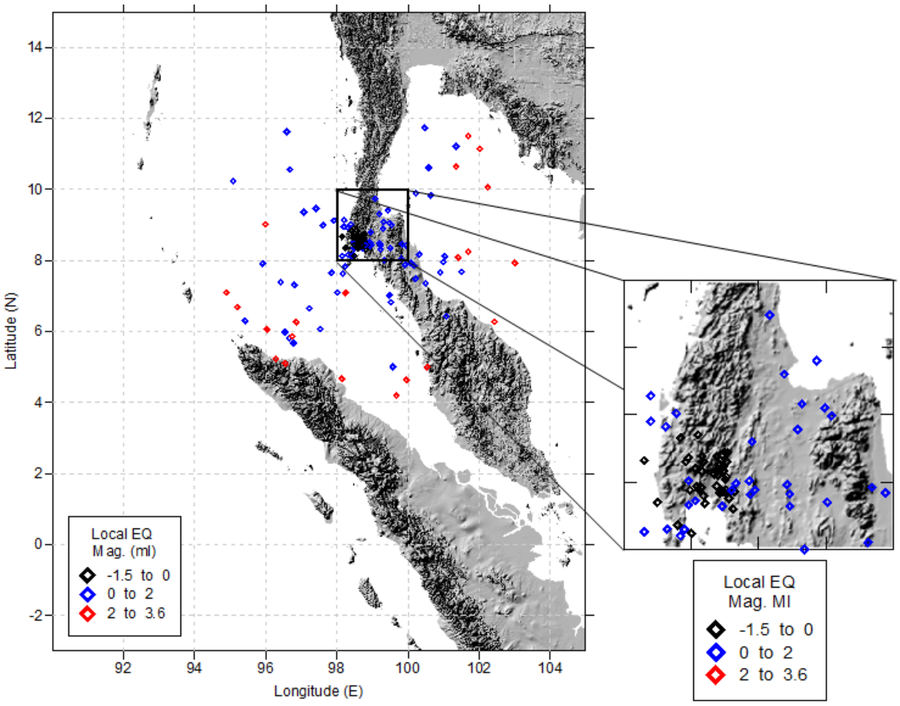

Figure 3. Locations of the local earthquakes in Southern Thailand in relation to their magnitudes, based on data from this study that was recorded from 14 January to 21 April 2007.

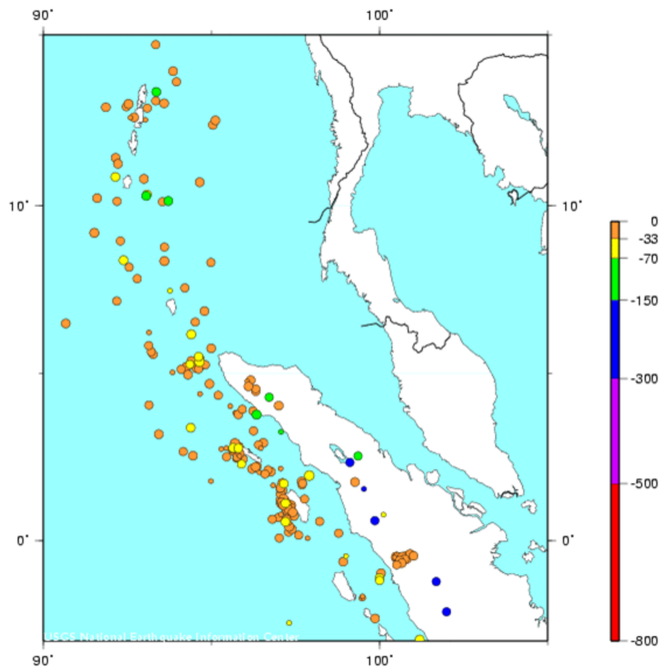

Figure 4. Locations of regional earthquakes in relation to their depth from 14 January to 4 May 2007, based on data from USGS (2008).

3. Results and Discussion

The meteorological parameters P (barometric pressure) and T (temperature) provided by the Thai Meteorological Department (TMD), were used for investigating their effect on the temporal radon variations by statistical tests. In this test the soil gas radon were measured using an automatic Radon Progeny Monitor (UGF, RPM-256, Czech Republic) in a period from February 12 to 29 April 2007. The result was shown in Figure 5a.

Analysis of the meteorological parameters of air pressure and temperature indicated a general trend showing an inverse proportionality between soil-gas radon and air pressure (Figure 5c), while a linear relation was observed for soil-gas radon and air temperature (Figure 5b). However, very small linear correlation coefficients (R^2=0.13 and 0.07) were obtained between radon and air pressure and temperature, respectively. This indicates an insignificant influence of the meteorological factors on the measured soil-gas radon data. This is likely because the soil gas was taken at 1 m depth as suggested by Wattananikorn *et al* (1998).

The measurements of radon concentration in soil gas were conducted at 10 fixed stations in Thap Put District, Phang Nga Province as shown in Figure 1. The cumulative radon track density over a week period was then calculated in a weekly average radon concentration in Bq/m^3 using Equation 1. The radon emission data cover three months in the period from 28 January to 25 April 2007, altogether 12 weeks for all 10 stations. To identify radon anomalies the data from each station were compared to each other over the period of measurement. The data in Table 1 show that for all ten stations the seven stations out of the ten stations have the average radon concentrations ranged 221-362 kBq/m^3. The rest three radon stations ST-10, ST-02, and ST-04 have an average radon concentration values higher at 2,241, 627, and 602 kBq/m^3, respectively (Figure 6). At Station ST-10, the radon concentration is in general higher than those at all other locations for every week (Figure 6). This probably indicates a high permeability to groundwater and soil gas in the ground below the Station ST-10 when comparing with those of the ground below other stations. Higher ground permeability resulted in a higher radon concentration measured at Station ST-10 is considered the most important factor explaining the connection between fluid flow in the fault zones and in the ground below this station. The high ground permeability at ST-10 is probably due to the underground cavities in the Permian limestone karst topography in this area (see Figure 1). Radon measurements along a road crossing outcrops of the Permian limestone also indicate a higher radon concentration comparing with those measured over others geologic formations (Pisapak, 2009).

Figure 7 shows the radon concentrations in soil gas at Station ST-10 in correlation with the occurrence and magnitude of local and regional earthquakes for the same period of time, as well as before and after. The average radon concentrations in the week 1, 2, 3, 4, 5, 6, and 9 are less than the mean value. Radon peaks indicating a radon anomaly that is observed when the radon values start to increase by 0.5s from the mean value in week 7 from 11 to 18 March 2007 with 3,251 kBq/m^3. The maximum radon concentration is observed in week 8 from 18 March to 25 March 2007 with 3,728 kBq/m^3.

Thereafter, an increase in the number of seismic events is observed correlating to a reduction (lower peak) in the radon concentration in Week 9, with 1,675 kBq/m^3. The

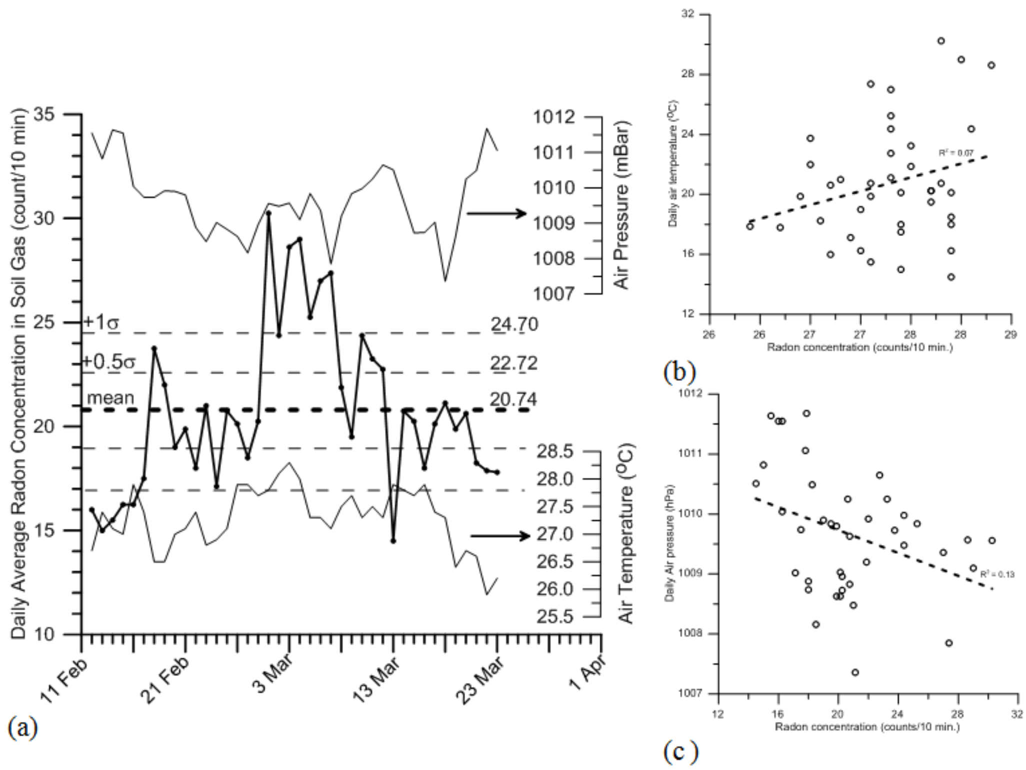

Figure 5. Radon concentration in soil gas at 1 m depth (a) with mean and standard deviations, in correlation with the meteorological parameters (b) daily air pressure (hPa) and (c) daily air temperature (°C) for the period between 7 February and 29 February 2007.

Table 1. Cumulative one week radon concentrations (kBq/m^3) at the ten monitoring stations in Phang Nga Province over a 12-week period from 28 January to 25 April 2007.

Time (week)	Radon concentration (kBq/m^3)									
	ST-01	ST-02	ST-03	ST-04	ST-05	ST-06	ST-07	ST-08	ST-09	ST-10
1	256	677	184	288	280	276	271	312	319	723
2	173	117	222	471	431	406	383	224	332	1903
3	235	302	226	399	235	205	306	275	152	1716
4	169	504	248	-	325	324	223	256	240	1466
5	289	1177	530	-	329	361	-	332	321	2179
6	213	481	277	450	226	272	-	269	275	1619
7	101	678	269	299	162	324	302	277	133	3251
8	268	610	328	631	61	392	260	346	258	3728
9	329	725	350	892	146	586	153	500	323	1675
10	432	780	416	870	134	505	264	504	236	2782
11	339	760	379	746	100	330	287	509	287	3615
12	231	713	339	969	95	358	167	483	172	-
Mean ±σ	253 ±88	627 ±264	314 ±97	602 ±255	211 ±113	362 ±103	262 ±68	357 ±110	254 ±70	2241 ±971

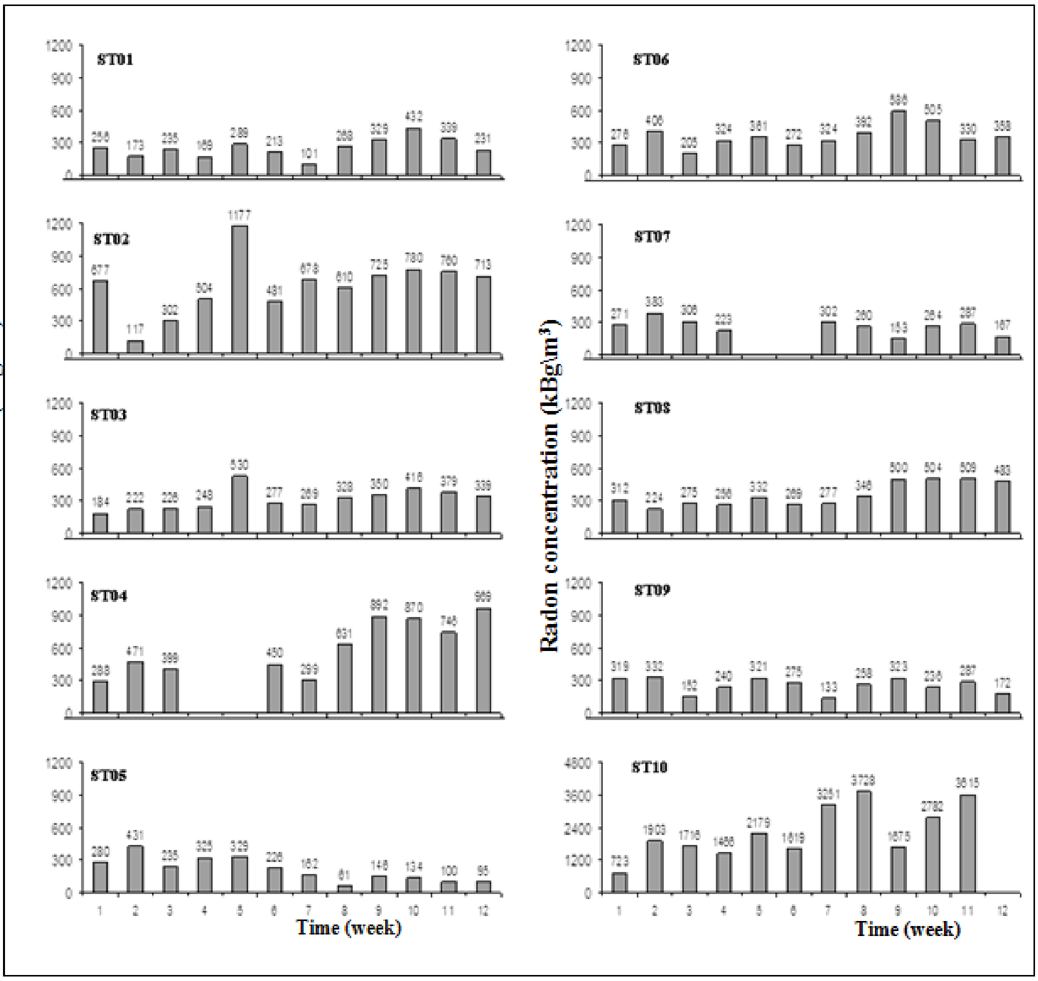

Figure 6. Cumulative one-week alpha track radon concentrations (kBq/m^3) for the ten stations in Phang Nga Province over a 12-week period from 28 January to 25 April 2007.

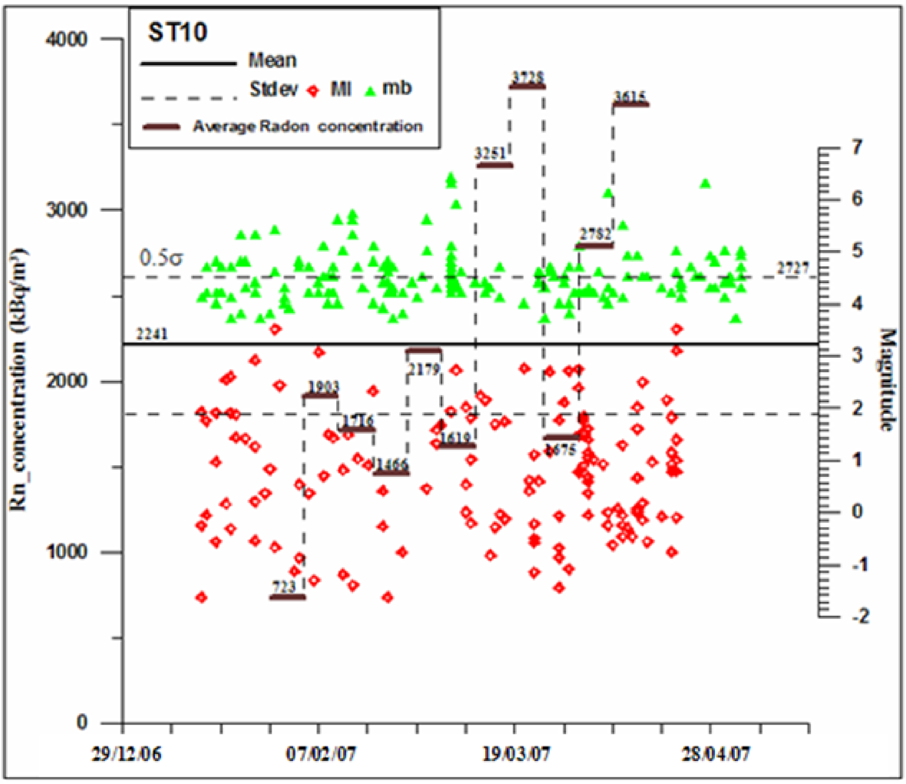

Figure 7. Average radon concentration in soil gas (kBq/m^3) at station ST-10 between 28 January and 25 April 2007 in one-week intervals (equal one bar) with mean and standard deviations. Diamond symbols show local earthquakes by occurrence time in UTC and magnitude (Ml); triangle symbols show regional earthquakes by occurrence time in UTC and magnitude (mb) (from USGS, 2008).

numbers of local earthquakes occurred in this period are 14 events with a local magnitude (Ml) ranging from -1.4 to 2.8 and 16 regional earthquakes occurred with a body-wave magnitude (mb) from 3.8 to 5.1. Further, in Week 10 from 1 to 8 April 2007, 19 local events with Ml ranging from -0.6 to 1.8 and 12 regional events with mb 4.0 to 6.1 occurred. That might be an effect from the highest radon anomaly in Week 8. Finally, in Week 11 from 8 to 15 April 2007 the radon anomaly increased again, with 16 local events with Ml ranging from -0.5 to 2.5 occurred in the same time interval, as well as 11 regional events with mb from 4.1 to 5.5.

An initial interpretation is that an increase in the radon concentration in soil gas is probably related to an increased tectonic compression as the result of the interaction between the Indian-Australian Plate and Eurasian Plate along the Sunda-Subduction Zone. This plate interaction increases the stress in the ground and the fluids pressure in the subsurface open pores and fractures. The underground fluid pressure certainly increases agitation in the fluids and results in an increase in radon emanation at the monitoring station. Releases of energy by earthquakes result in a lower tectonic stress and pressure and subsequently in a reduction of the radon concentration measured at the site. The interpretation is supported by an increase in the number of earthquakes in Week 6, 9-10, whereas the lower radon concentrations are observed as discussed before.

4. Conclusions and Suggestions

The identification of clear earthquake-related signals related to radon anomalies and the use of radon anomalies as earthquake precursors has been difficult because there are many influences from other factors (e.g. geology, meteorology, ground permeability) upon the emission of radon from the ground. As the influences of the tectonic activity on the permeability of aquifers or crack patterns linked to the fluids in the fault zone are difficult to estimate so it is difficult to find significances in the temporal variations of radon related to earthquake activities.

However, this study shows a promising precursor relationship between the radon in soil gas anomalies and the later earthquake occurrence (Figure 7). The average radon concentration in the time period of week 1, 2, 3, 4, 5, 6, and 9 is less than the mean value (2,241 kBq/m^3) with one standard deviations (971 kBq/m^3). Further, the ST10 station has the highest radon anomaly in Week 8 from 18 March to 25 March 2007 with 3,728 kBq/m^3. The maximum radon value increase can be related to a possible influence of the pressure and stress increases in the subsurface. After that, an increase in the number of seismic events can be observed correlating to a lower peak in the radon data in week 9 about 1 to 2 interval time period (week) later, with 1,675 kBq/m^3. Therefore, radon data can be a sensitive tracer for stress changes in the earth's crust. This stress, in turn, leads to a release of energy in the form of seismic waves, which manifest on the surface and associated with the earthquake occurrences. In the future, it would be preferable to have a continuous radon monitoring in the fault zones in Southern Thailand, like that one at the Thap Put Station, as it is a possible additional method for seismic hazard mitigation.

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